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Development of deflection measurement method using smart cables with distributed fiber optic sensors

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Abstract. The monitoring behavior of civil engineering structures under and after construction secures the quality and safety of structures. There is a possibility that spot measurements, which were frequently adopted in the past, fail to notice local deformation generated in non-measured points and such local deformation is sometimes generated in the ground and the concrete. Therefore, we paid attention to displacement measurement technology using fiber optic sensors capable of performing the distributed measurement. We considered measuring long civil engineering structures with a displacement accuracy of ±1 mm and conducted demonstration experiments to investigate this feasibility. In the experiment, we utilized 3DSensors (45 m and 170 m) that have the sufficient characteristic for application to civil engineering structures, such as high workability for the ground and structures and the actual achievements of field experiments, and the TW-COTDR system capable of performing measurements with high accuracy and at long distance. As a result, we demonstrated to measure the deflection of 2.5 mm with high accuracy.

Introduction

Monitoring the behavior of civil engineering structures under and after construction secures the quality and safety of structures. Currently, spot measurements are often adopted as a monitoring method; for example, displacement measurements using the total station are generally applied as the monitoring method around construction [1]. However, localized changes, such as cracks in concrete or sinking of the ground, sometimes occur, and it is difficult to predict where they will. Therefore, spot measurements of limited measurement points may miss the maximum displacement. In addition, the frequency of measurement by total station is limited because it takes labor and time, and it is difficult to continuous monitoring. Also, the measurement is performed only for the surface of structures, the internal behavior of civil engineering structures cannot be directly measured. Distributed fiber-optic sensors can perform distribution measurement and continuous monitoring and can be attached to the interior of civil engineering structures, and therefore paid attention to in recent years [2].

Since the optical fiber itself of the distributed fiber-optic sensor functions as a sensor, physical changes (such as strain and temperature) along the total length of the fiber-optic sensor can be identified. When light is made incident on the fiber-optic sensor scattered light is generated everywhere. Although these scattered lights cause the attenuation of an optical signal in communication applications, its spectrum includes various types of information. This scattered light measures the distribution of physical changes generated in the fiber by utilizing the property

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linearly related to elongation and contraction of the fiber. The scattered light consists of several types depending on the intensity. The Raman scattered light depends on temperature, it is widely used for the measurement of temperature distribution [3]. The Brillouin scattered light reacts to strain and temperature and has a feature capable of measuring comparatively large changes [4]. The Rayleigh scattered light is generated by particles smaller than the light wavelength and caused by the fluctuation of microscopic density and composition of molecules constituting fiber optics. This slight fluctuation has an inherent random pattern for each fiber-optic cable, and consequently, only peculiar wavelength satisfying conditions depending on a given strain is reflected. Since this is not a dynamic phenomenon, such as molecular vibration of the Raman and Brillouin scattered lights, the great advantage of strain measurement based on the Rayleigh scattered light is the high accuracy of strain distribution measurement [5]. OFDR (optical frequency domain reflectometry) and TW-COTDR (tunable wavelength coherent optical time domain reflectometry) are methods for analysis systems based on the Rayleigh scattered light. OFDR has a spatial resolution in the order of millimeters, and the measuring distance is less than 100 m [6]. TW-COTDR has a spatial resolution in the order of centimeters, and the measuring distance is 10 km or more [7].

There are several research topics related to the technology of displacement measurement using fiber-optic sensors. A multi-core fiber is a fiber containing multiple cores in a clad, and the shape of the multi-core fiber itself is calculated by sequentially integrating strain measured in each core from one end [8]. Since the multi-core fiber has a small diameter, a shape can be formed flexibly despite the hard glass, whereas it is twisted easily and the twist results shape sensing error. The 3DSensor is a cable containing optical fibers specialized for civil engineering structures, and under development. It is composed of a certain composite material in which multiple fiber optics are built and a coating material with high workability and durability designed to make it applicable to civil engineering structures. The field experiment using this 3DSensor successfully measured banking of 48 m high [9].

We consider realizing the measurement of a civil engineering structure several hundred meters length with a displacement accuracy of ±1 mm. Since high displacement accuracy is required and long-distance measurement is performed, we adopted the measuring system of TW-COTDR. The 3DSensor was also adopted because it has sufficient characteristics for application to civil engineering structures, such as high workability in the ground and structures and that has actual achievement in field experiments, was adopted. In this study we demonstrated the experiments utilizing 45 m and 170 m 3DSensors.

