



## An Analysis of Fibre Bragg Grating Strain and Induced Strain on Composite Materials

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### ABSTRACT

*This research presents an analysis of Fibre Bragg Grating (FBG) strain and induced strain on composite materials. Composite materials have obtained a great recognition in establishment such as telecommunication, spacecraft, oil and gas, marine, automotive, civil infrastructure, power industries and sport equipment, owing to their exceptional mechanical properties. Composites result from the combination of two or more different materials in an attempt to form a single material that has enhanced mechanical properties when compared to the individual properties of the constituting materials. However, during use, composite materials are subjected to loading and low-velocity impacts that can result in Barely Visible Impact Damage (BVID). In this research, the FBG strain was analyzed with that of the induced strain on Toray Carbon Fibre America composite material. Two FBGs models were examined in this work: the FBG with enhanced sensitivity (iFBG) and the conventional FBG. The simulation result shows that there is a linear relationship between the FBG strain and the induced strain on the composite material from the surrounding. Which implies that as induced strain on the composite material increases or decreases it reflects on the FBG strain which makes it suitable for monitoring the effect of physical parameters on composite materials. Furthermore, the FBG with enhanced sensitivity achieved 32.09% increment in FBG strain over the existing FBG.*

### ARTICLE INFO

Article History

Received: January, 2020

Received in revised form: April, 2020

Accepted: May, 2020

Published online: June, 2020

### KEYWORDS

FBG Strain, Strain, Composite Material, Bragg wavelength, CFRP and BVID

### INTRODUCTION

Composite materials have obtained a great recognition in establishment such as telecommunication, spacecraft, oil and gas, marine, automotive, civil infrastructure, power industries and sport equipment, owing to their exceptional mechanical properties [12]. Composites result from the combination of two or more different materials in an attempt to form a single material that has enhanced mechanical properties when compared to the individual properties of the constituting materials [3]. In the case of composite laminates, they comprise of two or more layers, reinforced with a matrix acting as the bonding medium [3].

However, during use, composite materials are subjected to loading and low-velocity impacts that can result in Barely Visible Impact Damage (BVID) [15]. This is because of the poor composition in the through thickness direction of the Carbon Fibre Reinforced Plastic (CFRP) [5]. Furthermore, in BVID, the effect on the outward does not result in a dent other than a minor hollow that is hard to recognise through visual examination. Though, the effect may result in impairment that spreads under different damage mechanisms [1]. This might affect the proper operation of the material, subsequently reduce the life cycle and raise safety issues [13]. Hence, the need to detect damage at its early stage of initiation

in composite materials is of high importance. Failure mechanisms in composite materials include matrix cracking, fibre fracture, de-bonding, fibre pull-out, micro-buckling, and kinking [17]. This may happen through a series of events such as extreme loading conditions or low velocity impacts [11]. Therefore, the need to monitor the adverse effect on composite materials deployed in harsh environment become very paramount. However, in this research the relationship between the FBG strain and the induced strain on the composite material due to environmental effects was examined and how it can be used to monitor the amount of deformation on the material.

#### LITERATURE OVERVIEW

[15] presented a fibre Bragg grating modeling characterization and optimization with different index profiles. The modeling and the characterization of the fibre grating of the maximum reflectivity and minimum side lobe power wastage were analyzed. The analysis of the reflection spectra and side lobes strength with different lengths and refractive index profiles were evaluated.

[5] Presented a temperature non-sensitive strain measurement technique for Structural Health Monitoring (SHM). By deploying two conventional Fibre Bragg Grating (FBG) sensors to eliminate cross sensitivity to temperature and strain.

[10] Proposed a simulation used for analyzing of fibre Bragg grating narrow bandwidth. The model equation of the cascaded uniform FBG and different cascade apodization functions were numerically obtained and further processed. Using the specialized software maximum reflectivity, narrow bandwidth without side lobes were actualized in the researched. In this work, an analysis of the strain in FBG sensor will be compared with that of the induced strain on the composite materials.

#### FUNDAMENTAL CONCEPT

**Strain on Composite Materials:** Strain is the elongation (contraction) per unit length when a material is strain elastically. The deformation is due to the force exerted on the material from the environment which can either be tensile or compressive as shown in Figure 1 and 2 respectively [4]. The modulus of elasticity ( $E$ ) is the material characteristics, that expresses its stiffness and it is an important property of solid materials.

