A study of FBG sensor and electrical strain gauge for strain measurements

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A comparative investigation on fiber Bragg grating (FBG) sensor and electrical strain gauge for strain measurements is carried out. The fiber Bragg grating system, consist of Excimer Laser, Mask Aligner, Optical Spectrum Analyzer and Tunable Laser Source was utilized to fabricate the fiber gratings. The experiment was performed on a specimen made of steel having dimension 400 x 100 x 2 mm^3. The fiber Bragg grating sensor was a piece of 1000 mm bare optical fiber with 100 mm stripped section in the middle, in which 10 mm was written with Bragg gratings. The type of electrical strain gauge was FLA-6-11. The data logger wires were soldered to the lead wires of electrical strain gauge through connecting terminals. The steel plate with the FBG sensor and strain gauge bonded was welded on one end, and the other end was depressed by a micrometer with equal increment of 2mm. Based on the results, the FBG sensor data correlates better with the theoretical calculation than the electrical strain cantilever gauge values. The fiber grating sensor did perform quite consistently over the two trails than the electrical strain gauge. There is a consistency in the results of electrical strain gauge but the electrical strain gauge gave low values of strain. The test results discussed in this research show a reasonable correlation between the strain values obtained from the fiber grating sensors and those obtained from conventional foil gauges, from a maximum difference of 13%. The findings provide an essential and useful basis for developing a fiber Bragg grating sensor system for real time and long term monitoring of mechanical and steel structures.

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1. Introduction

Fiber optic technology is a well established field in the world of smart structures. While optical communications systems date back as far as the late 1700s when the French engineer Claude Chappe invented the ‘optical telegraph’, advances in optical fibers did not really take off until Corning Glass Works (now Coming, Inc.) developed single-mode fibers with attenuation below 20 dB/km in 1970 [1]. It was imperative to evaluate the performance of fibre Bragg grating sensor system after successfully developing it. The study was conducted to check the flexibility and validity of the system with comparison to the existing method of strain measurements. The main objective was to discuss how efficient is the system in different criteria such as range, functionality, sensitivity and accuracy.

In this research, the approach was established and discussed to verify the feasibility of fibre Bragg grating sensor alongwith electrical resistance strain gauge. Initially the fibre Bragg grating sensor was tested on a specimen made of steel in a cantilever test and then again tested on a specimen made of steel but alongwith electrical strain gauge to check the validity of the system. There are two major aspects considered for verification of fibre Bragg grating sensor system, which are; First aspect is that the fibre Bragg grating sensor system work in a technical sense, i.e., data can be produced stored in the floppy and transferred. This aspect includes, the issues related to dynamic range, linearity and sensitivity of fibre Bragg grating sensor. The second aspect is during evaluation process to test the feasibility of the FBG sensor system [2]. This includes comparison and checks the FBG sensor system with existing practice or traditional system. The issues such as temperature sensitivity considered before running the fibre Bragg grating sensor system. This is much more difficult to measure. Setting up reliable experiments for these aspects is consequently quite difficult. The fiber grating sensors have acquired the most recognition among all in current researches, which shows huge potential in various application fields of this technique [3]

The main purpose of this study was to check the usability of the fiber Bragg grating system alongwith traditional methods and to improve the performance of fiber Bragg grating sensor system for practical applications. The performance of FBG sensor was evaluated and compared alongwith electrical strain gauge in terms of dynamic range, linearity, sensitivity and accuracy. On the basis of the comparison drawn from the results and useful discussion, the performance of the fibre Bragg grating sensor was evaluated. The findings from the results provided an essential and useful basis for developing a fibre Bragg grating sensor system for real time and long term monitoring of mechanical structures, condition of civil infrastructure and steel structures.

2. Experimental

A schematic experimental arrangement to measure the strain sensitivity of fibre Bragg grating system using fabricated fibre Bragg grating alongwith electrical strain gauge is shown in Figure 1. The experiment was performed on a specimen made of steel. The dimension of the steel plate is 400 x 100 x 2 mm (l x w x t). The fibre Bragg grating sensor was a piece of 1000 mm bare optical fibre with 100 mm stripped section in the middle, in which 10 mm was written with Bragg gratings. The stripped section was not recoated after FBG inscription. Cantilever setup was made by welding a one end of steel plate with a strong support and other end of the steel plate is remained free to deflect due to applied load. The strong support was screwed on the optical table firmly. Fibre Bragg grating was bonded onto the specimen surface carefully using araldite as an epoxy. Epoxy applied is circled in marker area. The type of electrical strain gauge was FLA-6-11 and made by Tokyo Sokki Kenkyujo Co., Ltd. CN (Cyanoacrylate) adhesive was used to bond the electrical strain gauge with the specimen i.e. steel plate. Before installation of electrical strain gauge, surface treat was done. For this purpose, removed the grease, rust, paint etc. from the bonding surface of a specimen, lightly polish with an abrasive paper, wiped with acetone and marked the gauge installation position. Then applied an adhesive to the back of a strain gauge and stick the gauge to a specimen. The data logger wires were soldered to the lead wires of electrical strain gauge through connecting terminals.

