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Pulse-Pre Pump Brillouin Optical Time Domain Analysis-based method monitoring structural multi-direction strain

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Abstract. The Pulse-Pre Pump Brillouin Optical Time Domain Analysis (PPP-BOTDA) technique is introduced to implement the multi-direction strain measurement. The monitoring principle is stated. The layout scheme of optical fibers is proposed. The temperature compensation formula and its realizing method are given. The experiments, under tensile load, combined bending and tensile load, are implemented to validate the feasibility of the proposed method. It is shown that the PPP-BOTDA technique can be used to discriminate the multi-direction strains with high spatial resolution and precision.

Keywords: multi-direction strain measurement; PPP-BOTDA; distributed optical fiber; experimental study

1. Introduction

The burst of Britain Sheffield reservoir dam caused 254 deaths in 1864. The sudden collision of Canada's Quebec Bridge induced 74 deaths in 1907. There were 12 deaths in the US in Carlsbad, California due to the natural gas pipeline leakage and explosion in 2000. In recent times, several other incidents of bridge/buildings collapse took place in different parts of the world (Brownjohn 2007, Su *et al*. 2015). After these accidents it has become paramount importance of early detection of the health of structures and the sensors must be developed to detect the problem (Ashtankar and Chore 2015). It is an important field which is eagerly needed for an improved future of the major projects and important equipment in many countries. A more advanced monitoring technology is needed whose features are large scale, long-distance, large quantity, high precision, and local small strain monitoring. The important issues are real-time, long-term and effective monitoring, and early warning before a structure suffers disaster.

The implementation of comprehensive structure health monitoring (SHM) in civil infrastructure is made possible by the use of optical fiber sensors and can substantially improve the safety of civil structures and help to manage them more efficiently. The Fiber Bragg Grating (FBG) is a high precision technology which reaches about 3με strain, however it is not truly distributed

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monitoring technology. The Brillouin optical frequency domain analysis (BOFDA) has the advantage for high spatial resolution, however the measurement range is too small. The Brillouin optical correlation domain analysis (BOCDA) only measures the single point of the fiber, and the sensing distance is too short. The precision of BOTDR is only ±50με and the spatial resolution is only about 1m (Zhang *et al*. 2013).

The high spatial resolution, precision and measurement range distributed monitoring technology is a cry needing to be answered based on the above research background. Kishida worked toward improving spatial resolution and precision by using the pre-pump method (Kishida *et al.* 2005). The Pulse-Pre Pump Brillouin Optical Time Domain Analysis (PPP-BOTDA) is a breakthrough over traditional limitation of BOTDA/R, significantly improving measurement spatial resolution and precision, and finally realizing the only centimeter order precision fiber-optic measurements system based on induced Brillouin. It presents a new way of thinking for project monitoring (Shu et al. 2009, Lin et al. 2012, Galindez-Jamioy and López-Higuera 2012). There are some mature applications in pile foundations, oil wells, composite materials and prestressed beams for PPP-BOTDA distributed fiber sensing technology.

However, there is no truly systematic study of spatial fiber-optic multi-direction strain monitoring (FOMDSM) based on this technology now. The article studies the highest spatial resolution for the current FOMDSM based on the PPP-BOTDA technology. The study is helpful for obtaining the basic information about the monitored structure in the maximum extent, and especially for different directional information by layout scheme, temperature compensation and fiber arrangement process and multi-directional deformation measurement.

2. Distributed strain sensing technology of PPP-BOTDA

The sensing principle of Brillouin Optical Time Domain Analysis (BOTDA) is based on the frequency of stimulated Brillouin scattering caused by the probe continuous wave and pump pulse injected into sensing fiber. The work described in this paper adopts a novel technique, named as Pulse-Pre Pump Brillouin Optical Time Domain Analysis (PPP-BOTDA), which is based on the development of BOTDA technology (Motamedi *et al*. 2013, Li *et al*. 2008).

2.1 Monitoring principle for strain based on Brillouin frequency shift

As shown in Fig. 1, monitoring principle of the BOTDA technique is based on the stimulated Brillouin back scattering which is inelastic scattering. Pulse laser and continuous laser are necessary for the BOTDA technique. The weaker signal will be amplified by the stronger one and the back Brillouin scattering will be stimulated as the Brillouin frequency shift (BFS), v_B is equal to frequency difference between the two lasers.