Overview of experiments

(1) Fiber-optic cable

The picture and cross-sectional diagram of the 3DSensor is shown in Fig. 1. Size of the cross-section is 15 mm high and 50 mm wide. In addition, four fiber-optic sensors are embedded inside the 3DSensor. The distance between the fibers is approximately 4.5 mm. In this study, 45 m and 170 m 3DSensors were utilized.

Materials Research Proceedings **27** (2023) 236-242
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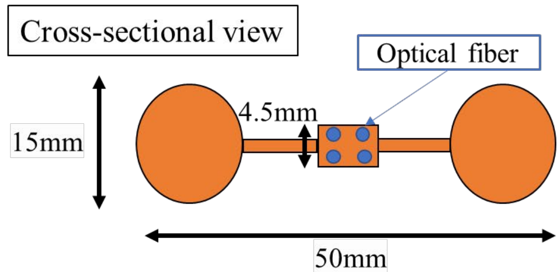

Fig. 1: Left:The photograph of the 3DSensor Right: cross-sectional diagram of the 3DSensor

(2) Measuring instrument

NBX-7031 manufactured by Neubrex Co. was adopted as the measuring instrument. It is a TW-COTDR system based on the Rayleigh scattered light, and the measuring distance was 27 km. In this study, the measuring instrument's readout resolution and spatial resolution were set at 5 cm and 5 cm, respectively, in the 45 m test and at 2.5 cm and 5 cm, respectively, in the 170 m test.

(3) Method of experiments

Figs. 2 and 3 show the schematic diagram and the general appearance of the experiment, respectively. the 3DSensor was installed on a flat surface linearly, and it was fixed by placing weights at intervals of 5 m. Forced displacement of 2.5 mm, 5 mm, and 7.5 mm was given in the vertical direction at the points 22.5 m (45 m test) and 85.5 m (170 m test) apart from the end of the 3DSensor connected to the measuring instrument, respectively. We utilized a jack to apply forced displacement (Table 1). Vertical displacement of the 3DSensor at 2.5 m forward and backward from the position provided with forced displacement was measured at intervals of 20 cm using a laser displacement transducer. Strains of fiber-optic sensors in the 3DSensor before and after deformation were measured, and deflection was calculated from the measurement of the strain.

