

# Activities About Applying Distributed Optical Fiber Sensors to Analyze the Internal Structure of Road Pavements

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## ABSTRACT

Structural health monitoring (SHM) using distributed optical fiber sensors (DOFS) is actively conducted in civil engineering and aviation fields. One such activity is establishing road infrastructure that supports mobility services by embedding DOFS in the pavement to capture vibrations from moving entities such as pedestrians and vehicles. Road pavements consist of multiple layers, including asphalt and gravel layers, with different physical properties, such as elastic modulus and density for each layer. While it is easy to evaluate amplitude values and surface temperature using sensors quantitatively, it is challenging to install sensors within the pavement, and few activities allow for quantitative evaluations. On the other hand, DOFS exhibit excellent workability, allowing them to be easily embedded within the internal structure of road pavements, which holds the potential for understanding the internal structure through measurement. Distributed acoustic sensing (DAS) is one measurement technology that uses optical fibers. It can measure the elongation strain applied to the optical fiber over its entire length at a high sampling rate of up to several kHz. Verifying the quantitative nature of DAS is crucial for enhancing the detection accuracy of moving entities. The authors focused on the Falling weight deflectometer (FWD) test, which is commonly used to determine the elastic modulus of road pavements. They comprehensively evaluated the measurement values obtained from the FWD test in conjunction with those from DAS.

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## **INTRODUCTION**

In structural health monitoring, sensors play a crucial role in assessing the condition of structures by monitoring physical quantities such as strain and displacement. Various types of sensors exist, tailored to specific structures and applications. Among these, distributed optical fiber sensors are increasingly popular because they can measure along the entire fiber length, allowing for multi-point measurements. These sensors have long lifespans because of their corrosion resistance [1]. Their excellent processability facilitates stable installation and evaluation in challenging environments like road pavements. To validate the effectiveness of the analytical and measurement methods for studying the dynamics of road pavements, we embedded optical fibers in a road pavement mock-up to investigate how vibrations propagate during service. By analyzing these vibration characteristics, we will be able to detect the movements of vehicles and pedestrians in real-time and predict their future trajectories. This capability will support the development of safe autonomous driving systems and help estimate vehicle weight, which is essential for identifying overloaded vehicles and enforcing traffic restrictions. Ultimately, this will lead to more effective road maintenance strategies. In Japan, the asphalt layer of road pavements is typically several tens of centimeters thick and exhibits rheological properties, including a high-temperature dependence of the elastic modulus. Consequently, even with the same load applied at the exact location, the responses in strain and deflection can vary significantly from one season to another. This study aims to embed optical fiber sensors within road pavements and employ a distributed acoustic sensor (DAS) system to capture the dynamic strain behavior throughout the season.

## **ABOUT THE DAS SYSTEM**

The DAS system measures vibrations (dynamic strain) that occur along the optical fiber sensor in a distributed manner [2][3]. When light from a light source is injected into the optical fiber sensor, it travels through the fiber while undergoing refraction. At each reflection point, backscattered light is generated and moves in the opposite direction to the original light path. By detecting this backscattered light with a detector, it is possible to obtain vibration information at the points of refraction. If there are changes in the optical fiber cable, the characteristics of the backscattered light will also change, allowing for the monitoring of environmental changes surrounding the optical fiber cable. Backscattered light can be classified into three types based on intensity and wavelength: Raman scattering, Brillouin scattering, and Rayleigh scattering. The DAS system utilizes Rayleigh scattering, where vibrations cause slight elongation and contraction along the length of the optical fiber cable. DAS detects the phase shift of the backscattered light that occurs during these changes. The use of this DAS system for monitoring the structural conditions of road pavements is expanding [4][5]. Relevant literature discusses methods for embedding optical fibers.

