Chapter 9
Fatigue Detection on Glass Fibre Reinforced Polymer Material Using Fiber Bragg Grating Sensor

Miminorazeansuhaila Loman and Mohd Hafizi Zohari

Abstract The effectiveness of monitoring systems for composite materials is improving owing to their increasing utilisation. Abrupt failure in composite requires an effective detection method and monitoring system. The fibre Bragg grating (FBG) sensor is one of the alternative sensors used for detecting and monitoring the structural health of an engineering structure. This study evaluated the applicability of the FBG sensor for fatigue damage monitoring in the composite. This study involved composite fabrication and experimental work. The glass fibre reinforced polymer specimens were fabricated using fibre glass and resin and made into flat workpieces. The workpieces were then utilised in a series of fatigue tests. Prior to the fatigue test, tensile tests were conducted to verify the ultimate strength of the material. Commencement of fatigue tests were recorded using the FBG sensor. Once the tests were started, the signals were acquired using the FBG sensor simultaneously. Data acquisition was continued during the fatigue test progression until the specimen failed. Results show the FBG wavelength shifted from its original position during tension loading and whenever the composite was released to its original position in the cyclic test. The FBG sensor seems a promising way to monitor fatigue damage and can be utilised in fatigue monitoring. Its wavelength shifts or changes is capable to monitor fatigue damage progression effectively.

Keywords Fatigue · Fibre bragg grating · Composite

9.1 Introduction

Composite seems to replace metal in many engineering structures such as aircraft [1, 2], automotive [3] and even in building construction and systems. It has a high strength-to-weight ratio compared to metal and effectively acts as an impact absorber in engineering applications [4]. Glass fibre reinforced polymer (GFRP) is a preferred type of composite utilised in engineering structures. Unlike metals and metallic

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alloys that generally fail due to a single identifiable crack, which then initiates and propagates [5], GFRP fails in a brittle manner [6, 7]. Therefore, the strain state of composite must be monitored so that techniques to predict the probable failure can be developed [8].

In recent decades, monitoring structural health has been interesting because of economic savings and safety factors. Engineering structures may fail after a particular service life duration, which may harm people and the environment if it happens unexpectedly. Regular strain state observation of composites under various substantial situations, especially repeated loads, is the most challenging part as strain state is the main cause of catastrophic destruction on composite assemblies during service. Therefore, a successful fatigue monitoring system for composites primarily relies on understanding the fatigue damage processes related to the internal structure strain. Fatigue damage inspection employing visual means is complicated. Generally, indirect sensing is the leading approach for damage sensing in a localised area [9]. The indirect method includes ultrasonic, thermography, interferometers and acoustic emission. Unfortunately, several drawbacks exist in the existing approaches. None of these techniques provides direct observations in the micrometre range to cater to fatigue damage late detection problems [10]. Furthermore, the utilisation of ultrasonic in fatigue damage detection is difficult due to the parallel direction of the crack growth and the sensing waves transmission path [11]. The same study reported that this difficulty is further increased in monitoring thin composites structures of less than 5 mm.

Seeing that GFRP failure is commonly immediate and without warning, a proper understanding of its fatigue properties is necessary. This paper aims to assess the characteristic of the FBG signal in detecting fatigue damage for GFRP materials. The assessment was conducted at a cyclic load of 40% of the ultimate load, as the scope of this study. Therefore, discussion on crack length is not included as it requires more loading conditions to have a representative correlational analysis. This study intends to take advantage of the FBG specialities that can sense an early crack initiation sign. With a proper monitoring scheme, detection of early-stage fatigue damage is possible and thus avoiding sudden failure or incident.

9.2 FBG in Fatigue Damage Sensing

The damage mechanisms depend on the extrinsic and intrinsic factors including the direction of the reinforcement, mechanical behaviour of the material constituents, matrix and reinforcement ratio and layup sequence. Any presence of even a single internal defect or flaw that resulted from manufacturing can make a difference to material properties. Thus, predicting the fatigue properties of composite is more complicated because of its multiple failure modes [12]. Various sensors are used to detect fatigue failure [13]. Acoustic emission can detect fatigue failure in engineering components [14]. Papazian et al. [15] utilised multiple sensors for early-stage fatigue cracking characterization by various sensing techniques on a similar specimen. They found that the techniques can be used in fatigue failure monitoring of laboratory-scale experiments.