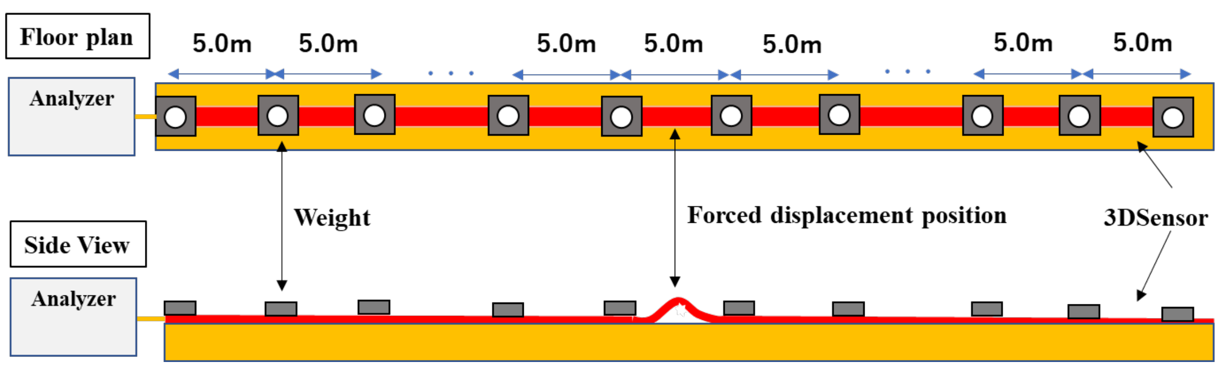

Fig. 2: Schematic diagram of the experiment

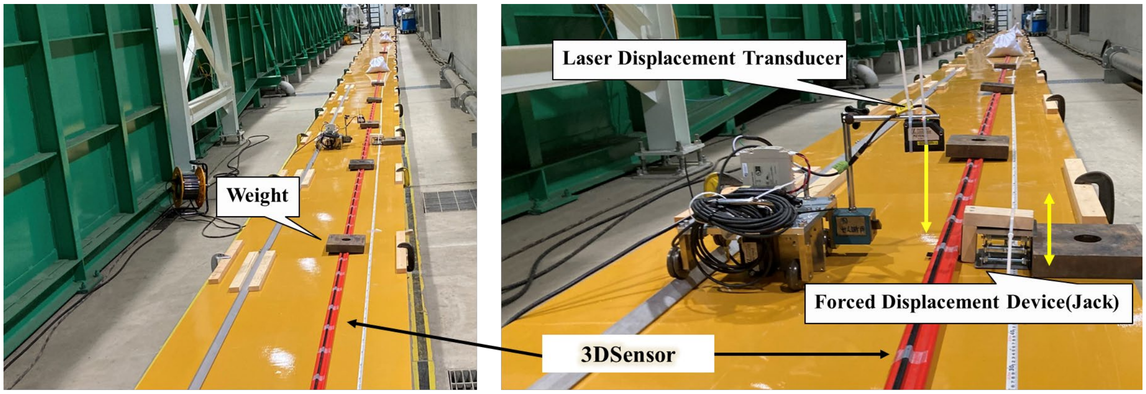

Fig. 3: General appearance of experiment

Table 1: Experiment cases

Cable length(m)	45	45	45	170	170	170
Forced displacement position(m)	22. 5	22. 5	22. 5	85. 5	85. 5	85. 5
Forced displacement amount(mm)	2. 5	5. 0	7. 5	2. 5	5. 0	7. 5

(4) Method for calculation

At the beginning, the averages of strains at upper and lower surfaces measured by fiber-optic sensors are calculated, and they are considered as upper and lower strains. The difference between the upper and lower strains is calculated as the bending strain. The bending strain is divided by the distance between the fibers to convert it to curvature. The curvature is integrated from the fixed point to calculate the deflection angle. The deflection angle is further integrated from the fixed point to calculate deflection. In addition, to correct the error of global deflection generated by the integration, the moving average of the curvature was subtracted from the curvature. In this study, width of the window of the moving average was set to be 7.5 m, which is sufficiently larger than the local deformation region of this experiment. As an example of the measurement result, the result of the experiment in which forced displacement was given at the 22.5 m point of the 45 m 3DSensor is shown in Fig. 4. The deflection before calibration is found to be excessive at the 45 m point, which is farthest from the 0 m point where the integration started, although the shapes at the position where forced displacement was given coincide. On the other hand, the deflection after correction is considered to have been well corrected because the shape at the point where forced displacement was given is well maintained, and the deflection error at the 45 m point is found to be sufficiently small.

