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A New Railway Tunnel Deformation Monitoring System using FBG Bending Gauges

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ABSTRACT

An online tunnel deformation monitoring system is developed in the present study for the early warning of intolerable tunnel deformation. It consists of cascaded unidirectional FBG Bending Gauges which can realize angle measurement and temperature compensation at the same time and reach adjustable sensitivity according to range limitation. Connected by using rigid rods, a series of the FBG Bending Gauges forms a chain. The chain can be placed in parallel with the rails in tunnel. Through the calculation of relative rotation angle between any two adjacent sensors in the chain, the displacement at one measurement position is obtained. The comprehensive consideration of displacements at all measurement positions enables the monitoring system to portray the longitudinal variation of tunnel deformation along along the longitudinal direction. A prototyped monitoring system composed of five cascaded FBG Bending Gauges was firstly examined in a lab test when different modalities of tunnel deformation were simulated.

Key Words: High-speed rail, FBG, bending gauge, tunnel deformation, derailment, online monitoring

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1. INTRODUCTION

Deformation of infrastructures such as bridges, tunnels and dams has been a big concern to government, industries, and researchers. Tunnels play an essential role in various types of transportation including railways, subways and high-way roads, and it is significantly important to monitor the structural conditions of tunnels to guarantee the security and prevent catastrophic disasters.

There have a lot of research work on different aspects of deformation measuring and monitoring of tunnels using a variety of techniques and tools, such as tape extensometers, using total stations, photogrammetry (Scaioni 2014), and 3D laser scanner (Kavvadas 2005).

The most accurate methods for tunnel deformation are using tape extensometers, which is easy to use and maintenance (Bernardo-Sánchez 2014). However, these methods are expensive and time-consuming and could only be used to measure the distance changes between two fixed points, which is inoperative for in-service tunnel deformation monitoring.

The total station survey methods are a wide used way to obtain tunnel deformation information, which have the advantages of non-contact and high accuracy (Kontogianni 2003, Luo 2016, Ordóñez 2016). Tse (2011) has developed an automatic deformation monitoring system (ADMS) by using total station, which has been widely deployed I Hong Kong. However, these total stations based methods are easy to be failure when obstacles such trains passing block the sensor in a rail tunnel.

Laser scanning technology provides a new way to monitoring the tunnel deformation in recent years. The main advantages of using laser scanning is that the deformation information can be obtained along the tunnel entire length in a very short time. However, these methods have a lower accuracy than the above mentioned methods, which is around $\pm$5mm (Yoon 2009, Pejić 2013).

Over the past several decades, there has been a significant progress on the commercialization of Fiber Bragg Grating (FBG) technology, which as a mature and adaptive strain measuring technique has been widely used in various health monitoring (SHM). There are several intrinsic advantages of FBG sensors over conventional electrical sensors such as small size, light weight, immunity to electromagnetic interference (EMI), resistance to harsh environments, embedding capability, etc. (Ye 2013).

Various kinds of FBG based inclinometer and deflectometer are developed and successfully used for measuring displacement of geotechnical structures. The primary application of FBG Bending Gauge, a kind of deflectometer, is to monitor the slop deformation directly (Yukimi 2001), in which the FBG Bending Gauge as an elastic joint and connected with rigid pipes each by each is implemented in a borehole. When the ground deformation arises, the elastic joint obtains the rotated relative angle of each rigid pipe which then be used to estimate the displacement of different depth of the ground.

This paper presents a new online monitoring system for estimating the tunnel operation condition by reconstructing the tunnel lateral displacement, vertical displacement and cross-sectional convergence. The mechanism of FBG Bending Gauge comprising the monitoring system and how the Bending Gauge measures tunnel deformation is introduced. The schematic layout of the proposed tunnel online monitoring system is elaborated. The feasibility of the proposed on-line monitoring system is tested and validated through a series of experiments in the lab under different deformation types.

