RaySensing

Structural Strain and Deflection Monitoring of Jinhai Bridge Using Ultra-Weak Fiber Bragg Grating Arrays

A professional application case article for long-span road-rail cable-stayed bridge health monitoring

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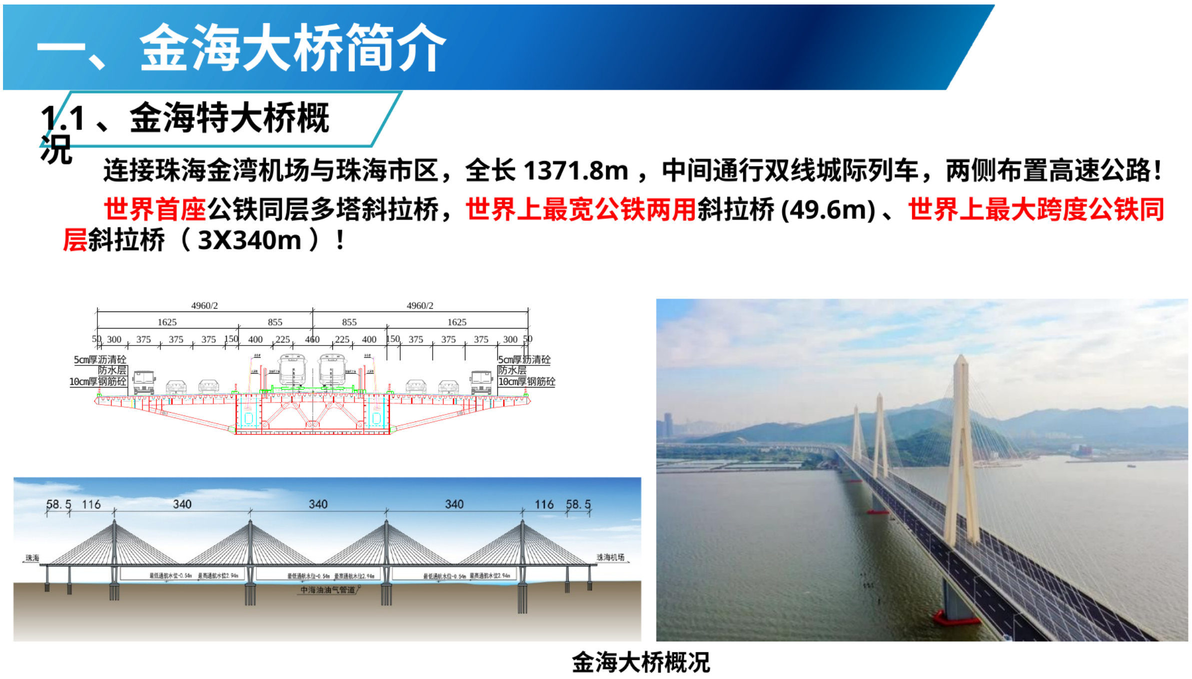
This article consolidates the provided Jinhai Bridge monitoring materials into an English case-study format suitable for a website download library. It explains the bridge context, the ultra-weak fiber Bragg grating (UW-FBG) sensing approach, the sensor cable design and installation, static and dynamic strain monitoring results, and strain-to-deflection inversion performance.

Project object	Jinhai Bridge, Zhuhai, China - 1,371.8 m total length, same-level road-rail multi-tower cable-stayed bridge.
Monitoring span	The 340 m span between Tower 1 and Tower 2, focused on the first span under static load testing and operational traffic conditions.
Sensing technology	Ultra-weak FBG array with high-density quasi-distributed strain sensing and temperature compensation.
Key output	Distributed strain field acquisition and deflection inversion under static and dynamic loading.



一、金海大桥简介

1.1 、金海特大桥概况

连接珠海金湾机场与珠海市区，全长 1371.8m ，中间通行双线城际列车，两侧布置高速公路!

世界首座公铁同层多塔斜拉桥，世界上最宽公铁两用斜拉桥 (49.6m) 、世界上最大跨度公铁同层斜拉桥（ 3X340m ）！

金海大桥概况

Figure 1. Jinhai Bridge overview: a same-level road-rail, multi-tower cable-stayed bridge with three 340 m main spans and a 49.6 m deck width.