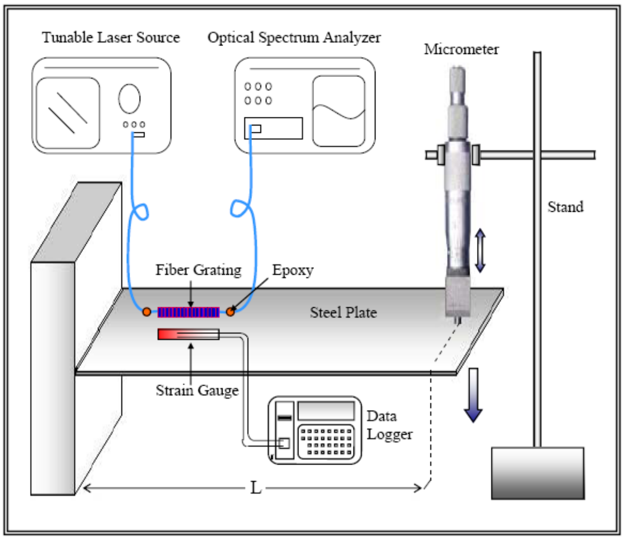


Fig. 1. A schematic experiment setup of fibre grating sensor alongwith electrical strain gauge for cantilever test.

In this experiment, effective sensor lengths are tested at 200 mm (only 200 mm of the entire sensing fibre is bonded). The steel plate with the FBG sensor and strain gauge bonded was welded on one end, and the other end was depressed by a micrometer. The goal of this experiment setup is to illustrate tension sensor displacement (strain) due to bending. Deflection is defined to be downward positive, which allows the result to be positive under tension. The total deflection of this experiment is ~16 mm. The micrometer was in units of millimeter; the interval between deflection-strain readings was 2mm. Once the components and equipments were ready to be used, tuneable laser source and optical spectrum analyzer were preset. The light from tuneable laser source was launched into the optical spectrum analyzer through fibre Bragg grating. The main objective of this experiment is to plot the deflection vs. strain on the surface of specimen.

2.1 Specification of the Fiber Bragg Grating

The results for inscribing Bragg grating with a phase mask technique have been obtained from optical spectrum analyzer. Perturbation of the grating results in a shift in the Bragg wavelength of the device which can be detected in either the reflected or transmitted spectra. The reflection method offers some advantages over the transmission method. In reflection only the light that matches the Bragg condition of the grating is measured over relatively small background intensity. A 3-dB coupler was used to split off the reflection of the grating.

The centre wavelength of the grating reflection was measured by an optical spectrum analyzer. The reflectivity of fiber grating centered at Bragg wavelength 1554.932 nm was calculated by measuring the dip peak of the transmission spectrum as shown in Figure 6.29 and the calculated reflectivity was about 72%. The bandwidth of the reflected signal depends on several parameters, particularly the grating length, but typically is ~ 0.1 to 0.4 nm in most sensor applications. The Bragg wavelength of this fiber grating was cantered at 1552.745 nm, and its bandwidth measured at full width at half maximum (FWHM) was 0.22nm. The specification of the tested fabricated fiber Bragg grating is given in Table 1.

Table 1. Specification of the tested fabricated fibre Bragg grating

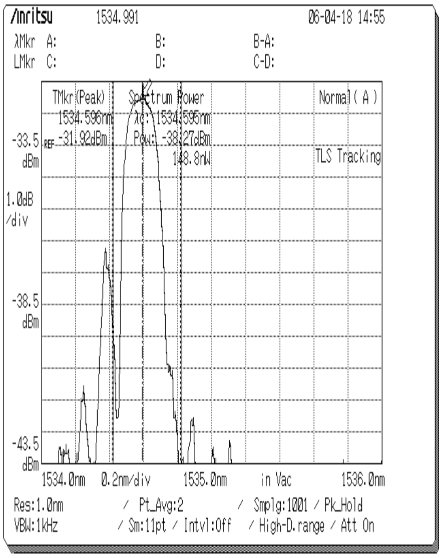
No.	Specifications	
1	Centre wavelength at 25^{0}C (nm)	1554.932
2	FWHM (nm)	0.22
3	Reflectivity (%)	72
4	Grating length (mm)	10.00
5	Fiber type	SMF-28 compatible