2. System scheme of Tunnel Deformation Monitoring System

2.1 Principle of FBG bending gauge

The FBG bending gauge is able to measure angle of rotation with temperature compensation taken into consideration. The mechanism of bending gauge is shown in Fig. 1, in which Turnable Arm Ⅰ and Turnable Arm Ⅱ constitute a revolution joint with one rotating degree of freedom which allowed these two arms occurs a relative angle at a range of ±1 °. Two pre-tensioned FBGs are attached to the opposite sides of the Turnable Arm Ⅱ (Fig. 1) to measure the relative angle change.

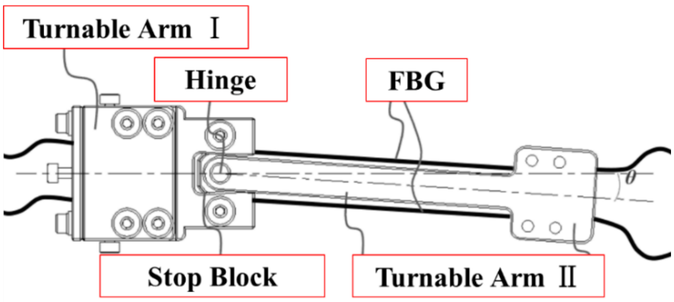


Fig. 1 Mechanism of FBG Bending Gauge

When a relative rotation occurs between the Turnable Arm Ⅰ and the Turnable Arm Ⅱ where the relative rotation angle is θ, the FBG on one side suffers a tensile force and the FBG on the other side suffers the an equivalent compressive force, where the changes of central wavelength is $\Delta\lambda_1$ and $\Delta\lambda_2$ respectively. These changes of central wavelength are induced by the variation of strain and the environmental temperature, shown in Eq. (1) ~ Eq. (2).

$$\Delta\lambda_1 = \lambda_{\varepsilon 1} + \lambda_t \tag{1}$$

$$\Delta\lambda_2 = \lambda_{\varepsilon 2} + \lambda_t \tag{2}$$

Where the $\lambda_{\varepsilon 1}$、$\lambda_{\varepsilon 2}$ represents strain changes caused by rotation on both sides of the FBG; and the λ_t represents the universal change of central wavelength induced by the ambient temperature variance, which is changing identically for the FBGs on both sides.

For the relative rotating angle θ, *the* corresponding central wavelength of Bending Gauge is defined as Eq. (3).

$$\Delta\lambda_\theta = \Delta\lambda_1 - \Delta\lambda_2 \tag{3}$$

Where the $\Delta\lambda_\theta$ is defined as the central wavelength shift of the FBG Bending Gauge induced by the relative rotation. Substituting Eq. (1) and Eq. (2) into Eq. (3).

Finally, the influence of temperature is eliminated. The angle of the FBG Bending Gauge is therefore only dependent on strain as Eq. (4).

$$\Delta\lambda_\theta = \lambda_{\varepsilon 1} - \lambda_{\varepsilon 2} \tag{4}$$

2.2 Measurement theory of tunnel deformation by using FBG Bending Gauge

When geological catastrophes such as landslides and settlement of groundwater take place, the tunnel is likely to deform along lateral, vertical directions and converge in the cross-sectional plane, as shown in Fig. 3(a).

In order to reconstruct a comprehensive plot of lateral and vertical displacement as well as cross-sectional convergence, from the cross-sectional perspective view, a pair of orthogonal orientated FBG Bending Gauges are mounted to each other on each point shown in Fig. 2. Fig. 3(a) shows the arrangement of equidistant FBG Bending Gauges at a same cross-sectional position along the longitudinal direction. These FBG Bending Gauges are connected by a rigid rod to form a chain parallel to the stretching direction of the tunnel. Through the calculation of relative rotation angle between any two adjacent sensors in the chain, the displacement at one position is obtained, as shown in Fig. 3(b). A profile can be plotted according to each chain indicating the displacement of the tunnel corresponding to the cross-sectional position of the FBG Bending Gauges. As with the content of this paper, one chain is tested for pilot and experimental studies.

