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Strain Measurement for Composite Materials During Mechanical Testing Based on Fiber Bragg Grating Monitoring

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ABSTRACT

Composite materials are widely used as repair materials in the oil and gas sector, particularly for vessels, piping, and pipelines. Inspection and monitoring of these composite repairs is a critical aspect of ensuring their integrity and long-term performance. The reason being that failure of composite repairs may lead to loss of production and incur additional costs for re-repair or equipment replacement. Conventionally, a visual inspection is generally performed to observe any irregularities on the external surface of the composite repairs. This will usually be followed by a series of Non-destructive Tests (NDT) to identify the extent of the damage. However, these NDT methods, merely allowing off-line testing in a local manner with complicated and heavy equipment, require extensive and time-consuming labour. Structural Health Monitoring (SHM) based on Fibre Bragg Grating (FBG) that utilizes strain-based signals is one of the best options for monitoring the damage mechanism in composite due to its unique advantages of light weight, high stability and reliability, a long-life cycle, and the ability to capture the online reading. In this paper, the application of the FBG monitoring approach was used to examine the strain characteristics of composite materials based on mechanical tests (tensile and flexural). Three types of samples were prepared to simulate the type of damage mechanism: healthy, delamination, and disbondment. Based on the results, it was shown that the FBG sensor has potential for detecting and distinguishing the types of failure mechanisms in composites, including cracks, delamination, and disbondment. Hence, it was suggested that the FBG sensor technology could be used for site deployment in industry.

1. Introduction

Embedded matrix materials such as epoxy resin and combinations of elements like carbon fibers or glass fibers are frequently used to produce composite materials. It is due to their extremely high specific modulus and strength while having a low density like a polymer. Carbon-fiber reinforced polymer composites (CFRPs), glass fiber reinforced plastics (GFRP), and fiber reinforced plastics (FRP)

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are the most utilized materials in industry [1-3]. Compared to conventional repair methods i.e. equipment replacement, application of steel sleeves or mechanical clamps, composite materials have several advantages. Composite materials are less complicated and easy to apply, greatly lighter than conventional materials especially for offshore environment application, lower transportation and installation costs [4,5]. Composite materials are applied via wrapping to fit the specific shape of the equipment being repaired and making it easy to install [6,7].

Composite materials are widely used as repair materials in the oil and gas sector, particularly for vessels, piping and pipelines [8]. Inspection and monitoring of composite repairs in the oil and gas industry application is a critical aspect of ensuring their integrity and long-term performance to avoid loss of production and additional cost for re-repair or equipment replacement. Numerous studies have been done to determine how the composite materials are damaged or degraded. Delamination, matrix cracking, disbondment, and other types of composite damage can occur during fabrication as well as during in service [9,10].

Conventionally, visual inspection is generally performed to observe any irregularities on the external surface of the composite repair such as cracks, chalking, blistering and discoloration. This will usually be followed by a series of Non-Destructive Testing (NDT) to identify the extent of the damage. For instance, a coin tap test is used to detect any possible delamination/voids in composite layers due to localized change in stiffness, whilst Barcol hardness testing is used to verify the curing of composite repairs. Advanced NDT inspection techniques may be applied after the repair as a baseline measurement or during the repair design lifetime. The NDT techniques are aimed to inspect both of substrate and composites repair system, to demonstrate the overall integrity of the repair system [11]. There are several NDT techniques such as Ultrasound, Thermography, Radiography and Eddy Current that can be used to inspect the composite repair condition. However, these NDT equipment's are sometimes complicated and heavy, labor extensive and time consuming especially when involves with large number of composite repairs to be inspected [12,13].