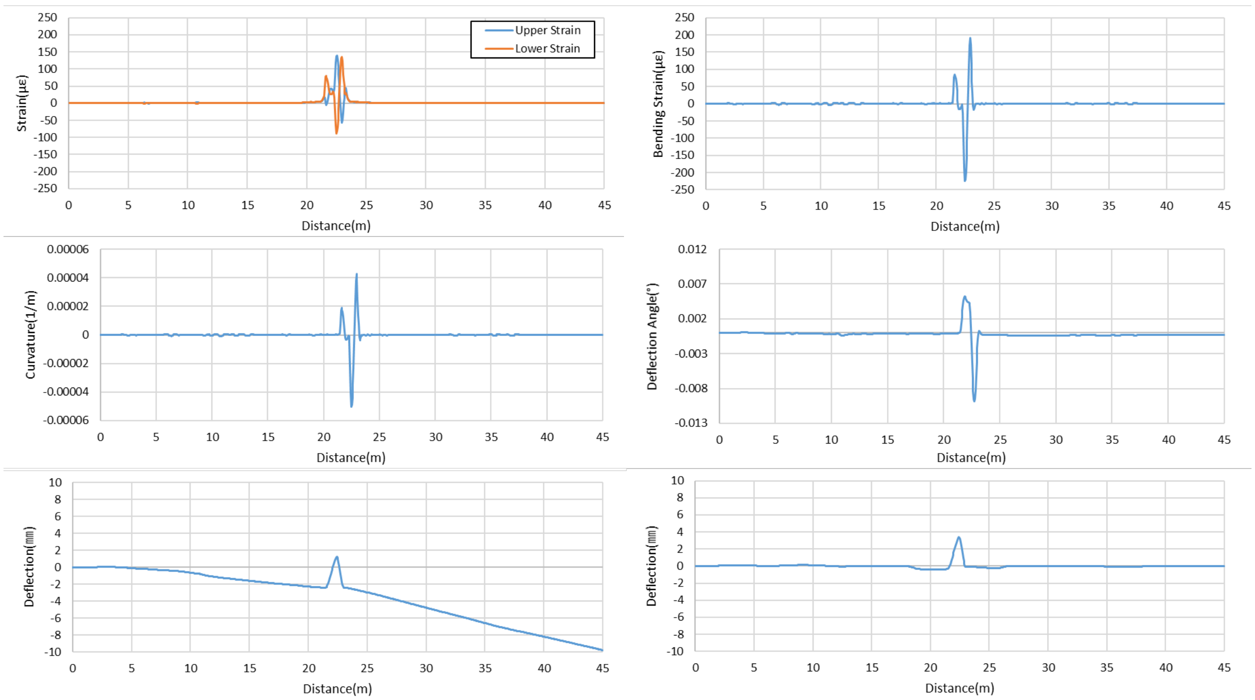

Fig. 4: Upper left: strain; upper right: bending strain; middle left: curvature; middle right: deflection angle; lower left: deflection; and lower right: deflection after correction

Results of experiments

Fig. 5 shows the results of experiments conducted using the 45 m 3DSensor, and Fig. 6 shows that using the 170 m 3DSensor. The each of the left graph shows the result of the calculation of deflection by the 3DSensor over the total length, and the right graph shows the comparison between the calculated deflection by the 3DSensor and the measured deflection by the laser displacement transducer. The place provided with forced displacement shows the maximum deflection in the local shape, and the result of the laser displacement transducer and the shape coincide. However, negative deflection is calculated in the areas on both sides of the area where the maximum deflection was calculated. The reason is that a large value is subtracted in the correction of the error of global deflection when a large strain exists locally within the width of the window. This tendency is significantly recognized with the increase in the forced displacement amount. Also, the error of global deflection is almost improved because deflection sufficiently close to zero was calculated at the 45 m and 170 m point, which is the farthest from the 0 m point where the integration starts. From the above results, we found that deflection could be calculated with high accuracy both in the 45 m and 170 m tests.

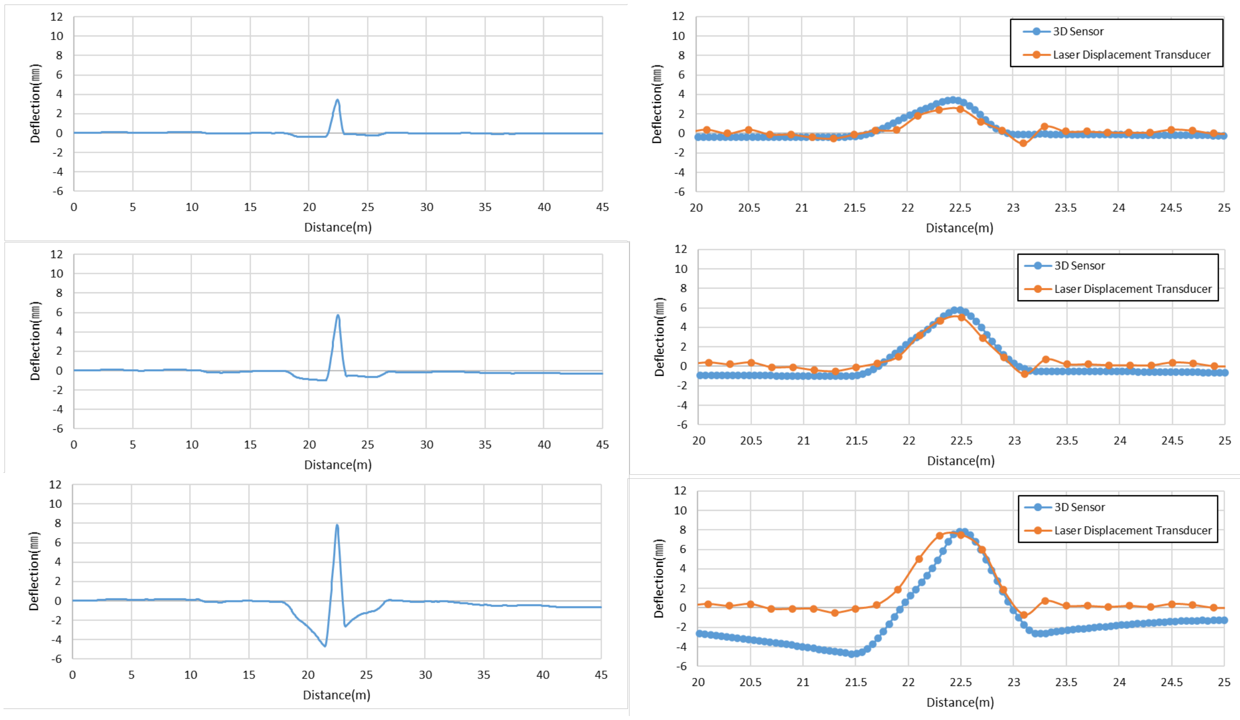

Fig. 5: Results of tests in which forced displacement was given at 22.5 m points of the 3DSensor 45 m long
(Forced displacement: Upper 2.5 mm, middle 5.0 mm, and lower 7.5 mm)

