AUTHOR(S): JOHNY, J., SUMMERS, J., BHAVSAR, K., JOSEPH, G.P., FUNG, W.K. and PRABHU, R.

TITLE: Theoretical investigation of positional influence of FBG sensors for structural health monitoring of offshore structures.

YEAR: 2017

Publisher citation: JOHNY, J., SUMMERS, J., BHAVSAR, K., JOSEPH, G.P., FUNG, W.K. and PRABHU, R. 2017. Theoretical investigation of positional influence of FBG sensors for structural health monitoring of offshore structures. In Proceedings of the 60th MTS/IEEE OCEANS conference (OCEANS'17): a vision for sustaining our marine futures, 19-22 June 2017, Aberdeen, UK. New York: IEEE [online], article ID 8084976. Available from: https://doi.org/10.1109/OCEANSE.2017.8084976

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Theoretical investigation of positional influence of FBG sensors for structural health monitoring of offshore structures

Jincy Johny*, Jade Summers, Kaushalkumar Bhavsar, Ginson P Joseph, Wai Keung Fung, Radhakrishna Prabhu
School of Engineering
Robert Gordon University, Aberdeen, United Kingdom
*j.johny@rgu.ac.uk

***Abstract*— Fibre Bragg Grating (FBG) is a key technology for condition monitoring of different offshore oil and gas structures. FBG sensors are used to sense different physical parameters such as strain, temperature, vibration, etc. This paper investigates the effect of FBG sensor positions on the reflected sensing signal, to optimise the sensor positioning plan for structural health monitoring of offshore structures. Theoretical investigations were carried out on a cantilever beam to analyze the strain effects. Effect of different cantilever beam shapes, materials and their thickness on strain was investigated. Theoretical studies were also carried out to evaluate the strain sensitivities of FBG sensors. Furthermore, micrometer displacement based strain analysis of cantilever beam was carried out using FBG sensors and electrical strain gauges to study the positional influence and compared it with the theoretical results obtained.**

Keywords - fibre optic sensors; strain analysis; cantilever beam structure; FBG

I. Introduction

Structural health and condition monitoring is a vital task in offshore oil and gas industry. It plays a critical role in protecting their valuable assets and working personnel's from health and safety hazards. In the present situation, most of the subsea assets (e.g. North Sea assets) are approaching their design lifetime, with still considerable amount of untapped hydrocarbon reserves. Consequently, the oil and gas companies are very keen on the structural integrity and maintenance of their deteriorating offshore platforms and structures to extend its life span. Offshore structural health monitoring (SHM) is gaining significant attention and importance considering the HSE (Health, Safety and Environment). However, SHM of offshore structures is very complicated owing to the harsh marine environment (HPHT, i.e. High-Pressure High-temperature field condition).

Different underwater monitoring approaches are: external visual inspections by skilled divers or remote operating vehicles (ROVs), internal gauging (e.g. Strain gauges), radiography, hydrostatic pressure test, eddy current method, acoustic emission monitoring system, X-ray tomography, laser leak testing, etc [1]. These traditional subsea monitoring approaches owing to the long distance and unfavourable environment return weak sensing signals. In addition, due to the hostile environment of the oil well installations, the traditional sensors either fail or poorly operate. Hence, there is an urgent need for smart condition monitoring systems for the offshore infrastructures, with increased transmission length and enhanced spatial coverage to retrieve the sensing data from deeper zones. The features of smart condition monitoring systems include : the ability to monitor structures remotely on a real-time basis, the ability to return stronger sensing signals (High SNR), ability to operate in a harsh environment, high reliability (continuously monitor with high accuracy and precision), higher sensor lifetime.

Optical fibre sensing technology offers immense potential and capabilities for real-time and remote monitoring of oil and gas structures. Compared to conventional electrical sensors, fibre optic sensors have many advantages such as immunity to electromagnetic interference (EMI), small size, noncorrosive, nonconductive, ability to operate in extreme environmental conditions, long reach, etc [2]. In addition, the same optical fibre serves both as the sensing system and also the data transmission system. All these mentioned advantages of fibre optic sensors contribute to smart offshore structural monitoring. Among the different fibre optic sensing technologies available, FBG (Fibre Bragg Grating) is the key technology which can sense almost all types of physical parameters and also offers to sense at multiple points simultaneously. Moreover, FBG gives wavelength encoded measurements and therefore sensing information is not susceptible to any light power fluctuations [3].

