USING DISTRIBUTED BRILLOUIN FIBER SENSOR TO DETECT THE STRAIN AND CRACKS OF STEEL STRUCTURES

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ABSTRACT

A distributed Brillouin fiber sensor was used to monitor the health of steel structures. We used this method on two steel beam specimens and longitudinal strain and cracks were detected well under different loads. The difference between the longitudinal strain measured by the distributed fiber sensor and that measured by strain gages is less than 4%. Traditional sensors or transducers that measure the average strain over a small region always miss cracks. The method proposed in this study gives very good results for the detection of cracks and the surrounding strain on a square pipe.

Keywords : Distributed fiber sensor, Health monitoring of steel structures, Crack detection.

1. INTRODUCTION

Structural health monitoring techniques have been developing rapidly. Designers and engineers are developing new techniques that allow the simple, regular inspection of structural health. Using these techniques, degradation of structures can be promptly identified and located and they can be immediately repaired, thus extending their life. This also prevents structural damage and the potential for serious casualties. Different structural health monitoring systems use different criteria, such as variation in strain, variation in temperature, and cracks in the structure, to detect imminent failure.

Conventional structural health monitoring systems can monitor the specific points where sensors are deployed, but they cannot respond immediately if cracks appear elsewhere. Conventional sensors are also affected by electromagnetic waves. On the other hand, optical-fiber structural health monitoring systems work well in any circumstances. The optical fiber sensor is light, sensitive, stable, and can work under high temperatures. It is not affected by electromagnetic waves in the environment, and the material used for the sensor is anticorrosive. One can easily imbed an optical fiber sensor in a composite material structure. These sensors are widely used in modern structural health monitoring systems [1]. The Bragg grating for optical fiber sensors has high resolution and is highly sensitive, so many monitoring systems are based on the FBG method [2-4]. However, these systems are expensive.

Distributed optical fiber sensors are widely used because, in contrast to other types of optical fiber sensors, they can continuously detect the strain and temperature of structures [5,6]. In recent studies, researchers have applied distributed optical fiber sensors to structural health monitoring [7,8]. However, the proposed systems do not have a sufficient spatial resolution.

In general, many factors, such as quenching and fatigue, can lead to cracks in a steel structure. Distributed optical fiber sensors can detect and measure these cracks [9,10]. However, the system accuracy is limited by the spatial resolution and the distribution of the sensors [11,12]. We propose a sensing system based on the Brillouin optical correlation domain analysis (BOCDA) technology introduced by Hotate *et al.* [13,14]. This technology is capable of distributed sensing. The detection area and the spatial resolution can be adjusted according to the requirements. The system can achieve centimeter-level spatial resolution and can perform online measuring. Such a high resolution has not been realized by the conventional time-domain method because its narrower temporal pulse increases the bandwidth and reduces the strain accuracy [15]. In this study, the measuring system uses a general single-mode optical fiber as the sensor. It can measure strain and cracks everywhere in the steel structure and allows us to monitor the safety of the structure.

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2. EXPERIMENTAL PROCEDURE

2.1 Distributed Brillouin Scattering Sensor System

We use a distributed Brillouin scattering system. The laser diode (LD) sinusoidal frequency modulation (f_m) generates a correlation peak at a specified position along the fiber under test (FUT). The pump and probe interact at a point related to the correlation peak. By changing the modulated frequency, we can adjust the position of the correlation peak. Stimulated Brillouin scattering (SBS) is generated exclusively at the specified position of the correlation peak. Figure 1 shows that the pump and probe light wave counter-propagate along the test area. The probe obtains Brillouin gain from the pump. The probe gain is detected by the photodetector, and the pre-adjusted frequency shift of the pump. The Brillouin frequency shifts according to changes in the strain and temperature. Therefore, such changes can be determined by measuring the Brillouin frequency. The Brillouin frequency shift ν_B, which is determined by the peak of the Brillouin gain spectrum (BGS), is known to be linearly related to the temperature and strain [16,17]:

$$\nu_B(T_0,\ \varepsilon) = C_\varepsilon(\varepsilon - \varepsilon_0) + \nu_{B0}(T_0,\ \varepsilon_0) \qquad (1)$$

$$\nu_B(T,\ \varepsilon_0) = C_T(T - T_0) + \nu_{B0}(T_0,\ \varepsilon_0) \qquad (2)$$

where C_ε and C_T are the strain and temperature coefficients, respectively, and T_0 and ε_0 are the strain and temperature corresponding to a reference Brillouin frequency, ν_{B0}.