1. Executive Summary

Jinhai Bridge is a technically demanding monitoring target because it combines road and rail traffic on the same deck, a very wide cross-section, and multiple long cable-stayed spans. For such structures, conventional point sensors can miss spatially distributed strain patterns, while manual inspections cannot provide the temporal resolution needed to distinguish static load effects, train passage, highway traffic and localized structural responses.

The presented solution deploys ultra-weak fiber Bragg grating arrays along the box girder to acquire a dense strain field across the monitored span. Four monitoring channels are arranged on the left web, bottom slab and right web, with approximately one sensing grating per metre over planned 320 m runs. The system therefore converts the bridge girder into a high-resolution sensing structure, allowing strain distributions to be captured along the span and further converted into deflection profiles through an inversion algorithm.

Primary value delivered:

- High-density field monitoring rather than isolated point measurement.
- Simultaneous visibility of static load response, operating-period response and short-duration dynamic events.
- Deflection inversion from distributed strain, reducing dependency on separate deflection instruments for every monitoring scenario.
- A scalable architecture suitable for long-span bridges and continuous structural health monitoring platforms.

2. Bridge Context and Monitoring Objectives

Jinhai Bridge connects Zhuhai Jinwan Airport with the urban area of Zhuhai. The bridge is 1,371.8 m long. Its central zone carries a double-track intercity railway, while highway lanes are arranged on both sides. According to the project material, it is the world's first same-level road-rail multi-tower cable-stayed bridge, the widest road-rail cable-stayed bridge at 49.6 m, and the largest-span same-level road-rail cable-stayed bridge with three 340 m spans.

The monitoring objective was to observe stress and strain variation in the first span during static load testing and operational service, and to capture the structural influence of dynamic loads on the bridge in real time. The monitored region was located between Tower 1 and Tower 2 over a 340 m span. This region is representative because it experiences combined effects from long-span girder behaviour, rail traffic, road traffic and cable-stayed load paths.

一、金海大桥简介

1.2 、金海特大桥的应变及挠度监测区域

目标：监测金海特大桥第一跨静载及运营时的应力应变变化，实时捕捉动载荷对桥梁的结构的影响

金海大桥实景

1# 和 2# 塔柱之间 340 m 跨度上的光缆及设备布设

金海大桥横断面图

桥梁箱梁内部

Figure 2. Target monitoring area: the 340 m span between Tower 1 and Tower 2, including cross-section and cable placement region inside the box girder.

3. Ultra-Weak FBG Array Technology

The sensing approach uses a large number of low-reflectivity fiber Bragg grating sensors written into a single optical fiber. Each grating has reflectivity below 0.1%, enabling large-capacity multiplexing while reducing shadowing and multiple-reflection effects that can limit conventional FBG arrays. In this application, the technology is used for high-density strain measurement and temperature compensation along structural members.

Compared with isolated point sensing, ultra-weak FBG arrays provide quasi-distributed and distributed measurement capability. The bridge application benefits from this because the structural response is not uniform: strain peaks, neutral-axis effects, cable-stayed support conditions and local traffic loads vary along the span. Dense spatial sampling enables the monitoring system to describe the complete strain field rather than only selected local points.

Technology advantages relevant to this case:

- Large sensing capacity for long bridge spans and high spatial density.
- High signal-to-noise performance for engineering environments.
- Multi-parameter expansion potential, including strain, temperature, vibration and deformation-related monitoring.
- Compatibility with compact demodulation hardware and real-time data processing workflows.