Considering the complicated size and shape of different offshore structures such as subsea manifolds, wellheads, submersible pumps, risers, flowlines, offloading lines, jumpers etc, positioning of sensors becomes vital to obtain accurate sensor measurements. Amongst these various structures, cantilevered structures are more likely to develop defects and shorten their life span due to lack of maintenance, repairs and combating natural weathering and therefore demand close monitoring. Hence, precise placement and alignment of FBG sensors becomes essential in these structures prior to securing them to offshore structures [4]. The positioning of FBG sensors is highly important because, it will facilitate stronger sensing or reflected signal from the FBG, thereby improving its SNR. Identifying the right position of FBG sensors with respect to the structural axis is very important because the FBG sensors show highest sensitivity and records peak intensity at specific points [5]. Moreover, this helps in the precise and accurate measurements of the physical parameters at longer distances and thereby smart remote monitoring can be achieved.

This paper reports theoretical strain analysis carried out on different structural shapes, materials and structural parameters using ANSYS finite element modeling software. Cantilever beam structure was used to study the effect of strain under different applied load conditions. The position of load applied to the cantilever beam was varied to evaluate the strain at various positions along the beam to optimize the placement of sensors on such structures. Obtained numerical results were compared to experimental work using strain gauge sensors. Furthermore, theoretical work was carried out using MATLAB to analyze the strain sensitivity of FBG sensors. Modeling results were compared with theoretical results to evaluate the positional influence of FBG sensors.

II. Theory

The fundamental principle of FBG sensor depends on the Bragg condition which states that any changes in physical parameters such as pressure, temperature, strain etc modifies the refractive index or grating period of the fibre grating, which in turn changes the Bragg reflected wavelength correspondingly [6].

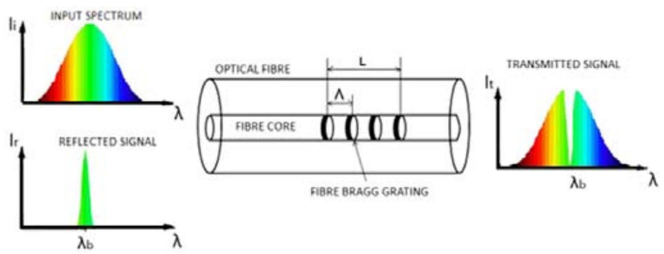

Fig. 1. Detection principle of FBG sensor

Fig. 1 illustrates the detection principle of FBG sensor. When a broad-spectrum of light is sent into the FBG sensor, reflections occur from each segment of alternating refractive index (gratings). These reflections interfere constructively only for a specific wavelength of light, known as the Bragg wavelength (λ_b). This effectively causes the FBG to reflect a specific wavelength of light while transmitting all others.

The Bragg reflected wavelength [7] is given by:

$$\lambda_b = 2.n_{eff}.\Lambda \quad (1)$$

Where n_{eff} is the effective refractive index and Λ is the period of the grating or spatial period.

A. Strain Sensitivity of FBG

Fractional change in Bragg wavelength [8] for applied strain $\left(\varepsilon = \frac{\Delta\Lambda}{\Lambda}\right)$ is given by:

$$\frac{\Delta\lambda_b(\varepsilon)}{\lambda_b} = (1 - \rho_e)\Delta\varepsilon \quad (2)$$

Where ρ_e is the photo-elastic coefficient and $\Delta\varepsilon$ is the variation in strain value.

B. Stress Strain relations of Cantilever Beam

For a cantilever beam, Stress, $\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A}}$ (3)

Where, $\boldsymbol{F}$ is axial force and $\boldsymbol{A}$ is the cross sectional area.

$$\text{Strain, } \boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{L}}{\boldsymbol{L}} \quad (4)$$

Where, $\Delta\boldsymbol{L}$ is the change in length and $\boldsymbol{L}$ is the original length [9].

Bending stress (MPa) is given by the equation is:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{My}}{\boldsymbol{I}} \quad (5)$$

Where, M is the calculated bending moment (N/m), y is the vertical distance away from neutral axis (m), I is the moment of inertia around neutral axis (m^4).

Young's Modulus (E) is the ratio of stress and strain. It is known as the limit of proportionality for a material and is a constant value.

$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A}}{\frac{\Delta L}{L}} \quad (6)$$

In conclusion, stress is proportional to load and strain is proportional to deformation.

The second moment of area (I) is the measure of a beam's: stiffness with respect to the cross section and its ability to resist bending [9].