According to Hotate *et. al.* [13], the sensing area, spatial resolution, and modulation frequency are interrelated. The spatial resolution is given as

$$\Delta x_r = \frac{\nu_g \Delta\nu_B}{2\pi\, f_m \cdot m} \qquad (3)$$

where ν_g is the light wave group velocity, $\Delta\nu_B$ is the intrinsic linewidth of the BGS, and mf_m is the f_m amplitude. In the current work, $\Delta\nu_B$ was about 35MHz, and mf_m was about 1.5GHz. The spatial resolution was about 7cm. The strain accuracy was about 50με.

2.2 Enhancement of Measurement System

In the measurement system, the experimental results are affected by the spatial resolution. If the strain region affected by the crack after loading is less than this resolution, the measuring system may fail to locate it. To improve the spatial resolution, the probe power level and polarization state are controlled so that we can locate the measurement position and optimize the Brillouin gain spectrum at the measurement points. By repeating and accumulating the calculations, we can improve the accuracy of the measurement system.

2.3 Preparation of Steel I-Beam

In this experiment, a general crack-free I-beam was used (shown in Fig. 2). The length of the I-beam is

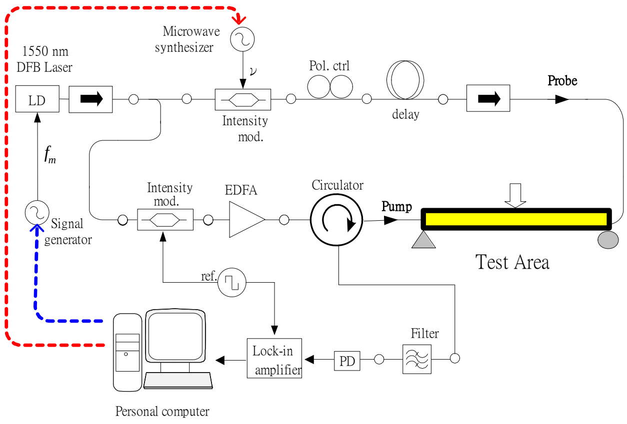


Fig. 1 Block diagram of measuring system [14]

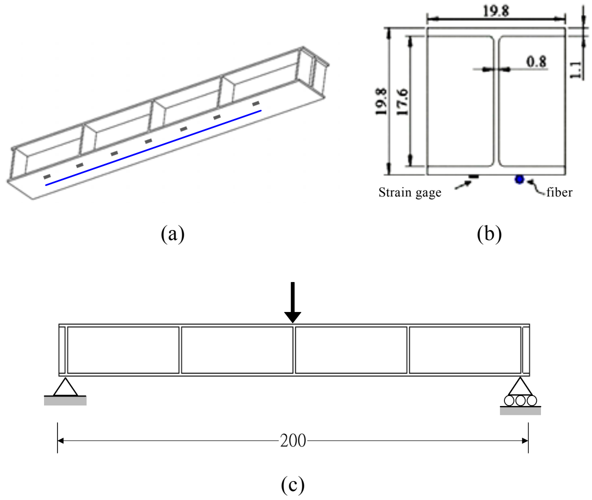


Fig. 2 (a) Optical fiber and strain gage for 2-m I-beam; (b) Cross-section; (c) Simple supported I-beam

2m, Young's modulus is 2.03×10^{11}N/m^2, and Poisson's ratio is 0.3 shown in Table1. Five rectangular reinforced steel plates were welded inside the I-beam to prevent local buckling caused by the hydraulic press.

To measure the strain along the I-beam, the irregularities at the welding seam were removed by grinding with sandpaper. The optical fiber was then slightly pre- strained to make it taut and stuck on the pipe with the epoxy adhesive Bondite. The adhesive was cured at 45°C for 3 hours to get an optimum joint. The Brillouin frequency was initially 10.81GHz. The room temperature was maintained by an air conditioner at 26°C, but slight fluctuations occurred. It is estimated that these temperature fluctuations caused a change of about ±10με in the strain; this value is small enough to be neglected. In addition, seven strain gages were adhered in different positions close to the optical fiber. Therefore, we can compare the results from the strain gages and the optical fiber sensor. Seven loads (3000kg, 4000kg, 5000kg, 6000kg, 7000kg, 8000kg and 9000kg) were applied to the I-beam shown in Fig. 3.

