Detecting delamination in a composite structure using an embedded FBG – AE hybrid system

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Abstract: Distorted spectra of Fibre Bragg Gratings (FBG) sensors have been using in most of research on identifying delaminations in composites which is the most common cause of failures of laminated composite structures. However, it has been shown that there are multiple causes which can produce a similar response spectrum of an FBG sensor. As a consequence an integrated additional monitoring system would enhance the prediction power of FBG based monitoring system. In this research paper we introduce a "FBG-AE hybrid system" concept for the detection of delaminations in composite structures which uses same FBG sensor network for monitor damage using two independent responses from the sensors. The proposed system use spectral responses from FBG sensors and extract strain and acoustic emission data for monitoring purpose. The proposed concept has experimentally investigated with convincing results.

Keywords: acoustic emission, FBG sensors, FRP structures, structural health monitoring.

1 Introduction

With the complex failure modes of FRP composites, SHM becomes vital. With the recent developments in the aerospace industry, utilization of FRP composites for primary aircraft structures, such as wing leading-edge surfaces and fuselage sections, has increased. This has led to a rapid growth in the research field of SHM. Impact, vibration, and loading can cause damage to the FRP composite structures, such as delamination and matrix cracking. Moreover, the internal material damage can be invisible to the human eye, making inspection of the structures for damage and clear insight into the structural integrity difficult using currently available evaluation methods. Delamination is the most significant and difficult to detect damage in FRP structures. It is for this reason that a large number of research works have been undertaken to detect delamination in composite structures over the past few decades.

The process of implementing the damage detection and characterization strategy for engineering structures is referred to as structural health monitoring (SHM). The SHM process involves the observation of a system over time using periodically sampled structural response measurements from an array of sensors. Most of the offline non-destructive test (NDT) methods do not fall into SHM.

The SHM system developed to monitor aircraft and space structures must be capable of identifying multiple failure criteria of FRP composites [1]. Since the behaviour of composites is anisotropic, multiple numbers of sensors must be in service to monitor these structures under multi-directional complex loading conditions. The layered structure of the composites makes it difficult to predict the structural behaviour by using surface mounted sensors only. To address this issue embedded sensors must be used and they must possess a sufficiently long lifespan as it is not possible to replace embedded sensors after fabrication of the parts.

The Fibre Bragg Grating (FBG) sensor is one of the most suitable sensors for the SHM of aircraft FRP structures. The FBG sensors can be embedded in FRP composites during the manufacture of the composite part with no effect on the strength of the part as the sensor is diminutive. This sensor is also suitable for networking because it has a narrowband response with a wide wavelength operating range, hence can be highly multiplexed. This nonconductive sensor can also operate in electromagnetically noisy environments without any interference. The FBG sensor is made up of glass which is more environmentally stable and with a long life time compared with FRP composites.

Because of its low transmission loss, sensor signals can be monitored from longer distances making the FBG sensor suitable for remote sensing [2, 3].

Its capability to detect stress gradients along its length can be used to identify the stress variations in FRP composites by means of chirp in the reflected spectra of the FBG sensor [4, 5]. This phenomenon can be used to detect damage in the composite structures [6, 7]. But, it has been reported that the chirp of the FBG spectrum is not limited to stress concentrations caused by damage [8]. There are other causes of chirp and it is necessary to eliminate such effects to identify damage origin accurately.

Using only distortion or chirp to the FBG response in order to identify damage in composites, is questionable. For reliable operation of the SHM system, it is desirable to have at least two independent techniques which can be used to verify each result.

