

Article

Baseline Response Characterization and Relative Vertical Displacement Reconstruction of Multi-Layer Asphalt Pavements Based on Quasi-Distributed FBG Monitoring Information

Jing-Cheng Zhou ¹ , Jia Rui ², Xiao-Wei Feng ³, Ke-Wei Xiao-Yan ¹ , Jin-Kui Zhang ¹, Hua-Ping Wang ^{1,*} 
and Ping Xiang ^{4,*} 

- ¹ School of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China; zhoujc0813@163.com (J.-C.Z.); xiaoykw2023@lzu.edu.cn (K.-W.X.-Y.); 17752103217@163.com (J.-K.Z.)
² Gansu Institute of Urban and Rural Planning and Design Institute Co., Ltd., Lanzhou 730070, China; richard800910@163.com
³ Gansu Provincial Transportation Science Research Institute Group Co., Ltd., Lanzhou 730030, China; 15309860930@163.com
⁴ School of Civil Engineering, Central South University, Changsha 410075, China
* Correspondence: wanghuaping1128@sina.cn or hpwang@lzu.edu.cn (H.-P.W.); pxiang2-c@my.cityu.edu.hk (P.X.)

Abstract

Internal responses of multilayer pavement structures are difficult to characterize using surface-based inspection alone. This study investigates a scaled multilayer pavement model instrumented with embedded quasi-distributed fiber Bragg grating (FBG) sensing lines to obtain baseline internal strain responses and FBG-derived relative vertical displacement distributions under controlled loading. Central single-point stepwise loading, symmetric two-point loading, and asymmetric two-point loading were applied, and FBG wavelength responses were converted into temperature-compensated strain and then into line-wise relative vertical displacement through strain–curvature conversion, curvature integration, and linear baseline correction. During loading, the ambient temperature ranged from 22.70 to 23.40 °C, and the maximum relative shift of the T-sensor was 0.008297 nm. Under 686 N central loading, SAL1 reached a maximum temperature-compensated strain of 1459.39 $\mu\epsilon$ and a maximum relative vertical displacement of 1.079 mm, whereas SAL2 reached 793.13 $\mu\epsilon$ and 0.583 mm. Under approximately 490 N asymmetric two-point loading, SAT2 reached 1699.48 $\mu\epsilon$ and 0.761 mm. Soil-base responses were substantially lower. Because no independent displacement measurement was acquired, the reconstructed quantity is interpreted as an FBG-derived relative deformation measure rather than an absolute displacement. The results establish intact baseline data for future, separately validated comparisons with abnormal conditions.

Keywords: structural health monitoring; quasi-distributed FBG sensing; multilayer pavement; temperature-compensated strain; relative vertical displacement reconstruction; eccentric loading response; baseline response



Academic Editor: Vasilis K. Oikonomou

Received: 7 July 2026

Revised: 21 July 2026

Accepted: 28 July 2026

Published: 5 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Multilayer pavements transfer traffic loads through materials with markedly different stiffness, deformation capacity, and interlayer conditions. The resulting load diffusion, attenuation, and spatial redistribution are layer- and direction-dependent and cannot be inferred reliably from surface distress alone. Cracking, rutting, and potholes are visible

manifestations of deterioration, whereas internal strain concentration, support changes, and deformation-pattern shifts may develop earlier. Pavement structural health monitoring therefore requires internal response information that distinguishes structural layer, sensing direction, load level, and loading path [1,2]. Ground-penetrating radar and other nondestructive methods can identify layer geometry and localized anomalies [3,4] but generally provide periodic inspection rather than continuous measurements of load-induced response. Embedded sensing can complement them by supplying time-continuous measurements at structurally relevant depths [5]. The engineering need is thus not only to detect large responses but also to determine where they occur, how they propagate through depth, and whether their spatial pattern is consistent with an intact structure.

Fiber Bragg grating (FBG) sensors are attractive for this purpose because their wavelength-encoded response is resistant to electromagnetic interference, their small dimensions facilitate embedment, and multiple gratings can be multiplexed along one fiber [6–9]. Representative pavement applications have progressed from feasibility studies to purpose-designed monitoring systems. Embedded optical fibers have measured strain and deformation in asphalt structures [10], three-dimensional FBG assemblies have been developed for highway pavements [11], and FBG systems have supported compaction-quality control and weigh-in-motion measurements [12,13]. Embedded gratings have also recorded vehicle-induced pavement responses [14]. More recent studies have broadened the measured quantities and test scales through in-situ multi-response monitoring [15], accelerated pavement testing combined with falling-weight-deflectometer measurements [16], distributed strain profiling under static vehicle loading [17], and cold-region monitoring of temperature, pressure, and deformation [18]. Collectively, these studies confirm that optical sensors can survive pavement embedment and respond to traffic and environmental actions. The key challenge is now to convert spatially non-uniform measurements into defensible comparisons of internal structural response.

That conversion depends strongly on monitoring architecture. Point sensors provide locally identifiable responses, but sparse layouts may miss narrow response zones or confound load-path migration with sensor offset. Quasi-distributed FBG lines retain discrete, wavelength-addressable sensing points while enabling longitudinal or transverse response profiles; however, their spatial resolution is bounded by grating spacing, and interpolation remains model-dependent [9–11,14]. Fully distributed sensing provides denser strain information and is well suited to locating spatial gradients [17] but differs in gauge length, interrogation principle, installation requirements, and data processing. These architectures are therefore complementary rather than interchangeable. For multilayer pavements, quasi-distributed lines offer a practical balance between identifiable sensing locations and profile-level comparison, provided that conclusions remain tied to the monitored lines rather than implying unmeasured full-field behavior. This distinction is especially important when discrete line measurements are converted into a continuous deformation representation.

Measurement architecture alone does not determine the fidelity of an embedded response. Strain transfer from pavement material to grating is governed by packaging, adhesive and coating layers, interface bonding, and deformation compatibility. Low-modulus sensing cables, industrialized assemblies, and flexible encapsulation have been developed to improve compatibility and field durability [19–21]. Analytical and experimental studies show that encapsulation stiffness, adhesive thickness, interfacial degradation, non-uniform host strain, and temperature can alter strain-transfer efficiency and recorded amplitude [22–25]. Because Bragg wavelength shifts contain both mechanical and thermal components, compensation removes only an estimated thermal contribution; imperfect temperature matching, residual thermal mismatch, and spatially varying transfer conditions may remain. Measured amplitudes and negative compensated increments must therefore

be interpreted with reference to the baseline wavelength, compensation procedure, and packaging configuration. Cross-study amplitude comparisons are meaningful only under sufficiently comparable sensor, embedment, temperature, and loading conditions.

A further interpretive step is required when strain is used to infer curvature and deformation. Pavement studies have reported embedded strain and deformation [10] and detailed strain distributions [17], while broader structural-health-monitoring research recognizes optical fibers as a basis for deformation assessment [26–29]. However, a strain profile is not a displacement field. Strain-to-curvature conversion requires assumed section kinematics, a neutral-axis location, and the sensor-to-neutral-axis distance; interpolation between gratings and double integration then introduce additional model dependence and low-frequency bias. In multilayer pavements, stiffness contrast, interlayer slip, viscoelasticity, variable strain transfer, and uncertain boundary conditions make these assumptions especially restrictive. Endpoint correction can define a repeatable relative reference shape but removes rigid translation and overall inclination and therefore cannot recover absolute settlement. Deformation reconstruction can thus provide mechanically interpretable line-wise information beyond isolated strain peaks only when its assumptions, reference dependence, and validation status are explicit.

These limitations make an intact-state baseline indispensable. Environmental and operational variability can produce response changes comparable to those associated with structural deterioration, so monitoring data should be interpreted relative to normal response patterns rather than a universal strain threshold [30–32]. For multilayer pavements, the baseline should include load magnitude, loading position, structural layer, line orientation, and sensor-to-load distance. Central stepwise loading tests whether response magnitude and reconstructed deformation change consistently with load. Symmetric two-point loading provides a balanced transverse reference, whereas asymmetric two-point loading examines whether the layout can resolve an ordinary loading-path shift without misclassifying redistribution as damage. Their comparison therefore identifies spatial changes that may occur in an intact structure when load symmetry is lost. Such a reference is essential for future anomaly studies, because a displaced high-response zone could otherwise be attributed incorrectly to a void, crack, or support change rather than eccentric loading or sensing-line offset. It also provides future abnormal-condition tests with a physically matched control.

Against this background, three connected research gaps remain. First, pavement FBG studies have seldom provided matched measurements from upper and lower structural layers while simultaneously comparing longitudinal and transverse quasi-distributed lines under the same controlled loading programme. This limits interpretation of through-depth attenuation, directional dependence, and spatial redistribution. Second, discrete FBG measurements are commonly reported as wavelength shifts, local strains, or peak responses; fewer studies integrate temperature compensation, equivalent-section strain–curvature mapping, interpolation, double integration, and reference correction into a line-wise relative-deformation framework while retaining the assumptions of that transformation. Third, intact-condition datasets often emphasize one loading position or response metric and therefore do not separate load-level amplification from response migration caused by symmetric-to-asymmetric loading. These gaps are interdependent: without an adequate layer–direction layout, reconstruction lacks spatial context; without a controlled intact baseline, a reconstructed change cannot be assigned confidently to loading path, structural condition, or measurement configuration.

This study addresses these gaps using a scaled multilayer pavement instrumented with longitudinal and transverse quasi-distributed FBG lines in the asphalt surface and soil base. Central single-point stepwise loading, symmetric two-point loading, and asym-

metric two-point loading generated controlled changes in load magnitude and path. The study integrates three contributions within a single processing and interpretation chain: (1) synchronized comparison of temperature-compensated strain across structural layer, line direction, and distance from the load; (2) conversion of discrete line strains into FBG-derived relative vertical deformation through equivalent-section strain–curvature mapping, interpolation, double integration, and endpoint baseline correction, with explicit assessment of assumptions and modulus sensitivity; and (3) construction of an intact reference set that distinguishes load amplification, through-depth attenuation, and transverse response migration. The contribution lies in the coordinated use of sensing layout, controlled loading, multilayer comparison, and mechanics-based line reconstruction rather than in any operation considered separately.

The conclusions are deliberately bounded by the experiment. The reconstructed quantity is an FBG-derived, line-wise relative deformation referenced by endpoint correction, not an independently validated absolute pavement displacement, because no simultaneous LVDT or digital image correlation measurement was acquired. The scaled model does not reproduce complete full-scale similitude, so its absolute strain and deformation amplitudes should not be extrapolated directly to field pavements. No void, base-weakening, or crack case was tested. The study therefore establishes an intact-condition baseline and a reconstruction framework for future, separately validated comparisons with abnormal states; it does not claim demonstrated defect identification or field-scale settlement prediction.

2. Experimental Design and Data Acquisition

2.1. Scaled Multilayer Pavement Model

A scaled multilayer pavement model was constructed under controlled laboratory conditions. The model had plan dimensions of 1.2 m × 0.5 m and a total thickness of 0.30 m. From bottom to top, the structure consisted of a soil base layer, a gravel base layer, and an asphalt concrete surface layer, with thicknesses of 0.18 m, 0.04 m, and 0.08 m, respectively. Steel plates were installed along the outer sides of the model to restrain lateral deformation during loading and to reduce boundary disturbances in the analysis of internal responses.

The scaled model was designed to serve as a representative layered pavement structure for controlled FBG sensing tests. By embedding quasi-distributed FBG sensing lines in different structural layers, the internal response differences between the upper asphalt concrete surface layer and the lower soil base layer under static loading could be compared. The combined use of longitudinal and transverse sensing lines also enabled the spatial distribution of load transfer and diffusion to be evaluated in different directions.

According to the layer thicknesses, the centroidal elevations of the soil base layer, gravel base layer, and asphalt concrete surface layer from the model bottom were 0.09 m, 0.20 m, and 0.26 m, respectively. These geometric parameters were used for equivalent neutral axis calculation and strain–curvature conversion. The geometric parameters of the scaled multilayer pavement model are listed in Table 1, and the model structure and FBG-sensing-line layout are shown in Figure 1.

Table 1. Geometric parameters of the multilayer pavement model (dimensions in centimetres).