Structural Health Monitoring (SHM), an emerging approach was developed by combining advanced sensor technology with intelligent algorithms to continuously monitor the composite repairs structural 'health' condition. In SHM, various sensors are integrated with target structures to obtain different structural information, such as temperature, stress, strain, vibration, degradation mechanisms and so on. The typical SHM sensors used are strain gauges, fiber optic sensors, piezoelectric sensors, eddy current sensors, and microelectromechanical systems (MEMS) sensors. Fiber Bragg Grating (FBG) that utilizes strain-based signals is one of the best options in monitoring the damage mechanism in composite. FBG is viable candidate for SHM applications due to its unique advantages of light weight, high stability and reliability, long life cycle, low power utilization, EMI immunity, high bandwidth, compatibility with optical data transmission and processing [13-15]. Freire et al. in 2013, used FBG to understand and describe how the reinforcement layers of a composite material can enable a steel line pipe specimen with metal loss to withstand pressure loading [16]. Other researcher investigated the pressure in a full composite lightweight epoxy sleeve strengthening system using FBG sensor [17]. Kakei and Eparachchi in 2018 used FBG sensors for monitoring delamination damage propagation in glass-fiber reinforced composite structures [18].

For this entire study, it is focused on the application of FBG monitoring approach or procedure to observe the strain characteristic of composite materials based on simulated damage mechanism during the mechanical test. Three types of damage mechanisms that usually occurred at composite such as fiber crack, delamination and disbondment were simulated and observed in this study. The intent is to come out with the proper monitoring system of the composite repairs. Hence, the capability of FBG technology was tested in monitoring and investigating the performance of composite repair material under the simulated damage mechanisms.

2. Methodology
2.1 Composite Sample for Mechanical Test

In this study, the composite sample preparation for mechanical test was performed using the fiber glass sheet as well as mixing of epoxy resin and hardener. An accurate ratio is the essential for epoxy to fully cure and developed its physical properties. Three types of samples were prepared to simulate the different condition of composite materials which consist of healthy samples for control, composite with Teflon insertion for delamination and composite with Teflon and stainless-steel plate insertion for disbondment case studies. Teflon is commonly used in composite preparation to simulate the delamination process. Delamination is a failure mode in composite materials where layers of the material separated or detached from each other. For disbondment, the Teflon plate is placed between the composite and the stainless-steel plate to create a weak interface, while the stainless-steel plate acts as a rigid adherent surface [19,20]. The details of composite samples for mechanical testing were shown in Table 1. Figure 1 illustrate the example of the composite samples for mechanical testing.

Table 1
Details of composite samples for mechanical testing

Test	Type of sample	Type of defect
Flexural	T1- healthy composite	Healthy
	T2 – composite with Teflon	Delamination
	T3 - healthy composite healthy SS304 –FBG on composite	Healthy
	T4 - healthy composite plus healthy SS304	Disbondment
	T5 - healthy composite plus hole SS304	Disbondment
	T6 - healthy composite plus notch SS304	Disbondment
Tensile	T7-healthy composite	Healthy