When one certain part of optical fiber is strained, its Brillouin frequency shift v_B will become $v_B{}'$, which results in rapid decrease of Brillouin scattering signal. The frequency difference between the two lasers could be tuned to make it equal to $v_B{}'$. Then, the Brillouin scattering signal of this strained part could be obtained again. The distributed strain can be detected by relationship between Brillouin frequency shift and strain. The Brillouin frequency shift changes in proportion to the variation of strain along the fiber sensor. The linear relationships between the BFS and strain or temperature are present

$$v_B(x) = v_B(0) \times \left[1 + C_{v\varepsilon}\varepsilon(x)\right] \tag{1}$$

where $v_B(x)$ is the center frequency under the exciting strain of fiber at point x after deformation; $v_B(0)$ is the initial value; $C_{v\varepsilon}$ is the strain coefficient.

The strain value of point *x* can be obtained by measuring the BFS variable quantity as

$$\Delta v_B(x) = v_B(x) - v_B(0) = v_B(0) C_{v\varepsilon}\varepsilon(x) \tag{2}$$

And then

$$\varepsilon(x) = \frac{\Delta v_B(x)}{C_{v\varepsilon}} \tag{3}$$

where $\Delta v_B(x)$ is the variable quantity of BFS; $\varepsilon(x)$ is the strain.

When the temperature and the strain all exist at the same time, it can be expressed as follows

$$\Delta v_B = C_{v\varepsilon}\Delta\varepsilon + C_{vT}\Delta T \tag{4}$$

That is

$$v_B(\varepsilon, T) = v_B(0) + C_{v\varepsilon}\varepsilon + C_{vT}\Delta T \tag{5}$$

A differential expression is shown as follows

$$v_B(\varepsilon, T) = v_B(0) + \frac{dv_B(\varepsilon)}{d\varepsilon}\varepsilon + \frac{dv_B(T)}{dT}\Delta T \tag{6}$$

where $v_B(\varepsilon, T)$ denotes the Brillunion frequency shift when the strain is ε, and the temperature is T; $v_B(0)$ is the original Brillunion frequency shift; $\frac{dv_B(\varepsilon)}{d\varepsilon}$ and $\frac{dv_B(T)}{dT}$ are separately strain coefficient and temperature coefficient.

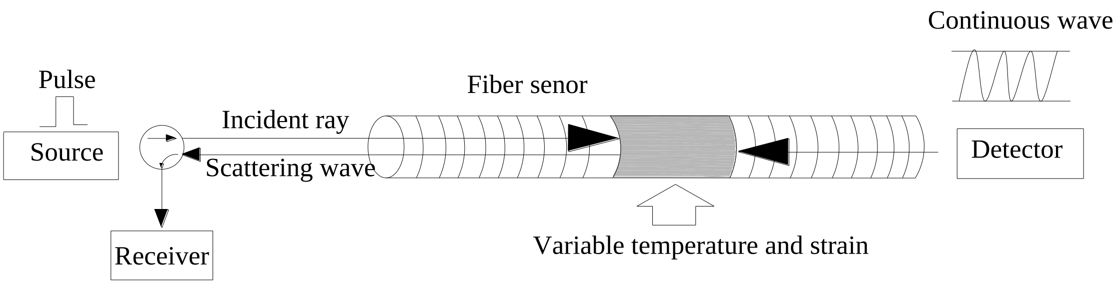

Fig. 1 Sensing principle of BOTDA

2.2 Measurement principle of PPP-BOTDA technology

A higher spatial resolution is very important and it is related with the pump pulse width. A narrower pump pulse width will result in a higher spatial resolution. However, the pump pulse width is approximately up to 28 ns to stimulate the phonon waves in the fiber, the consequence of a small pulse width of the pump may decrease and distort the stimulated Brillouin scattering (SBS) gain (Guo *et al.* 2009, Mao *et al.* 2011).

In this work, the pulse shape in the pump laser is modified to a step function. This allows one to stimulate the phonon moves prior to the arrival of measuring pump pulse. Thus, a pre-pump pulse is used in front of the traditional laser pulse to enhance the accuracy and the spatial resolution, which is called PPP-BOTDA technique (Kwon and Kim 2003, Wu *et al*. 2007) shown in Fig. 2.