Structural Layer	Thickness /cm	Centroidal Elevation from Model Bottom/cm	Description
Soil base layer	18	9	Lower supporting layer
Gravel base layer	4	20	Intermediate load-transfer layer
Asphalt concrete surface layer	8	26	Upper load-bearing layer
Total thickness	30	—	Model plan dimensions: 120 cm × 50 cm

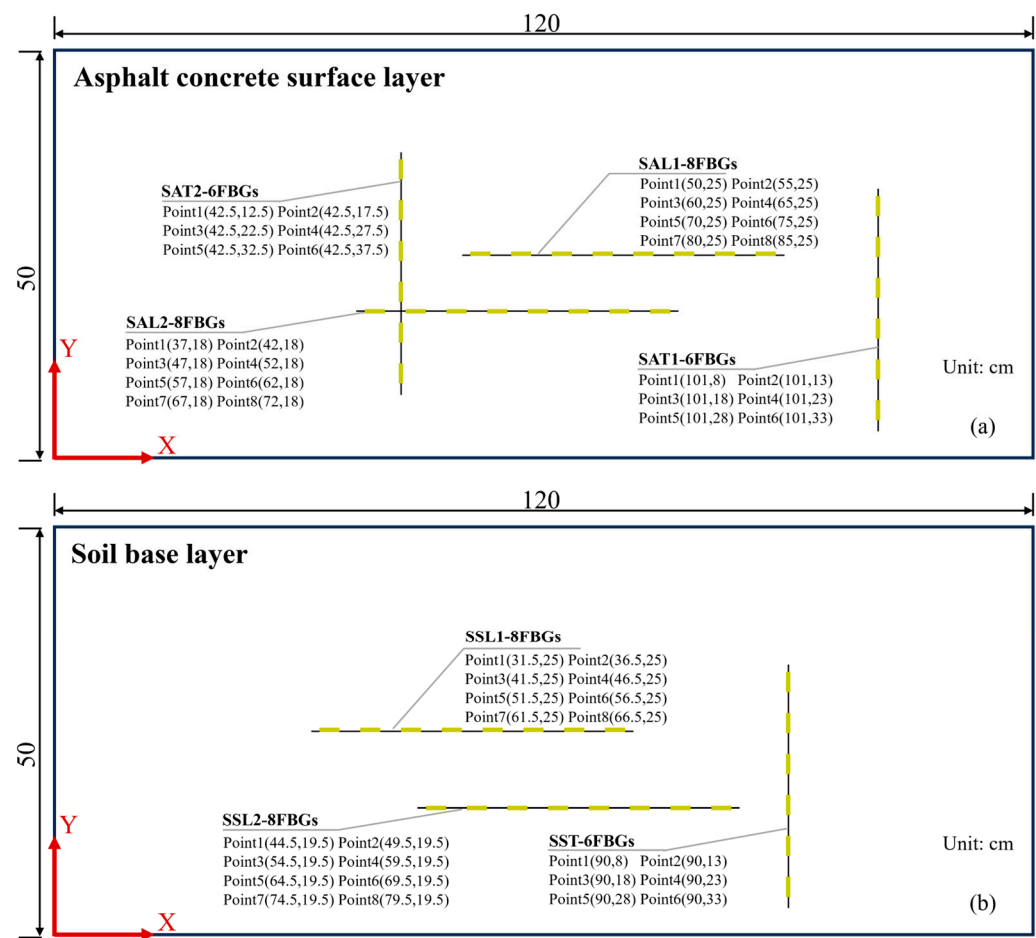


Figure 1. Layout of FBG sensing lines: (a) asphalt concrete surface layer; (b) soil base layer. The yellow segments indicate the locations of the FBG sensing points.

2.2. Layout of Quasi-Distributed FBG Sensing Lines

To obtain internal responses in different structural layers and along different directions, quasi-distributed FBG sensing lines were embedded in both the asphalt concrete surface layer and the soil base layer. In the asphalt concrete surface layer, two longitudinal sensing lines, SAL1 and SAL2, were installed, each containing eight FBG sensing points. Two transverse sensing lines, SAT1 and SAT2, were also installed in the asphalt concrete surface layer, each containing six FBG sensing points. In the soil base layer, two longitudinal sensing lines, SSL1 and SSL2, were installed, each containing eight FBG sensing points. In addition, one transverse sensing line, SST, was installed in the soil base layer, containing six FBG sensing points. The spacing between adjacent FBG sensing points was 0.05 m, and the total number of FBG sensing points was 50.

Based on the embedding elevations, the FBG sensing points in the asphalt concrete surface layer were located approximately 0.26 m above the model bottom, whereas those in the soil base layer were located approximately 0.13 m above the model bottom. The sensing points in the asphalt concrete surface layer were close to the centroidal elevation of the asphalt concrete surface layer, while the sensing points in the soil base layer were embedded within the lower supporting layer. This layout allowed synchronous responses of the upper load-bearing layer and lower soil base layer to be obtained within the same model, providing a basis for analyzing layer-dependent differences.

Figure 1 shows the plan layout of the FBG sensing lines in the asphalt concrete surface layer and soil base layer. In the asphalt concrete surface layer, SAL1 was located at $y = 25$ cm, with sensing-point coordinates from (50 cm, 25 cm) to (85 cm, 25 cm), while SAL2 was

located at $y = 18$ cm, with sensing-point coordinates from (37 cm, 18 cm) to (72 cm, 18 cm). SAT1 was a transverse sensing line located at $x = 101$ cm, with sensing-point coordinates from (101 cm, 8 cm) to (101 cm, 33 cm), and SAT2 was located at $x = 42.5$ cm, with sensing-point coordinates from (42.5 cm, 12.5 cm) to (42.5 cm, 37.5 cm). In the soil base layer, SSL1 was located at $y = 25$ cm, with sensing-point coordinates from (31.5 cm, 25 cm) to (66.5 cm, 25 cm), while SSL2 was located at $y = 19.5$ cm, with sensing-point coordinates from (44.5 cm, 19.5 cm) to (79.5 cm, 19.5 cm). SST was a transverse sensing line in the soil base layer located at $x = 90$ cm, with sensing-point coordinates from (90 cm, 8 cm) to (90 cm, 33 cm). The complete sensing-line layout information is summarized in Table 2.

Table 2. Layout information of FBG sensing lines.

Sensing Line	Structural Layer	Direction	Number of Sensing Points	Spacing/cm	Sensing-Point Elevation/cm
SAL1	Asphalt concrete surface layer	Longitudinal	8	5	26
SAL2	Asphalt concrete surface layer	Longitudinal	8	5	26
SAT1	Asphalt concrete surface layer	Transverse	6	5	26
SAT2	Asphalt concrete surface layer	Transverse	6	5	26
SSL1	Soil base layer	Longitudinal	8	5	13
SSL2	Soil base layer	Longitudinal	8	5	13
SST	Soil base layer	Transverse	6	5	13

The layout was defined a priori from the prescribed loading coordinates and the intended comparisons; no preliminary numerical simulation was used to optimize line locations. For central loading at (60 cm, 25 cm), SAL1 approximately intersected the loading line and SAL2 provided a transversely offset surface comparison. SSL1 and SSL2 served the analogous lower-layer comparison. For two-point loading, SAT2 was placed close to the asymmetric loading point at (40 cm, 15 cm), whereas SAT1 was farther from both asymmetric loading points, allowing local concentration and remote response to be contrasted.

Only one transverse line (SST) was installed in the soil base because its role was to provide a lower-layer reference for transverse attenuation and inter-case trends, not to localize the transverse load field. Two surface transverse lines were required to distinguish the strong location dependence expected near and away from the eccentric loading point. This intentionally unequal layout supports the stated comparisons but does not provide full-field coverage; the resulting line-specific limitation is retained in the interpretation.

The longitudinal sensing lines were used mainly to analyze the load-level effect under central single-point stepwise loading, whereas the transverse sensing lines were used mainly to examine transverse response redistribution induced by different loading configurations under the same total load level. Because the FBG sensing lines in different structural layers differed in plan location and embedding condition, the response of each sensing line was interpreted as a line-specific internal response. The comparison therefore focused on response amplitude, response range, and curve morphology.

2.3. Static Loading System and Loading Cases

The static loading system consisted of the scaled multilayer pavement model, loading weights, an FBG interrogator, a data acquisition computer, an ambient temperature recording device, and a surface FBG reference point. During loading, the FBG interrogator synchronously collected the Bragg wavelength variations in the embedded FBG sensing lines and the surface reference point. The data acquisition computer recorded the wavelength signals in real time, while the ambient temperature recording device recorded temperature variations during the tests. The surface FBG reference point is referred to

as the T-sensor in this study. The T-sensor was placed in a region not directly subjected to loading and was used as an unloaded reference grating for checking the consistency between ambient-temperature variation and reference FBG wavelength response.

Three static loading cases were considered: central single-point stepwise loading, symmetric two-point loading, and asymmetric two-point loading. Central single-point stepwise loading was used to analyze the effect of load level on longitudinal FBG responses and longitudinal relative vertical displacement curves. The symmetric and asymmetric two-point loading cases were used to evaluate the influence of loading-point arrangement on transverse response distributions under the same total load level.

The central single-point loading position was (60 cm, 25 cm), and the loading range was 49–784 N, corresponding to 5–80 kg weights. Four representative load levels, namely 98 N, 294 N, 490 N, and 686 N, were selected, corresponding to 10 kg, 30 kg, 50 kg, and 70 kg weights, respectively. The symmetric two-point loading positions were (60 cm, 15 cm) and (60 cm, 35 cm), while the asymmetric two-point loading positions were (40 cm, 15 cm) and (80 cm, 35 cm). For the two-point loading cases, a 25 kg weight was applied at each loading point, corresponding to an equivalent load of approximately 245 N per point and a total equivalent load of approximately 490 N. This total load was consistent with the central single-point loading case using a 50 kg weight. The loading design allowed the effect of loading-point arrangement on transverse response distributions to be compared under the same total equivalent load. The loading cases and loading positions are listed in Table 3, and the loading system and loading positions are shown in Figure 2.

Table 3. Loading cases and loading positions.

Loading Case	Loading Position/cm	Load Level
Central single-point stepwise loading	(60, 25)	98 N, 294 N, 490 N and 686 N
Symmetric two-point loading	(60, 15), (60, 35)	245 N per point; total equivalent load of 490 N
Asymmetric two-point loading	(40, 15), (80, 35)	245 N per point; total equivalent load of 490 N

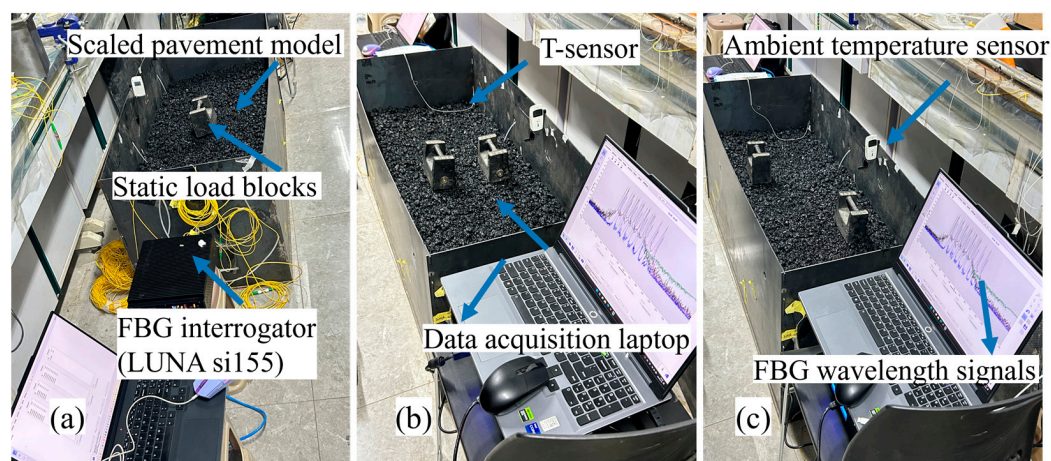


Figure 2. Static loading system and data acquisition setup: (a) scaled pavement model, loading weights, and FBG interrogator; (b) T-sensor and data acquisition computer; (c) ambient temperature recording device and FBG wavelength acquisition interface.