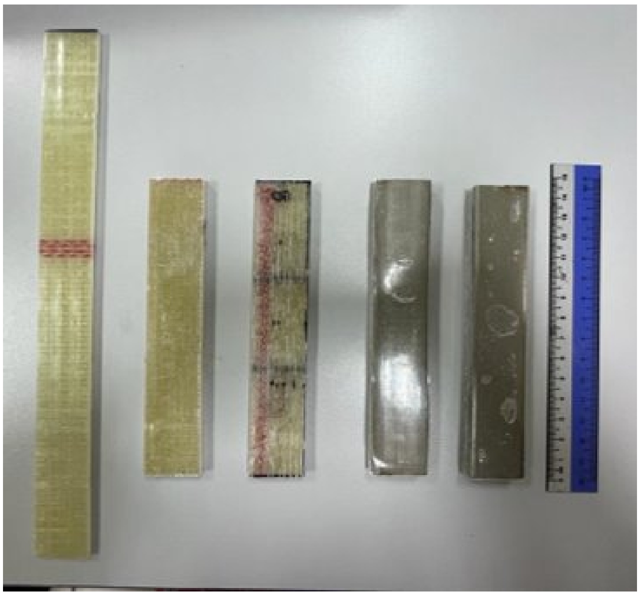


Fig. 1. Example of composite samples for mechanical test

2.2 Fiber Bragg Grating Sensor

To measure the strain response during the mechanical test for the composite, FBG sensor with its data acquisition system (DAQ) was utilized. FBG is known as a multi-sensing technique to detect and measure strain, temperature, pressure, acceleration, and displacement. Based on its physical changes on the specimens, FBG can measure strain, temperature and pressure based on the shifting of the reflected Bragg wavelength spectrum. Bragg wavelength is a narrowband spectral output or a peak reflected wavelength from the FBG sensor after being illuminated by broadband light source and the light interacts with the grating of an FBG [21]. For this study, the FBG sensor only used to measure the strain during the mechanical test as shown in Figure 2.

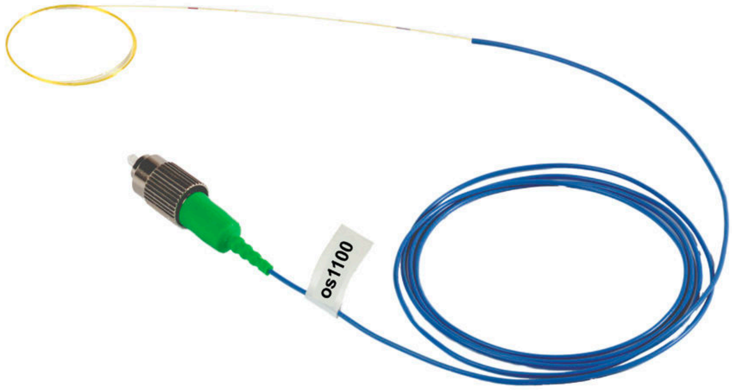


Fig. 2. Example of FBG sensor

A broadband light source is used to illuminate the FBG sensor. Once the illuminated light encounters the Bragg grating, a specific wavelength of the light signal is reflected from the broadband light signal known as reflected light or reflected wavelength. The un-reflected light signal passed through and over the Bragg grating as transmitted light. The reflected light spectrum plays a significant role in strain sensing by undergoing left and right shifting as the optical fiber experience tension and compression strain. When there is a presence of tension on the strain, the gap between grating will be wider and vice versa. Resonant wavelength can be obtained by Bragg's law in Eq. (1).

$$\lambda_B = 2\eta_e\Lambda \tag{1}$$

The Bragg wavelength shifts are strain sensitive which can be denoted in Eq. (2).

$$\frac{\Delta\lambda}{\lambda_B} = (\hat{a} - \xi)\Delta T + (1 - p_e)\mathcal{E} \tag{2}$$

where $\lambda_B$is the resonant wavelength, $\eta_e$is the effective refractive index of the fiber core, Λ is the pitch length of the grating or period of the grating, $\Delta\lambda$ is the change in the wavelength, $\hat{a}$ is the thermal expansion, ξ is the thermo-optic coefficient, ΔT is the change in temperature p_e is the effective photo-elastic constant of the fiber and $\mathcal{E}$ is the strain induced [22].

2.3 Mechanical Test and Data Collection

Prior to mechanical test, FBG sensors were directly attached to the samples to obtain the signals response during the period of testing when subjected to specific loading. The data collection for FBG sensor have been performed continuously and simultaneously to ensure the sensors capture the same condition of loading during the test. Table 2 shows the summary of details samples for tensile and flexural test based on simulated damage mechanism. For flexural test, hole and notch was introduced to initiate the crack on the samples. Figure 3 shows the schematic diagram of composite material with FBG sensor location placement prior the mechanical testing.

