FBG Bending Gauge on bridges – An effort towards standardization of bridge structural health monitoring

I-Wen Wu*[a], Chung-Yue Wang[b], Ming-Hung Chen[b], Hao-Lin Wang[b], Allen Cheng[a], Patrick Tsai[a], David Wu [a], Hung-Wei ChangChien [a], Hentai Shang [a]
[a]Prime Optical Fiber Corporation, Chu-Nan, Miao-Li County, Taiwan
[b]Center for Bridge Engineering Research, Central University, Chungli, Taiwan

ABSTRACT

The FBG bending gauge developed by POFC is applied in several situations involving bridge safety/health monitoring. Under static loading conditions, the FBG bending gauge serves as an excellent tool to deduce an overall deflection curve on the bridge section under study. The gauge also works well in dynamic situations where instantaneous vertical deflections of bridge structures resulting from a cruising dump truck were accurately measured.

Keywords: FBG Bending Gauge, loading test, deflection, static monitoring, dynamic monitoring

1. INTRODUCTION

Bridge safety is an important topic in the study of civil infrastructures in Taiwan and other parts of the world. Normal aging, increasing traffic and heavier traffic loads are a few factors that contribute to the overall health status of tens of thousands of bridges big and small across the island. In addition, occasional natural disasters such as typhoon, earthquake and flood severely cut short the useable life-span of bridges, sometimes destroying a bridge altogether. This sets people's lives and properties in danger. As such, monitoring of certain bridges, in particular, bridges under poor health and suffer severe deterioration, is a necessity to ensure safe passage of civilians and vehicles as well as maintaining routine economic activities in the adjacent area. No one would argue that it is critical to standardize a method/sensor which can be applied to bridges of different types which offers high reliability, repeatability, and accuracy. However, such a solution is not readily obvious, and none accepted the true standard for bridge monitoring. With the abundance of sensor and sensor technology available for monitoring bridges, optical fiber sensors, especially FBG sensors, come in as a good choice considering its numerous qualities such as immunity to EMI, highly durable and corrosion resistant, long-distance signal transmission, and its multiplexing capability. It is the main focus of this paper to present applications of the FBG bending gauge, with it being a potential solution towards the standardization of bridge monitoring in general.

2. METHODOLOGY

2.1 The sensor in short

FBG bending gauge is an optical fiber sensor capable of measuring deflection and rotational angle between two or multiple points, see Figure 1. The multi-linking design of the gauge offers tailor-made applications, linking two to dozens of sensors and inter-connectors in series, and is capable of providing an overall deflection or deformation curve for the structure or site of interest. Through the use of various fixtures, multi-linked FBG bending gauges may be installed inside borehole casing tube vertically or directly mounted onto horizontal surface of civil or industrial structures. Routing and connection of fiber cables inside the inter-connectors enhances installation feasibility and offers cable protection. Measurement readings are taken with FBG interrogators, such as the Micron Optics sm125 for static readings or si425 for dynamic readings. With the use of computer software, both angular and displacement information are immediately calculated upon wavelength reading input. This pre-warning monitoring tool, used in conjunction with customized software and its real-time, long-term, remote monitoring capabilities, may be the solution of choice for providing around the clock information on the structure of interest.

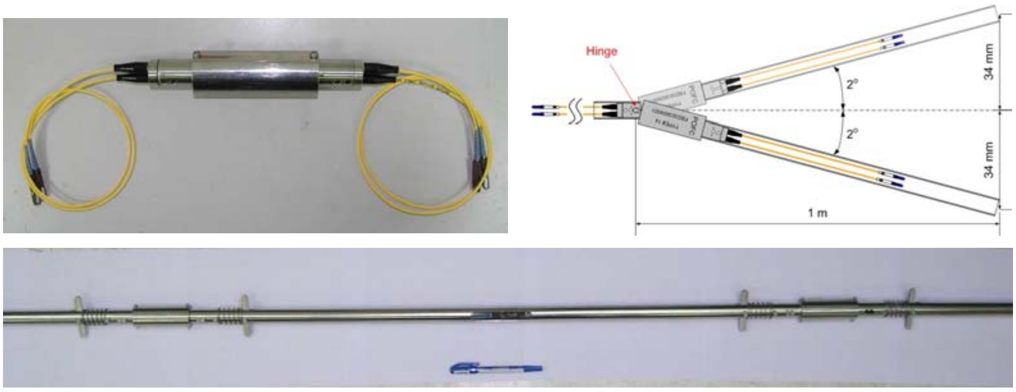

Figure. 1. Top left, photo of FBG bending gauge. Top right, rotational motion of the FBG bending gauge allows the determination of angle between 2 points. Bottom, FBG bending gauges linked by inter-connector, signal transmission cables are neatly placed inside the inter-connector.