3. Tensile experiment of spatial FOMDSM

The BOTDA technique was based on the backscattering of the Brillouin component, which followed the pump pulses along with the direction of the fiber (Zhang *et al*. 2012). The Brillouin frequency shift was determined by the non-uniform distribution in the refractive index of the sensing fiber. Vertical extension strength to the fiber will change the refractive index of the fiber, and thereby shift the corresponding Brillouin frequency in this tensile experiment of spatial fiber-optic multi-direction strain monitoring (FOMDSM). In case of 90°, the fiber will be vertically to the direction of the applied strength and this will change little of the fiber properties. Therefore, the fiber-optic two-direction strain monitoring (FOTDSM) is experimented to well introduce the FOMDSM technology based on the PPP-BOTDA. To give the most intuitive tensile experiment of spatial FOMDSM, the 0°/60° strain monitoring is presented.

The FOTDSM based on the PPP-BOTDA technology was aiming to discriminate the direction of the strain and no detailed studies about FOMDSM was found. The existing studies do not involve many core parts, such as, the rational layout scheme, the concrete test process, and the reasonable temperature compensation, etc. It is also limited to the pure axial tensile test while there must be various combination loads in practical project. However, there is nothing about the important issue until now. The article expands the study to include a combination load test under bending and stretching, excepting the purely axial tensile test.

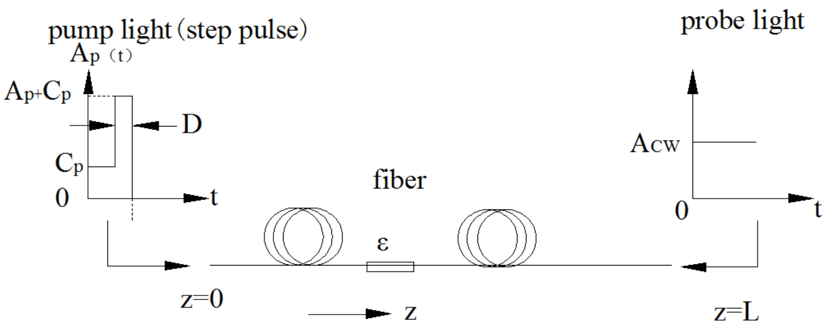

Fig. 2 Monitoring principle of PPP-BOTDA technology

3.1 Fiber-optic layout scheme

The fiber-optic segment attached to the monitored structure has the sensing function in practical application and fiber section connecting the sensing fiber with the monitoring instrument is only used for propagating fiber-optic signal. Different layout request should be noted for different functions of the two parts in the monitoring process. Therefore, it is necessary to study the fiber-optic layout which could be used to establish the relationship between the spatial structure physical coefficient and physical coefficient of the fiber.

3.1.1 Monitoring fiber layout

A reasonable layout process could mostly guarantee the functions of the fiber sensors, which are not always running well in an actual project or laboratory test. Thus, a detailed study for the FOMDSM layout is presented: First, two or more fibers are parallel laid in an arrangement to provide backup and replacement. Second, the type "×" of rubberized fabric should be firstly applied at the key points of the fibers to be laid on the structure. It can eliminate the obvious barrier effect between two times pasting processes due to the solidification time for epoxy resin adhesive and the width after the solidification. Adjustments will be easy as some problems are found in the process. Third, the key post positions should be bonded by rapid cementing agent. It can effectively prevent the degummed effect leading to departure of the fiber from its original position, especially for the existence of bending stress with the liquid epoxy resin adhesive. Fourth, the excessive bending loss should be controlled strictly to avoid failure detection for no signal.

3.1.2 Temperature compensation

The temperature compensation is a necessary step for a more precise result. Some methods are analyzed as follows: First, a circular cycle fiber layout is controlled at the beginning monitoring section keeping the condition of zero force. It is a simple way and saves laying cost of another optical fiber. However, the condition of zero force is very difficultly kept. Second, the same return is laid by the end of the fibers. However, it is a very complex process which is difficult to keep the fibers free for overabundance bending. Third, a single fiber is embedded in a larger circular tube, and then laid along the fiber layout. For this method, synchronous monitoring is not finished for the two parallel fibers because one monitoring device is only open for one fiber. The third method is chosen for this experimental FOMDSM while its disadvantage could be neglected as the monitoring duration for one time is short and changeable outside temperature could be ignored.