Each loading case lasted 5 min. The sampling frequency of the FBG interrogator was 30 Hz; therefore, each loading case contained approximately 9000 sampling points. To reduce the influence of initial contact adjustment, transient responses, and acquisition disturbances at the early loading stage, data from the later stable segment of each loading case were used as the representative response for that case.

2.4. Acquisition of Pre-Loading Wavelengths, Stable Loading Wavelengths, and Temperature Data

The pre-loading stable-segment wavelength was used as the initial reference state for each FBG sensing point, thereby preventing mechanical responses under low load levels from being included in the strain calculation. For the i -th FBG sensing point, the mean wavelength in the pre-loading stable segment is denoted as $\lambda_{i,0}$. For loading case P , the mean wavelength of the same sensing point within the loading stable segment is denoted as $\lambda_{i,P}$.

The stable segment was extracted according to the loading type. For central single-point stepwise loading, the last 30% of the loading stage was selected as the stable segment. For symmetric two-point loading and asymmetric two-point loading, the last 30 s of the loading stage was selected as the stable segment. The wavelength of each sensing point within the stable segment was averaged and then used to calculate the wavelength shift under the corresponding loading case. Temperature data were processed consistently with the wavelength stable-segment extraction. The temperature corresponding to the pre-loading stable segment is denoted as T_0 and the temperature corresponding to the stable segment of loading case P is denoted as T_P . In the calculation of temperature-compensated strain, the temperature variation $\Delta T_P = T_P - T_0$ was substituted into the FBG wavelength–strain–temperature coupling relationship to remove the temperature contribution to the wavelength shift.

In the raw FBG data, each row first recorded the number of peaks in different channels, followed by the peak wavelengths of each channel. Because peak loss, peak jumping, or peak mismatch could occur during data acquisition, this study did not directly average fixed column numbers. Instead, peak records were dynamically separated according to the number of peaks recorded in each channel in each row, and sensing-point matching was performed using the median peak position within the stable segment. Abnormal records that clearly deviated from the stable wavelength range of the same sensing point were removed. This processing procedure was used to reduce the influence of peak-tracking errors on strain calculation and relative vertical displacement reconstruction.

3. Data Processing and Relative Vertical Displacement Reconstruction

3.1. Overall Data Processing Workflow

The purpose of the data processing procedure was to transform the raw wavelength responses recorded by the quasi-distributed FBG sensing lines into temperature-compensated strain and then into relative vertical displacement curves along the sensing lines. As shown in Figure 3, the workflow consisted of stable-segment wavelength extraction, temperature-compensated strain calculation, equivalent neutral axis calculation, strain–curvature conversion, curvature interpolation, curvature integration, and linear baseline correction.

For the i -th FBG sensing point, the mean wavelength in the pre-loading stable segment, $\lambda_{i,0}$, and the mean wavelength in the stable segment under loading case P , $\lambda_{i,P}$, were first extracted from the raw wavelength data. Meanwhile, the temperature in the pre-loading stable segment, T_0 , and the temperature in the stable segment under loading case P , T_P , were obtained to determine the temperature variation. The temperature contribution to the wavelength response was then removed using the FBG wavelength–strain–temperature coupling relationship, yielding the temperature-compensated strain $\varepsilon_{i,P}$.

After the temperature-compensated strain had been obtained at each FBG sensing point, the distance d_i between the sensing point and the equivalent neutral axis was determined from the equivalent neutral axis position z_n of the multilayer structure and the sensing-point elevation z_i . The strain response was then converted into the equivalent curvature κ_i along the sensing-line direction. Because the FBG sensing points were discretely arranged, the discrete curvature values were interpolated to approximate the

curvature distribution within the sensing-line range. Finally, the relative vertical displacement $w_c(x)$ along the sensing line was reconstructed through curvature integration and linear baseline correction. The reconstructed curves were subsequently used to compare relative vertical displacement distributions under different load levels, loading modes, and structural layers.

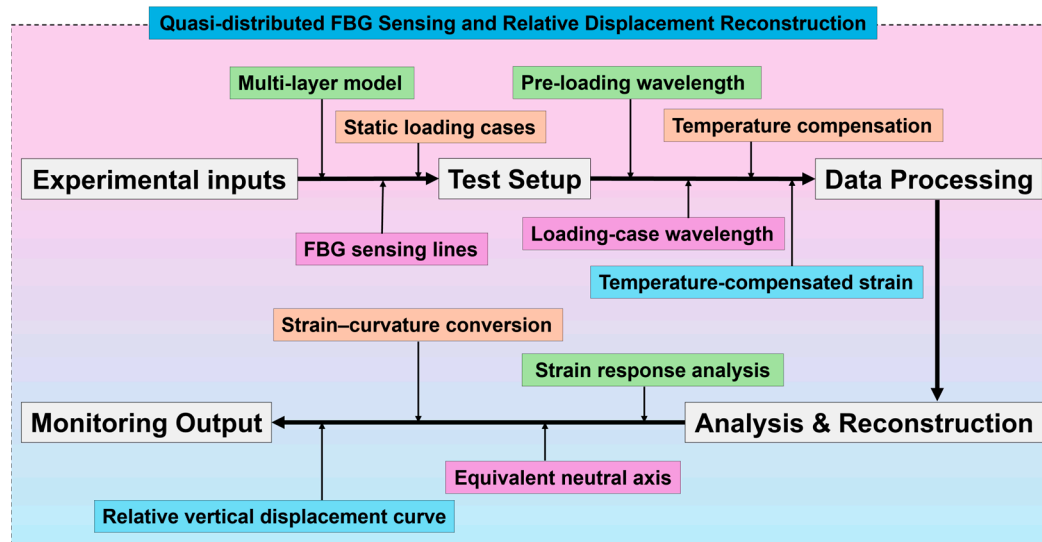


Figure 3. Data processing workflow from FBG wavelength responses to relative vertical displacement reconstruction along sensing lines. Thick arrows indicate the primary sequence; thin arrows connect supporting inputs and processing steps.

3.2. Temperature-Compensated Strain Calculation Based on Pre-Loading Reference Wavelengths

The Bragg wavelength of an FBG sensor is affected by both mechanical strain and temperature. In this study, the pre-loading stable state was adopted as the reference state. After the wavelength shift associated with temperature variation was removed, the remaining load-induced strain response was defined as the temperature-compensated strain and denoted by ϵ . For a single FBG sensing point, the relative change in the Bragg wavelength can be expressed by the wavelength–strain–temperature relationship as:

$$\frac{\Delta\lambda_B}{\lambda_B} = k_\epsilon \epsilon + k_T \Delta T \quad (1)$$

where λ_B is the Bragg wavelength of the FBG sensor, $\Delta\lambda_B$ is the Bragg wavelength shift, ΔT is the temperature variation, k_T is the temperature sensitivity coefficient of the optical fiber, and k_ϵ is the strain sensitivity coefficient of the optical fiber. In this study, $k_\epsilon = 0.79$ and $k_T = 7.55 \times 10^{-6}/^\circ\text{C}$ were adopted as the FBG wavelength–strain–temperature conversion parameters under the test conditions.

The pre-loading stable-segment wavelength was used as the initial reference wavelength for each FBG sensing point. For the i -th FBG sensing point, the wavelength shift relative to the pre-loading state under loading case P was calculated as:

$$\Delta\lambda_{i,P} = \lambda_{i,P} - \lambda_{i,0} \quad (2)$$

where $\lambda_{i,0}$ is the mean wavelength of the i -th sensing point in the pre-loading stable segment, $\lambda_{i,P}$ is the mean wavelength of the same sensing point in the stable segment under loading case P , and $\Delta\lambda_{i,P}$ is the wavelength shift relative to the pre-loading state.

The corresponding temperature variation for loading case P is given by:

$$\Delta T_P = T_P - T_0 \quad (3)$$

where T_0 is the temperature in the pre-loading stable segment, and T_P is the temperature in the stable segment under loading case P .

Combining Equations (1)–(3), the temperature-compensated strain of the i -th FBG sensing point under loading case P can be obtained as:

$$\varepsilon_{i,P} = \frac{[(\lambda_{i,P} - \lambda_{i,0}) / \lambda_{i,0}] - k_T(T_P - T_0)}{k_\varepsilon} \quad (4)$$

where $\varepsilon_{i,P}$ denotes the temperature-compensated strain obtained by using the pre-loading stable state as the reference state and removing the temperature contribution from the measured wavelength response. The temperature compensation in this study was performed at the loading-case level, using the temperatures corresponding to the pre-loading stable segment and the stable segment of each loading case. Therefore, the interpretation of low-amplitude response zones should consider the possible influence of local temperature differences and measurement noise.

The gratings were not intentionally pre-strained to create a bidirectional measurement range. All reported strains are incremental values referenced to the pre-loading stable wavelength of each grating. A negative temperature-compensated value therefore denotes a wavelength decrease relative to that reference after subtraction of the temperature term, not a negative absolute strain or loss of signal. It may arise from a local reversal of the bending-related response; for small responses near zero, the compensation term, residual local thermal mismatch, and measurement noise can also change the sign. Pre-strain is not required for this referenced incremental formulation provided that the reflected peak remains within the interrogator range.

3.3. Temperature Variation and T-Sensor Verification

The ambient temperature record was used to determine T_0 and T_P in Equation (3), which were then introduced into Equation (4) for temperature-compensated strain calculation. In addition to ambient temperature monitoring, a surface FBG reference point, denoted as the T-sensor, was used to check temperature variation and slow system drift during loading. The T-sensor was placed in a region not directly subjected to loading. It was therefore not treated as a structural response sensing point and was not used to interpret high-strain response zones induced by mechanical loading.

During the tests, the ambient temperature ranged from 22.70 to 23.40 °C, with a maximum temperature difference of 0.70 °C and an average temperature of 23.061 °C. The stable-segment mean wavelength of the T-sensor ranged from 1539.101 to 1539.109 nm. The maximum relative shift was 0.008297 nm, and the mean standard deviation of stable segments was 0.000929 nm. These values indicate that both temperature variation and reference wavelength drift remained limited during loading, satisfying the requirements for temperature compensation and stability assessment.

Under the maximum temperature difference of 0.70 °C, the equivalent strain associated with the temperature term can be estimated as:

$$\varepsilon_T = k_T \Delta T_{\max} / k_\varepsilon \quad (5)$$

namely, $\varepsilon_T \approx 6.69 \mu\varepsilon$. This magnitude is much lower than the hundreds to thousands of microstrain observed in the high-response zones of the asphalt concrete surface layer, but it is close to the response magnitude of some low-amplitude zones in the soil base layer and

at sensing points far from the loading area. Accordingly, the subsequent analysis focuses on high-response zones, inter-case variation trends, and spatial distribution relationships.

3.4. Equivalent Neutral Axis Calculation

To convert the FBG temperature-compensated strain into curvature, an equivalent-section method was adopted to calculate the equivalent neutral axis position of the multilayer structure. From bottom to top, the model consisted of a soil base layer, a gravel base layer, and an asphalt concrete surface layer. The thicknesses of the three layers were $h_s = 0.18$ m, $h_g = 0.04$ m, and $h_a = 0.08$ m, respectively. The centroidal elevations of the three layers from the model bottom were $z_{sc} = 0.09$ m, $z_{gc} = 0.20$ m, and $z_{ac} = 0.26$ m, respectively.

Representative elastic moduli were used only for the equivalent neutral axis calculation: $E_s = 80$ MPa for the soil base layer, $E_g = 275$ MPa for the gravel base layer, and $E_a = 3000$ MPa for the asphalt concrete surface layer. These values served as input parameters for the equivalent-section calculation and were not obtained through material parameter inversion. If absolute vertical displacement validation or numerical model calibration is required in future work, the actual mechanical parameters of each layer should be determined through material tests.

For a unit-width layered section, the elevation of the equivalent neutral axis from the model bottom is calculated as:

$$z_n = \frac{E_s h_s \cdot z_{sc} + E_g h_g \cdot z_{gc} + E_a h_a \cdot z_{ac}}{E_s h_s + E_g h_g + E_a h_a} \quad (6)$$

where z_n is the distance from the equivalent neutral axis to the model bottom; E_s , E_g and E_a are the elastic moduli of the soil base layer, gravel base layer, and asphalt concrete surface layer, respectively; h_s , h_g and h_a are the thicknesses of the three layers; and z_{sc} , z_{gc} and z_{ac} are the centroidal elevations of the three layers from the model bottom.