Nowadays, Acoustic Emission (AE) becomes one of the most popular non-destructive (NDT) techniques. This technique became popular today, owing to its ability to reveal in advance any impending failure of composite structures, but more than that, it be used for real-time monitoring. AE is also well known as highly sensitive technique for detection of various types of damage using a small number of sensors, thus is very attractive for SHM [9, 10]. In composites, researchers were interested to study the AE parameters that can be correlated to composite's early failure such as fibre breakage, fibre-matrix debonding, delamination, matrix cracking and etc. For instant, Barre and Benzeggagh [11] reported that different damage modes will give different AE signal amplitude range. Furthermore, some other studies also successfully observed that composites failure varies with AE frequency [12, 13]. Recently, by using modal acoustic emission (recent AE analysis approach) Scholey et al [14] have found that matrix cracking and delamination growth can be distinguished by the mode of wave propagation; and So (symmetric) and Ao (asymmetric) mode, respectively. By combining all the information from previous studies, a pattern recognition technique can be used to well correlate AE data with any of composites failure [15].

Implementing two completely different systems for SHM of composite structure makes the system complicated. It is difficult to have two types of sensor networks in the same structure. Therefore it is desirable to use the same sensor network for SHM with two independent techniques. The excellent sensitivity of FBG sensors make it possible to use them as dynamic acoustic sensors while sensing the static strain distribution (gradient). In this paper the use of FBG sensors for damage detection using strain gradient and AE is discussed.

2 FBG sensors

Fibre Bragg Gratings (FBGs) are formed by constructing periodic changes in the index of refraction in the core of a single mode optical fibre. This periodic change in index of refraction is typically created by exposing the fibre core to an intense interference pattern of UV radiation.

The FBG sensors have been using for the SHM of composite materials efficiently for more than two decades. Recent advances in FBG sensor technologies have provided great opportunities to develop more sophisticated in-situ SHM systems. There have been a large number of research efforts on the health monitoring of composite structures using FBG sensors. The ability to embed inside FRP material in between different layers provides the closer look upon defects. The attractive properties such as small size, immunity to electromagnetic fields, and multiplexing ability are some of the advantages of FBG sensors. The lifetime of an FBG sensor is well above the lifetime of the FRP structures and so it also allows the measuring of multiple parameters such as load/strain, AE, vibration and temperature [16].

The FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibres. The grating is the laser-inscribed region which has a periodically varying refractive index. This region reflects only a narrow band of light corresponding to the Bragg wavelength λ_B, which is related to the grating period Λ_o

$$\lambda_B = \frac{2 n_o \Lambda_o}{k} \tag{1}$$

Where k is the order of the grating and n_o is the initial refractive index of the core material prior to any applied strain.

Due to the applied strain, ε, there is a change in the wavelength, $\Delta\lambda_B$, for the isothermal condition,

$$\frac{\Delta\lambda_B}{\lambda_B} = \varepsilon\, P_e \tag{2}$$

where P_e is the strain optic coefficient and is calculated as 0.793.

The Bragg wavelength is also changing with the reflective index. Any physical change in the fibre profile will cause variation of reflective index. The variation of Bragg wave length λ_B,as a function of change in the refractive index $\Delta\delta n$, and the grating period $\delta\Lambda_o$, is given below.

$$\delta\lambda_{Bragg} = 2\Lambda_o\eta\Delta\delta n + 2n_{eff}\delta\Lambda_o \tag{3}$$

where η is the core overlap factor of about 0.9 times the shift of the Bragg wavelength, n_{eff} is the mean refractive index change, and Λ_o is the grating period.
For the Gaussian fit, the sensor reflectivity can be expressed as

$$s(\lambda,\lambda_s) = y_0 + S_0\,exp[-\alpha_s(\lambda - \lambda_s)^2] \tag{4}$$

where y_0 is the added offset to represent the dark noise, αs is a parameter related to the full width at the half maximum (FWHM), λ is the wavelength, λ_s is the central wavelength, and S_0 is the initial reflectivity of the fibre.
In the layered FRP composite structure, it is difficult to use surface or external sensors to monitor inside damage effectively. The ability to embed FBG sensors inside FRP sandwich panels between different layers provides a closer look at defects such as delaminations and cracks. The FBG sensor is sensitive to stress gradients along the gauge length of the sensor and displays it as a chirp (or distortion) from its response spectra.