## **ABOUT A MOCK-UP OF ROAD PAVEMENT**

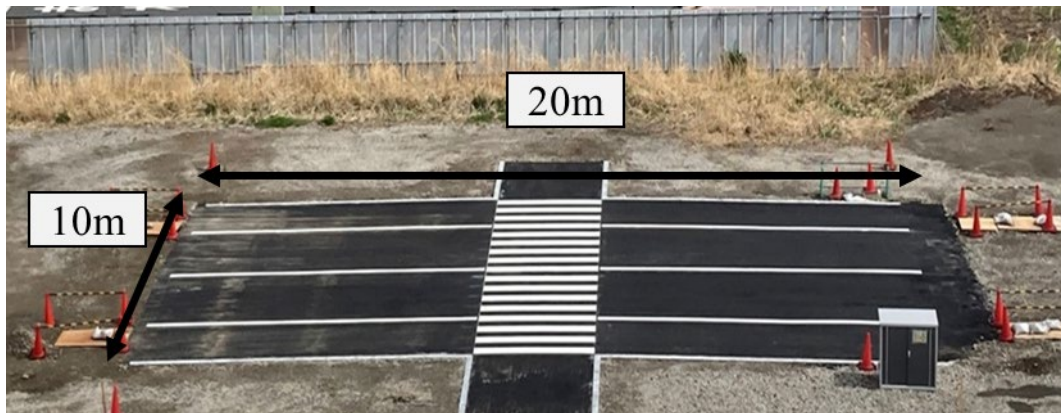
We created a mock-up of road pavement embedded with optical fibers to investigate behaviors within the road pavement. Figure 1 shows an overview of the construction process. The road pavement consisted of five layers, including the subgrade: a lower

layer roadbed (hereafter referred to as roadbed (lower)) of RC-40, an upper layer roadbed (hereafter referred to as roadbed (upper)) of recycled asphalt, a base layer, and a surface layer made of mixed asphalt. We created grooves in each layer to install the optical fibers, using indoor cables made by Sumitomo Electric.



(a) View of construction

(b) Installation of optical fiber



(c) At the time of completion of construction

Figure 1. Road pavement overview

## FWD TEST

The Falling Weight Deflectometer (FWD) is a type of non-destructive testing widely used in Japan to evaluate the condition of road pavement structures [6]. This test involved attaching displacement sensors to the surface and measuring the deflection caused by the weight as it fell to the ground. Based on the acquired data, the Back Analysis for Layer Moduli (BALM) software estimated the elastic modulus [7]. This software used a forward analysis tool called General Analysis of Multi-layered Elastic Systems (GAMES) to verify whether the calculated elastic modulus corresponded with the measured deflection [8]. The following equations define the evaluation function and degree of agreement used in BALM. Initial values were assumed arbitrarily, and the parameters were determined to minimize the difference between the analyzed and measured deflection, thereby maximizing the degree of deflection agreement. In this formula,  $N$  is the number of sensors (up to a maximum of 10),  $u_i$  is the measured deflection at sensor position  $i$ , and  $z_i$  is the analyzed deflection at sensor position  $i$ .

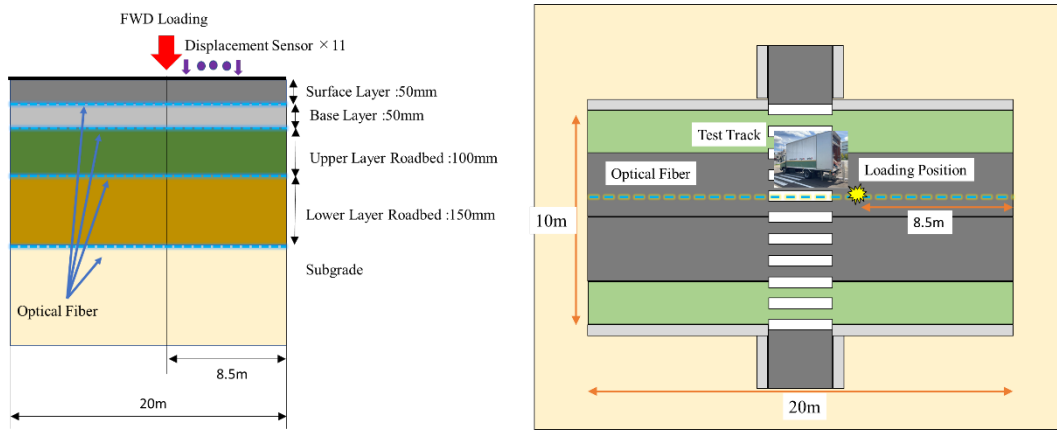
$$\text{Evaluation function} = \sqrt{\frac{\sum_{i=1}^N (u_i - z_i)^2}{N}} \quad (1)$$