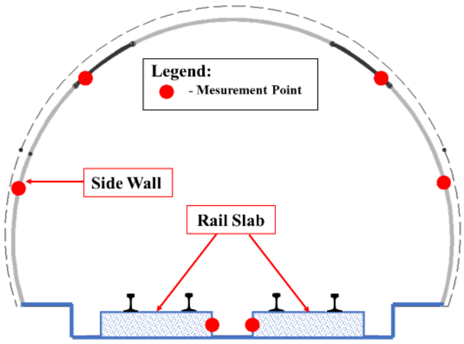
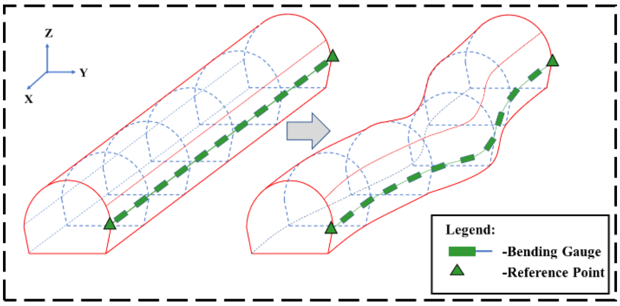


Fig. 2 Section layout of FBG Bending Gauge



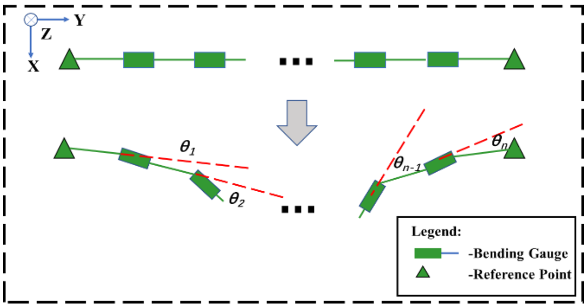


Fig. 3(a) Arrays of FBG Bending Gauges along the longitudinal direction

Fig. 3(b) Measurement principle of one chain of FBG Bending Gauges

Fig. 3 Measurement theory of tunnel deformation based on FBG Bending Gauge

2.3 Overall scheme of online tunnel deformation monitoring system

The FBG Bending Gauge based online tunnel deformation monitoring system is designed for High speed rail operation safety control. The overall scheme of the system is shown in Fig. 4. The hardware system is composed of three main modules, which are shown as followings:

1) Monitoring Points: Array of FBG Bending Gauges are deployed on the tunnel side wall and rail slab to collect measurement data to transfer them to the monitoring base station.
2) Monitoring Base Station: The FBG interrogator is implemented in the monitoring base station at the entrance of target tunnel to obtain and store the wavelength readings from each measurement point.
3) Online Cloud Database: After collecting the data from the FBG interrogator, workstation will process the data automatically, archive the calculated deformation results in the database and upload to the cloud, which are authorized to users via

internet. The tunnel operation condition, such as the trend of movement of each measurement point, the overall tunnel deformation condition, is visualized in graph for users.

4) Automatic Warning System: When the system detects the deformation of any of the measurement points excessing the given threshold, the alarm information, which contains the alarm position, the deformation type and the alarm level would be sent to the specified operators automatically as a reference for their appropriate action.

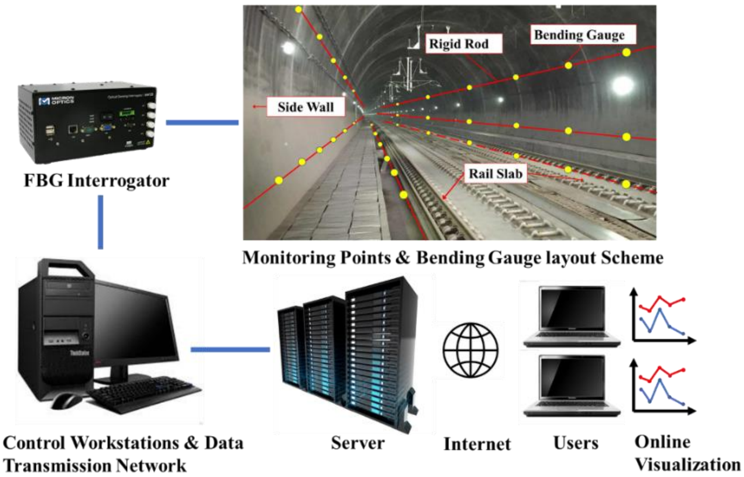


Fig. 4 Overall scheme of Tunnel Deformation Monitoring System

3. Experimental Investigation

3.1 Experimental setup

To verify the feasibility of the proposed on-line monitoring system, a series of simulative experiments have been conducted at the Industrial Centre of The Hong Kong Polytechnic University. The experimental setup is shown in Fig. 5~Fig. 6 which consists there three main components:

1) The deformation actuator and control system: This system consists of test platform, electronic liner module, zigbee wireless node and control panel, the main function of which is to generate different types of deformation. The test platform made by five $50\text{cm} \times 50\text{cm} \times 50\text{cm}$ solid concrete cubes is fixed on the ground to provide an referencing coordinate. The electronic linear module fixed on each concrete cube is to initiate movement in a straight line with a $\pm$25mm range to simulate the displacement of tunnel. Each electronic linear module is connected with a zigbee wireless node to receive commands from the control panel.
2) LVDT based test control system: In order to provide a high accuracy measurement results to estimate the performance of the proposed tunnel deformation, a LVDT

(Linear Variable Differential Transformer) based test control system is considered in this experiment, where the hardware components include 5 LVDTs, a LVDT Data logger and a control panel. The LVDT is produced by Tokyo Sokki Kenkyujo Co., Ltd. whose measurement range and resolution are ±25mm and 0.05mm respectively.

3) FBG Bending Gauge based tunnel deformation test system: Five FBG Bending Gauges connected by rigid rods (3000 mm) each by each are tested to verify the proposed methods.

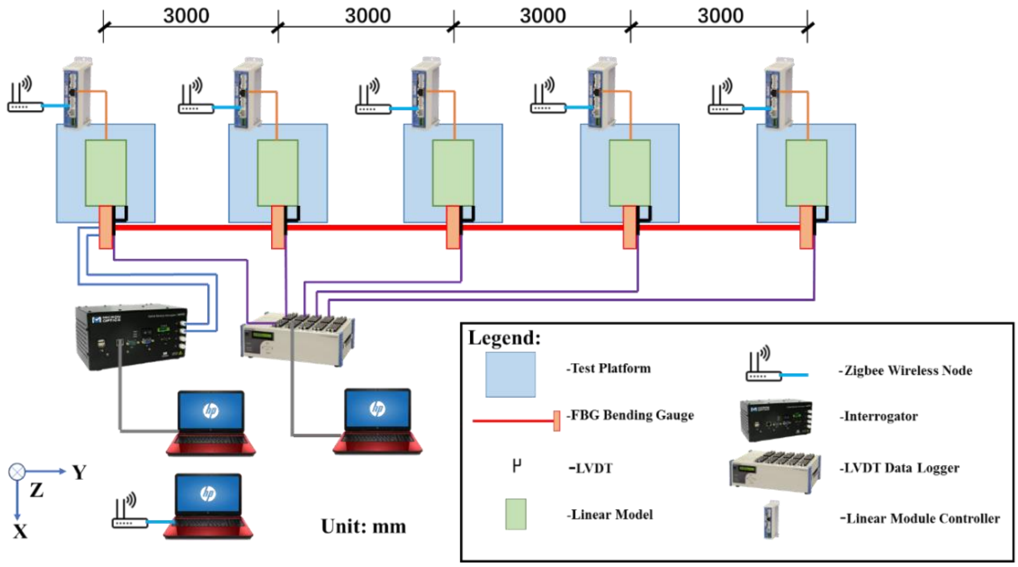


Fig. 5 Experimental set-up of tunnel deformation simulation test

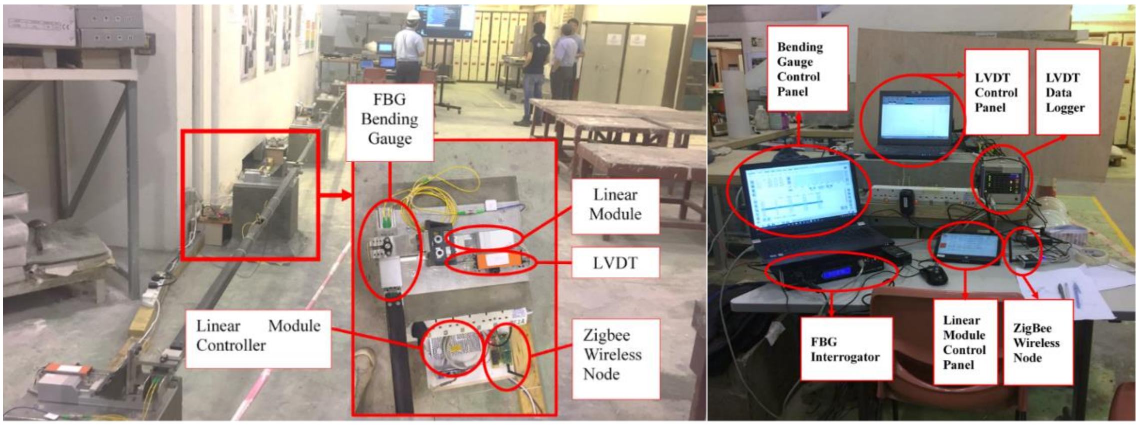


Fig.6 Experimental site of tunnel deformation simulation test

3.2 Different deformation patterns and test procedure

Different deformation patterns are considered in the simulative experiment. Viewed from the longitudinal perspective, the possible deformation types include: Parallel type, Half Wave type and Inflection Point Type (Fig. 7). All Bending Gauge have been calibrated. Table 1 shows the resolution of each Bending Gauge respectively.

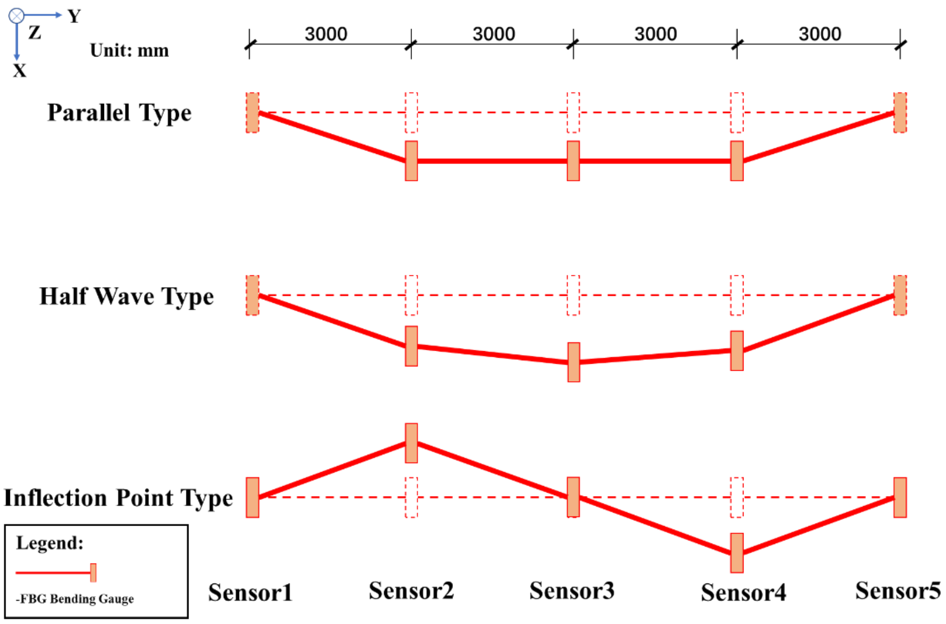


Fig.7. Deformation patterns in the simulation experiments

Table 1 Resolution of Test FBG Bending Gauge (degree/nm)

	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
Resolution	0.000165543	0.00016688	0.000167788	0.000202818	0.00016086