Table 1 Material specifications for steel

Poisson's Ratio	Young's Modulus (GPa)	Length (mm)	Ultimate Stress (Kgf/mm^2)	Yield Stress (Kgf/mm^2)
0.3	203	2000	47	33

Fig. 3 Hydraulic press system for loading

2.4 Square Pipe with Crack

In this experiment, a 2-m-long 20cm × 20cm square pipe was used. An artificial crack was produced on the bottom and lateral surfaces by laser piercing of the pipe to a thickness of 8mm at the position of the dotted line shown in Fig. 4(a). The optical fiber runs along the pipe as indicated by solid line in Fig. 4(a). Figure 4(b) shows the positions where the fiber sensor crossed the crack. The width of the crack is 1mm. A 360-με pre-strained optical fiber that is 4.2m long runs across the bottom and lateral surfaces. The Brillouin frequency is initially 10.817GHz. The loads are applied to the simple supported square pipe.

We measured not only the strain distribution around the crack, but also the position of the crack. The strain and Brillouin shift at the crack were predicted to be higher than in other areas of the FUT. Therefore, the Brillouin frequency was set to sweep at a higher range than that used in the I-beam.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Measurement of Axial Strain in an Steel I-Beam

Under the three-point bending set-up, maximum deflection and axial strain will occur at the center of the beam. A load varying from 3000kg to 9000kg has been applied. From Eq. (3), the spatial resolution is related to the modulated frequency. The modulated frequency affects the size of the measured region and the accuracy: the lower the modulated frequency, the larger is the area that can be detected, but the lower is the accuracy. The modulation frequency f_m of the light source was set to sweep from 10.72 to 10.78MHz, which was the range of the FUT. The Brillouin frequency was set to sweep from 10.78 to 11.0GHz. The 54th correlation peak was used to measure the Brillouin gain along the fiber.

In general, the Brillouin frequency shift will be higher for a strained fibers. We used a single-mode fiber as the sensor. The experimental results from this sensor were used to establish the relationship between the strain and the Brillouin frequency shift. The strain coefficient was approximately 0.047MHz/με.

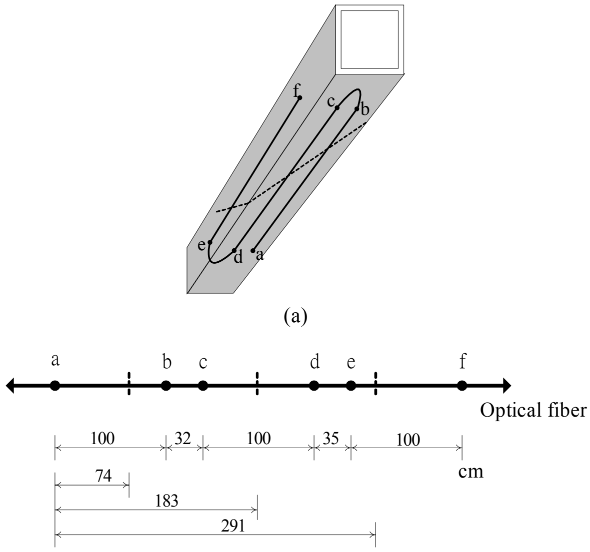


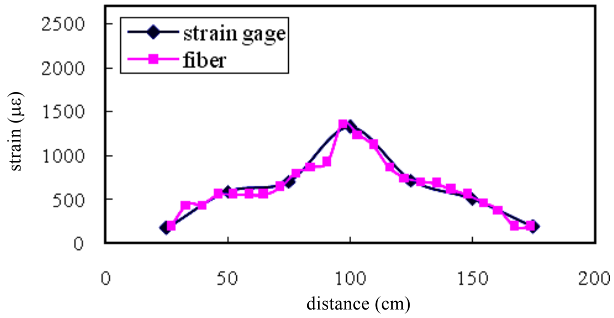
Fig. 4 Square pipe with crack: (a) Optical fiber sensor (dotted line shows position of crack) (b) Fiber sensor crossing the crack. The glued regions are *a* to *b*, *c* to *d* and *e* to *f*. The segments of *b* to *c* and *d* to *e* are loosed

The fiber in the test region was pre-strained with the Brillouin frequency shift set to 10.81GHz, corresponding to a strain of about 210με. Figure 5 compares the strain measured by the optical fiber sensor and that measured by the strain gages.