4. Monitoring System Design

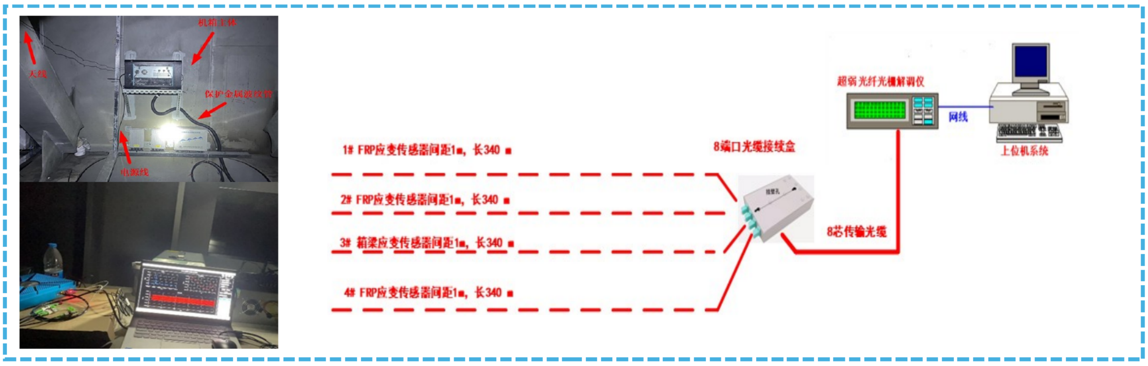
The Jinhai Bridge monitoring system adopted four sensing channels. Two were positioned on the left web plate at 1.5 m and 2.2 m locations, one was positioned on the bottom slab, and one was positioned on the right web plate at 1.5 m. Each channel was planned for approximately 320 m, with one grating point per metre. The resulting layout allowed the system to compare different structural positions while preserving a continuous view of the spanwise strain distribution.

The field architecture consists of the ultra-weak FBG array cables, optical connection hardware, an ultra-weak FBG demodulator and an upper-computer monitoring platform. This arrangement supports real-time acquisition, channel management, sensor positioning and later analysis of strain-field evolution.

三、应变场监测

3.1 金海特大桥监测系统设计

4 个监测通道，箱梁左腹板 1.5m 、 2.2m 位置各 1 条，底板 1 条，右腹板 1.5m 位置 1 条，每条规划 320m ， 每米 1 各栅点!



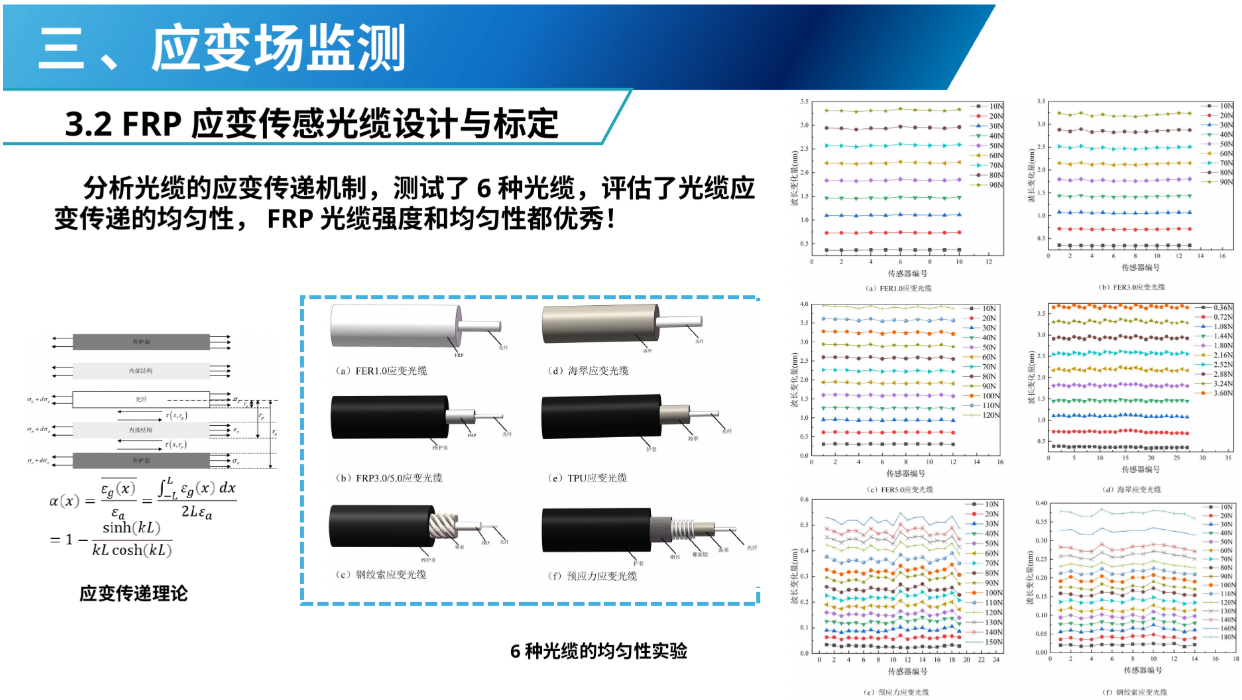
金海特大桥光栅阵列监测系统

Figure 3. Ultra-weak FBG array monitoring system design with four channels across the left web, bottom slab and right web.