For a solid rectangular cross section [10], I is given by

$$I = \frac{bh^3}{12} \quad (7)$$

Where, b is the breadth of cross sectional area (m) and h is the height of cross sectional area (m).

The deflection of a cantilever beam at a specific point of application of force is given by [10]:

$$\delta = \frac{FL^3}{3EI} \quad (8)$$

Where, δ is the deflection (mm), F is applied force (N), L is length of the beam, E is the Young's Modulus (MPa) and I is the second moment of area (m^4).

III. Results And Discussions

A. Theoritical Analysis of Cantilever Beam

Strain analysis of different cantilever beams under applied load was carried out. The strain was calculated at various positions along the 300 mm cantilever beams of different shapes. The load was applied by 2 mm displacement at the free end of the cantilever. Fig. 2 shows the strain at various positions along the beam (where 0 mm represents the free end) for different cantilever beam shapes such as circular, I-beam, T-beam, rectangular and square. All the beam shapes show higher strain at the fixed end. The strain experienced by applied load was maximum for T shape and lowest for the rectangular shape. The obtained results further depend on the type of material and dimensions. All the cantilever beams used to analyse strain effect of different shapes were made of Stainless Steel.

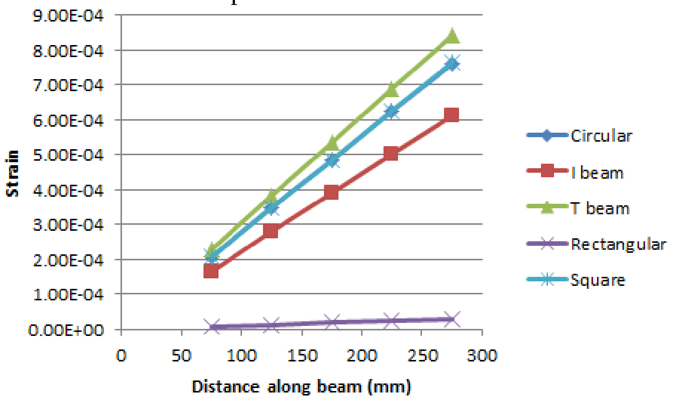

Fig. 2. Strain at various positions along the beam for different cantilever shapes.

Fig. 3 shows the computational modeling results of strain at various positions on a rectangular cantilever beam of 25 mm x 1 mm x 300 mm. The force was applied by 2 mm displacement to the free end of the cantilever.

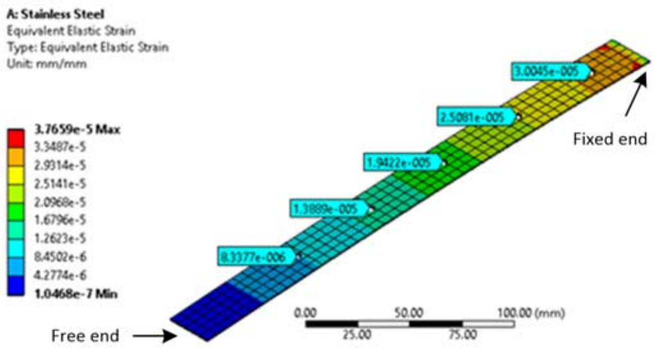

Fig. 3. Stain on a stainless steel rectangular cantilever beam.

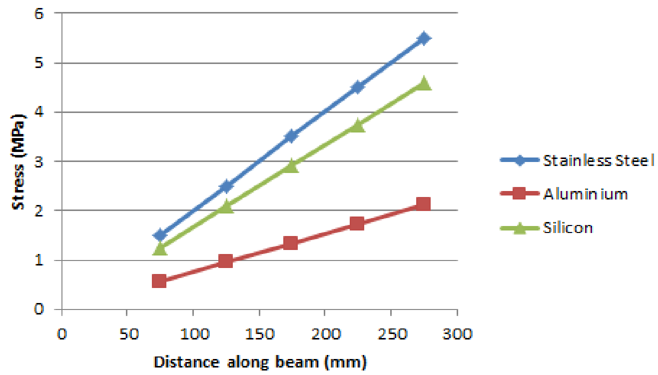

Fig. 4. Stress at various position on a rectangular cantilever beam for different materials.

Further, the effect of material was investigated on the same rectangular cantilever beam. Stainless steel, aluminium and silicon materials were used to analyse the stress at various positions along the beam caused by the applied force (2 mm displacement) as shown in Fig. 4. The higher stress value observed for the stainless steel can be atrributed to high Young's modulus. All the three cantilever beams have shown the high-stress value at the fixed end of the cantilever.