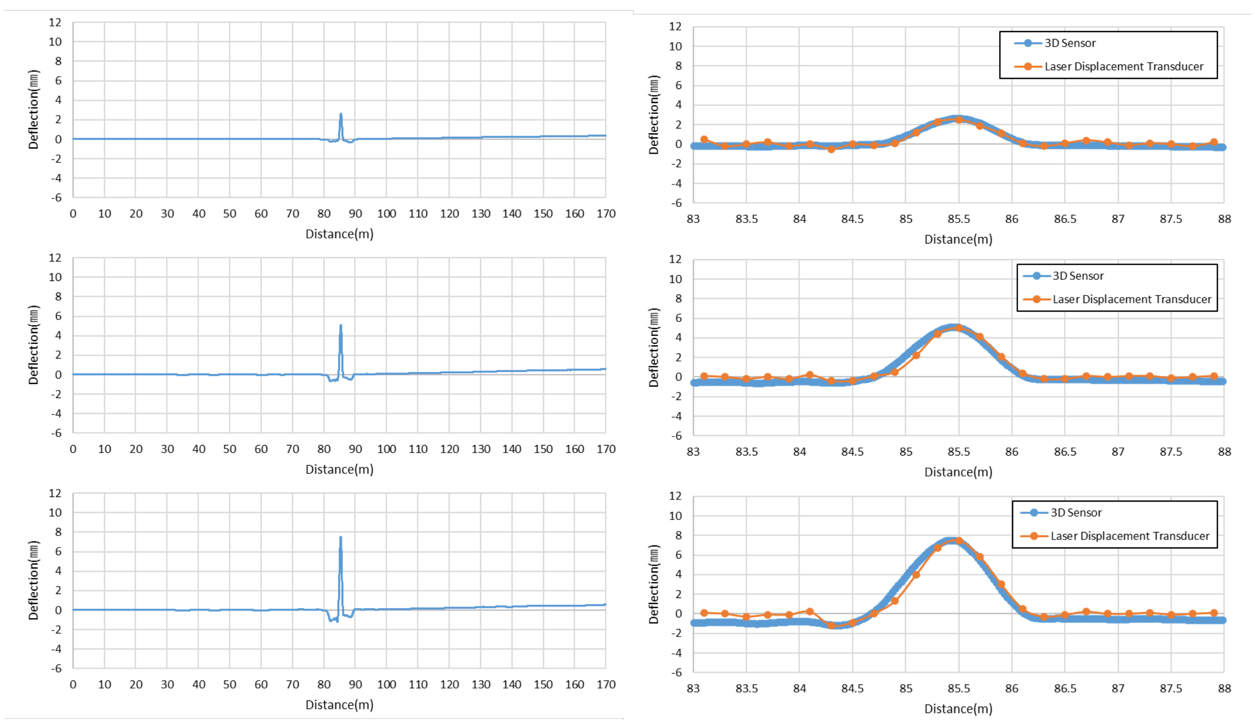

Fig. 6: Results of tests in which forced displacement was given at 85.5 m points of the 3DSensor 170 m long
(Forced displacement: Upper 2.5 mm, middle 5.0 mm, and lower 7.5 mm)

Materials Research Proceedings **27** (2023) 236-242 https://doi.org/10.21741/9781644902455-30

Conclusion

This study conducted demonstration experiments to investigate feasibility of deflection measurement of long civil engineering structures based on distributed fiber-optic sensor. We adopted using the method for measuring strain distribution in the TW-COTDR system capable of performing measurements with high accuracy and at long distances and utilized 3DSensors (45 m and 170 m) that have the sufficient characteristic for applying to civil engineering structures of high workability for the ground and structures and the actual achievements of field experiments. As a result, we successfully estimated the local shapes with high accuracy in both 45 m and 170 m tests.

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