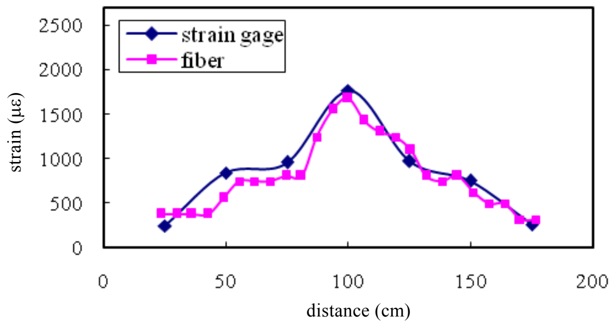
Figure 6 compares the results from the strain gages, the fiber sensor, and Ansys analysis at the center of the I-beam. It can be seen that the trend of each strain curve is similar. When the load increases from 3000kg to 5000kg, the strain magnitudes are almost identical. As shown in Fig. 5(a), the difference between the seven strain gages and the fiber sensor is less than 4%. The difference is greater when the load increases from 6000kg to 9000kg. This is may be attributed to the deterioration of the adhesive joint under high strain. If part of the fiber separates from the beam, the result will not be accurate. This is why the fiber-sensor result is lower than the results from the ANSYS analysis and the strain gages.

When the load was increased to 6000kgf, local yielding caused by the hydraulic press may occur at the center. It is more obvious when the load increases to 9000kgf. In this situation, the deformation of the beam is permanent rather than elastic. Thus, the curve will not be a straight line.

In general, the distributed Brillouin fiber sensing system is not as accurate as the strain gages. However, a single strain gage does not provide enough data for the safety evaluation of an entire steel structure. Using a series of strain gages gives better results but is too expensive. It is also difficult to analyze the signals and the signal quality. In this experiment, we have shown that using a single low-cost optical fiber as the sensor can achieve the accuracy required. Moreover, the distributed sensing ability of the system is the best choice for monitoring the safety of the steel structure.



(a) 5000kg load



(b) 7000kg load

Fig. 5 Comparison of strains measured by optical fiber sensor and strain gages

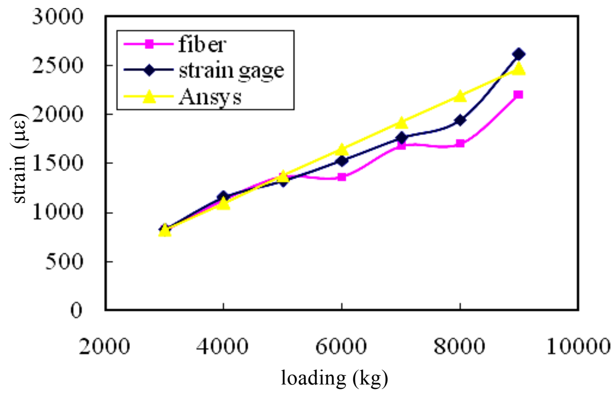


Fig. 6 Results from strain gage, BOCDA system, and Ansys at center of I-beam

3.2 Crack Detection for Steel Beams

This experiment focused on the distributed strain in the neighborhood of a crack, crack detection, and the propagation of cracks. Based on the BOCDA theory, the position of the correlation peak along the FUT can be shifted by changing f_m. Since the spatial resolution was in inverse proportion to the range of FUT and we need to measure a range of 10m in the current test, f_m was set to sweep from 10.7 to 10.8MHz. The Brillouin gain spectrum along the fiber was obtained and the strain at any position can be deduced from the Brillouin frequency. Figures 7(a) to 7(e) illustrate the distribution of the strain along the fiber under loads from 600 to 6000kg.

When the load is small, the strain in every section will present a smooth profile which is similar to the deformation of the simple supply beam. But when the load increases, the strain on cracks will become higher.