2.1 Acoustic Emission (AE)

The AE method can be called a s a passive ultrasonic method, where the ultrasonic wave; which can be continuous or burst signals, released from any source (e.g. flaws, cracks) travel in medium of solid materials (e.g. concrete, metals, composites) and can be easily captured by the AE sensory systems as shown in Figure 1. The AE signal is generally found in the frequency range of 20 kHz to 2000 kHz. The AE transducer (usually piezoelectric) is like a human ear; where it collects all acoustic data from the surroundings; as example, the acoustic signals from a material's flaws. All the information then will be transformed into electrical signals and submitted to the brain (computer) for interpretation.
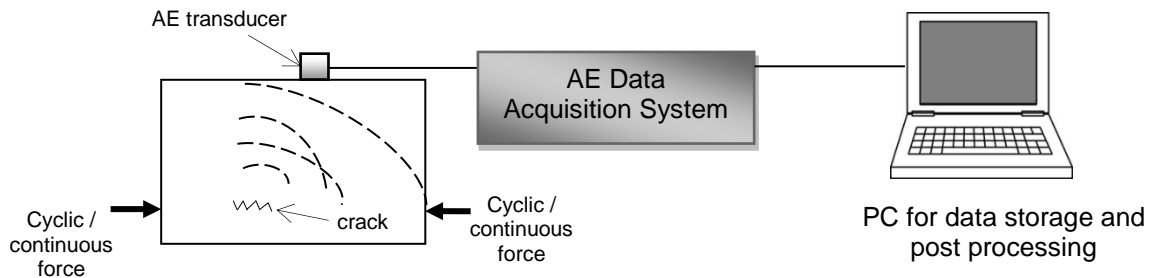

Figure 1: Material under stress and typical AE system

3 Damage detection using FBG sensors

The majority of research works on FBG sensors in SHM of composite structures have focused on the investigation of the spectrums of FBG sensors embedded in the vicinity of damage. Observations of the distorted sensor spectrums, due to stress concentrations caused by delaminations and cracks, have been used to estimate the damage conditions. Many researchers have investigated purposely damaged axially loaded specimens, and the changes of FBG spectra were attributed to the damage and successfully identified the damage [17]. In real life situations, the applied loads are not limited to uni-axial loads and hence the performance of FBGs in multi-axial loading situation needs to be investigated for a complete understanding of damage status. The FBG spectral response is significantly complicated under multi-axial loading conditions [18, 19]. The distortion of FBG spectra not only depends on the consequences of accumulated damage, but also the loading types. Recently, it has been shown that embedding FBGs in between non parallel fibre layers and the application of torque has caused substantial distortions to the FBG spectra [20]. The pressure load applied on the

FBG sensor by the outer glass fibre layers, can distort the circular-cross section of FBG to an oval shape. Since the FBG sensor is placed in between non-parallel fibre layers, micro-bending of the sensor is also possible. Due to the large diameter of the FBG sensor, compared to the diameter of glass fibres, there are additional transverse forces on the FBG sensors which lead to a micro bending. Both these effects will lead to a variation of the refractive index of the core material, causing the distorted spectrum. This explanation also supports the observations reported in the last decade [21-24].

From the observations, it is clear that the multiple causes lead to distortion to the FBG response spectra. Most of the effects, such as embedment of FBG sensor only in between parallel fibre laminates, parallel to the fibre orientation, and multidirectional loading on FBG sensor, cannot be eliminated in advanced aerospace applications. In order to identify damage from the distortions to the FBG response spectra, the individual effect from each effect needs to be identified and eliminated. To identify the pure effects from the damage, distinguished from the other effects, extensive computational power is required for post-processing of the spectral data. Figure 2 shows FBG response spectra from an FBG embedded near a damaged location and the part is under the complex multi-directional loading.
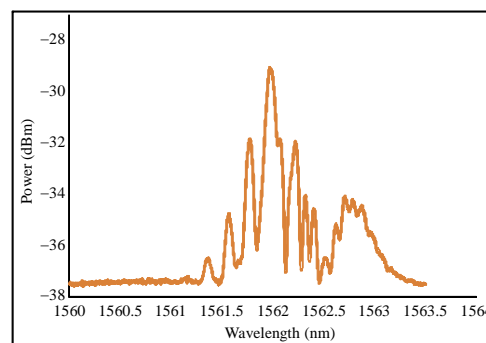