$$\text{Deflection agreement} = 1 - \left| \frac{u_i - z_i}{u_i} \right| \quad (2)$$

We utilized a loading condition of 5 tons in the test. We installed deflection sensors at the positions indicated in TABLE I, with the 0m mark representing the loading position. Figure 2 displays the cross-sectional and plain views of the road pavement mock-up, while Figure 3 illustrates the measurement setup.

TABLE I. TEST CONDITIONS

Exciting Force [tf]	Measurement Point [cm] (Deflection Sensor)
5	0, 20, 30, 45, 60, 75, 90, 120, 150, 200



(a) Cross-section of road pavement

(b) The location of the equipment

Figure 2. Test overview



(a) FWD test track

(b) The scene of monitoring

Figure 3. Test overview (pictures)

TABLE II shows the implementation dates and the number of tests conducted. Additionally, the measurement parameters for the DAS are shown in TABLE III. The strain derived from the spatial resolution corresponds to the strain derived from the gauge length in strain gauges. To ensure that the dynamic strain response caused by the falling weight impact is accurately captured, the measurement interval was set finely at 1000 Hz. Both the sampling resolution and spatial resolution were set to the highest possible resolution, as specified by the analyzer's settings.

TABLE II. IMPLEMENTATION DATES AND NUMBER OF TESTS CONDUCTED

Implementation Dates	6/14/2025	10/17/2024	2/18/2025
Number of tests conducted	8	8	12

TABLE III. MEASUREMENT PARAMETERS (DAS)

Measurement Interval [Hz]	1000
Sampling resolution [m]	1.0
Spatial resolution [m]	2.0

## RESULTS

TABLE IV presents the calculated elastic modulus results obtained from loading and average analysis at various times by BALM. The surface layer and base layer were considered the same for evaluation purposes, as they were composed of nearly identical asphalt materials. In this case, the initial values of BALM were set to be constant regardless of the season. The elastic modulus tended to decrease as one moved deeper into the layers. Figure 4 shows the results of plotting each layer, where the y-axis represents the elastic modulus calculated using BALM based on the deflection values measured by FWD, and the x-axis represents the surface pavement temperature using a radiation thermometer. While the base layer, the roadbed (upper), and the roadbed (lower) exhibited a consistent correlation with surface temperature, the subgrade was less affected by changes in surface temperature. Furthermore, due to the absence of temperature dependency in the constituent materials, the subgrade showed minimal variation throughout the year.

TABLE IV. THE RESULT OF THE ELASTIC MODULUS (AVERAGE)

	Surface Layer	Base Layer	Roadbed (upper)	Roadbed (lower)	Subgrade
6/14/2024 [MPa]	2180	2180	1630	1270	210
10/17/2024 [MPa]	4440	4400	3160	2530	210
2/18/2025 [MPa]	4230	4230	3220	1750	212