2.2 The sensor design

The FBG bending gauge is of a dual-FBG design. The FBG's are pre-stressed and mounted adjacent a rotary joint, which is linked to inter-connectors at the ends. External force or movement is translated to the FBG's, which is elongated on one side and shortened on the other side of the rotary joint. The dual-FBG design offers enhanced accuracy and consistency. The self-temperature compensating design of the sensor eliminates the need for thermal-couples or other temperature monitoring devices. Multiple-gauge applications combined with customized graphic interface can directly provide real-time visual structure deformation profiles and trigger pre-set alarm for emergency response purposes.

2.3 Calculation method of angle and deflection

Each rotational angle is determined by the difference in wavelengths of the 2 FBGs within each FBG bending gauge, shown as α_i. Once the angle value is determined, the sectional deflection, d_i, is calculated through the length of the inter-connector, indicated as L. Overall deflection, D_i, is summed as the aggregate of prior sectional deflection and the current sectional deflection. M is the correction angle. Detailed calculations are shown in Figure 1.

$$\left\{\begin{array}{c} A_1' = A_1 - M \\ A_2' = A_2 - M \\ A_3' = A_3 - M \\ \cdots \\ A_n' = A_n - M \end{array}\right\} \Rightarrow \left\{\begin{array}{c} A_1' = \alpha_1 - M \\ A_2' = (\alpha_1 + \alpha_2) - M \\ A_3' = (\alpha_1 + \alpha_2 + \alpha_3) - M \\ \cdots \\ A_n' = (\sum_{i=1}^{n} \alpha_i) - M \end{array}\right\} \qquad (1)$$

$$\uparrow$$

$$\because \left\{\begin{array}{c} A_1 = \alpha_1 \\ A_2 = \alpha_1 + \alpha_2 \\ A_3 = \alpha_1 + \alpha_2 + \alpha_3 \\ \cdots \\ A_n = \sum_{i=1}^{n} \alpha_i \end{array}\right\} \qquad d_i' \approx L * A_i' \Rightarrow \left\{\begin{array}{c} D_1' = d_1' = L*(\alpha_1 - M) \\ D_2' = d_1' + d_2' = L*((2\alpha_1 + \alpha_2) - M) \\ \cdots \\ D_n' = \sum_{i=1}^{n} d_i' = L*((n\alpha_1 + (n-1)\alpha_2 + \cdots + \alpha_n) - M) \end{array}\right\} \qquad (2)$$

Figure. 1. Calculation method of individual and overall deflections through the use of FBG bending gauge.

3. APPLICATION CASES

3.1 Bridge SH01

The bridge under investigation is a 30-year old, two-lane bridge in the mountains. It is a self-supported suspended bridge with two spans and a free gap at the center. As such, when vehicles cross the center of the bridge, a notable bump is experienced. The purpose of the test is to determine the extent of bridge sinking under heavy load throughout the length of the bridge, see Figure 2. A total of 26 FBG bending gauges were installed across the middle of one of the bridge spans. Results shown that as the load is moved from the edge towards the center of the bridge, the deflection profile, as determined by the FBG bending gauge, shows gradual downward trend, see Figure 3. With the load placed at the middle of the bridge, the maximum vertical deflection observe at the gap is -28mm.

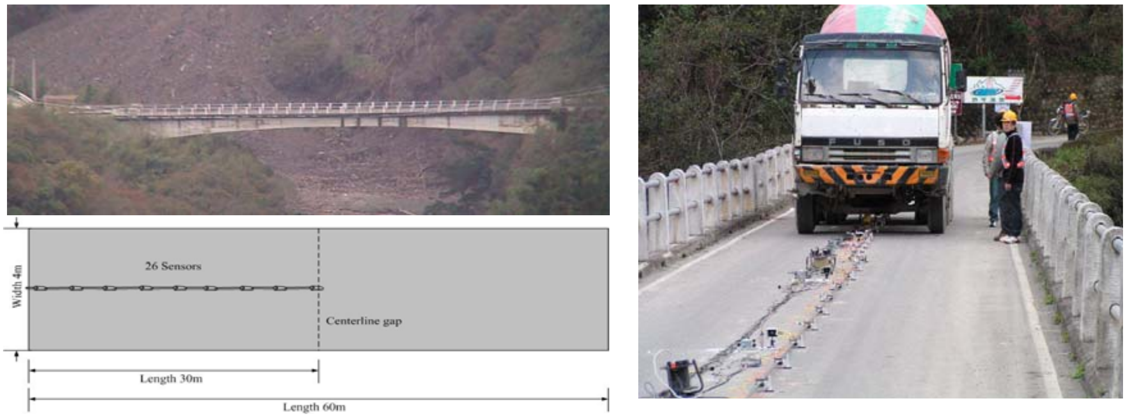

Figure. 2. Left top, side view of Bridge SH01. Left bottom, Layout of 26 FBG bending gauges, only the left span of the bridge is monitored. Right, static loading test is being conducted.