3.1.3 Range and size for fiber-optic layout

As shown in Fig. 3, for the test plate, the elastic modulus of a 5052 aluminum alloy plate is 70 GPa and poisson ratio is 0.33. It is finally chosen for its good tensile property, convenient production, and so on. Its tensile strength has reached to 210MPa-230MPa. The elongation of this material has reached 12-20%. The NBX-6050A of the test has successfully achieved a range of 25 km, 5 cm spatial resolution, 1cm sampling interval and ±7.5 $\mu\varepsilon$ strain precision. Therefore, the total length of the test plate is 820 mm for saving cost. Based on the result of FEM, the most ideal fiber layout is between 230-400 mm from the stretched end bottom of the plate, which could successfully avoid the stress concentration area. The length of the fixture is 120 mm however reservation gap is 10 mm due to the oil pressure port, i.e., the length of the fixture is 110 mm. The plate of fixed and stretched ends need a grooved treatment to increase the friction with the fixture.

The fibers, strain gauges and test specimen are designed one by one as follows. The fiber length in every direction is 150 mm. In Fig. 4, 1, 2, 3 are respectively the monitoring fiber, the remedy fiber, and the temperature compensation fiber. The distance between monitoring equipment and the fiber adherence end is not allowed to be less than the minimum stripping length. Therefore, 1m is left for this space. The junction position between the monitoring section and the transmission section should be especially protected. The BX120-10AA strain gauge lies in the middle of every direction and 1/2 bridge connection signal line is used for temperature compensation. The test specimen needs to be stretched by a universal testing machine.

3.2 Temperature compensation calculation

A simple and practical temperature compensation calculation method is important for the FOMDSM in a longer laboratory test, field tests or practical applications except a short time monitoring with almost certain outside environment temperature. For the FOMDSM, the temperature compensation calculation process is shown below.

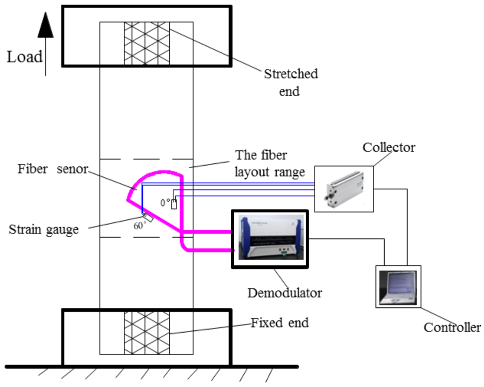

Fig. 3 Mathematical model of isolated bridge

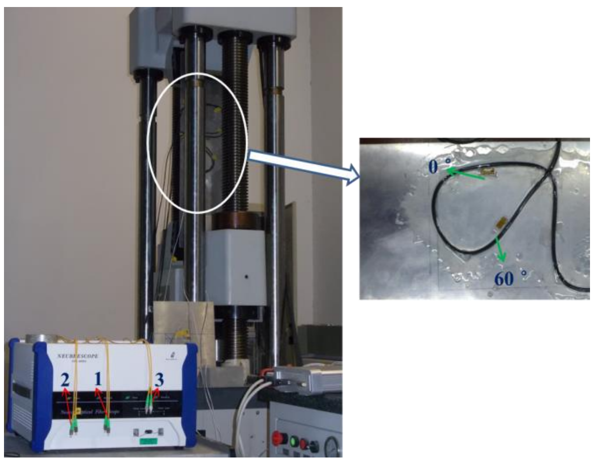

Fig. 4 Testing process of FOMDSM based on PPP-BOTDA

For the monitoring fiber, the strain could be calculated by

$$\begin{aligned}\Delta_{\nu B1} &= \Delta_{\text{Measured}} - \Delta_{\text{Initial}} = \left(\delta_{\text{Stress}} + \delta_{\text{Temperature}}\right)_{\text{Measured}} - \left(\delta_{\text{Stress}} + \delta_{\text{Temperature}}\right)_{\text{Initial}} \\ &= \Delta\left(\delta_{\text{Stress}} + \delta_{\text{Temperature}}\right)\end{aligned} \tag{7}$$

where $\Delta_{\nu B1}$ denotes the relative strain value of the monitoring fiber; Δ_{Measured} and Δ_{Initial} are respectively the final and initial monitoring strain results; δ_{Stress} and $\delta_{\text{Temperature}}$ are strain values caused by load and temperature.