3. Results and discussion

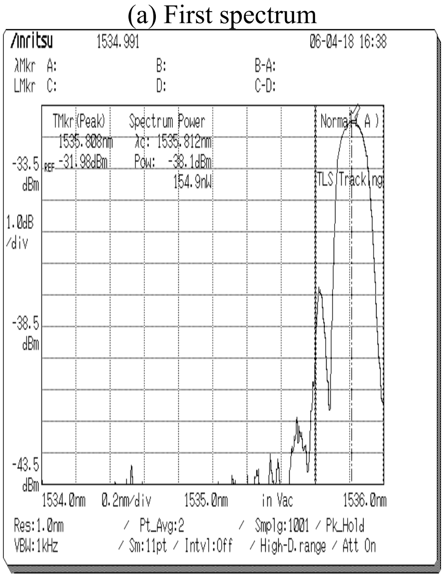
Following sections discuss the two studies on which a fibre Bragg grating sensor system was evaluated. The first study was taken as a dynamic range i.e. strain and second study was taken as linearity of fibre Bragg grating sensor and then compares it with electrical strain gauge for the same load application. The main purpose of this study was to check the usability of the fibre Bragg grating system and what ever lesson learned should be improved before implementing the fibre Bragg grating sensor system for any practical applications. The performance tests were carried out using two experimental setups to compare the dynamic range, functionality, sensitivity and accuracy with electrical strain gauge.

3.1 Results of Fibre Bragg Grating sensor

For the experimental setup, the Bragg wavelength λ_B and Bragg wavelength shift $\Delta\lambda_B$ were obtained from Optical Spectrum Analyzer after the FBG was strained during the deflection produced by moving the micrometer. The corresponding reflection spectrums (first & last only) obtained from OSA to show the tracking of Bragg wavelength shifts due to the variation in deflection conditions by moving the micrometer with equal increment of 2mm are shown in Figure 2.



(a) First spectrum



(b) Last spectrum

Fig. 2. Results samples of reflection spectrum.

The operating principle is that the grating reflects different wavelength component of the signal for different section along the grating. It also shows from the reflection display that the value of peak wavelength and hence the Bragg wavelength shift is gradually increasing by enhancing the value of deflection. If the deflection is uniform, then the Bragg wavelength shifts occur without modification of the initial spectrum shape. The Bragg wavelength λ_B is 1554.932nm and the strain for the experimental setup was calculated against each value of deflection using the equation: $\varepsilon = \Delta\lambda_B / (1 - p_e)\lambda_B$. Where p_e is an effective strain-optic constant is defined as $p_e = n^2/2\ [p_{12} - \nu\ (p_{11}+p_{12})]$. Where p_{11} and p_{12} are components of the strain optic tensor, n is the index of the core, and ν is the Poisson's ratio. For a typical optical fibre $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.16$ and $n = 1.482$. The strain was calculated under variable deflection conditions i.e. with equal interval of 2mm and Bragg wavelength shift at a constant temperature of 25 ^{0}C. The calculated values of strain corresponding to the deflection are obtained. It is noted that the values of strain are gradually increased with the increasing value of applied deflection. It is observed that the strain has shifted through with negligible proportions, in length elongation of fiber grating. Therefore, the plot between deflection and strain can be drawn as a straight line and is shown in Figure 3.

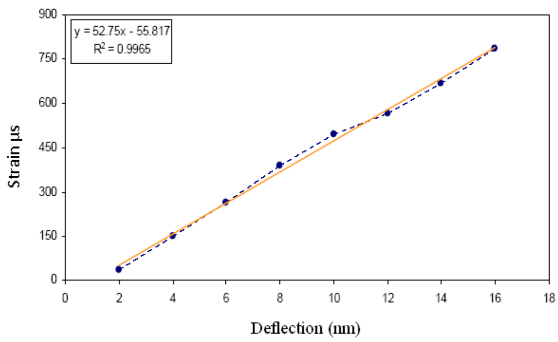


Fig. 3. Strain verses applied deflection (fibre Bragg grating sensor)

The Fig. 3 shows the result under variable deflection from 2 to 16mm at constant temperature 25 ^{0}C, have shift in the strain ranging from 36.28 to 786.2με as a function of applied deflection for a 1554.932 nm grating. Experimentally, a 99% linear response has been observed between applied deflection and calculated strain throughout the measured region. From these results it can also be observed that the wavelength of Bragg grating increases with applied deflection.

The primary measurand influence of interest in the sensor community is the strain dependence of the Bragg wavelength. From Fig. 3, the calculated strain response at a constant temperature is found to be:

Wavelength-strain sensitivity at λ_B = 1554.932 nm; <0.121nm / 100με

3.2 Results of Electrical Strain Gauge

The electrical strain gauge was bonded alongwith fibre grating sensor on the steel plate as shown in Fig. 1. The electrical strain gauge is connected directly with data logger to get the values of strain corresponding to the deflection application. The values of strain obtained from data logger against gradually increasing value of deflection by moving the micrometer with equal increment of 2mm are obtained. The strain obtained from data logger is increasing linearly corresponding to the increasing value of deflection. It is observed that the strain has shifted through with negligible proportions, in length elongation of fiber grating. Therefore, the plot between strain and deflection can be drawn as a straight line and are shown in Fig. 4.