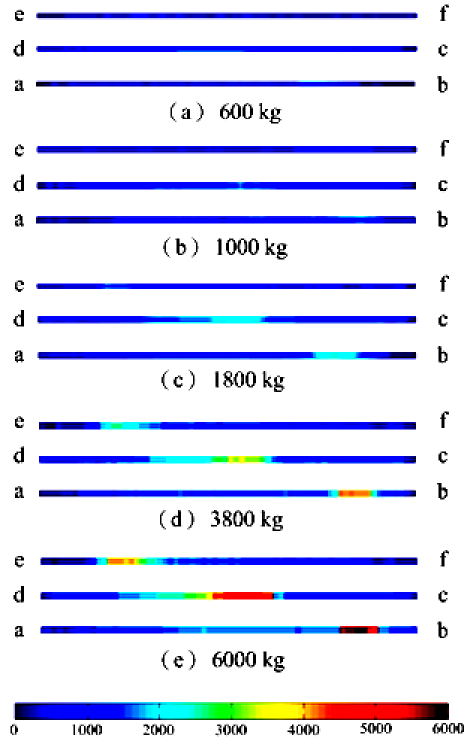


Fig. 7 Distribution of strain along the fiber under different applied loads. The unit under the color code is με

Besides, the fiber near by the high strain will generate smaller bending curvature, it will affect the partial strength of light signals. In this experiment, the strength of light signal under load of 6000kg was smaller than that under load of 600kg about 15%. But the change of signal noise ratio (SNR) value was only slight variation, it didn't affect the measuring result of strain obviously.

When the load increases, the Brillouin shift will increase quickly because of the increase in the crack opening. Figure 8 shows the increase of the strain at the crack under different loads. It is impossible to locate a failure a priori using traditional sensors that perform discrete measurements. Our system can measure continuously and gives reliable results for structural monitoring.

As shown in Fig. 7, when loaded to 600kg, the influence of crack on strain distribution starts to appear. Strain peaks arise at position where the fiber crosses the crack as the crack opening will induce large local strains. The crack opening was in the order of 1mm. However, the length of the highly strained regions extend to about 10cm in Figs. 7(a) to 7(e). There are two reasons for this. Firstly, because of the fiber and glue is elastic. The large local strain on crack will make a diffusive influence on the fiber where the crack locates position and the adjacent regions. Secondly, the spatial resolution of the system is about 7cm. During the experiment, slight fluctuation of temperature occurred but its effect on all part of the fiber is basically the same. Since we detect the crack by means of local strain peaks, the uniform changes on the strain profile induced by temperature fluctuation will not affect our detection scheme.

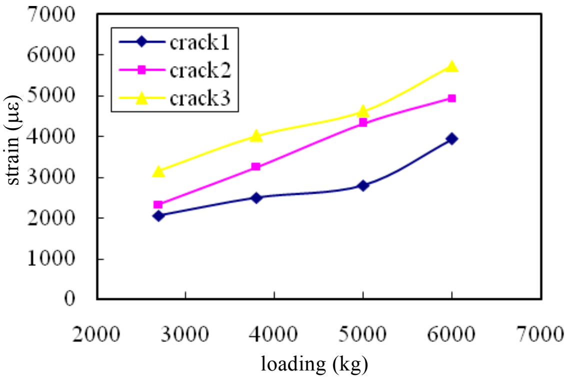


Fig. 8 Increase in strain at position of each crack under different loads

4. CONCLUSIONS

We have demonstrated that the distributed Brillouin fiber sensing system is able to monitor the axial strain in an I-beam and detect the occurrence of a crack in a beam. Although the region monitored is extensive, the distributed optical fiber is still affordable and practicable. This is more advantageous in contrast with the pointwise monitoring by conventional strain gages. With good bonding between the fiber and the structure, there is only a 4% difference in measured strains between the optical fiber sensor and the strain gages. Thus, the distributed optical fiber is affordable and effective for monitoring structural health.

Without the existence of a crack, the longitudinal strain along a beam will stay more or less constant or change gradually. When a crack comes into existence and intersects the fiber, the crack opening displacement will create intensified local strain. In an actual structure, the initial distribution of strain along the fiber can be recorded before a crack occurs. By monitoring and comparing the strain distribution periodically, we can diagnose whether a crack has occurred.

An important challenge is that the location of cracks in structures may not be known a priori. It will be impracticable to monitor the occurrence of a crack with conventional sensors or transducers that measure the average strain over a small region. Using the high- resolution distributed Brillouin sensor, it will be much easier to detect the crack. Our research verifies that a distributed Brillouin sensing system can be used to accurately measure strain and detect cracks in steel structures.