Figure 2: Distorted FBG spectra due to multiple effects

As a consequence, in the laboratory environment it is possible to discuss and interrelate the FBG response spectra with the damage by creating artificial damage and observing spectrum of an FBG which is embedded closer to the damage location. But, in the real application, if such spectrum is observed, it is very difficult to interpret the spectrum in order to identify the damage. The one directional accuracy, which is if there is a known damage in the structure, response spectra (distortion) of embedded FBG can be explained, but if distorted response spectrum is observed, it is not possible to identify it as a presence of damage. This incongruity disappointed and discouraged some SHM researchers.

There was a huge demand for an out-of-the-box approach to overcome the discrepancy. To overcome the complications mentioned above, a hybrid approach for damage detection can be used. By using the sensitivity of FBG sensors to AE, it is possible to use same FBG sensor for detection of the AE signal. The AE signal has been used by many researchers to detect damagers successfully.

3.1 Experimentation

An experimental study was conducted to investigate the detection of damage in a FRP panel. Test specimens, specimens 1 and 2, were manufactured using glass fabric with epoxy composite with a stack sequence of [0/0/90/90/-45/45/90/0]s. Artificial delamination was created during the fabrication of the specimen 2 as shown in the figure below (Figure 3(a)). In the specimen 2, delamination of size 5x5 mm and two FBG sensors were placed between layers 4 and 5.
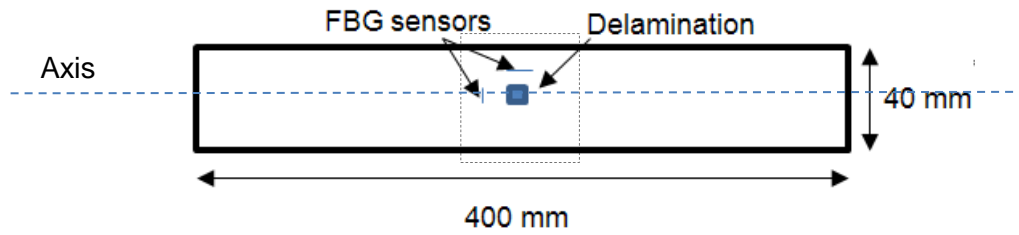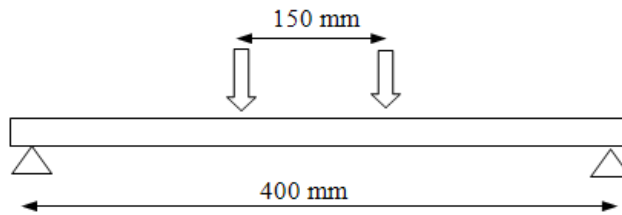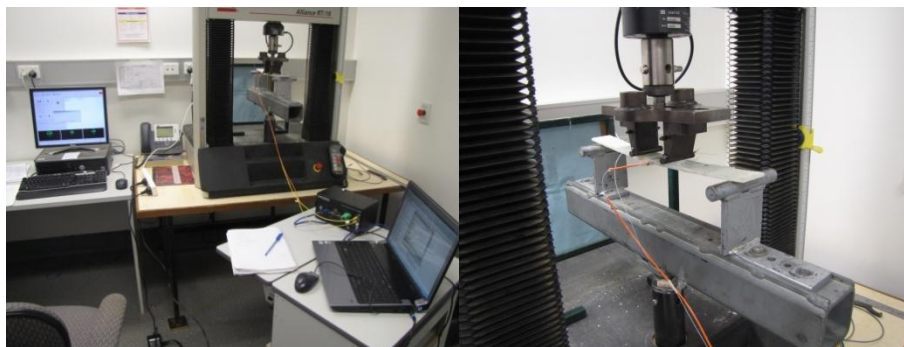
(a)
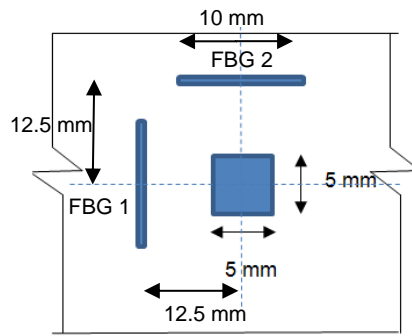
(b)