5. Sensor Cable Design, Calibration and Installation

The project evaluated the strain transfer mechanism of different sensing cable structures. Six cable types were tested to assess transfer uniformity. The FRP-based sensing cable showed strong performance in both mechanical strength and uniformity, making it suitable for bridge girder installation. For the bottom slab, the selected structure combined weak grating fiber, FRP reinforcement, steel strand twisting and a PE sheath. The reported strain transfer efficiency was 1.1 pm per microstrain, with a temperature drift coefficient of 22.4 pm per deg C.

Installation quality is crucial for strain-field monitoring. The bottom slab surface was prepared by removing rust and cleaning dust and residue. The sensing cable was then pre-laid and tensioned to avoid twist-induced stress or fiber breakage. Carbon-fiber cloth was cut to section length, epoxy adhesive was mixed at a 2:1 ratio, and the cable was covered and consolidated with adhesive and roller pressure to ensure tight bonding without bubbles. After installation, red-light continuity testing and grating-point verification were performed before trial operation.



三、应变场监测

3.2 FRP 应变传感光缆设计与标定

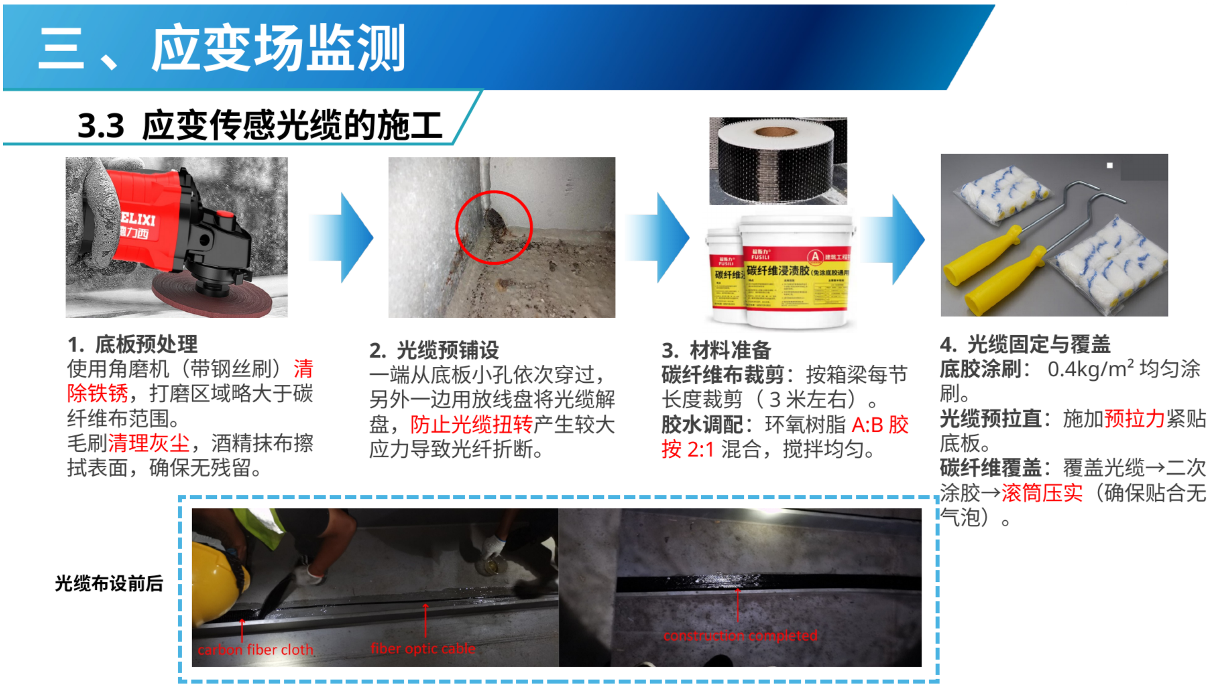
分析光缆的应变传递机制，测试了 6 种光缆，评估了光缆应变传递的均匀性， FRP 光缆强度和均匀性都优秀！

$$\alpha(x)=\frac{\overline{\varepsilon_g(x)}}{\varepsilon_a}=\frac{\int_{-L}^{L}\varepsilon_g(x)\,dx}{2L\varepsilon_a}=1-\frac{\sinh(kL)}{kL\cosh(kL)}$$

应变传递理论

6 种光缆的均匀性实验

Figure 4. FRP strain-sensing cable design and calibration. Six cable structures were compared to evaluate strain transfer uniformity and robustness.