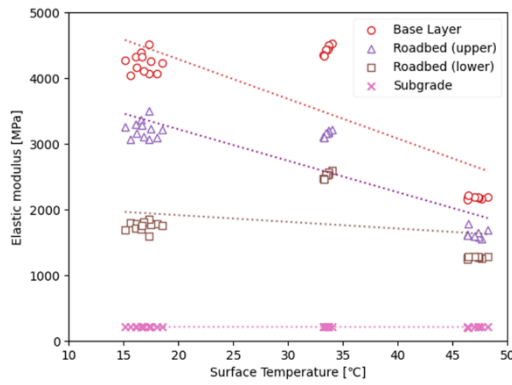
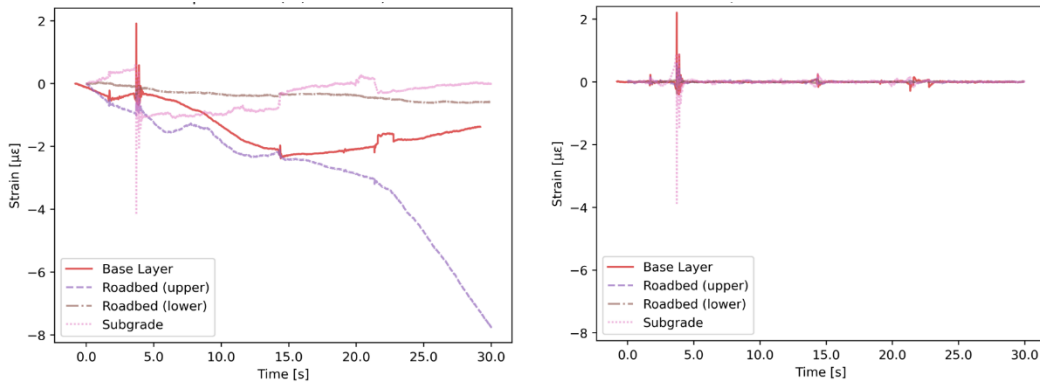


Figure 4. The relationships between surface temperature and elastic modulus

Figure 5 shows part of the measurement results obtained from the optical fiber sensors during the loading process. The vertical axis represents strain, while the horizontal axis represents measurement time. Figure 5(a) shows the raw data that was obtained. Since low-frequency strain drift was observed, a 0.5Hz Butterworth filter was applied to mitigate this drift, as shown in Figure 5(b).



(a) Measurement results (raw)

(b) Measurement results (filtered)

Figure 5. Measurement results overview

Next, Figure 6 presents the measurement results plotted for each layer at the loading position for each measurement period. The response time due to loading was very short, so the data was plotted on an expanded scale. The results showed similar behavior across all layers at each measurement period. Additionally, the response from the subgrade was observed to be in the direction of compression.