Table 2
Summary of samples for mechanical test

Type of test/defect	Samples condition	No.	Location of FBG
Flexural test: Crack	Healthy Composite	T1	FBG as per Teflon location
Flexural test: delamination	Unhealthy Composite (Teflon)	T2	FBG as per Teflon location
Flexural test: Crack	Healthy Composite + SS304	T3	FBG (composite) as per Teflon location
Flexural test: disbondment	Unhealthy Composite (Teflon) + SS304 (no hole)	T4	FBG as per Teflon location
Flexural test: disbondment	Unhealthy Composite (Teflon) + SS304 (hole)	T5	FBG as per Teflon location
Flexural test: disbondment	Unhealthy Composite (Teflon) + SS304 (notch)	T6	FBG as per Teflon location
Tensile test: Crack	Healthy Composite	T7	FBG at center

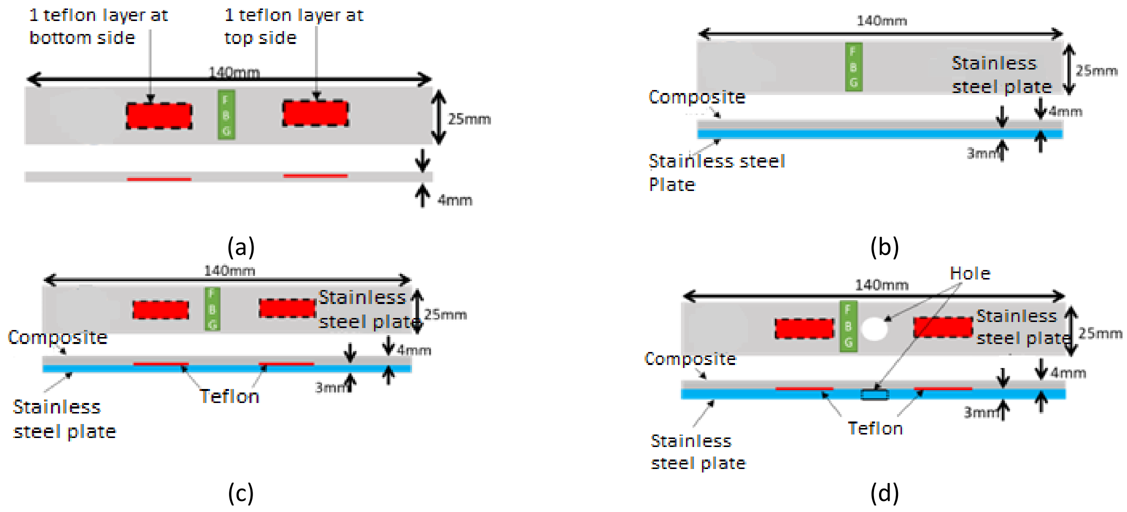


Fig. 3. Schematic diagram of composite with FBS sensor location placement (a) Composite with Teflon only, (b) stainless steel with patched composite only (c) Stainless steel with patched composite and Teflon, (d) holed stainless steel patched with composite and Teflon

Tensile testing was performed with controlled tension loading applied to a sample until fracture. It was performed to determine the strength of a composite and also to identify how much it can be elongated (i.e., strain) before it breaks. The objective of this testing is to obtain the fiber fracture damage mechanism in accordance with the ASTM D3039 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials [23]. The tensile test was performed using Universal Testing Machine (UTM) with 100 kN load.

Flexural testing was performed to measure the required force to bend a beam of composite materials and determine the resistance to flexing or stiffness of the composite. Flex modulus is indicative of how much the material can flex before permanent deformation occur. The objective of this testing is to obtain and investigate the crack, delamination and disbondment damage mechanism accordance to the ASTM D7264 Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials [24]. There are two types of testing machine used for flexural test, i.e. UTM 5kN machine for composite without substrate and UTM 100kN machine for composite with substrate. The example of overall experimental setup for flexural tests is illustrated in Figure 4.