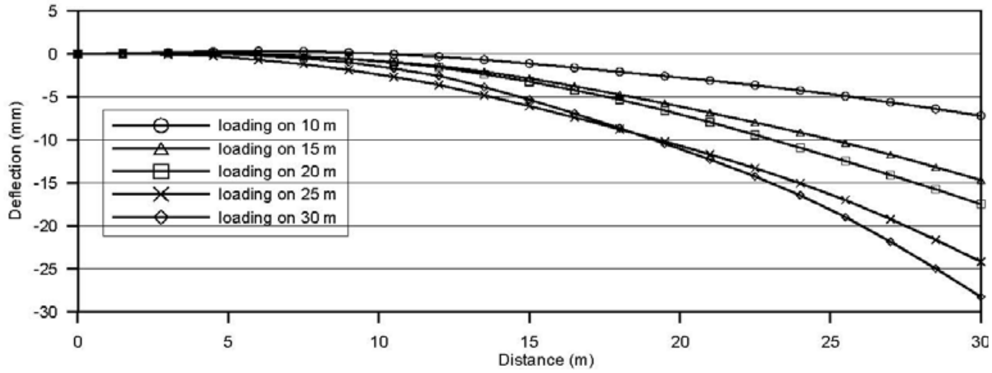

Figure. 3. Various displacement profile of the left span of the bridge, with loading on different locations of the bridge.

3.2 Bridge MD01

Bridge MD01 is situated in the suburb area north of Taipei city, and it is a 25-meter, single span bridge, see Figure 4.

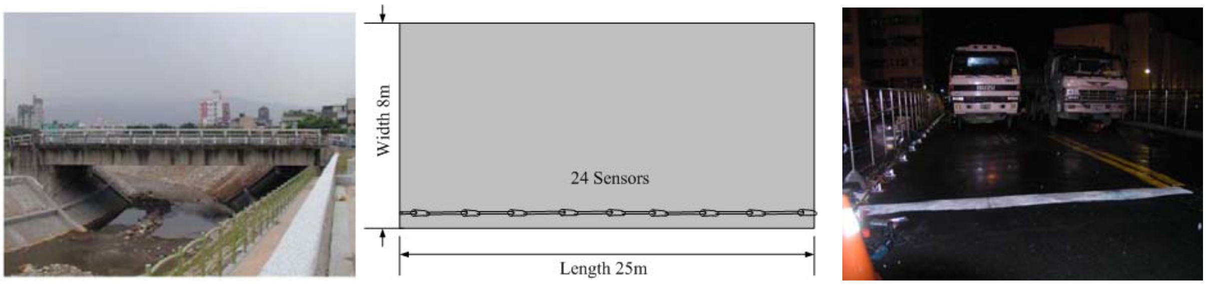

Figure. 4. Left, side view of bridge MD01. Center, layout of 24 FBG bending gauges on one side of the bridge above a main beam. Right, static loading test being conducted.

Since the bridge experiences heavy commuting traffic everyday, the only suitable time available for safety inspection and monitoring is after 12 o'clock midnight. A little bit of rain was also experienced at the time the monitoring was being conducted, but the unexpected moisture did not have any effect on the monitoring process nor the sensors. The bridge safety factor was determined through both static and dynamic loading tests. A total of 24 FBG bending gauges were used for the tests.

3.3 Bridge DM01

The 60-meter bridge under investigation is located in a rural area about 60km south of Taipei. The bridge was designed for typical civilian usage, however, the bridge is routinely subjected to of ultra-heavy dump trucks (~40 tons) which jeopardize its structural integrity. Both static and dynamic ultra-heavy loading tests were conducted to examine the behavior of the bridge throughout 7-day period, see Figure 5. Results of the static loading tests are shown in Figure 6.

Figure. 5. Left top, slanted view of bridge MD01. Left bottom, layout of 15 FBG bending gauges on the bridge. Right, ultra-heavy loading tests being conducted.