The existing method of strain gauge utilization in fatigue monitoring has weaknesses that may be overcome by replacing it with other types of sensors. Embedment of strain gauge into a structure for fatigue monitoring alters the mechanical properties of the composite material [16]. Fibre bragg grating (FBG) embedment does not change or alter any of the material properties of the structures where it is embedded [17]. A tiny size of FBG installed on a glass structure exerts minor effect on its look. Its impact is minimal because the size is small [18]. The technology of FBG is even adopted in the conservative aerospace [19].

Arena and Viscardi [20] reviewed the different novel strain measurement methods utilised. Their review involves a few techniques to sense strain and failure growth such as FBG, strain gauges, infrared thermography and digital image correlation. They presented that strain gauge or strain gauge-based extensometers have various weaknesses. They are very responsive towards electromagnetic fields, they do not save space and they are unsuitable for embedment in structure layups. Its low fatigue resistivity property makes strain gauge an unreliable fatigue strain monitoring sensor. FBG is not only lightweight, but it is also multiplex and has absolute measurement capability, making it ideal to handle strain and structural monitoring tasks. Its manufacturability from a single optical wire into possibly numerous gratings is also beneficial.

The best features of FBG in composite applications are that it can penetrate a dense sensing network with minor structural impact. FBG sensors have become a reliable, non-destructive, in situ tool not only to monitor but also to do diagnostics and control in civil structures. A comprehensive review on FBG monitoring by Sahota et al. [21] presents various interrogation methods of FBG strain sensors. FBG technology is a favourable sensor choice of optical fibre category because it is easily manufactured and possesses a relatively strong reflected signal. A periodic modulation of the index of refraction applied on the fibre core along the longitudinal direction produces functioning FBG [22]. That is, the fiber now acts as a dichroic mirror, reflecting part of the incoming spectrum. Equation (9.1), developed for vacuum, has to be adapted for silica, since the distances traveled by light are affected by the index of refraction of the fiber. The relationship between Bragg wavelength and core refractive index is given by

$$\lambda_B = 2\Lambda n_{eff} \tag{9.1}$$

where Λ is the grating period measured as the distance between two adjacent grating planes, n_{eff} is the effective core refractive index and λ_B is the Bragg wavelength. Rao et al. [23] showed that FBG sensors are better than conventional foil strain gauges in terms of sensitivity and durability. These characteristics make FBG sensors ideal for structural health monitoring of large structures.

9.3 Materials and Methods

To test the mechanical behaviour of GFRP, the workpieces were fabricated. Mechanical tests (i.e. tensile and fatigue testing) were then conducted. Signals generated from the loadings on the workpieces undergoing fatigue tests were acquired and analysed to obtain the association. Each procedure is explained as follows.

9.3.1 Workpiece Preparation

Workpieces made of GFRP to be used in mechanical and fatigue tests were prepared. In fabricating the polymer, epoxy resin was combined with four layers of fibre glass fabric to form a laminate sheet. Epoxy resin and hardener were combined in the ratio of 2:1. The fibre glass fabric was stacked alternately between the resin which was then clamped using a big wooden block. It was then left to compress well and dry. A panel was then formed as shown in Fig. 9.1 which was then cut into smaller pieces of rectangular shapes with the dimensions of 20 mm long, 5 mm wide and 2 mm thick, as shown in Fig. 9.2. In the scope of this study, a flat composite panel which was then cut with the aforementioned dimensions was fabricated. The hand layup method was