3.3 Experimental results and discussion

Fig. 8 shows the plot of the deformation patterns under a series of increasing displacement measured from LVDT and FBG Bending Gauges. Fig. 9(a), Fig. 9(b), and Fig. 9(c) represents parallel type, half wave type and inflection point type respectively. It can be seen from the plots under all the work conditions (WC), the measured deformation patterns from FBG Bending Gauges generally match up with those from LVDT. The absolute error is no larger than ±1.2mm and doesn't have a positive correlation with the displacement, and the relative error is basically around 10%, except for some cases where the displacements are small (Table 2~Table 4). The error mainly comes from trivial loosening at the connection point between the Bending Gauge and the rigid rod. This leads to a insufficient angle of rotation which results in a smaller displacement output. However, generally speaking, the technique has been proved useful and it is confident enough to use the FBG Bending Gauge for tunnel deformation monitoring. Moreover, the proposed technique will be refined both in hardware and software aspect to further enhance the accuracy.

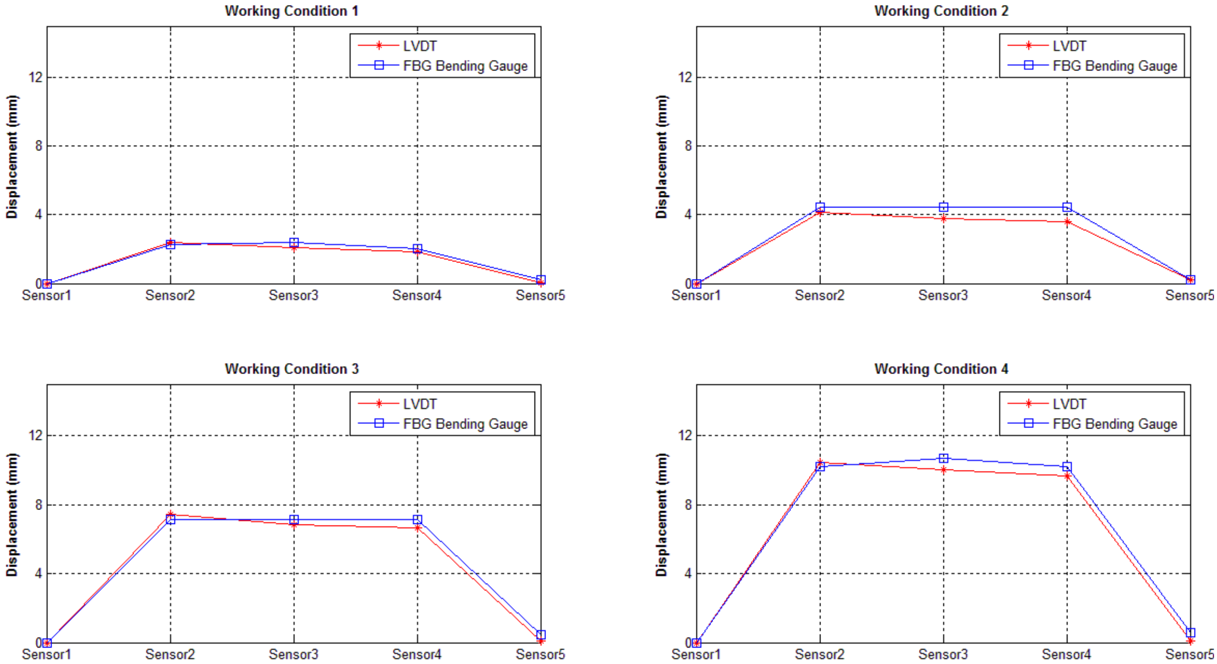


Fig. 8(a). Comparison of LVDT & FBG Bending Gauge on parallel type

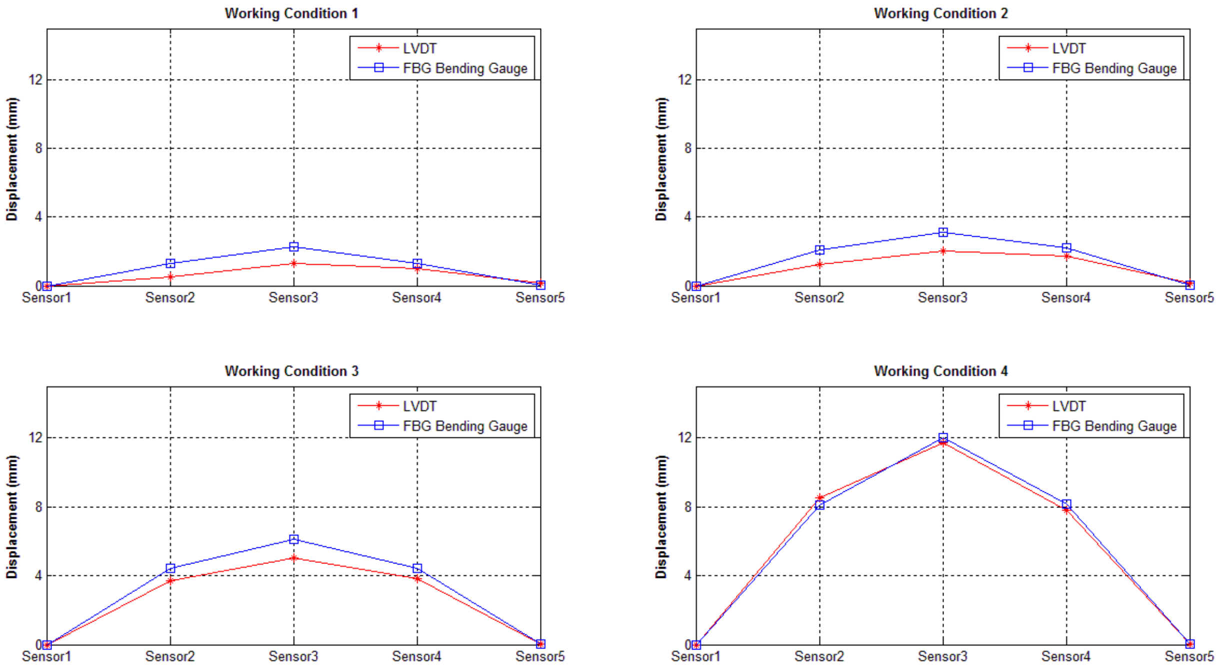


Fig. 8(b). Comparison of LVDT & FBG Bending Gauge on half wave type

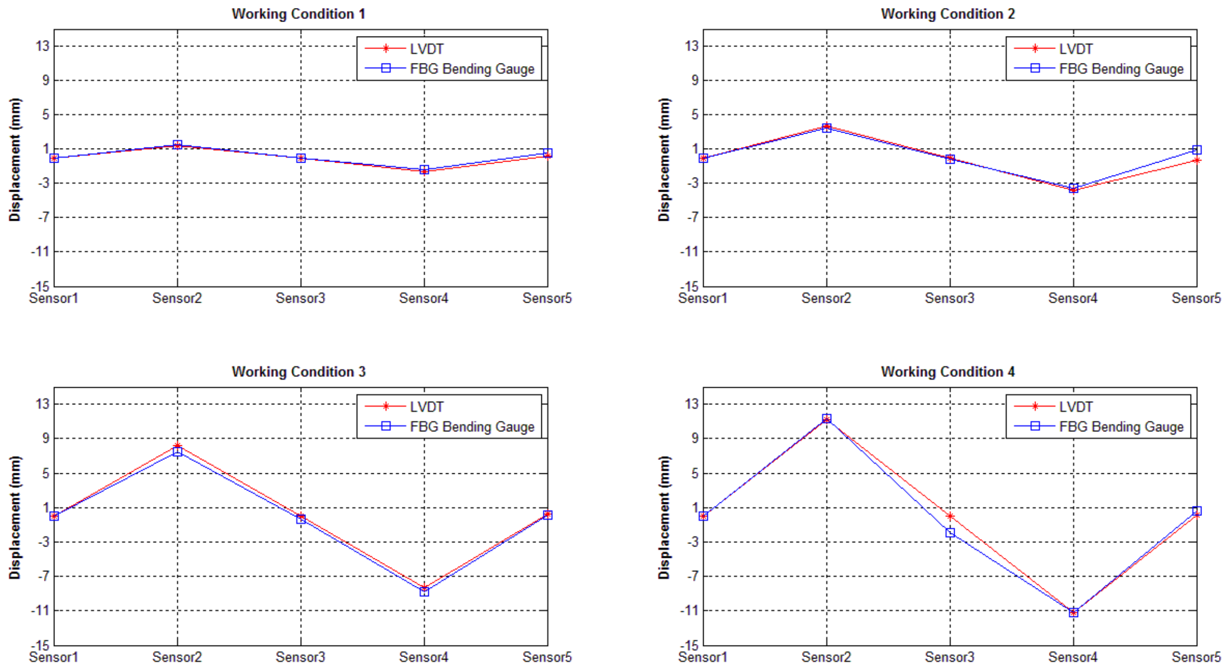