Effect of varying the beam thickness was investigated for the same stainless steel rectangular cantilever beam. The thickness of the rectangular beam was increased from 1 mm to 4 mm which leads to increase in the strain at all the positions along the beam as shown in Fig. 5. The observed increase can be attributed to the increase in the second moment of area due to increased cross section value.

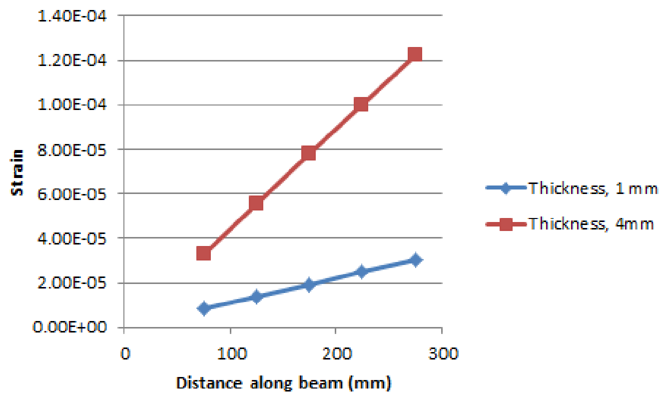

Fig. 5. Strain at various positions along the rectangular cantilever beam.

Effect of application of force at different positions was investigated and the strain was measured along the rectangular cantilever beam corresponding to each position. The force was applied by 2 mm displacement at 50 mm interval along the length starting from 300 mm (free end). The strain measured was increased as the position of the applied force was moved towards the fixed end. The stain was increased gradually closer to the fixed end while a small increase was observed at the free end, as shown in Fig. 6. When the applied displacement was 50 mm and 100 mm away from the fixed end, strain values close to the fixed end increased considerably compared to other strain results. These observed high strain values might be the result of slight deformation experienced by the material.

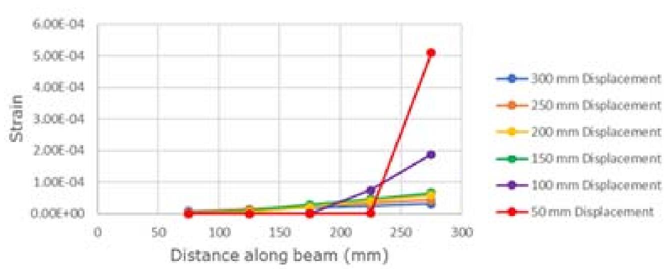

Fig. 6. Strain along the rectangular cantilever beam for the displacement applied at different positions.

Obtained results through computational modeling work were verified by experimental work. Three strain gauges were fixed on the stainless-steel cantilever (25 mm x 1 mm x 300 mm) at 275 mm (strain gauge 1), 250 mm (strain gauge 2) and 225 mm (strain gauge 3) position from the fixed end. Strain measurements were performed by varying the displacement of the cantilever. As the displacement increased, higher strain values were observed along the cantilever at all the positions as shown in Fig. 7. A higher strain was observed towards the fixed end of the cantilever for each displacement.

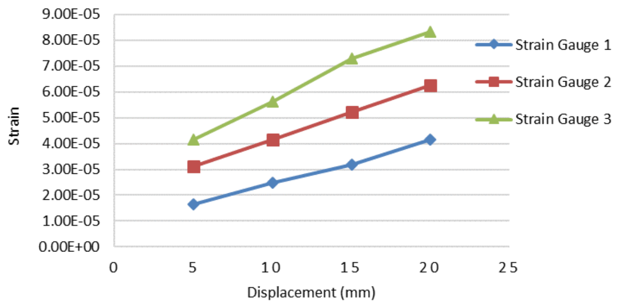

Fig. 7. Strain measured along the rectangular cantilever beam for the different displacements.

B. *FBG Modeling and Experimental Results*

Theoretical modeling of FBG was performed in MATLAB solving coupled mode equations [11]. Previous study carried out on FBG sensors confirmed that proper optimization of fibre grating parameters aids in obtaining a sharper reflection signal from the fibre sensor [12]. Furthermore, fine tuning of grating parameters also enhances FBG sensor capabilities by improving its sensing range, accuracy and the number of sensors that can be accommodated.