Substitution of the above parameters gives $z_n = 0.2483$ m. This position is close to the asphalt concrete surface layer because the elastic modulus of the asphalt concrete surface layer is much higher than those of the gravel base layer and soil base layer, and because the asphalt concrete surface layer is located in the upper part of the structure. All strain–curvature conversions in this study were performed based on this equivalent neutral axis position.

For the fixed measured strain field used in this post-processing sensitivity test, a change in the assumed modulus affects the reconstruction through the neutral-axis position and the corresponding sensing-point distance. Because all sensing points on a given line share the same elevation, the perturbation introduces a common positive scale factor within that line. Under the adopted linear interpolation, integration, and endpoint-correction procedure, this factor changes the reconstructed amplitude but not the normalized curve shape or peak coordinate. This conclusion is conditional on the equivalent-section assumptions and does not describe how the actual pavement strain field would change if the material moduli varied. The $\pm 20\%$ range is an illustrative symmetric perturbation used for local sensitivity screening, rather than an experimentally determined modulus uncertainty or a confidence bound for the reconstructed displacement.

3.5. Strain–Curvature Conversion

Under the assumptions of small-deformation bending and an approximately linear strain distribution through the section thickness, the strain at an FBG sensing point can be related to its distance from the equivalent neutral axis. For the i -th FBG sensing point,

$$\kappa_i = \varepsilon_i / d_i \quad (7)$$

where κ_i is the equivalent curvature corresponding to the i -th sensing point, with a unit of m^{-1} ; ε_i is the temperature-compensated strain at the sensing point; and d_i is the distance from the sensing point to the equivalent neutral axis and is given by $d_i = z_i - z_n$. If the strain is expressed in $\mu\varepsilon$, it must be converted into dimensionless strain before curvature calculation, namely $1 \mu\varepsilon = 10^{-6}$.

The FBG sensing points in the asphalt concrete surface layer were located at an elevation of $z_a = 0.26$ m from the model bottom, whereas those in the soil base layer were located at $z_s = 0.13$ m. Combined with $z_n = 0.2483$ m, the distance from the asphalt-layer sensing points to the equivalent neutral axis was $d_a = z_a - z_n = 0.0117$ m, and the distance from the soil-base sensing points to the equivalent neutral axis was $d_s = z_s - z_n = -0.1183$ m.

Therefore, the curvature conversion for asphalt-layer sensing points is:

$$\kappa_a = \varepsilon_a / 0.0117 \quad (8)$$

and the curvature conversion for soil-base sensing points is:

$$\kappa_s = \varepsilon_s / (-0.1183) \quad (9)$$

where κ_a and κ_s are the equivalent curvatures corresponding to the asphalt-layer and soil-base sensing points, respectively, and ε_a and ε_s are the temperature-compensated strains of the asphalt-layer and soil-base sensing points, respectively. Because the soil-base sensing points are located below the equivalent neutral axis, d_s is negative, and the curvature sign is affected by the relative position of the sensing point with respect to the equivalent neutral axis. In this study, downward relative vertical displacement is defined as positive, and the same sign convention is maintained in the reconstructed relative vertical displacement curves.

3.6. Curvature Integration and Linear Baseline Correction

Because the FBG sensing points were discretely distributed along each sensing line, cubic spline interpolation was applied to the discrete curvature values κ_i according to the sensing-point positions and their corresponding curvatures. This interpolation provided an approximate curvature distribution $\kappa(x)$ within the sensing-line range, where x denotes the coordinate along the sensing-line direction. Since the unit of curvature is m^{-1} , the coordinates used for curvature integration must be expressed in meters. If the original sensing-point coordinates are given in centimeters, they should be converted into meters before integration. The final relative vertical displacement results are output in millimeters.

The rotation angle along the sensing line can be obtained by integrating the interpolated curvature function $\kappa(x)$ once:

$$\theta(x) = \int \kappa(x) dx + C_1 \quad (10)$$

where $\theta(x)$ is the rotation angle at position x along the sensing line, and C_1 is an integration constant. The displacement curve obtained from curvature integration is then calculated by integrating the rotation angle:

$$w(x) = \int \theta(x) dx + C_2 \quad (11)$$

where $w(x)$ is the displacement curve obtained by integration and C_2 is an integration constant. Curvature double integration introduces a rigid-body translation term and a linear inclination term. In addition, the endpoints of an FBG sensing line are not equiv-

alent to the structural boundaries of the model. Therefore, the directly integrated $w(x)$ should not be interpreted as the absolute vertical displacement measured by an external displacement sensor.

To remove the linear reference difference between the two endpoints of a sensing line, the line connecting the two endpoint values was taken as the linear baseline. For the starting point x_1 and ending point x_n of a sensing line, the linear baseline is defined as:

$$w_b(x) = w(x_1) + \frac{w(x_n) - w(x_1)}{x_n - x_1} \cdot (x - x_1) \quad (12)$$

The relative vertical displacement after linear baseline correction is:

$$w_c(x) = w(x) - w_b(x) \quad (13)$$

where $w_c(x)$ is the relative vertical displacement after linear baseline correction. After correction using Equation (13), the relative values at the two endpoints of the sensing line are zero, namely $w_c(x_1) = 0$ and $w_c(x_n) = 0$. In this study, downward relative vertical displacement is defined as positive, and $w_c(x)$ is converted into millimeters for subsequent analysis.

The reconstructed $w_c(x)$ represents the relative vertical displacement within the FBG sensing-line range with respect to the line connecting the two endpoints. It is used to compare vertical deformation trends and displacement concentration zones under different load levels, loading modes, and structural layers.

3.7. Method Assumptions and Scope of Application

The proposed workflow transforms discrete wavelength responses recorded by quasi-distributed FBG sensing lines into relative vertical displacement curves along the sensing lines through temperature compensation, strain conversion, equivalent curvature conversion, curvature integration, and linear baseline correction. This procedure enhances the spatial representation capability of FBG data and extends the interpretation from point-based strain responses to relative deformation trends along sensing lines.

Several assumptions and treatments should be noted when interpreting the reconstructed curves. First, temperature compensation was performed using the temperature of the pre-loading stable segment and that of each loading-case stable segment, rather than through independent temperature compensation at each embedded FBG sensing point. Second, representative elastic moduli were adopted for equivalent neutral axis calculation, and the material parameters were not obtained through inverse identification. Third, the strain–curvature conversion was based on small-deformation bending and an approximately linear strain distribution through the section thickness; therefore, it mainly characterizes the equivalent bending response along the sensing-line direction. Fourth, curvature interpolation, double integration, and endpoint baseline correction can affect both the amplitude and shape of the reconstructed relative vertical displacement curves.

Accordingly, the reconstructed result represents the relative vertical displacement within the FBG sensing-line range with respect to the line connecting the two endpoints. It is suitable for comparing vertical deformation distributions and concentration-zone variations under different loading cases, rather than for deformation mapping outside the sensing-line range or for measuring absolute vertical displacement with an external displacement sensor. This interpretation is consistent with the subsequent analysis, which focuses on temperature-compensated strain, high-response zones, and relative vertical displacement concentration zones under different load levels, loading modes, and structural layers.

The assumptions affect different aspects of the output. The linear through-thickness strain assumption and the equivalent neutral axis determine curvature scale; local interface

slip, non-uniform strain transfer, or shear-dominated deformation would violate this mapping. The sensitivity analysis in Table 4 shows that assumed-modulus perturbations affect the surface-layer reconstruction amplitude more strongly because the surface gratings are close to the calculated neutral axis. Cubic-spline interpolation can smooth or shift local extrema, while double integration accumulates low-frequency bias. Endpoint baseline correction removes rigid-body translation and linear inclination and therefore fixes the reference shape, but it also prevents recovery of absolute displacement.

Table 4. One-at-a-time sensitivity of the equivalent neutral axis and reconstructed relative-deformation amplitude to $\pm 20\%$ elastic-modulus perturbations.

Case	z_n/cm	$ d $ Asphalt/cm	$ d $ Soil/cm	Relative Change—Asphalt/%	Relative Change—Soil/%
Baseline	24.829	1.171	11.829	0.00	0.00
$E_s - 20\%$	25.003	0.997	12.003	+17.41	−1.45
$E_s + 20\%$	24.659	1.341	11.659	−12.67	+1.46
$E_g - 20\%$	24.869	1.131	11.869	+3.57	−0.34
$E_g + 20\%$	24.789	1.211	11.789	−3.28	+0.34
$E_a - 20\%$	24.570	1.430	11.570	−18.09	+2.23
$E_a + 20\%$	25.008	0.992	12.008	+18.09	−1.49

No LVDT, DIC, or other independent displacement measurement was acquired during these tests; consequently, the reconstruction has not been experimentally validated as absolute pavement displacement. The curves are used only as FBG-derived, line-wise relative deformation measures for within-study comparison of amplitude, morphology, and concentration zones. Spatial agreement between strain and reconstructed-displacement zones is an internal consistency check, not independent validation. Absolute-displacement claims require simultaneous external measurements and calibrated material and strain-transfer parameters.

4. Results and Analysis

4.1. Temperature Variation and T-Sensor Response During Loading

Before analyzing the load-induced strain response, the ambient temperature variation and the T-sensor wavelength response were examined to support temperature compensation and stability assessment. The ambient temperature data were used to determine T_0 and T_P for each loading case, while the T-sensor served as a surface reference grating for checking temperature variation and slow reference wavelength drift. The T-sensor was not treated as a structural response sensing point. The ambient temperature variation and the corresponding T-sensor wavelength shift across the loading cases are shown in Figure 4.

During the loading tests, the ambient temperature ranged from 22.70 to 23.40 °C, with a maximum temperature difference of 0.70 °C and an average value of 23.061 °C. The stable-segment mean wavelength of the T-sensor ranged from 1539.101 to 1539.109 nm. The maximum relative shift was 0.008297 nm, and the mean standard deviation of stable segments was 0.000929 nm. These results indicate that the thermal environment and the reference wavelength remained relatively stable during loading.

The following strain analysis is therefore based on temperature-compensated strain, namely the load-induced strain response relative to the pre-loading stable state after removal of the temperature contribution. Because the compensation was performed at the loading-case level rather than through independent layer-by-layer and point-by-point temperature compensation, low-amplitude response zones, especially in the soil base layer and at sensing points far from the loading area, should be interpreted with appropriate caution.