Figure 3: Fabrication of the specimen with damage

The configuration of the delamination and the embedded FBG sensors is given in Figure 3(b). FBG 1 is placed perpendicular to the axis of the specimen and FBG 2 was placed parallel to the axis. Figure 4 illustrates the experimental setup.


(a)

(b)

Figure 4: Experimental setup

The possibility of sensing AE signals using FBG sensors is explained below.

The full set up for FBG–AE was as shown in Figure 5. The FBG-AE circuit was developed with a broadband light source and a 1550 mm range FBG sensor according to Tsuda et al [9]. A piezoelectric sensor was placed at the same location with FBG for comparison purposes. A pencil break test was conducted at the embedded FBG location area (thick arrow in Figure 5) to create an artificial AE source. The signal was recorded using a Tektronix Digital Storage Oscilloscope (TDS 2014B, four channels, 1 GS/s). For validation, the AE signal from a piezoelectric sensor was also acquired at the same time using commercial AE DAQ from a Physical Acoustic Corporation (PAC); with sampling rate set to 1 MS/s and threshold 60dB. An example of a detected AE signal is shown in Figures 8 and 9.
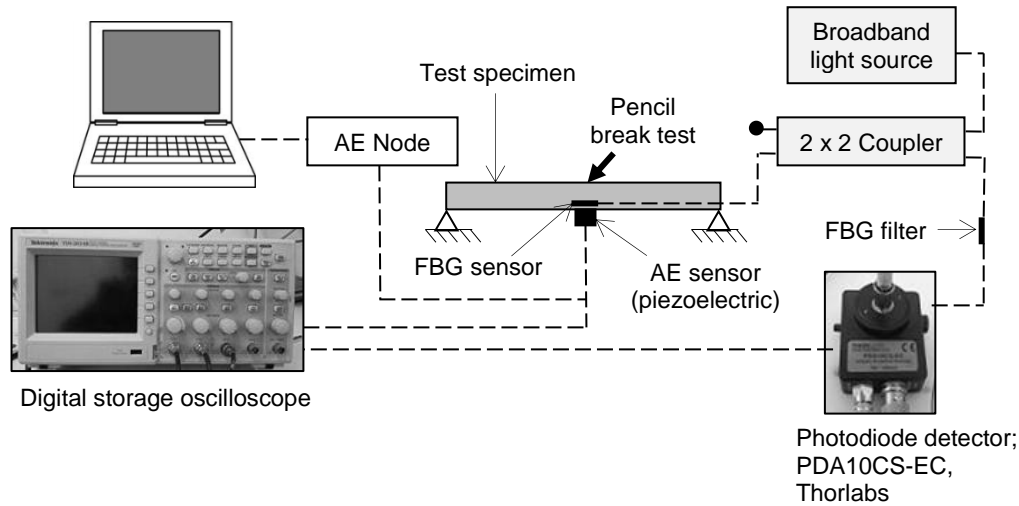

Figure 5: FBG – AE set up

3.2 Results and observations

The experimental setup of the specimens is given in Figure 4. The spectral response of the sensors was recorded for loading in 10N steps up to 100N. Figure 6 shows the response spectra of two FBG sensors at no-load and at 100N load.