三、应变场监测

3.3 应变传感光缆的施工

1. 底板预处理
使用角磨机（带钢丝刷）清除铁锈，打磨区域略大于碳纤维布范围。
毛刷清理灰尘，酒精抹布擦拭表面，确保无残留。

2. 光缆预铺设
一端从底板小孔依次穿过，另外一边用放线盘将光缆解盘，防止光缆扭转产生较大应力导致光纤折断。

3. 材料准备
碳纤维布裁剪：按箱梁每节长度裁剪（3 米左右）。
胶水调配：环氧树脂 A:B 胶按 2:1 混合，搅拌均匀。

4. 光缆固定与覆盖
底胶涂刷：0.4kg/m² 均匀涂刷。
光缆预拉直：施加预拉力紧贴底板。
碳纤维覆盖：覆盖光缆→二次涂胶→滚筒压实（确保贴合无气泡）。

光缆布设前后

Figure 5. Field installation workflow for the bottom slab sensing cable, including surface preparation, cable pre-laying, material preparation, bonding and protection.

6. Strain Monitoring Results: Static Load and Operational Dynamics

Static load testing in November 2023 demonstrated that the distributed strain field reflected the bridge response under controlled loading. At a selected moment, the strain profiles from the left web, bottom slab and right web showed different spatial patterns, consistent with the structural position and load path. The testing results indicated that the strain gradually decreased as the train moved from the midspan region toward the span end, matching the expected working condition.

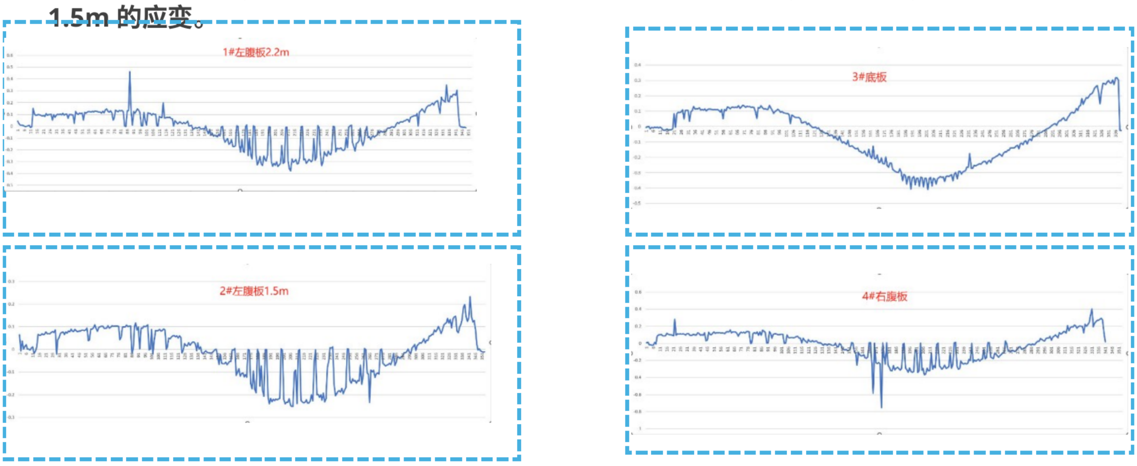
Operational monitoring between May 18 and June 18, 2024 further showed that strain magnitude and distribution varied by time and load type. The system could distinguish whether the corresponding time window was dominated by train movement or automobile traffic, providing a basis for load-state identification and long-term structural behaviour evaluation.

Dynamic strain monitoring captured the bridge response within an 8-second interval. The whole-span dynamic strain distribution and selected sensor traces at positions such as No. 60, No. 160 and No. 240 reveal the transient propagation of structural response under moving loads.