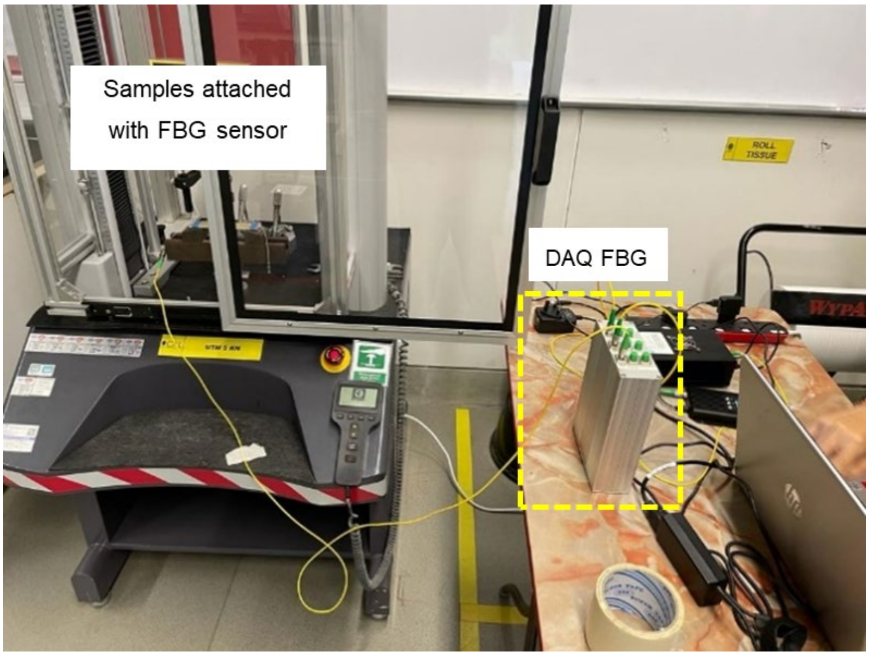
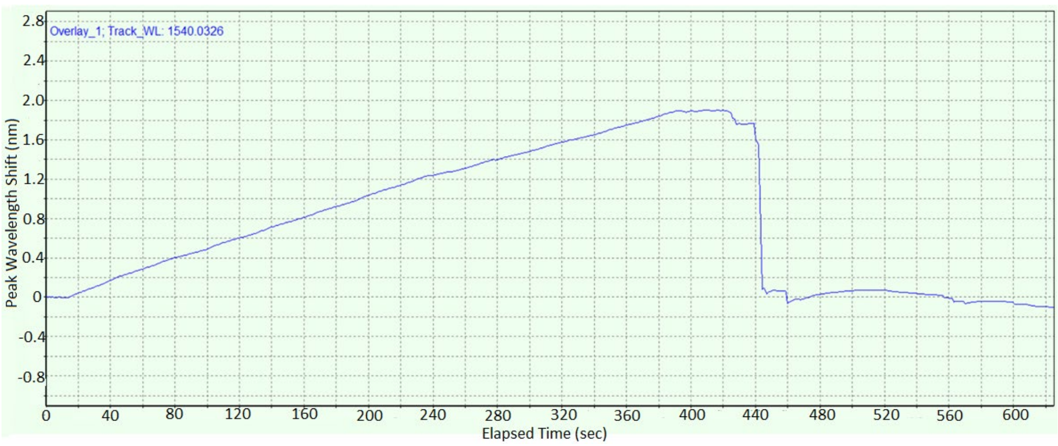