(a)   (b)
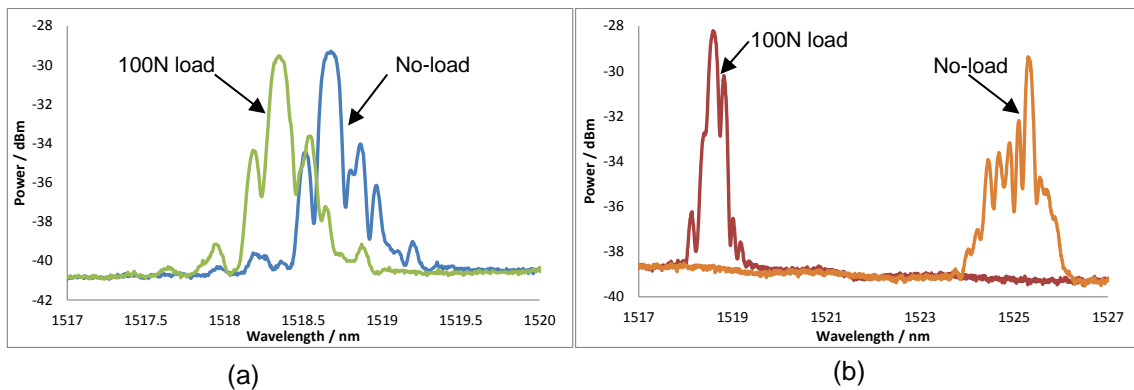
Figure 6: Response spectra of two FBG sensors embedded in specimen 1 (a) FBG 1 (b) FBG 2

The FBG 1 in the specimen 1 (which is without delamination) is perpendicular to the axis of the specimen and Figure 6(a) shows the movement of the sensor spectrum. Figure 6(b) shows the spectrum of FBG sensor 2 which is parallel to the axis of the specimen.
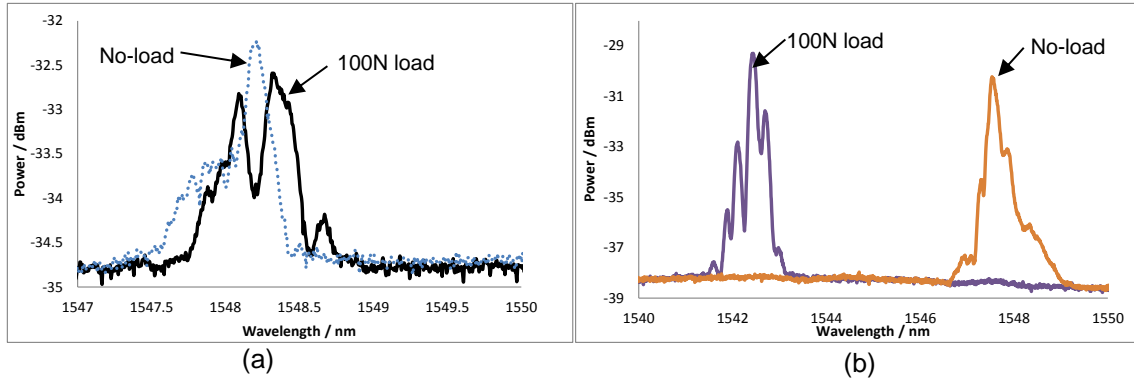
Figure 7: Response spectra of two FBG sensors embedded in specimen 2 (a) FBG 1 (b) FBG 2

The FBG 1 in the specimen 2 (which is with delamination) is perpendicular to the axis of the specimen and Figure 7(a) shows the split of the sensor spectrum due to strain concentrations caused by delamination. Figure 7(b) shows the spectrum of FBG sensor 2 which is parallel to the axis of the specimen.

By considering the FBG1 in specimens 1 and 2, it is possible to identify the delamination. In specimen 1, the spectrum of FBG 1 has moved a little but the peak of the spectrum is intact. The spectrum of FBG1 in specimen 2, has divided into two peaks and the track of the peak is not clear. The observation of divided peaks of FBG sensors has been reported by several researchers in the vicinity of delaminations [17].