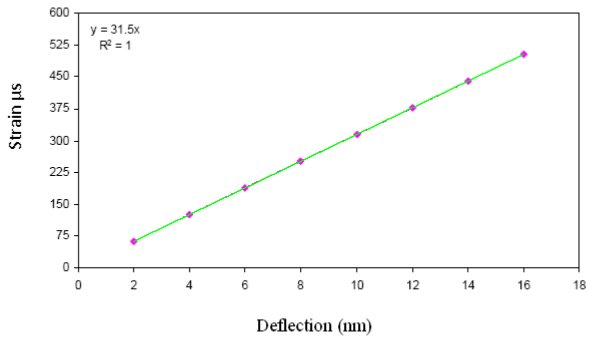


Fig. 4. Strain versus applied deflection (electrical strain gauge)

The Figure 4 shows the plotting of results obtained under variable deflection conditions having a shift ranging from 63 to 504με at in the strain as a function of deflection ranging from 2 to 16mm at a constant temperature of 25^0C. The figure above shows the linearity of the electrical strain gauge against applied deflection. There is a good agreement between deflection and strain obtained from the experiment. A linear response has been observed between strain and deflection throughout the measured region.

3.3 Comparison of FBG Sensor and Electrical Strain Gauge

To evaluate the performance of fiber grating sensor, the results comparison of fiber sensor and electrical strain gauge was imperative. The comparison values of strain for fibre grating sensor and electrical strain gauge corresponding to the same deflection are recorded. Strain measurements in fibre Bragg grating sensor and electrical strain gauge were conducted experimentally. A comparison plot of the fiber grating sensor and electrical strain gauge between the values of deflection and strain was drawn in Figure 5. The difference of average strain between fiber grating sensor and electrical strain gauge value was 134.4με for the same deflection. The strain response arises due to both the physical elongation of the sensor (and corresponding fractional change in grating pitch) and the change in the refractive index due to photoelastic effects.

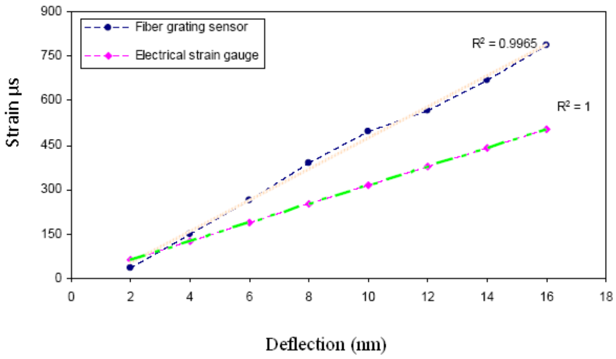


Fig. 5. Strain versus deflection (fiber grating sensor /electrical strain gauge).

The results show that the fibre grating sensor data correlates better with the theoretical calculation than the electrical strain gauge values. The fibre grating sensor performs better than the electrical strain gauge. There is a consistency in the results of electrical strain gauge but the electrical strain gauge gave low values of strain. The tests discussed in this research show a reasonable correlation between the strain values obtained from the fibre grating sensors and those obtained from conventional foil gauges, from a maximum difference of 19%. Result of reflection spectrum and reflectivity of light in fiber Bragg grating have shown a relationship with Bragg wavelength, when resulted of the strain effect on optical fiber Bragg grating. This is corresponds to change in the grating spacing and the refractive index of fiber. Therefore, it shifted the Bragg wavelength. The good linear relationship between strain and deflection has shown the potential of using for a device sensing applications, water tank, and metallic and steel structures monitoring. The strain measurement can be used for such monitoring.

The discrepancy between the fibre grating sensor and electrical strain gauge values could have been due in part to the fact that a specimen undergoes a minimal amount of bending in a tensile test. Due to the limitation of experimental conditions, as well as the uncertainty of the instruments involved in the measurement, substantial errors are induced in the conclusion. The deviation is resulted from OSA uncertainty error, uncertainty of displacement readings, temperature fluctuation effect and optical fibre length error.

4. Conclusions

Overall, the test results of fibre Bragg grating sensor and electrical strain gauge were as good as the results were expected. The Bragg grating sensor did perform quite consistently over the two trials, which suggests that the fibre grating sensor was functioning well. The factors that most limits the strain values are the variation in effective gauge length of fibre grating sensor and position of installation of electrical strain gauge on the specimen. Based on the results, it is inferred that the performance of the fabricated fibre Bragg grating sensor is quite satisfactory. Therefore, the purposed fabricated fibre Bragg grating sensor is recommended for the practical field application of strain/ temperature measurements on a metallic surface.

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