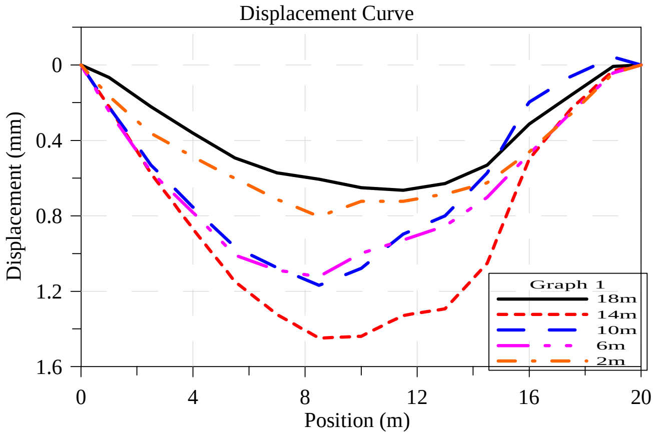

Figure. 6. Displacement curve of the bridge profile at with loading on various locations of the bridge.

3.4 Bridge HS01

The bridge girder under investigation is of very high stiffness, and it is expected that very high speed trains passing atop will still result in minor structural vibration and deformation. For the dynamic test, 2 test lines of FBG bending gauges were installed and monitored simultaneously, which, in addition to monitoring length-wise profile variations, also offers information on potential transverse rotation of the structure, see Figure 7. The results of high speed train traveling through top of the girder are shown in Figure 8, which shows instantaneous structural variations of the girder.

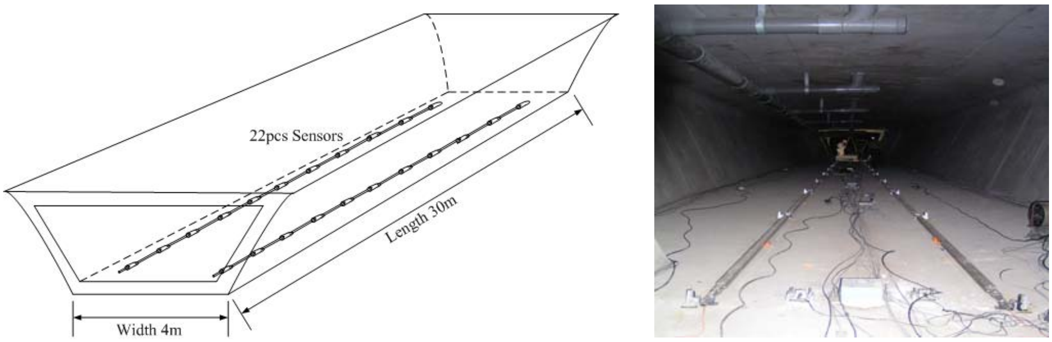

Figure. 7. Left, 3-D pictorial drawing of the girder structure with sensor layout. Right, actual sensor layout inside the girder, shown with other conventional sensors installed.

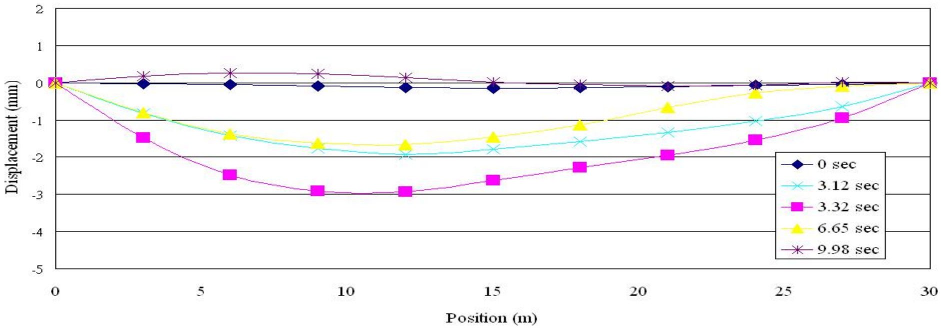

Figure. 8. Girder profile variation observed at different temporal locations.

4. CONCLUSION

Several applications cases using the FBG Bending Gauge for the monitoring of bridge structural health are presented. Test results showed that the FBG bending gauge is a viable optical fiber sensor capable of providing repeatable and reliable dynamic and long-term measurements on critical structures such as bridges. With features like multiplexing capability, immunity to EMI, corrosion resistance and durability, this sensor bests conventional electronic sensors and other optical sensors as the choice for bridge monitoring. With larger bridge projects using the FBG bending gauge under plan, the sensor and its related techniques are well positioned to become the next standard in bridge monitoring.

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