Fig. 4. Example of data collection for flexural test with FBG monitoring

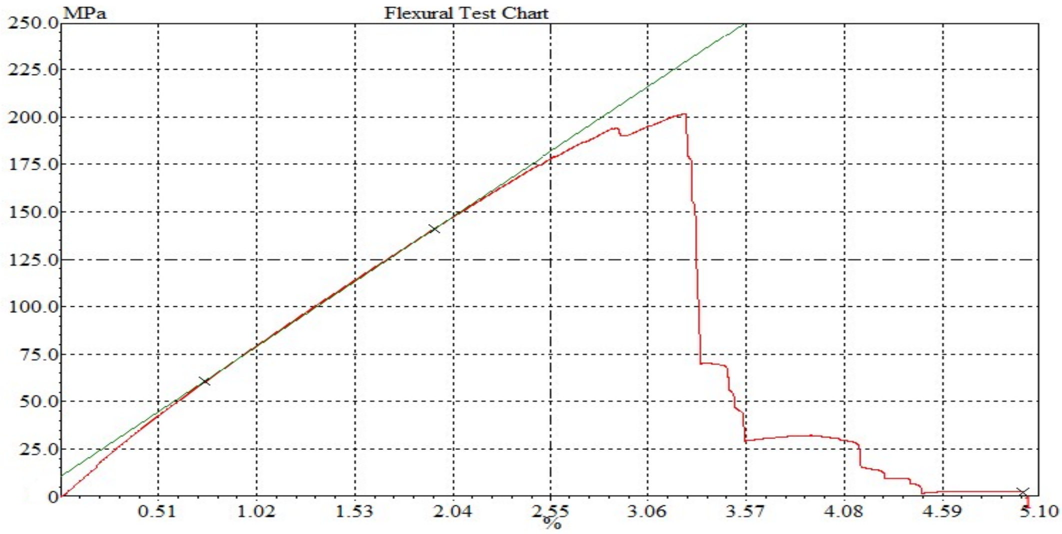
3. Results

3.1 FBG Signal Responses for Composite Mechanical Testing

Figure 5 (a) and (b) shows the response curves for comparison between FBG sensor and UTM machine. For FBG sensor, the data captured was in the form of peak wavelength shift (nm) against time (s). Meanwhile, the data captured from the UTM machine was in the form of stress (MPa) against strain (ε). From the comparison, it was clearly seen that both response curves are similar in trend. Based on Figure 5 (a), the peak wavelength shows 0 nm at time 0 s to 20 s, indicating that no strain occurs during this moment. From 20 s to 400 s, a steep increase of peak wavelength shift was observed. The highest peak wavelength shift was recorded at about 1.9 nm, indicating that the FBG sensor has experienced tension strain during this time. From 420 s to 440 s, the peak wavelength shifts instantly dropped to 0 pm. This indicates that catastrophic failure has happened on the composite material.



(a)



(b)

Fig. 5. Examples of graph from composite mechanical test (a) FBG sensor response curve (b) UTM machine response curve

Figure 6 shows the strain against time response curve captured by FBG sensor for composite samples T1, T3 and T7. All the samples were subjected to either tensile or flexural testing to initiate crack failure on the composite. All the fabricated samples were healthy samples. Sample T1 and T3 were tested using flexural test while sample T7 was tested using tensile test. The FBG response were plotted throughout the testing until the samples failed. From the results, it is clearly seen that all the samples experienced high strain value during the samples breaking/failure. The lowest failure strain was captured at 5800 με where bending load was given whereas the highest strain given by tensile loading is more than 8000 με. Hence, it can be suggested that the composite will be experienced the crack failure when it reaches to 5800 με and above.