For the temperature compensation fiber

$$\Delta_{\nu B3} = \Delta_{\text{Measured}} - \Delta_{\text{Initial}} = \left(\delta_{\text{Temperature}}\right)_{\text{Measured}} - \left(\delta_{\text{Temperature}}\right)_{\text{Initial}} = \Delta\left(\delta_{\text{Temperature}}\right) \tag{8}$$

where $\Delta_{\nu B3}$ is the relative strain value of the temperature compensation fiber.

The follows can be is obtained.

$$\begin{aligned}\Delta\left(\delta_{\text{Stress}}\right) &= \Delta\left(\delta_{\text{Stress}} + \delta_{\text{Temperature}}\right) - \Delta\left(\delta_{\text{Temperature}}\right) = \Delta_{\nu B1} - \Delta_{\nu B3} \\ &= \left[\nu B(\varepsilon) - \nu B(0)\right] - C_{\nu T}\frac{T - T_0}{C_{\nu\varepsilon}}\end{aligned} \tag{9}$$

The different calculation steps can be used for different known coefficients. Therefore, the temperature compensation calculation formula for FOMDSM is established.

4. FOMDSM test and ITS results analysis

4.1 Multiple parameters test

The multiple parameters test is essential for the FOMDSM practical application based on the PPP-BOTDA technology. The multiple parameters test mainly covers average count, repeatability, measurement frequency range, measurement frequency scan step, spatial resolution, measurement duration. The above parameters are of great significance to determine the stability and reliability of the monitoring process, which plays a decisive role in the field of hydraulic and health monitoring, and it needs to be tested and analyzed.

In this test, the repeatability index is defined as the maximum value of standard deviation though continuous monitoring 100 points of one fiber for five times under free state. The average count is related to the measurement result of the signal to noise ratio (SNR) and the measurement speed, which is related to the velocity and the frequency scanning step. In order to verify the most parameters by least tests, 10 m length of SMF-28e optical fiber is selected under normal temperature environment without external force. The measurement frequency range is scheduled to 10.750~10.950 GHz. The measurement frequency scan steps are 5 MHz and 2 MHz respectively corresponding to Frequency count of 41 and Frequency count of 101. The average count is 2×10^{12}, 2×10^{14} under five times continuous observations. One measured count is collected per 5 cm distance. Spatial resolution is 5 cm. The monitoring results are shown in Table 1.

From Table 1, it shows that test performance meets the monitoring requirements of FOMDSM test. Monitoring results reflects good performance, stability and reliability, for the structure with smaller size or the strain with smaller amount.

4.2 FOMDSM test

10 kN-30 kN is loaded by stepwise loading, and the step is 4 kN. The initial strain value is not zero due to the performance of the universal testing machine. 1 minute 30 seconds of load holding is for the monitoring duration time request of fiber monitoring equipment. For the sustained strain during the load holding process, the final comparative analyses results will adopt the average value. The strain gauge result is collected through the INV1861A dynamic strain gauge and INV3060A data acquisition instrument. NBX-6050A is used for the fiber monitoring equipment based on the PPP-BOTDA. It is the highest technology for this field study. The process to obtain the tensile test is shown in Fig. 5 and the final test result is shown in Fig. 6. According to Figs. 5 and 6, the conclusion is:

Firstly, the measured values of optical fiber and strain gauge almost take on the same strain variation trend though the results of optical fiber take on volatility.

Secondly, the strain variation trend of optical fiber and strain gauge in the 60° direction is better than in the 0° direction.

Thirdly, the measured values between optical fiber and strain gauge are basically closer with the time.

The existing error is due to the limited number of the measured load step and the personal test machine characteristic. Comparing the results of fiber senor and strain gauge by themselves, larger strain amount will be detected with smaller angle between the optical fiber and the direction of load. It also certifies that the FOMDSM test is believable and successful.

A combination of outside loads is a common condition in practical projects for FOMDSM. Therefore, the paper also carries out the exploratory study by combining bending and tensile drawing. The test instruments are the same as the above test. 14 kN-38 kN is loaded by stepwise loading, and the step is 4kN. The initial strain value is not zero and the load holding time is also 1 minute 30 seconds. The final results of the test are shown in Fig. 6.