Fig. 8(c). Comparison of LVDT & FBG Bending Gauge on inflection point type

Fig. 8 Comparison of LVDT & FBG Bending Gauge on different deformation patterns

Table 2 Test results of parallel type (Unit: mm)

	Sensor 2			Sensor 3			Sensor 4			Sensor 5		
	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error
WC 1	2.38	2.25	0.13	2.1	2.39	-0.29	1.85	2.05	-0.2	0.06	0.19	-0.13
WC 2	4.17	4.46	-0.29	3.77	4.44	-0.67	3.61	4.42	-0.81	0.19	0.23	-0.04
WC 3	7.46	7.16	0.3	6.84	7.12	-0.28	6.66	7.16	-0.5	0.11	0.44	-0.33
WC 4	10.43	10.24	0.19	10.01	10.67	-0.66	9.68	10.19	-0.51	0.09	0.56	-0.47

Table 3 Test results of half wave type (Unit: mm)

	Sensor 2			Sensor 3			Sensor 4			Sensor 5		
	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error	LVDT	FBG Bending Gauge	Absolute error
WC 1	0.51	1.3	0.79	1.28	2.24	0.96	1	1.29	0.29	0.17	1.29	0.12
WC 2	1.26	2.1	0.84	2.03	3.1	1.07	1.72	2.2	0.48	0.16	2.2	0.04
WC 3	3.7	4.4	0.7	5.03	6.1	1.07	3.82	4.4	0.58	0.01	4.4	-0.14

WC 4	8.51	8.11	-0.4	11.73	12.01	0.28	7.78	8.19	0.41	0.02	8.19	-0.26

Table 4 Test results of inflection point type (Unit: mm)

	Sensor 2			**Sensor 3**			**Sensor 4**			**Sensor 5**		
	LVDT	**FBG Bending Gauge**	**Absolute error**	**LVDT**	**FBG Bending Gauge**	**Absolute error**	**LVDT**	**FBG Bending Gauge**	**Absolute error**	**LVDT**	**FBG Bending Gauge**	**Absolute error**
WC 1	1.39	1.56	-0.17	0	-0.1	0.1	-1.58	-1.41	-0.17	0.15	0.56	-0.41