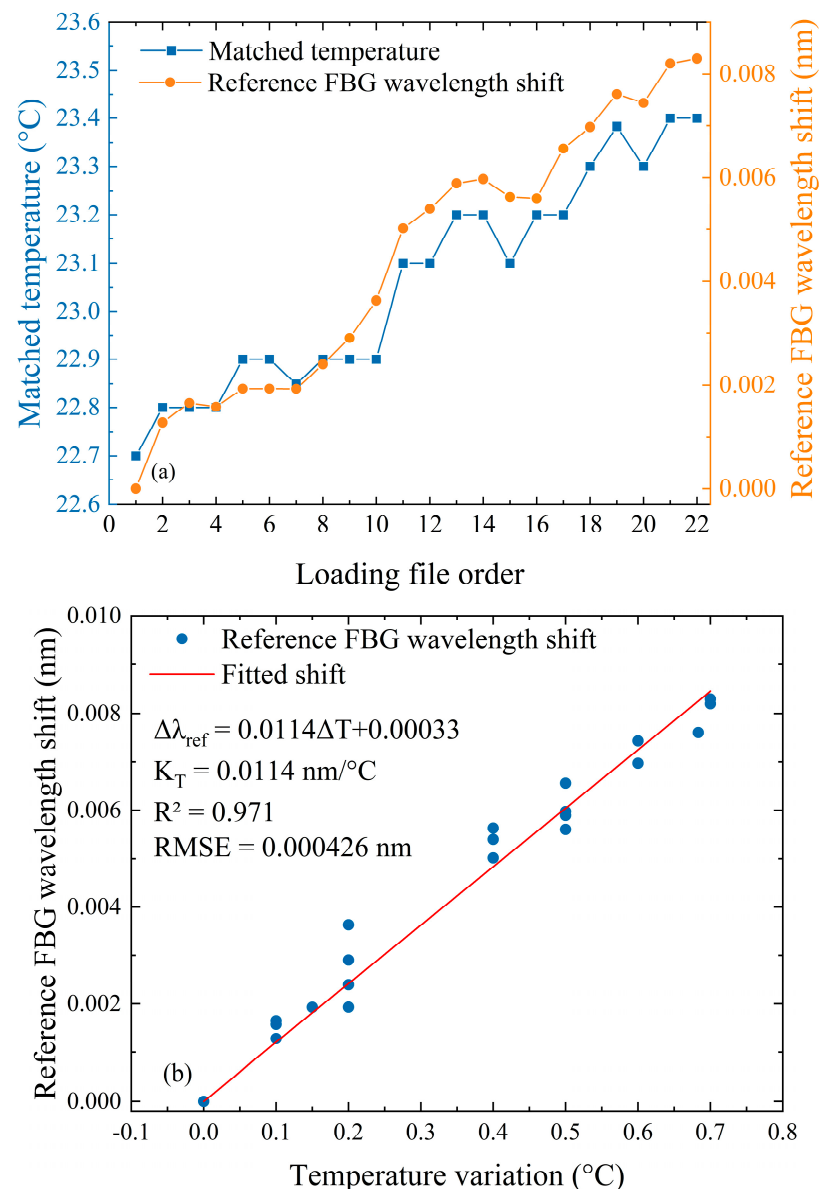


Figure 4. Relationship between ambient temperature variation and T-sensor wavelength shift during loading: (a) ambient temperature matched with loading files and relative shift of the T-sensor; (b) fitted relationship between relative wavelength shift of the T-sensor and ambient temperature variation.

4.2. Longitudinal FBG Strain Responses and Layer-Dependent Differences Under Central Single-Point Loading

The longitudinal FBG strain responses under central single-point stepwise loading were analyzed to evaluate the load-level effect and layer-dependent response differences. The loading position was (60 cm, 25 cm), and four representative load levels, 98 N, 294 N, 490 N, and 686 N, were selected. Figure 5 shows the temperature-compensated strain responses of the asphalt-layer longitudinal sensing lines SAL1 and SAL2 and the soil-base longitudinal sensing lines SSL1 and SSL2.

SAL1, which approximately passed through the central loading line, showed the strongest longitudinal response in the asphalt concrete surface layer. A high-response zone developed near 60–65 cm. The maximum positive strains were 212.64 $\mu\epsilon$ at 60 cm under 98 N and 534.42 $\mu\epsilon$ at 60 cm under 294 N. Under 490 N and 686 N, the peak position shifted to 65 cm, with peak values of 1152.10 $\mu\epsilon$ and 1459.39 $\mu\epsilon$, respectively. The responses at 60 cm

remained high, reaching 1147.86 $\mu\epsilon$ under 490 N and 1413.63 $\mu\epsilon$ under 686 N. Negative incremental strains within 75–85 cm indicate a sign reversal relative to the pre-loading reference outside the principal loading zone. Their interpretation follows Section 3.2: larger, spatially coherent negative values are consistent with a change in the local bending-related response, whereas values close to zero may also be affected by temperature subtraction and measurement noise.

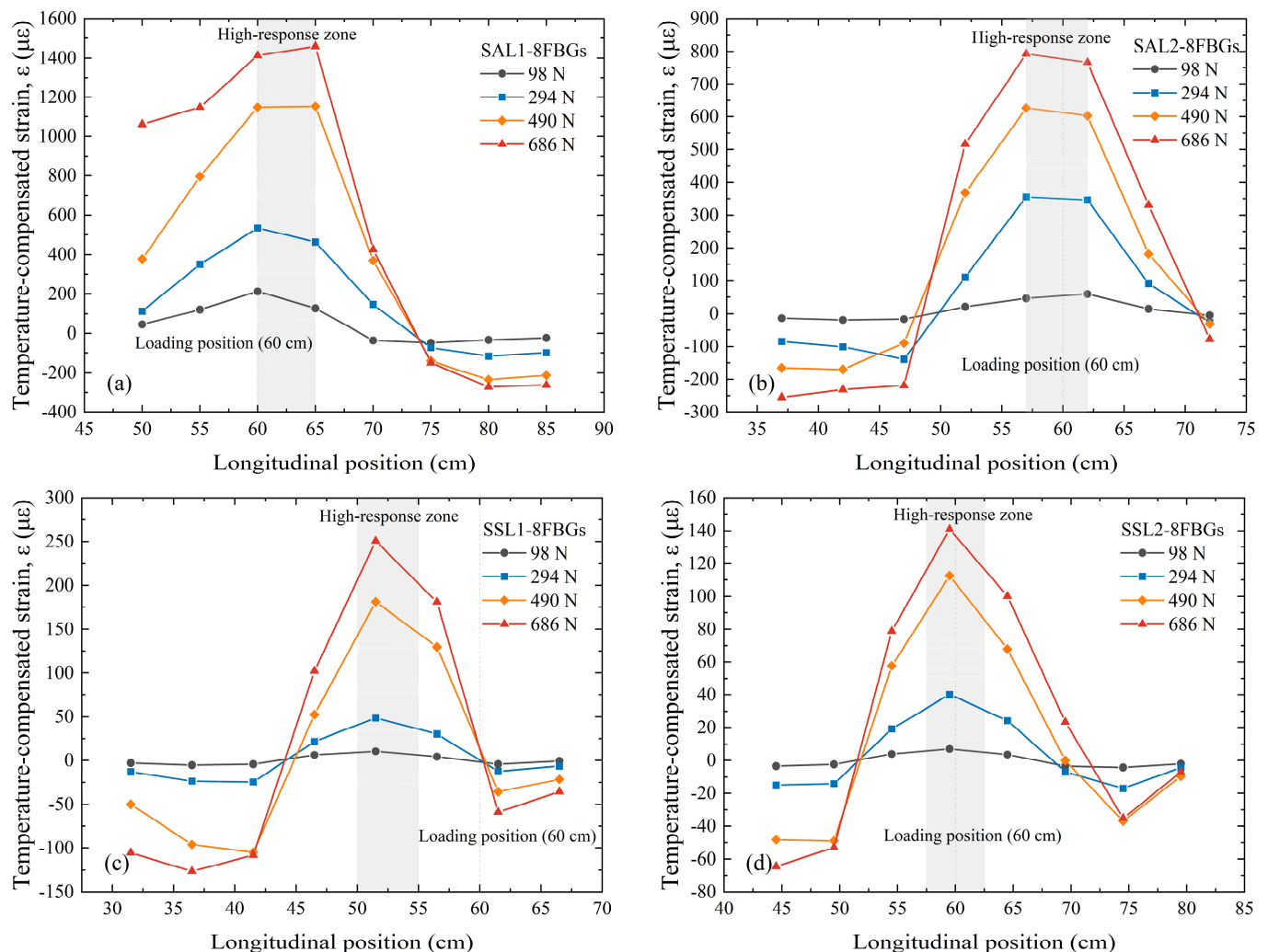


Figure 5. Temperature-compensated strain responses of longitudinal FBG sensing lines under central single-point loading: (a) SAL1; (b) SAL2; (c) SSL1; (d) SSL2.

SAL2 also exhibited increasing strain amplitudes with increasing load, but its response was lower because of its transverse offset from the central loading point. The maximum positive strains were 59.44 $\mu\epsilon$ at 62 cm under 98 N, 355.28 $\mu\epsilon$ at 57 cm under 294 N, 626.02 $\mu\epsilon$ at 57 cm under 490 N, and 793.13 $\mu\epsilon$ at 57 cm under 686 N. Its high-response zone was mainly concentrated within 57–62 cm. The comparison between SAL1 and SAL2 indicates that the asphalt-layer longitudinal strain response was governed by both load level and sensing-line location.

The soil-base longitudinal sensing lines showed much lower amplitudes. For SSL1, the peak response mainly occurred near 51.5 cm, with a maximum value of 250.59 $\mu\epsilon$ under 686 N. For SSL2, peak values occurred at 59.5 cm, and the maximum value was 140.87 $\mu\epsilon$ under 686 N. Compared with SAL1 and SAL2, the lower response amplitudes of SSL1 and SSL2 reflect load diffusion and attenuation during downward load transfer through the multilayer pavement structure. Therefore, the longitudinal strain results

reveal a clear layer-dependent difference: the asphalt concrete surface layer captured concentrated load-level responses, whereas the soil base layer mainly recorded attenuated low-amplitude responses.

4.3. Transverse FBG Strain Responses Under Different Loading Cases

Transverse FBG strain responses were analyzed under a total equivalent load of approximately 490 N to evaluate transverse response redistribution induced by loading-point arrangement. The central single-point loading position was (60 cm, 25 cm), the symmetric two-point loading positions were (60 cm, 15 cm) and (60 cm, 35 cm), and the asymmetric two-point loading positions were (40 cm, 15 cm) and (80 cm, 35 cm). Figure 6 compares the responses of SAT1, SAT2, and SST.

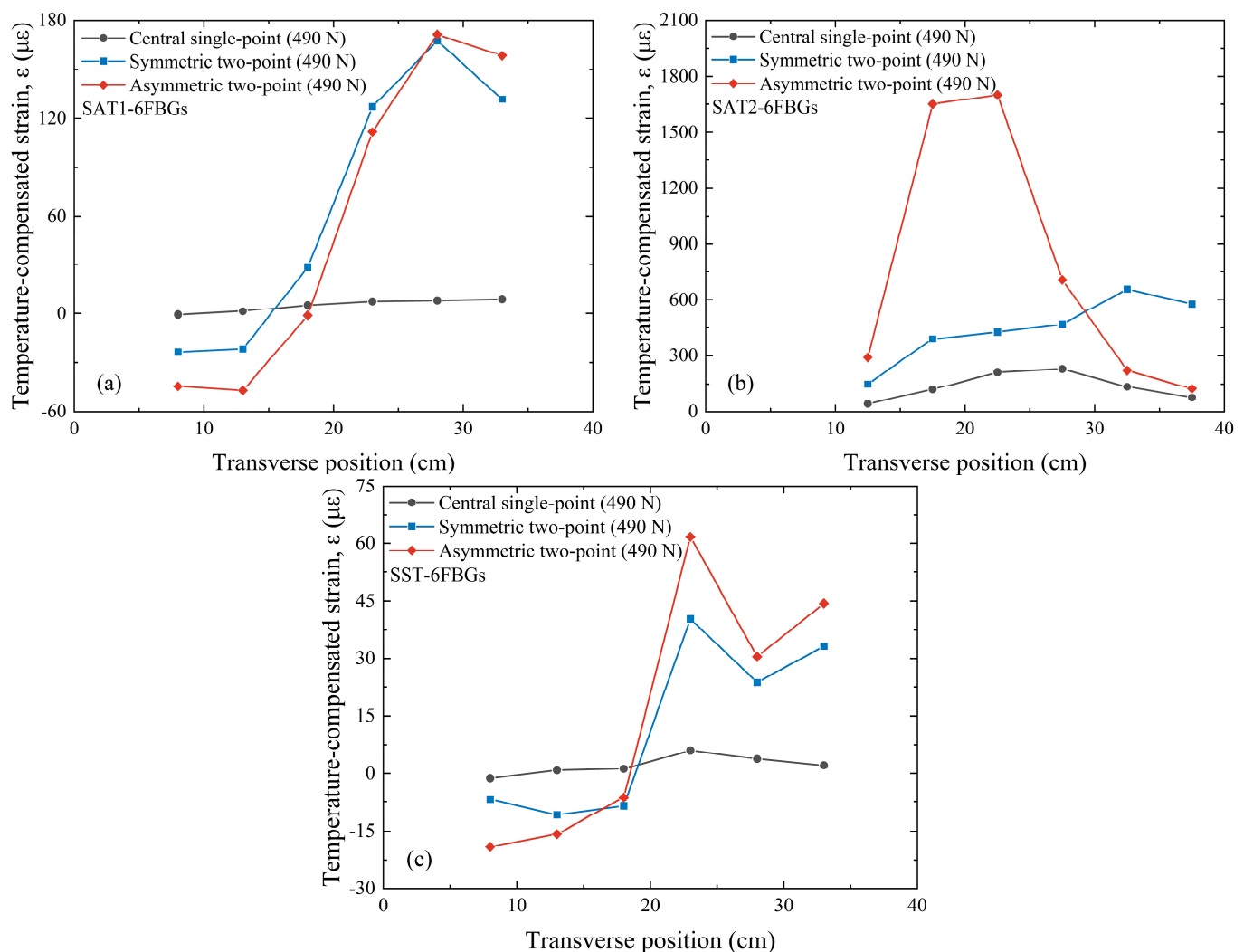


Figure 6. Temperature-compensated strain responses of transverse FBG sensing lines under different loading cases: (a) SAT1; (b) SAT2; (c) SST.