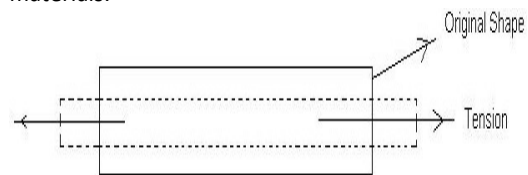


Figure 1: Material Subjected to Tension Force [12]

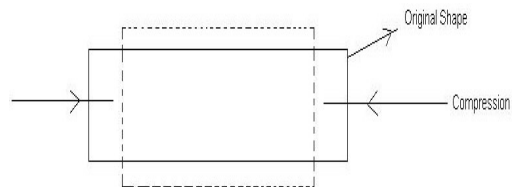


Figure 2: Material Subjected to Compression Force [12]

**FBG Strain:** FBG are sensitive to physical parameters induced by the environment. As a strain sensor it is sensitive to this disturbance exerted from the surrounding. When it is subjected to any physical perturbations or disturbance from the environment it will change in length. The change in length depend on the nature of induced physical parameters. When it elongates it means the disturbance is tensile in nature and when it shrinks the disturbance is compressive. FBG strain is the proportionate change in the FBG length due to induced physical parameter from the environment. In order words, it is the change in the FBG length to the original length. Furthermore, it can be defined as the ratio of the FBG sensitivity to its Bragg wavelength. The FBG strain is largely depended on the thermo-optic and strain

optic properties of the fibre optic cable. The variations introduced by strain and temperature on the core of the Bragg grating influences the effective refractive index and the spatial periodicity of the FBG [7]. The effective refractive profile is changed via the thermo-optic and strain optic properties [7].

### INDUCED STRAIN MODEL

Strain is the change in length of a material subjected to external force to its original length as shown in equation (1):

$$\varepsilon = \Delta l / l \quad (1)$$

where ( $\varepsilon$ ) is the induced strain,  $\Delta l$  is the change in length and  $l$  is the original length of the material. Strain and stress are related by Hooke's Law as shown in equation (2). From the Hook's modulus of elasticity which is the ratio of stress to strain on the structure is expressed by equation (3) [4];

$$\sigma = E \times \varepsilon \quad (2)$$

$$\varepsilon = \sigma / E \quad (3)$$

where  $\sigma$  is stress and  $\varepsilon$  is strain. For equation (4), (5) and (6),  $F$  is the applied load and  $A$  is the area. They express the relationship between stress, strain and applied load on the composite structures [4].

$$\sigma = \Phi / A \quad (4)$$

$$\varepsilon = \Phi / E \times A \quad (5)$$

$$\Phi = \varepsilon \times E \times A \quad (6)$$

In this research the modulus of elasticity of the composite material is 135GPa it was adopted from the Technical Data Sheet No.CFA-005 of the Toray Carbon Fibre America, INC [18].

### FBG STRAIN MODEL

The grating wavelength is expressed in equation (7) (Matthew *et al.*, 2016):

$$\lambda_B = 2n_{eff} \times \Lambda \quad (7)$$

where  $\lambda_B$  is the Bragg wavelength of FBG sensor,  $n_{eff}$  is the effective refractive index of the FBG and  $\Lambda$  is the grading period of the FBG sensor and equation (8) is the

expression for the sensitivity of FBG sensor [2].

$$\Delta \lambda_B = \lambda_B [1 - P_e] \Delta \varepsilon \quad (8)$$

where  $\Delta \lambda_B$  is the FBG sensitivity,  $P_e$  is the strain optics coefficient,  $\lambda_B$  is the Bragg wavelength and  $\Delta \varepsilon$  is the change in strain. The expression for the strain optics coefficient is shown in equation (9) [2].

$$P_e = \frac{n_{eff}^2}{2} \{p_{12} - v[(p_{11} + p_{12})]\} \quad (9)$$

where  $v$  is the Poisson's ratio and  $p_{11}$ ,  $p_{12}$  are the Pockel's coefficient of the strain-optic tensor [2]. Substituting equation (3) into (10) gives the expression for the FBG strain.

$$\Delta \lambda_B / \lambda_B = (1 - p_e) \times \sigma / E \quad (10)$$

The flow chart of the proposed work is shown in Figure (3).