When considering the FBG 2 in specimens 1 and 2, it is difficult to predict the delamination. Both the FBG peaks have distorted. Even with no load condition, the response spectrum has distorted since the FBG sensor was embedded between non-parallel fibre layers [25]. From the observations of the experiment, it can be concluded that with single technique only, it is questionable whether damage can be identified accurately.

The Figures 8 (a) shows capture AE signal with PTZ sensor and 8(b) shows the captured AE signals from the FBG sensors. These signals can be readily analysed using Lamb theory and confirm the damage and the source location.
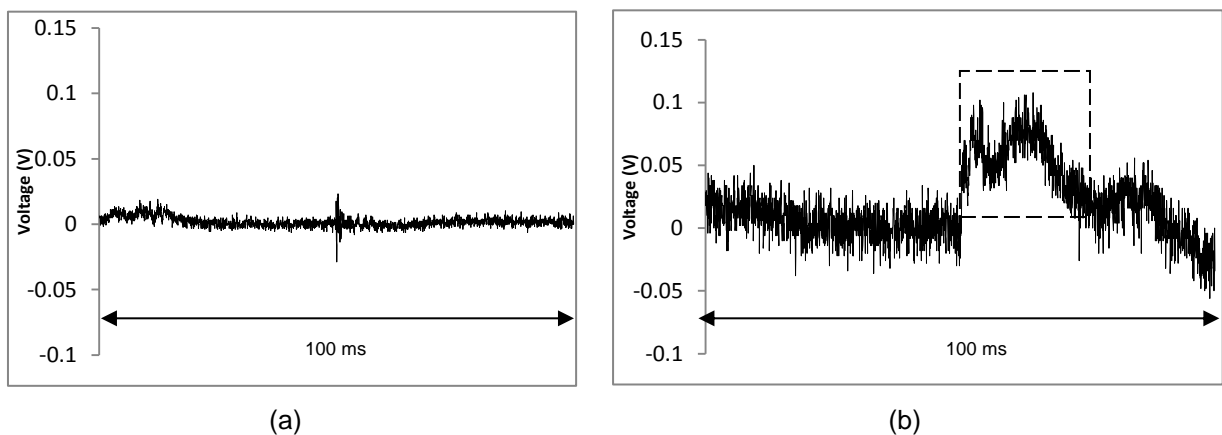
Figure 8: AE signal from oscilloscope; (a)captured by piezoelectric sensor and, (b) FBG sensor

Figure 9 shows the analysed AE signal captured by PTZ sensor and the analysis of AE signal captured from FBG sensors are not shown here.
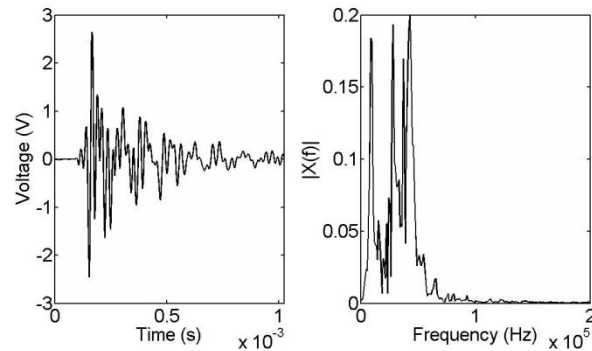
Figure 9: AE waveform and its frequency spectrum acquired using AE Node system

4 Conclusions and recommendations

It has been shown that there is an ambiguity involved in the damage detection using FBG sensors when it only considers the distortion of FBG response spectra. It is clear that the use of a second independent method for verification of identified damage is essential to overcome the ambiguity. The use of two different systems with two different sensor types makes SHM systems complicated and expensive. It was shown that with using only one FBG sensor network, it is possible to use two independent damage monitoring techniques, such as distortion to FBG spectra and AE signal propagation, for the identification of damage in FRP structures.

Acknowledgements

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