SAT1 showed a weak response under central single-point loading, with a strain range of approximately -0.71 – $8.83 \mu\epsilon$. Under symmetric two-point loading, the peak value increased to $167.44 \mu\epsilon$ at 28 cm. Under asymmetric two-point loading, the peak value was $171.45 \mu\epsilon$, also at 28 cm. Thus, SAT1 was sensitive to the transition from single-point loading to two-point loading, but the difference between symmetric and asymmetric two-point loading was not pronounced on this sensing line.

SAT2 displayed a stronger dependence on loading mode and sensing-line location. Under central single-point loading, the peak value was $229.06 \mu\epsilon$ near 27.5 cm. Under symmetric two-point loading, it increased to $657.32 \mu\epsilon$ near 32.5 cm. Under asymmetric two-point loading, a high-response zone developed within 17.5–22.5 cm, and the peak value reached approximately $1699.48 \mu\epsilon$ at 22.5 cm. This high response was mainly associated with the spatial relationship between SAT2 and the asymmetric loading point at (40 cm, 15 cm), which was close to the front sensing points of SAT2.

The contrast between SAT1 and SAT2 demonstrates the strong influence of sensing-line location. Under asymmetric two-point loading, the peak value of SAT1 was approximately $171.45 \mu\epsilon$, whereas that of SAT2 was approximately $1699.48 \mu\epsilon$, nearly one order of magnitude higher. Because the total equivalent load was the same, this difference should be attributed mainly to the relative spatial relationship between the loading point and the sensing line rather than to load magnitude.

SST, embedded in the soil base layer, showed much lower transverse responses than SAT1 and SAT2. Under central single-point loading, its strain range was approximately -1.25 – $6.02 \mu\epsilon$. The peak value increased to $40.36 \mu\epsilon$ at 23 cm under symmetric two-point loading and to $61.68 \mu\epsilon$ at 23 cm under asymmetric two-point loading. These low-amplitude responses indicate that the transverse loading effect was substantially attenuated after load transfer to the soil base layer. Therefore, SST is more suitable for characterizing amplitude attenuation and inter-case variation trends than for interpreting local loading-point positions.

4.4. Relative Vertical Displacement Curves of Longitudinal Sensing Lines

The longitudinal relative vertical displacement curves were reconstructed from the temperature-compensated strain responses through strain–curvature conversion, curvature integration, and linear baseline correction. Downward vertical displacement is defined as positive. Because linear baseline correction sets the relative values at the two endpoints of each sensing line to zero, Figure 7 represents the relative vertical displacement within the sensing-line range, rather than the absolute vertical displacement measured by an external displacement sensor.

For SAL1, the maximum relative vertical displacement increased from 0.09883 mm under 98 N to 1.079 mm under 686 N. The peak position shifted from 61.589 cm to 63.579 cm, and the displacement concentration zone was mainly located within 60–65 cm. This range is consistent with the high-strain response zone and the central loading coordinate of $x = 60$ cm. The slight shift in the peak toward 63–64 cm relative to the geometric loading point can be attributed to curvature interpolation, double integration, and linear baseline correction.

For SAL2, the maximum relative vertical displacement increased from 0.03391 mm to 0.583 mm, with peak positions concentrated near 57–59 cm. Because SAL2 had a transverse offset of approximately 7 cm from the central loading point, its amplitude was markedly lower than that of SAL1; under 686 N, the maximum relative vertical displacement of SAL2 was approximately half that of SAL1. The relative vertical displacement peak of SAL2 was still within the loading influence range and corresponded to its high-strain response zone within 57–62 cm.

The soil-base longitudinal sensing lines exhibited low-amplitude relative vertical displacement responses. For SSL1, the maximum value increased from 0.000448 mm under 98 N to 0.0118 mm under 686 N, with peak positions near 51–53 cm. For SSL2, the maximum value increased from 0.003039 mm to 0.091087 mm, while the peak position shifted from 59.249 cm to 60.888 cm and remained generally near $x = 60$ cm. Although SSL2 showed a clearer response than SSL1, its maximum amplitude remained below 0.1 mm. Overall,

the longitudinal displacement results transformed the strain response differences into relative deformation patterns, with higher amplitudes in the asphalt-layer sensing lines and attenuated responses in the soil-base sensing lines.

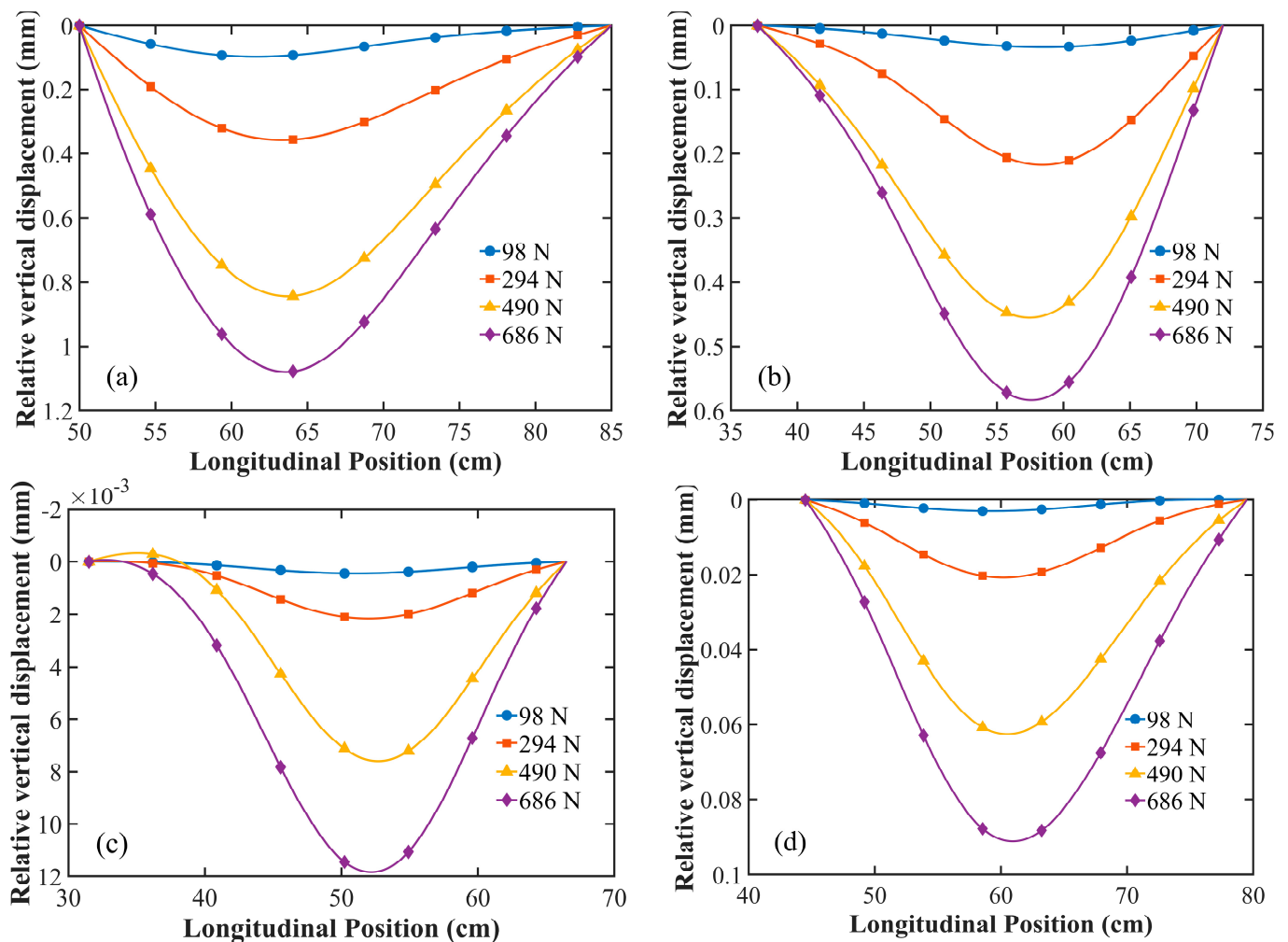


Figure 7. Relative vertical displacement curves of longitudinal sensing lines under central single-point loading: (a) SAL1; (b) SAL2; (c) SSL1; (d) SSL2.

4.5. Relative Vertical Displacement Curves of Transverse Sensing Lines

The transverse FBG-derived relative vertical displacement curves were used to evaluate line-wise deformation patterns under different loading modes with the same total equivalent load of approximately 490 N. Figure 8 shows the results for SAT1, SAT2, and SST.

For SAT1, the maximum relative vertical displacement under central single-point loading was 0.003888 mm at 23 cm. Under symmetric two-point loading, the maximum value increased to 0.055990 mm; under asymmetric two-point loading, it was 0.045787 mm. In both two-point loading cases, the peak position was located at 23 cm. These results indicate that two-point loading increased the relative vertical displacement amplitude of SAT1, but the difference between symmetric and asymmetric two-point loading was not pronounced.

SAT2 showed a much stronger transverse relative vertical displacement response. Under central single-point loading, the maximum value was 0.119120 mm at 27.5 cm. Under symmetric two-point loading, it increased to 0.310970 mm, with the peak remaining at 27.5 cm. Under asymmetric two-point loading, the maximum relative vertical displacement reached 0.761 mm, and the peak shifted to 22.5 cm. Relatively high amplitudes were

maintained within 17.5–27.5 cm, reflecting the proximity of SAT2 to the influence region of the asymmetric loading point at (40 cm, 15 cm).