Fig. 8 shows the FBG strain sensitivity graph calculated theoretically, which varies linearly for applied strain. FBG strain sensitivity is the plot of shift in Bragg wavelength to change in strain. The linear trend of strain sensitivity graph attributes to the linearity of FBG sensor. FBG strain sensitivity depends on the compression and expansion of its grating period and also the strain-optic effect; which is defined as the strain-induced change in glass refractive index [13].

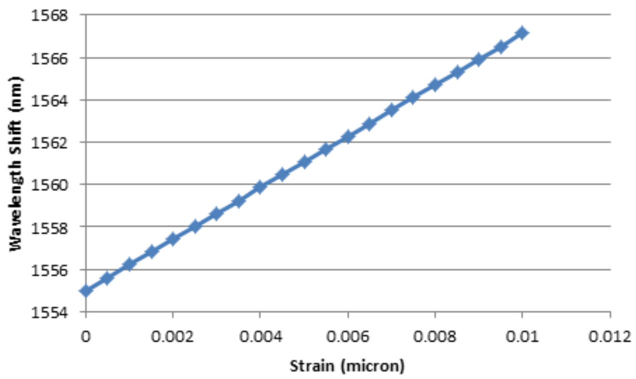

Fig. 8. Strain sensitivity of FBG sensor

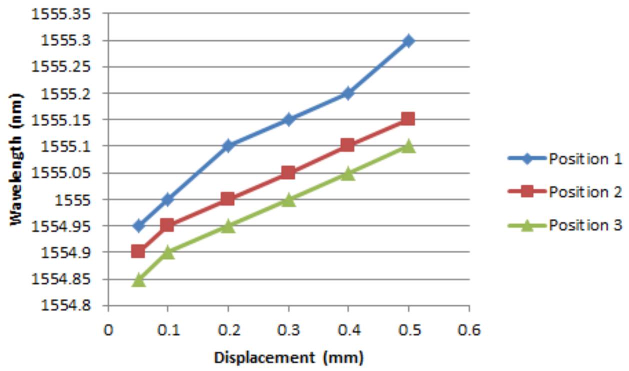

Fig. 9. FBG strain responses at different cantilever positions

A micro-displacement based strain analysis was carried out using a rectangular cantilever beam, in order to analyse the positional influence of FBG on the sensing signal. A cantilever setup was used for the experimental investigation of strain because it resembles most of the elongated offshore structures like flare booms, cranes, etc. Experiments were carried out using cantilever beam of Aluminium material with dimensions of 300 mm x 30 mm x 3 mm. One end of the cantilever was fixed and strain was applied at different positions of the cantilever by a micrometer. The micrometer was varied in steps of 0.05 mm in order to take the readings. FBG sensor was attached on to the cantilever beam to analyse the impact of varying positions of strain application on the reflected signal from FBG. Optical instruments like Optical Spectrum Analyzers (OSAs), broad band light sources and coupler were used in the experiment to obtain the shift in Bragg wavelength for any strain transferred on to the FBG sensor from the cantilever beam. Strain was applied at 3 different cantilever positions, each at a distance of 7.5 cm from each other. Position 1 is at the free end and position 3 is closer to the fixed end of the cantilever beam.

From the graph shown in Fig. 9, it is clear that FBG reflected wavelength decreases with increasing distance from the cantilever free end, maintaining the linear trend. The reflected wavelength experienced a shift with changing positions of strain application. From the graph, it is also clear that FBG's strain sensitivity is dependent on the position of strain application. Hence, by properly positioning the FBG sensor, we can get a stronger reflected signal, which in turn improves the signal to noise ratio (SNR) of the sensor. This positional influence of FBG sensors can be utilised in the structural health and condition monitoring of different offshore and subsea structures.

IV. Conclusion

Access to offshore structures, especially subsea structures is difficult and expensive. Hence, a significant amount of cost and time could be saved by fibre optic sensor installations for offshore sensing and monitoring. Identifying the right position of FBG sensors with respect to structural axis, enhances the sensor capabilities and also facilitates smart structural health monitoring (SHM). Theoretical study conducted on the cantilever beam has confirmed that the stress and stain distribution along the beam varies for changing parameters like cross section, material, thickness, etc. Furthermore, the theoretical and experimental results conducted on the cantilever beam have confirmed that the strain distribution varies with changing positions. Therefore, properly positioned FBG sensors will have higher sensitivity. Hence, FBG sensor positioning aids in the precise and accurate measurement of physical parameters, particularly in long distance remote monitoring applications. These improved capabilities of FBG sensors make it the best possible replacement for existing offshore SHM sensors.

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