三、应变场监测

3.5 静载应变数据采集试采

2023.11 静载测试，某时刻左 1# 腹板 1.5m 、 2# 腹板 2.2m 应变， 3# 底板，右侧腹板 1.5m 的应变。



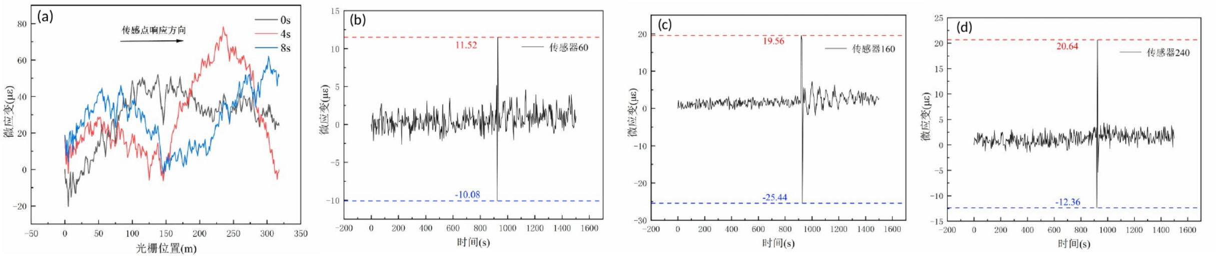
静载某时刻的应变

Figure 6. Static strain acquisition during the November 2023 load test across four monitored positions.

三、应变场监测

3.6 动态应变数据采集

8s 时间内，动载作用下桥梁的响应
(a) 桥梁主跨整体过程应变分布； (b) 同一时刻 60# 传感器； (c) 同一时刻 160# 传感器； (d) 同一时刻 240# 传感器。



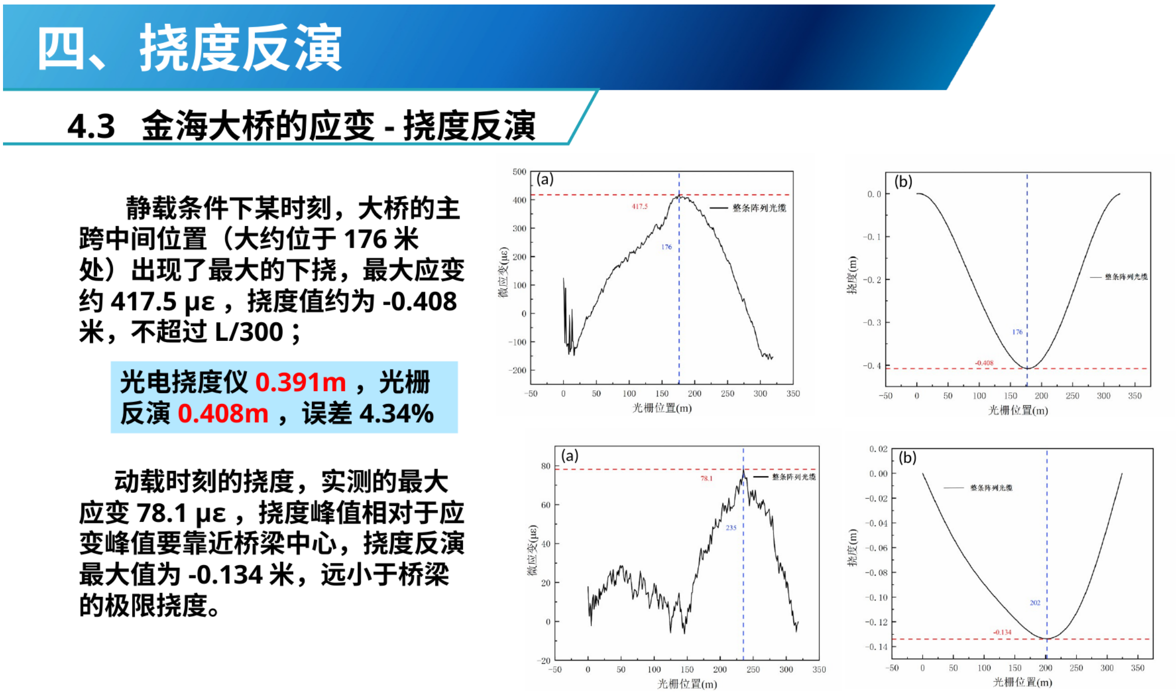
某时刻的动态应变

Figure 7. Dynamic strain response of the bridge over an 8-second interval, including the whole-span strain distribution and selected sensor positions.