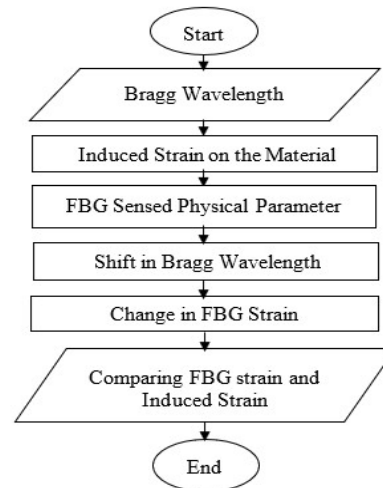


Figure 3: Flow Chart of the Analysis of FBG Strain and Induced Strain on the Material

### SIMULATION RESULTS

The results gotten from this work are discussed in this section. The following results are based on the FBG strain to induced strain, on the composite material are discussed below.

In Figure 4, the strain in the fibre Bragg grating sensors was plotted against the strain induced on the composite material. The plot was obtained, from the simulation values in Table 1. Table 1 was

generated using equation (10). From the plot, a linear plot was observed with shows that as the induced strain on the composite material increases the FBG strain also increases. The more force exerted on the material the more strain exhibited by the FBG sensor. Furthermore, it was observed that the strain in the FBG with the enhanced sensitivity (*i*FBG) is higher than that of the existing model. The *i*FBG sensor achieved 32.09% increment in strain against the existing FBG model. The percentage increment was obtained from the expression:

$$\frac{\sum iFBG \text{ Strain} - \sum FBG \text{ Strain}}{\sum FBG \text{ Strain}} \times 100\%$$

where  $\sum iFBG$  strain and  $\sum FBG$  strain is the summation of the enhanced FBG (*i*FBG) strain and the existing FBG strain values.

**Table 1:** FBG Strain and Induced Strain on the Composite Material

| Induced Strain ( $\mu\epsilon$ ) | <i>i</i> FBG Strain ( $\mu\epsilon$ ) | FBG Strain |
|----------------------------------|---------------------------------------|------------|
| 0                                | 0                                     | 0          |
| 50                               | 42.613                                | 32.260     |
| 100                              | 85.2226                               | 64.520     |
| 150                              | 127.840                               | 96.780     |
| 200                              | 170.450                               | 129.04     |
| 250                              | 213.06                                | 161.30     |

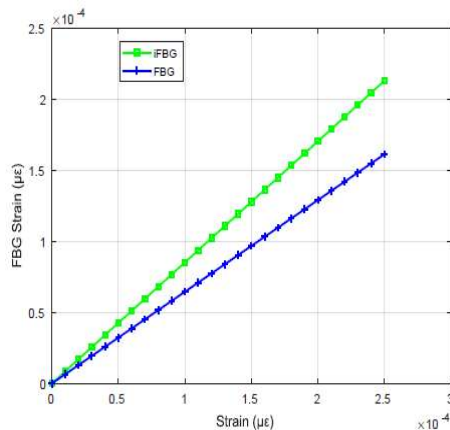


Figure 4: Plot of FBG Strain against Induced Strain on the Material

## CONCLUSION

This research work presents an analysis of FBG strain and induced strain on composite material. Composite materials have obtained a great recognition in establishment such as telecommunication, spacecraft, oil and gas, marine, automotive, civil infrastructure, power industries and sport equipment, owing to their exceptional mechanical properties. In this research, the FBG strain was analyzed with that of the induced strain on Toray Carbon Fibre America composite material.

The strain in the FBGs were compared with that of the induced strain on the composite material. In other to measure the extent of deformation on composite materials deployed in harsh environment. The simulation result shows that there is a linear relationship between the FBG strain and the induced strain on the composite material. Which implies that as induced strain on the composite material increases or decreases it reflects on the FBG strain which makes it suitable for monitoring the effect of physical parameters on composite materials. Furthermore, the FBG with enhanced sensitivity achieved 32.09% increment in strain over the existing FBG.

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