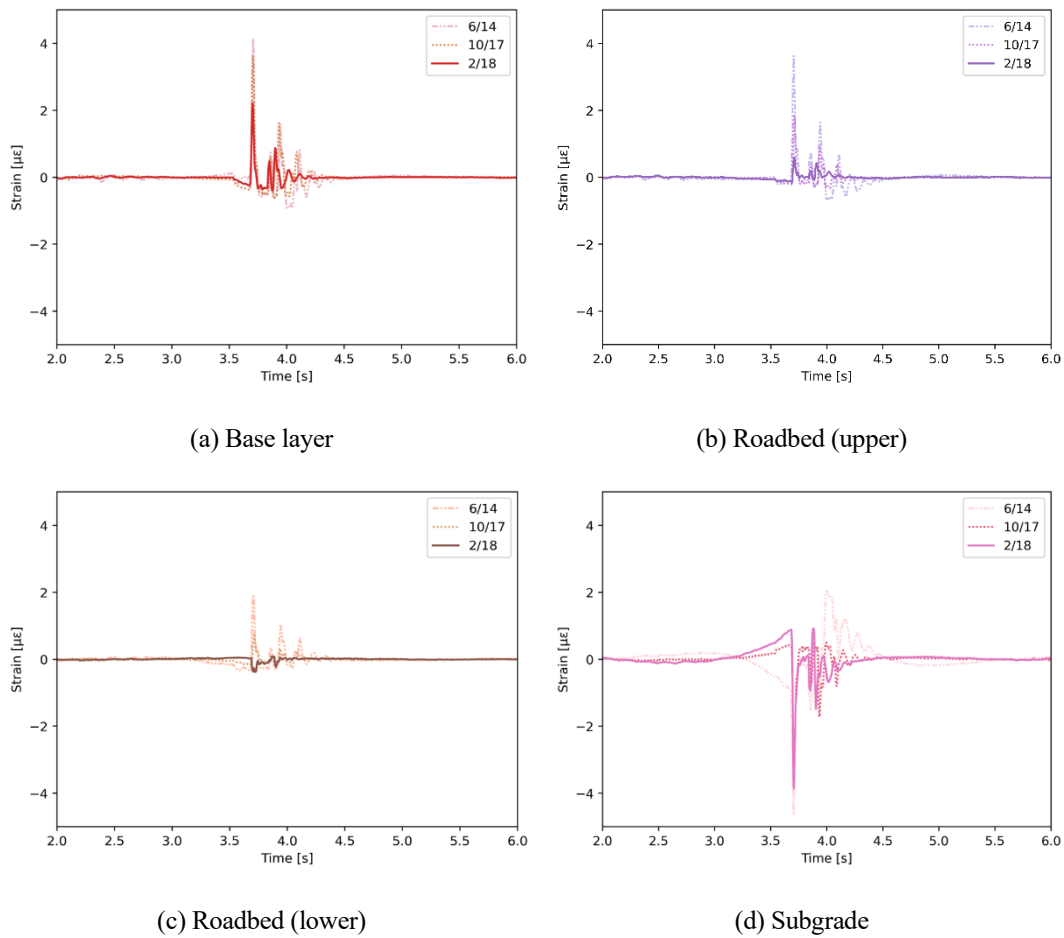


Figure 6. Measurement results

Figure 7 illustrates the relationship between the strain generated during loading and the surface layer temperature for each test. Similar to the evaluation using BALM, optical fiber measurements showed a correlation between strain and surface temperature in the base layer, the roadbed (upper), and the roadbed (lower). At the same time, the subgrade was found to have no temperature dependency. Additionally, the applied load during testing was constant throughout the year, assuming the structural changes were within the elastic range, the elastic modulus and strain in each layer exhibited a roughly consistent correlation. In other words, it can be inferred that the strain obtained through the optical fiber corresponded to the elastic modulus calculated using BALM.

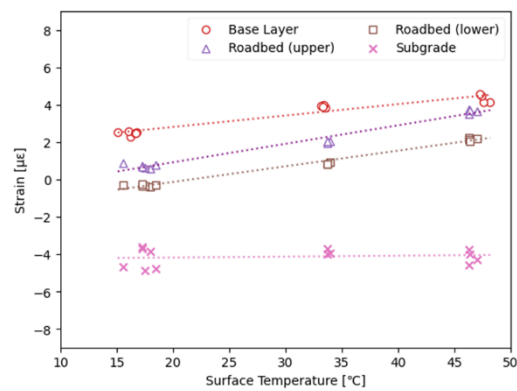


Figure 7. The relationships between surface temperature and loading strain

## CONCLUSIONS

We created a mock-up embedded with optical fiber sensors to investigate the seasonal variability of road pavement. We conducted the FWD test, a widely used method in Japan for evaluating the structural integrity of road pavements, to assess the strain response of each pavement layer under loading. We expected the strain response to decrease as the elastic modulus of asphalt increased with lower temperatures. It was confirmed that layers other than the subgrade exhibited a consistent correlation between surface temperature and strain, whereas the subgrade showed no correlation. In the future, if we confirm a consistent correlation between road temperature and strain response for lower loading cases, such as those from vehicles and pedestrians, we will be able to predict strain generated from the temperature history of the road pavement. This capability would facilitate the detection of vehicle and pedestrian movements, leading to more rational maintenance and management of road pavements.

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