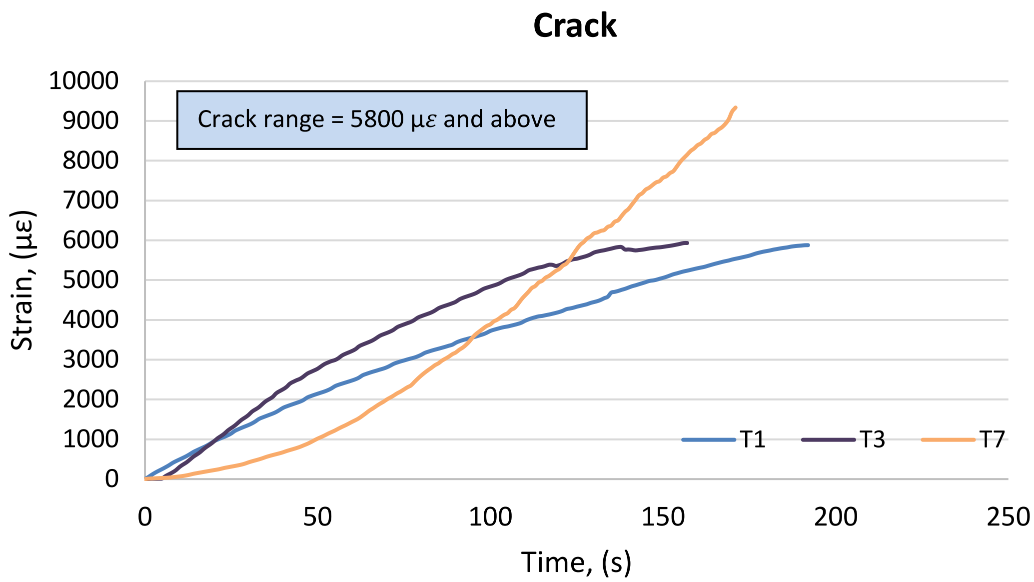


Fig. 6. Strain values form FBG sensor for crack-type of composite failure

In all samples, the Teflon layers act as a stress concentrator, leading to the initiation and propagation of delamination and disbondment in the composite. Figure 7 shows the strain response captured by FBG sensor for the delamination type of composite failure during the flexural test. Here, sample T2 were fabricated with the presence of Teflon at the top and bottom layer of the composite as discussed previously. From the results, the lowest strain value was captured at 2800 με (orange line) whereas the highest strain was captured at 3588 με (green line). As compared to crack type failure, a difference of 38% to 52% in strain values were observed. Therefore, it gives the indication that the FBG sensor is capable to differentiate between crack and delamination failure of the composite sample.

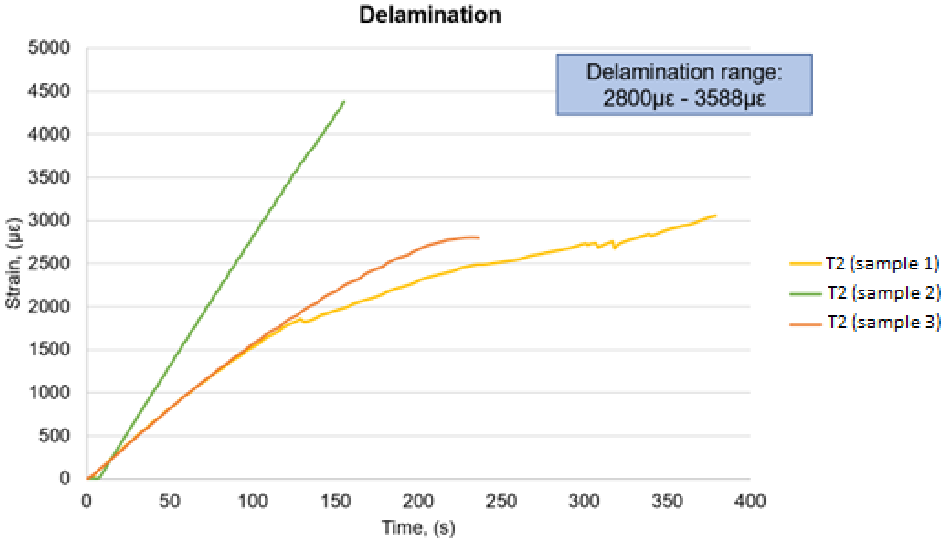


Fig. 7. Strain values form FBG sensor for delamination-type of composite failure

During mechanical testing of the composite material, the weak interface created by the Teflon and stainless-steel plate can lead to the initiation and propagation of disbondment in the composite. For the testing involved disbondment of composite failure, the strain against time response curve captured by FBG sensor is shown in Figure 8, for samples T4, T5 and T6. Sample T4 were healthy composite bonded with SS 304 substrate and served as the baseline for disbondment failure. Sample T5 were healthy composite bonded with SS 304 and a hole was presence on the substrate. Sample T6 were healthy composite bonded with SS 304 with a notch was presence on the substrate. All the samples were subjected to flexural test. From the results, the lowest strain value was captured at 1200 με whereas the highest strain was captured at 5500 με.