WC 2	3.75	3.44	0.31	0	-0.13	0.13	-3.81	-3.58	-0.23	-0.25	0.87	-1.12
WC 3	8.24	7.5	0.74	0	-0.34	0.34	-8.27	-8.79	0.52	0.27	0.17	0.1
WC 4	11.25	11.36	-0.11	0	-1.97	1.97	-11.22	-11.25	0.03	0.13	0.65	-0.52

4. CONCLUSION

In this study, a new method for online tunnel deformation monitoring system based on FBG Bending Gauge has been developed and experimentally verified in laboratory.

The hardware modulus of the system, *i.e.,* monitoring points, monitoring base station, online cloud database, automatic warning system has been described in detail. The feasibility of the proposed tunnel deformation monitoring method has been demonstrated through laboratory experiments by considering three deformation patterns: parallel type, half wave type and inflection point type. The experimental results measured from the FBG Bending Gauges showed a good agreement with measurements from the LVDT under all three deformation types stated above, and satisfactorily reconstructs the deformation.

Improvements is being made to both hardware and software part of the proposed system for more accurate and stabilized tunnel deformation monitoring. Currently the FBG Bending Gauges are being implemented onto a tunnel of an operating railway line in mainland China, and hopefully more field test data will be available to further prove the capability of the method.

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