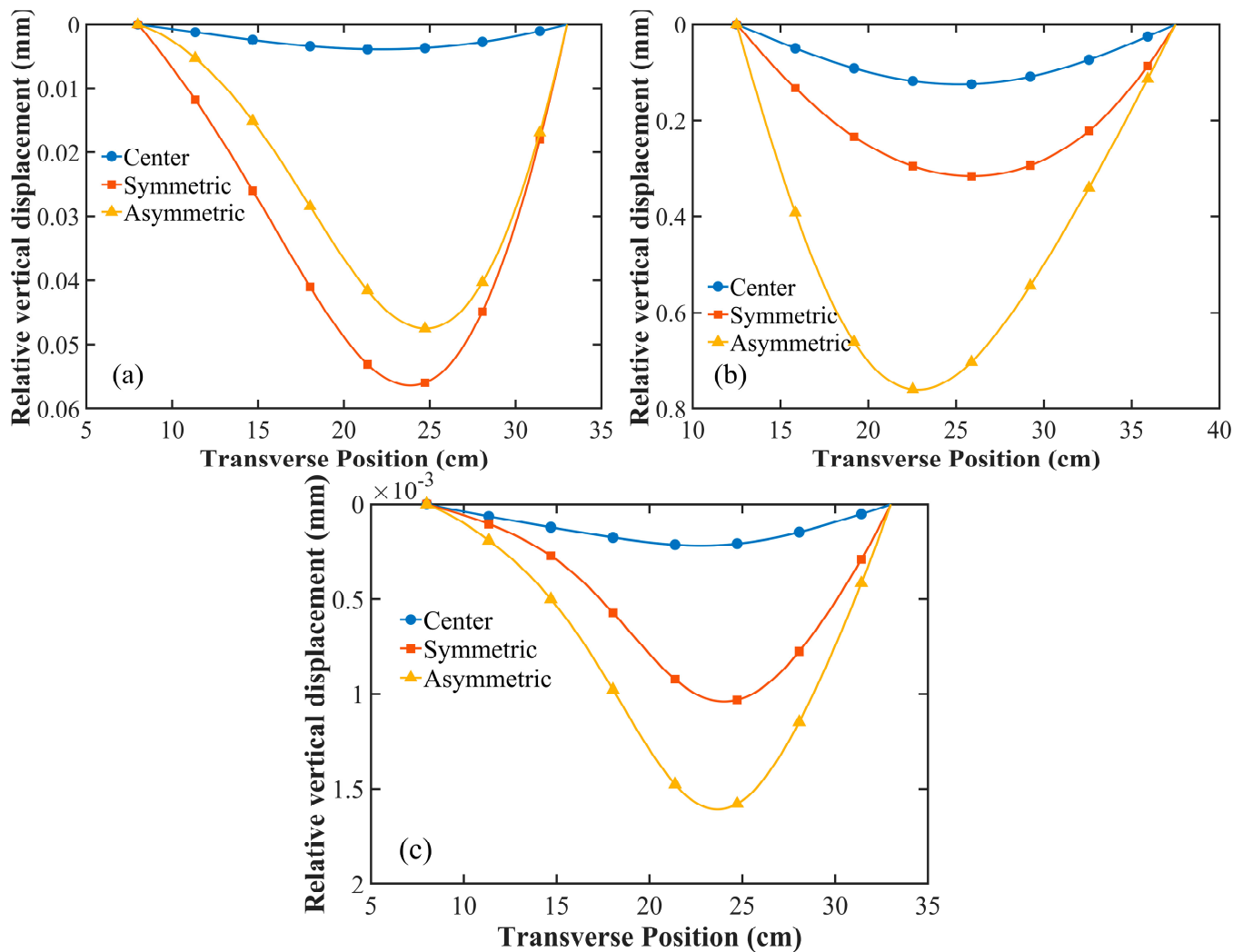


Figure 8. FBG-derived relative vertical displacement curves of transverse sensing lines under different loading cases: (a) SAT1; (b) SAT2; (c) SST. The curves are equivalent bending-related relative deformations and are not direct measurements of densification or shear flow.

The SAT2 displacement results are consistent with the transverse strain results in Section 4.3: asymmetric loading caused the response to concentrate toward the side close to the local loading point. The positions of maximum strain and maximum relative vertical displacement did not completely coincide in all cases, which is expected because the relative vertical displacement curve was obtained after strain–curvature conversion, curvature integration, and linear baseline correction. Compared with SAT1, whose maximum relative vertical displacement under two-point loading was approximately 0.046–0.056 mm, SAT2 reached 0.761 mm under asymmetric two-point loading. This difference mainly reflects the relative position between the loading point and the sensing line rather than the total load.

For SST, the relative vertical displacement amplitude remained much lower than those of SAT1 and SAT2. The maximum value was 0.000217 mm under central single-point loading, 0.001023 mm under symmetric two-point loading, and 0.00160 mm under asymmetric two-point loading. The peak positions under all three loading cases were located at 23 cm, and the magnitudes remained within 10^{-4} – 10^{-3} mm. Thus, SST mainly

reflects amplitude attenuation and inter-case variation trends after load transfer to the soil base layer. Its local peak position should not be used as a primary basis for precise spatial interpretation.

Accordingly, Figure 8 should not be interpreted as direct evidence of either material densification or shear flow. Demonstrating densification would require volumetric strain or density measurements, whereas identifying shear flow would require shear-strain, interface-slip, or full-field displacement measurements; none were acquired. The plotted curve is reconstructed from axial FBG strain under an equivalent bending assumption. It may contain the integrated effect of several physical mechanisms, but the present measurement set cannot separate them.

4.6. Correspondence Between High-Strain Response Zones and FBG-Derived Relative Vertical Displacement Concentration Zones

Temperature-compensated strain and relative vertical displacement provide two complementary interpretations of the same FBG dataset. The former describes the local mechanical response near FBG sensing points, whereas the latter represents the reconstructed relative deformation pattern along the sensing line after strain–curvature conversion, curvature integration, and linear baseline correction.

Clear spatial correspondence was observed in the asphalt-layer sensing lines. For SAL1 under 686 N, the maximum temperature-compensated strain was $1459.39 \mu\epsilon$ at 65 cm, while the maximum relative vertical displacement was 1.079 mm at 63.579 cm; both were concentrated within 60–65 cm. For SAL2 under 686 N, the maximum temperature-compensated strain was $793.13 \mu\epsilon$ at 57 cm, and the maximum relative vertical displacement was 0.583 mm at 57.602 cm. Under asymmetric two-point loading, SAT2 showed the most pronounced transverse correspondence: the maximum temperature-compensated strain was approximately $1699.48 \mu\epsilon$, and the maximum relative vertical displacement was 0.761 mm, both occurring at 22.5 cm.

In contrast, the soil-base sensing lines mainly reflected low-amplitude responses after load transfer. SSL1, SSL2, and SST recorded amplitude variations induced by increasing load or changes in loading mode, but their relative vertical displacement magnitudes were substantially lower than those of the asphalt-layer sensing lines. In particular, the maximum relative vertical displacement of SST under asymmetric two-point loading was only 0.00160 mm, indicating that the transverse loading effect was markedly attenuated after being transferred to the soil base layer. Overall, the correspondence between high-strain response zones and relative vertical displacement concentration zones provides a baseline reference for analyzing response migration and amplitude changes under abnormal conditions.

5. Discussion

5.1. Engineering Implications of Quasi-Distributed FBG Sensing for Multilayer Pavement Monitoring

The results demonstrate the feasibility of using embedded quasi-distributed FBG sensing lines to characterize internal responses in a multilayer pavement structure under controlled loading conditions. Compared with surface observations, the embedded sensing-line layout provides internal strain information along predefined longitudinal and transverse paths, enabling the response characteristics of different structural layers and sensing-line directions to be compared within the same scaled multilayer pavement model.

The longitudinal sensing lines were effective in capturing load-level effects and longitudinal response concentration under central single-point stepwise loading. The stronger responses of SAL1 compared with SAL2 show that the measured strain amplitude is

closely related to the spatial relationship between the loading point and the sensing line. The transverse sensing lines further revealed response redistribution caused by different loading-point arrangements. In particular, SAT2 was sensitive to the eccentric loading effect under asymmetric two-point loading, whereas SAT1 showed a weaker difference between symmetric and asymmetric two-point loading. These results indicate that both sensing-line direction and sensing-line location should be considered when interpreting FBG monitoring data in pavement structures.

The comparison between the asphalt concrete surface layer and the soil base layer provides insight into layer-dependent load transfer. The asphalt-layer sensing lines recorded higher response amplitudes and clearer response concentration, while the soil-base sensing lines mainly reflected low-amplitude responses after load diffusion and attenuation through the upper layers. This difference is consistent with the mechanical role of the asphalt concrete surface layer as the upper load-bearing layer and the soil base layer as the lower supporting layer. Therefore, embedded quasi-distributed FBG sensing lines can extend pavement monitoring from surface condition observation to internal response characterization along sensing paths.

Compared with previous pavement-monitoring studies based on local FBG measurements [10,14] or distributed strain sensing [17], the present study provides synchronized comparisons between longitudinal and transverse sensing lines embedded in the upper and lower pavement layers. Its contribution lies in resolving layer-dependent attenuation, directional differences, and loading-path migration within the same controlled model, together with line-wise relative-deformation reconstruction from quasi-discrete measurements. Because sensing configurations and strain-transfer conditions differ among studies [21,23], the measured amplitudes and attenuation relationships identified here are treated as model-specific intact-state baselines rather than universal values directly applicable to field pavements.

The monitoring information obtained in this study is line-based rather than full-field. The response interpretation depends on the location, direction, and embedding condition of each sensing line. Thus, the results should be regarded as baseline responses under controlled loading conditions, providing comparative data for future studies involving abnormal conditions such as local voids, base weakening, and crack simulation.

5.2. Significance of Relative Vertical Displacement Reconstruction Along Sensing Lines

Temperature-compensated strain describes the local mechanical response near individual FBG sensing points. However, local strain peaks alone cannot fully describe the range and morphology of relative deformation concentration along a sensing line. By converting temperature-compensated strain into equivalent curvature and then applying curvature integration and linear baseline correction, the discrete strain responses were further transformed into relative vertical displacement curves along the sensing lines.

The reconstructed relative vertical displacement provides an integrated representation of relative deformation within the sensing-line range. The quantity $w_c(x)$ represents the relative vertical displacement with respect to the line connecting the two endpoints of the sensing line after linear baseline correction. It should therefore be interpreted as an FBG-derived line-wise relative deformation measure along the FBG sensing line, rather than the absolute vertical displacement measured by an external displacement sensor. This distinction is important because curvature integration and endpoint correction remove rigid-body translation and linear inclination components but do not provide an independent measurement of absolute displacement.

The relative vertical displacement curves complement the temperature-compensated strain results. High-strain response zones describe local mechanical concentration near

FBG sensing points, whereas relative vertical displacement concentration zones describe the spatial range of reconstructed relative deformation. In the asphalt concrete surface layer, the spatial correspondence between these two response types indicates that the reconstructed curves retained the main features of the loading influence zone. In the soil base layer, the low-amplitude relative vertical displacement curves reflected attenuation after downward load transfer and are more suitable for evaluating amplitude trends and inter-case differences than for interpreting local peak positions.

From an engineering perspective, the FBG-derived line-wise relative vertical displacement profiles provide a consistent basis for comparing spatial response migration and amplitude variation across load levels, loading paths, and sensing-line locations. The intact-state profiles established here may serve as reference baselines for future controlled comparisons with abnormal or damaged states; they are not, by themselves, diagnostic criteria or anomaly-detection thresholds.

5.3. Limitations and Future Work

Several limitations should be considered. First, the laboratory model was scaled geometrically, but a complete similitude law for aggregate size, viscoelastic time–temperature behavior, tire-contact footprint, layer stiffness ratios, interface behavior, and load magnitude was not imposed. The steel side plates also create boundary restraint that is stronger and closer to the loading region than in a field pavement. Therefore, measured strain and reconstructed-displacement amplitudes must not be extrapolated directly to full scale. The transferable findings are limited to qualitative within-model trends such as layer attenuation, load-level dependence, and response migration with loading position.

Second, the measurements are line-based rather than full-field. The layout was selected for the prescribed loading comparisons and was not optimized by prior simulation. In particular, the single SST line provides only one lower-layer transverse reference and cannot establish the complete transverse soil-base field. Future layout design should be supported by numerical influence-field analysis and additional transverse lines before spatial localization is attempted.

Third, temperature compensation used the pre-loading and loading stable segments rather than independent temperature measurements at every embedded grating. Residual local thermal differences may therefore influence low-amplitude zones, especially in the soil base and far from the load. Additional embedded reference gratings or multi-point temperature measurements are needed for low-amplitude field applications.

Fourth, representative rather than experimentally measured elastic moduli were used for neutral-axis calculation. Table 4 quantifies the resulting scale sensitivity, but it does not replace material calibration. The reconstruction also depends on a linear through-thickness strain field, equivalent bending, interpolation, double integration, and endpoint correction. No independent LVDT or DIC measurement was available, so the resulting curves are not validated absolute displacements and should be used only for relative comparisons within the sensing-line range.

Future work will combine calibrated material properties, numerical modelling, simultaneous LVDT or DIC measurements, repeated loading, and full-scale or field-scale tests. Local voids, base weakening, and pre-induced cracks will be introduced only in those future experiments and compared with the intact baseline established here. Because no abnormal-condition case was tested in the present study, no void- or crack-detection capability is claimed.

6. Conclusions

In this study, a scaled multilayer pavement model instrumented with embedded quasi-distributed FBG sensing lines was tested under central single-point stepwise loading, symmetric two-point loading, and asymmetric two-point loading. Temperature-compensated strain responses and relative vertical displacement curves along sensing lines were obtained and analyzed. The following conclusions can be drawn.