7. Strain-to-Deflection Inversion

When the optical fiber and the continuous elastic structure deform together, the measured strain field can be used to reconstruct the deformation curve. The project material describes a tangent-angle recursive inversion method, supported by laboratory validation on a simply supported beam. This creates a bridge between distributed strain measurement and deflection evaluation, which is particularly valuable for long-span bridges where direct deflection measurement is difficult to deploy over every critical position.

For Jinhai Bridge, the static-load inversion indicated that the largest downward deflection occurred near the middle of the main span, approximately 176 m along the span. The maximum strain was about 417.5 microstrain, and the inverted deflection was about -0.408 m, which did not exceed L/300. The optoelectronic deflectometer reported 0.391 m, while the grating-based inversion produced 0.408 m, corresponding to an error of 4.34%. Under dynamic loading, the measured maximum strain was 78.1 microstrain, and the maximum inverted deflection was -0.134 m, far below the bridge limit deflection.



四、挠度反演

4.3 金海大桥的应变 - 挠度反演

静载条件下某时刻，大桥的主跨中间位置（大约位于 176 米处）出现了最大的下挠，最大应变约 417.5 με，挠度值约为 -0.408 米，不超过 L/300；

光电挠度仪 0.391m，光栅反演 0.408m，误差 4.34%

动载时刻的挠度，实测的最大应变 78.1 με，挠度峰值相对于应变峰值要靠近桥梁中心，挠度反演最大值为 -0.134 米，远小于桥梁的极限挠度。

Figure 8. Strain-to-deflection inversion results: static and dynamic deflection profiles derived from the distributed strain field.

8. Engineering Value and Application Significance

This case demonstrates how ultra-weak FBG arrays can upgrade bridge health monitoring from isolated measurements to continuous strain-field sensing. The technology is especially suitable for long-span, wide-deck and multi-load-path bridges where structural response varies significantly across position and time.

Key application benefits include:

- Spatial completeness: dense sensing points help reveal strain distribution along the span, including midspan behaviour and local response differences between web plates and bottom slab.
- Load-state visibility: static load, train passage and road-traffic effects can be interpreted from the strain-field evolution.
- Deflection insight: distributed strain can be transformed into deflection information, enabling additional structural assessment without relying solely on separate deflection instrumentation.
- Maintainability: a fiber-based sensing network is suitable for long-term deployment in bridge boxes and complex civil infrastructure environments.

- Scalability: the architecture can be extended to multi-span monitoring, cable force-related analysis, fatigue evaluation and digital twin platforms.

9. Additional Recommendations for Website Resource Deployment

For use in an independent website download library, the case should not be positioned merely as a project note. It is more effective to present it as a reference application article showing how RaySensing technology supports long-span bridge monitoring. The following metadata and resource configuration are recommended.

Recommended resource title	Jinhai Bridge Structural Health Monitoring with Ultra-Weak FBG Arrays
SEO description	A technical application case on distributed strain-field monitoring and deflection inversion for a long-span road-rail cable-stayed bridge using ultra-weak fiber Bragg grating arrays.
Suggested keywords	ultra-weak FBG, UW-FBG, bridge health monitoring, distributed strain sensing, deflection inversion, cable-stayed bridge, structural monitoring
Recommended CTA	Contact RaySensing to discuss long-span bridge strain, temperature, vibration and deflection monitoring requirements.
Download filename	jinhai-bridge-uwfbg-structural-monitoring-case.pdf

10. Conclusion

The Jinhai Bridge case confirms the practical value of ultra-weak FBG array technology for large civil infrastructure. By combining dense strain sensing, engineered sensor cable design, robust installation practice, static and dynamic data acquisition, and strain-to-deflection inversion, the system provides a comprehensive monitoring method for long-span bridge operation and safety assessment. It also provides a replicable technical route for future smart bridge monitoring projects that require high-density sensing, long-distance coverage and actionable structural insight.

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