REFERENCES

1. Lee, B., "Review of the Present Status of Optical Fiber Sensors," *Optical Fiber Technology*, **9**, pp. 57–79 (2003).
2. Takeda, N., Okabe, Y., Kuwahara, J., Kojima, S. and Ogisu, T., "Development of Smart Composite Structures with Small-Diameter Fiber Bragg Grating Sensors for Damage Detection: Quantitative Evaluation of Delamination Length in CFRP Laminates Using Lamb Wave Sensing," *Composites Science and Technology*, **65**, pp. 2575–2587 (2005).
3. Miao, P., Kukureka, S. N., Metje, N., Chapman, D. N., Rogers, C. D. F. and Henderson, P., "Mechanical Reliability of Optical Fibre Sensors and Smartrods for Tunnel Displacement Monitoring," *Smart Materials Structures*, **16**, pp. 382–390 (2007).
4. Liu, H. B., Liu, H. Y., Peng, G. D. and Chu, P. L., "Strain and Temperature Sensor Using a Combination of Polymer and Silica Fibre Bragg Gratings," *Optics Communications*, **219**, Elsevier Science, pp. 139–142 (2003).
5. Zou, L., Ferrier, G. A., Afshar, V., Shahraam, Q. Y., Chen, L. and Bao, X., "Distributed Brillouin Scattering Sensor for Discrimination of Wall-Thinning Defects in Steel Pipe Under Internal Pressure," *Applied Optoelectronics*, **43**, pp. 1583–1588 (2004).
6. Carrillo, A., Gonzalez, E., Rosas, A. and Marquez, A., "New Distributed Optical Sensor for Detection and Localization of Liquid Leaks Part I. Experimental Studies," *Sensors and Actuators A 99*, pp. 229–235 (2002).
7. Ravet, F., Zou, L., Bao, X., Chen, L., Huang, R. F. and Khoo, H. A., "Detection of Buckling in Steel Pipeline and Column by the Distributed Brillouin Sensor," *Optical Fiber Technology*, **12**, pp. 305–311 (2006).
8. Zhang, W., Shi, B., Zhang, Y. F., Liu, J. and Zhu, Y. Q., "The Strain Field Method for Structural Damage Identification Using Brillouin Optical Fiber Sensing," *Smart Materials Structures*, **16**, pp. 843–850 (2007).
9. Gao, J., Shi, B., Zhang, W. and Zhu, H., "Monitoring the Stress of the Post-Tensioning Cable Using Fiber Optic Distributed Strain Sensor," *Measurement 39*, pp. 420–428 (2006).
10. Wan, K. T. and Leung, C. K. Y., "Applications of a Distributed Fiber Optic Crack Sensor for Concrete Structures," *Sensors and Actuators A 135*, pp. 458–464 (2007).
11. Wan, K. T. and Leung, C. K. Y., "Fiber Optic Sensor for the Monitoring of Mixed Mode Cracks in Structures," *Sensors and Actuators A 135*, pp. 370–380 (2007).
12. Zhang, H. and Wu, Z., "Performance Evaluation of BOTDR-Based Distributed Fiber Optic Sensors for Crack Monitoring," *Structural Health Monitoring*, **7** (2008).
13. Tanaka M. and Hotate, K., "Distributed Fiber Brillouin Strain Sensing with 1-Cm Spatial Resolution by Correlation-Based Continuous-Wave Technique," *IEEE Photonics Technology Letters*, **14**, pp. 179–181 (2002).
14. Hotate, K., "Correlation-Based Continuous-Wave Technique for Optical Fiber Distributed Strain Measurement Using Brillouin Scattering," *Optical Fiber Sensors (OFS-17)*, Bruges, TH-1, pp. 62–67 (2005).
15. Inaudi, D. and Glisic, B., "Application of Distributed Fiber Optic Sensory for SHM," 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-2'2005).
16. Horiguchi, T., Kurashima, T. and Tateda, M., "Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers," *IEEE Photon. Technol. Letters*, **1**, pp. 107–108 (1989).
17. Kurashima, T., Horiguchi, T. and Tateda, M., "Thermal Effects on Brillouin Frequency Shift in Jacketed Optical Silica Fibers," *Applied Optoelectronics*, **29**, pp. 2219–2222 (1990).

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