- (1) The ambient temperature ranged from 22.70 to 23.40 °C during loading, with a maximum temperature difference of 0.70 °C. The maximum relative shift of the T-sensor was 0.008297 nm, and the mean standard deviation of stable segments was 0.000929 nm. These results indicate that the temperature variation and reference wavelength drift remained limited during the tests, supporting temperature compensation and stability assessment.
- (2) Under central single-point stepwise loading, the longitudinal sensing lines in the asphalt concrete surface layer showed clear load-level effects. SAL1, which was close to or passed through the central loading line, exhibited the strongest response and reached 1459.39 $\mu\epsilon$ under 686 N. SAL2 reached 793.13 $\mu\epsilon$ under the same load level. The soil-base sensing lines showed lower response amplitudes, reflecting load diffusion and attenuation during downward load transfer.
- (3) Under a total equivalent load of approximately 490 N, the transverse strain responses were strongly affected by loading-point arrangement and sensing-line location. SAT2 showed the strongest response under asymmetric two-point loading, with a maximum temperature-compensated strain of approximately 1699.48 $\mu\epsilon$. In contrast, SAT1 and SST recorded much lower responses, indicating that eccentric loading mainly affected the sensing line close to the local loading point and that the response was markedly attenuated after transfer to the soil base layer.
- (4) Relative vertical displacement curves were reconstructed through strain–curvature conversion, curvature integration, and linear baseline correction. Under 686 N, the maximum relative vertical displacement reached 1.079 mm for SAL1 and 0.583 mm for SAL2. Under asymmetric two-point loading, SAT2 reached 0.761 mm. The relative vertical displacement amplitudes of the soil-base sensing lines were substantially lower, with SST reaching only 0.00160 mm under asymmetric two-point loading.
- (5) High-strain response zones and FBG-derived relative vertical displacement concentration zones showed spatial correspondence in the asphalt-layer sensing lines. For example, the main response zone of SAL1 was concentrated within 60–65 cm, and SAT2 showed both its maximum strain response and maximum reconstructed relative displacement at 22.5 cm under asymmetric loading. This agreement supports the use of the curves as within-study relative deformation measures, but it is not a substitute for independent displacement validation. The present intact-condition results provide a baseline for future abnormal-condition experiments; void, base-weakening, and crack-detection capabilities were not tested or demonstrated here.

Author Contributions: Conceptualization, H.-P.W. and P.X.; methodology, J.-C.Z. and H.-P.W.; formal analysis, J.-C.Z.; investigation, J.-C.Z., J.R., X.-W.F., K.-W.X.-Y. and J.-K.Z.; data curation, J.-C.Z.; writing—original draft preparation, J.-C.Z.; writing—review and editing, J.R., X.-W.F., K.-W.X.-Y., J.-K.Z., H.-P.W. and P.X.; visualization, J.-C.Z.; supervision, H.-P.W. and P.X.; project administration, H.-P.W.; funding acquisition, H.-P.W. and P.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Provincial Education Department of Gansu, grant number (2024B-005); the Fundamental Research Funds for the Central Universities, grant number (lzujbky-2024-05); the Industrial Support Plan Project of Provincial Education Department of Gansu, grant

numbers (2025CYZC-003 and CYZC-2024-10); and the Scientific Department of Gansu, grant numbers (24CXGA083, 24CXGA024, JK2024-28, JK2024-32, 18YF1GA096 and 23CXJA0007).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank the laboratory members who provided technical support during the experimental work.

Conflicts of Interest: Author Jia Rui was employed by Gansu Institute of Urban and Rural Planning and Design Institute Co., Ltd. Author Xiao-Wei Feng was employed by Gansu Provincial Transportation Science Research Institute Group Co., Ltd. The remaining authors declare no conflicts of interest. The companies were not funders of this study and had no commercial role in the study design, data analysis or interpretation, or the decision to publish. The authors' individual research contributions are reported in the Author Contributions statement.

References

1. Di Graziano, A.; Marchetta, V.; Cafiso, S. Structural health monitoring of asphalt pavements using smart sensor networks: A comprehensive review. *J. Traffic Transp. Eng. (Engl. Ed.)* **2020**, *7*, 639–651. [\[CrossRef\]](#)
2. Kara De Maeijer, P.; Vuye, C.; Blom, J.; Bowers, B.; Van den Bergh, W. Fiber optics sensors in asphalt pavement: State-of-the-art review. *Infrastructures* **2019**, *4*, 36. [\[CrossRef\]](#)
3. Saarenketo, T.; Scullion, T. Road evaluation with ground penetrating radar. *J. Appl. Geophys.* **2000**, *43*, 119–138. [\[CrossRef\]](#)
4. Marecos, V.; Solla, M.; Fontul, S.; Antunes, V. Assessing the pavement subgrade by combining different non-destructive methods. *Constr. Build. Mater.* **2017**, *135*, 76–85. [\[CrossRef\]](#)
5. Alavi, A.H.; Hasni, H.; Lajnef, N.; Chatti, K. Continuous health monitoring of pavement systems using smart sensing technology. *Constr. Build. Mater.* **2016**, *114*, 719–736. [\[CrossRef\]](#)
6. Kersey, A.D.; Davis, M.A.; Patrick, H.J.; LeBlanc, M.; Koo, K.P.; Askins, C.G.; Putnam, M.A.; Friebele, E.J. Fiber grating sensors. *J. Light. Technol.* **1997**, *15*, 1442–1463. [\[CrossRef\]](#)
7. Othonos, A. Fiber Bragg gratings. *Rev. Sci. Instrum.* **1997**, *68*, 4309–4341. [\[CrossRef\]](#)
8. Majumder, M.; Gangopadhyay, T.K.; Chakraborty, A.K.; Dasgupta, K.; Bhattacharya, D.K. Fibre Bragg gratings in structural health monitoring—Present status and applications. *Sens. Actuators A Phys.* **2008**, *147*, 150–164. [\[CrossRef\]](#)
9. López-Higuera, J.M.; Cobo, L.R.; Incera, A.Q.; Cobo, A. Fiber optic sensors in structural health monitoring. *J. Light. Technol.* **2011**, *29*, 587–608. [\[CrossRef\]](#)
10. Imai, M.; Igarashi, Y.; Shibata, M.; Miura, S. Experimental study on strain and deformation monitoring of asphalt structures using embedded fiber optic sensor. *J. Civ. Struct. Health Monit.* **2014**, *4*, 209–220. [\[CrossRef\]](#)
11. Zhou, Z.; Liu, W.; Huang, Y.; Wang, H. Optical fiber Bragg grating sensor assembly for 3D strain monitoring and its case study in highway pavement. *Mech. Syst. Signal Process.* **2012**, *28*, 36–49. [\[CrossRef\]](#)
12. Tan, Y.Q.; Wang, H.P.; Ma, S.J.; Xu, H.N. Quality control of asphalt pavement compaction using fiber Bragg grating sensing technology. *Constr. Build. Mater.* **2014**, *54*, 53–59. [\[CrossRef\]](#)
13. Al-Tarawneh, M.; Huang, Y.; Lu, P.; Bridgelall, R. Weigh-in-motion system in flexible pavements using fiber Bragg grating sensors part A: Concept. *IEEE Trans. Intell. Transp. Syst.* **2020**, *21*, 5136–5147. [\[CrossRef\]](#)
14. Braunfelds, J.; Senkans, U.; Skels, P.; Janeliukstis, R. Road pavement structural health monitoring by embedded fiber-Bragg-grating-based optical sensors. *Sensors* **2022**, *22*, 4581. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Wang, H.-P.; Wu, Y.-B.; Chen, C.; Guo, Y.-X. In-site health monitoring of cement concrete pavements based on optical fiber sensing technology. *J. Road Eng.* **2023**, *3*, 113–123. [\[CrossRef\]](#)
16. Liu, Z.; Cui, B.; Yang, Q.F.; Gu, X.Y. Sensor-based structural health monitoring of asphalt pavements with semi-rigid bases combining accelerated pavement testing and a falling weight deflectometer test. *Sensors* **2024**, *24*, 994. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Hauswirth, D.; Tsirantonaki, D.; Puzrin, A.M. Measuring strain distributions in an asphalt pavement using fibre optic sensors under static loading by test vehicles. *Road Mater. Pavement Des.* **2025**, *26*, 1023–1040. [\[CrossRef\]](#)
18. Wang, H.-P.; Wang, S.-K.; Li, G.-Z.; Gong, X.-S.; Liu, X.-W.; Xiang, P. Improved optical fiber sensors specially designed for monitoring multiple parameters of asphalt pavements in cold regions. *IEEE Sens. J.* **2026**, *26*, 3860–3871. [\[CrossRef\]](#)
19. Meng, L.; Zhong, K.; Sun, M. A research on low modulus distributed fiber optical sensor for asphalt pavement strain monitoring. *Sensors* **2017**, *17*, 2386. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Wang, H.P.; Liu, W.Q.; He, J.P.; Xing, X.Y.; Cao, D.D. Functionality enhancement of industrialized optical fiber sensors and system developed for full-scale pavement monitoring. *Sensors* **2014**, *14*, 8829–8850. [\[CrossRef\]](#) [\[PubMed\]](#)

21. Liu, W.Q.; Wang, H.P.; Zhou, Z.; Xing, X.Y.; Cao, D.D. Optical fiber-based sensors with flexible encapsulation for pavement behavior monitoring. *Struct. Control Health Monit.* **2015**, *22*, 301–313. [[CrossRef](#)]
22. Wang, H.P.; Xiang, P. Strain transfer analysis of optical fiber based sensors embedded in an asphalt pavement structure. *Meas. Sci. Technol.* **2016**, *27*, 075106. [[CrossRef](#)]
23. Li, G.Z.; Wang, H.P.; Zhou, J.C.; Liu, Y.H.; Guo, Y.Q.; Dai, J.G. Theoretical model updating on interfacial degradation and transfer mechanisms of multi-layer pavement structures based on FBG monitoring information in field. *Measurement* **2026**, *278*, 121628. [[CrossRef](#)]
24. Hou, Z.; Cao, D.; Peng, P.; Ding, X. Analysis of strain transfer characteristics of fiber Bragg gratings for asphalt pavement health monitoring. *Materials* **2025**, *18*, 3489. [[CrossRef](#)] [[PubMed](#)]
25. Guo, T.; Guo, X.; Chen, Y.; Fang, C.; Yang, J.; Li, Z.; Feng, J.; Kong, J.; Chen, H.; Wang, J. Study on the Adaptability of FBG Sensors Encapsulated in CNT-Modified Gel Material for Asphalt Pavement. *Gels* **2025**, *11*, 590. [[CrossRef](#)] [[PubMed](#)]
26. Deng, Z.; Huang, M.; Wan, N.; Zhang, J. The current development of structural health monitoring for bridges: A review. *Buildings* **2023**, *13*, 1360. [[CrossRef](#)]
27. Bao, X.; Chen, L. Recent progress in distributed fiber optic sensors. *Sensors* **2012**, *12*, 8601–8639. [[CrossRef](#)] [[PubMed](#)]
28. Barrias, A.; Casas, J.R.; Villalba, S. A review of distributed optical fiber sensors for civil engineering applications. *Sensors* **2016**, *16*, 748. [[CrossRef](#)] [[PubMed](#)]
29. Senkans, U.; Silkans, N.; Merijs-Meri, R.; Haritonovs, V.; Skels, P.; Porins, J.; Lima, M.S.S.; Spolitis, S.; Braunfelds, J.; Bobrovs, V. Fiber-Optical-Sensor-Based Technologies for Future Smart-Road-Based Transportation Infrastructure Applications. *Photonics* **2026**, *13*, 106. [[CrossRef](#)]
30. Keshmiry, A.; Hassani, S.; Mousavi, M.; Dackermann, U. Effects of environmental and operational conditions on structural health monitoring and non-destructive testing: A systematic review. *Buildings* **2023**, *13*, 918. [[CrossRef](#)]
31. Posenato, D.; Lanata, F.; Inaudi, D.; Smith, I.F.C. Model-free data interpretation for continuous monitoring of complex structures. *Adv. Eng. Inform.* **2008**, *22*, 135–144. [[CrossRef](#)]
32. Farrar, C.R.; Worden, K. An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical. Phys. Eng. Sci.* **2007**, *365*, 303–315. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.