Table1 Results of multiple parameters test

Measurement frequency range / GHz	10.750 ~10.950														
Measurement frequency scan step / MHz	2 (Frequency count : 101)														
Average count	2×10^{12}					2×10^{14}					2×10^{16}				
Repeatability /$10^{-6}\varepsilon$	10.05					4.40					2.62				
Measurement duration /s	22	22	22	22	22	29	29	28	29	29	52	52	49	53	52
Measurement frequency range /GHz	10.750 ~10.950														
Measurement frequency scan step /MHz	5 (Frequency count : 41)														
Average count	2×10^{12}					2×10^{14}					2×10^{16}				
Repeatability /$10^{-6}\varepsilon$	13.61					7.90					4.83				
Measurement duration /s	21	20	21	21	21	23	23	23	23	23	32	32	33	32	32

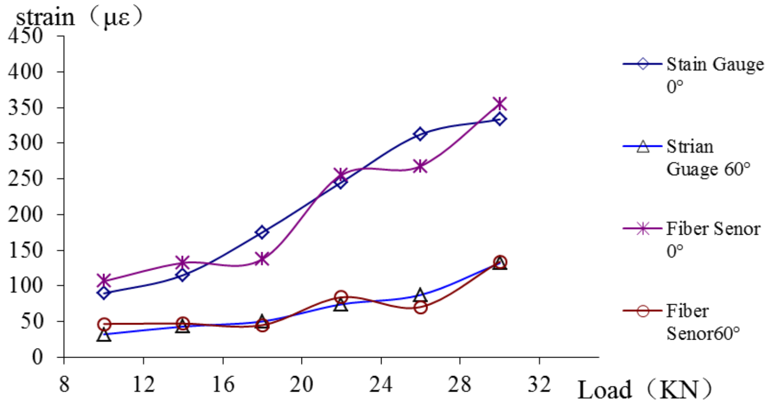

Fig. 5 Results for fiber senor and strain gauge

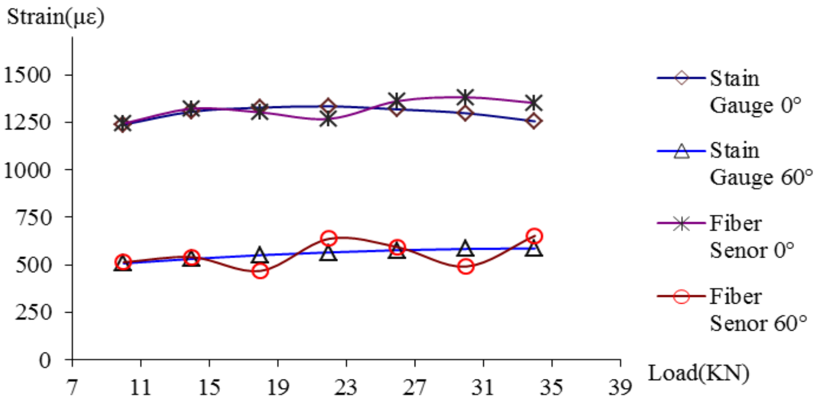

Fig. 6 Results of fiber senor and strain gauge under the bending and stretching load

From Fig. 6, the measured results between optical fiber and strain gauge are all consistent, not only the amount but also the tread in the 0° and 60° directions. From the comparative analyses about the results of fiber senor, strain is very sensitive to the variable bending and tensile drawing in the 0° and 60° directions. The results are satisfactory for the initial idea of the test.

From the above results, the conclusion is that the FOMDSM put forward by the article has a high capacity for the laboratory test and the practical application for the multi-direction strain monitoring based on the PPP-BOTDA technology.

5. Conclusions

This study is mainly for the FOMDSM research based on the PPP-BOTDA technology.

(1) This paper gives a series of important monitoring links by the test study and FEM method.

The tensile test and combination of the bending and drawing test are all studied by fiber layout scheme, temperature compensation calculation formula, etc.

(2) The comparative analyses between the strain gauge and the fiber senor have be proved that FOMDSM technology can well measure the multi-direction deformation from the whole measured process under all kinds of situations.

(3) For future application, the distributed fiber senor can be connected as a type of serial connection and parallel connection, like the circuit. The final purpose of putting forward the spatial multi-direction stress and strain monitoring idea based on the PPP-BOTDA technology is also proved to be reasonable and applicable.

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