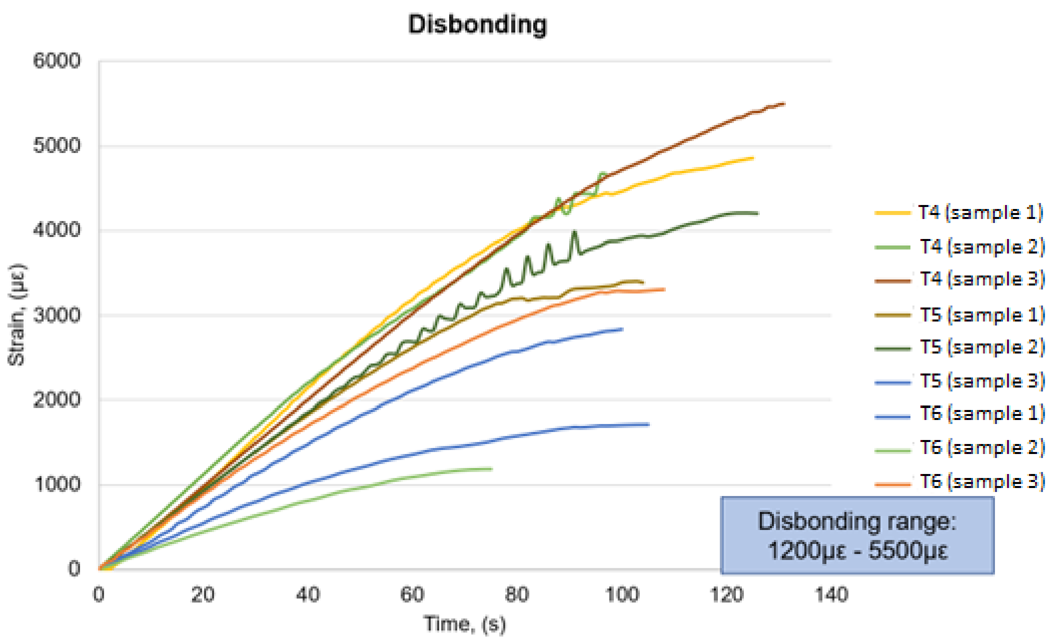


Fig. 8. Strain values form FBG sensor for disbondment-type of composite failure

3.2 FBG Strain Value Based on Composite Damage Mechanism

The strain values captured by FBG sensor during the mechanical test based on type of sample were compared. Table 3 summarized the higher strain values based on types of composite failures mode. From the results, crack contributed the higher strain values compared to delamination and disbondment. Based on the strain values, it can be suggested crack occurred when the strain values were above than 5800 με, delamination occurred in between the strain values at 2800 με to 3588 με while for disbondment occurred in between strain values at 1200 με to 5582 με. It was also observed that the strain values for delamination was overlapped with disbondment type damage mechanism. This can be justified as the damage mechanism of both the failures were similar which is based on the materials separation of layers within a composite material.

Table 3
Summary of strain values capture by FBG sensor for all samples

Test	Type of sample	Type of defect	Strain Value (με)
Flexural	T1- healthy composite	Crack	6135
	T2 – composite with Teflon	Delamination	3588
	T3 - healthy composite healthy SS304 –FBG on composite	Crack	5807
	T4 - heathy comp plus healthy SS304	Disbondment	5582
	T5 - heathy comp plus hole SS304	Disbondment	3517
	T6 - heathy comp plus notch SS304	Disbondment	1448
Tensile	T7-healthy composite	Crack	8566

4. Conclusions

As a conclusion, this study has been carried out to determine the feasibility and capability of FBG sensor to distinguish and correlate the signal response based on strain value with the different damage mechanism of composite materials such as crack, delamination and disbandment. The above work and findings can be summarized as follows:

i. From the results, the FBG sensor has a potential in detecting and distinguishing the type of failure mechanisms of composite materials, including crack, delamination and disbondment.
ii. It was apparent the FBG sensor can clearly detect the crack with the strain value more than 5800 $\mu\varepsilon$. However, the signals from the delamination and disbondment damage could not be clearly distinguished as the mechanism of these two damages is quite similar. The signals collected from mechanical test (tensile and flexural test) showed the strain values ranged between the 1200-5582 $\mu\varepsilon$.
iii. Based on the findings, FBG technology have capability to identify the damage mechanism for the composite materials hence it is suggested that the FBG sensor technology to be used for site deployment in industry.

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