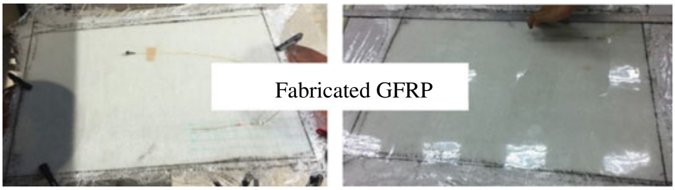


Fig. 9.1 Fabricated GFRP panel

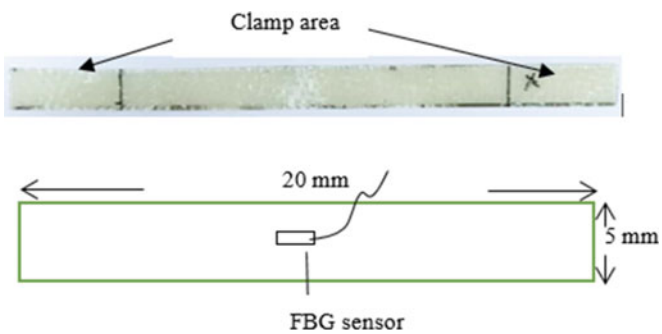


Fig. 9.2 Dimensions of workpiece for tensile and fatigue tests and position of FBG sensor during fatigue test

utilised to manufacture the GFRP composite panel. FBG sensor was attached to the specimen as in Fig. 9.2.

Each workpiece was bonded with an FBG sensor at the gauge length section. A total of eight workpieces were tested during the fatigue test the load ranges from 30 to 80% of the ultimate stress of the GFRP material. The FBG sensor was connected to the FBG interrogator system. The epoxy resin was mixed with hardener, and 1 mm-long FBG sensors with Bragg wavelengths of 1540, 1550 and 1560 nm were written on the same fibre optic. This wavelength shows the range of wavelengths that will shift during the test. The FBG sensor was aligned along the loading direction. All tests were performed on the Instron universal fatigue testing machine with a 25 kN load capacity. Load and displacement information was recorded in the incorporated Instron software by the built-in load cell and extensometer.

9.3.2 Tensile Test

Tensile test. Before the fatigue test was conducted, a similar workpiece and material were tested using the uniaxial tensile static test. The uniaxial static or tensile test had to be performed to verify the material's ultimate strength. The ultimate strength must be determined for any materials that are going to go through a fatigue test so that the workpiece does not fail because of reaching its ultimate strength. The average ultimate strength was set as a baseline parameter during the fatigue test where the maximum stress applied could not be higher than that. In this study, flat composite workpieces were subjected to constant amplitude strain and stress.

Fatigue test. For dynamic loading, a fatigue test was performed on the similar workpiece dimension of GFRP as a tensile test by referring to ASTM D3479 [24]. Different loads or stresses were applied to each specimen during the fatigue test. Tests were conducted on one loading condition three times. The fatigue test was started with minimum stress, and then the stress value was increased until close to its maximum or ultimate strength. The ultimate strength is the maximum stress that the material can bear before it fails. To ensure that the workpiece was not overly heated during the fatigue test, the Instron universal testing machine was applied with a 2 Hz frequency [25]. This frequency was selected as not too high to avoid overheating of the workpiece which might affect the FBG sensor as has been conducted by Kocaman et al. [26]. Fatigue tests were commenced in tension–tension mode of sinusoidal strain waveform at constant amplitudes. The workpieces were tested at one stress amplitude for 12,000 cycles. Figure 9.3 shows the experimental setup of the FBG sensor on the GFRP fatigue test specimen.

Data acquisition. In this study, FBG signal data were acquired during fatigue test progression. FBG wavelength was acquired using an FBG sensor with 1540 and 1550 nm wavelengths. The FBG sensor was bonded on the specimen gauge length area using a strong adhesive and left dried for one day. It was purposely

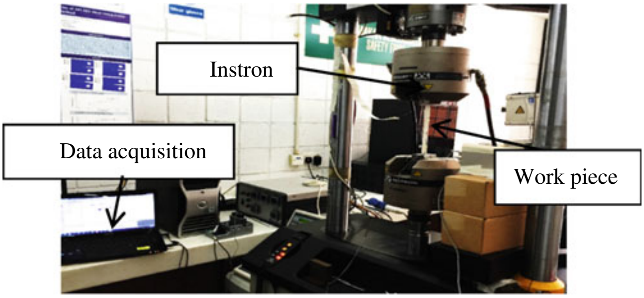


Fig. 9.3 Schematic of fatigue test and FBG data acquisition rig set up

done to ensure that it bonded well to the workpiece surface. The FBG sensor was connected to the FBG interrogator system, including an optical spectrum analyser (OSA), circulator, light and power source which were connected to software for data acquisition, display, record and further analysis.

9.4 Results and Discussion

Signal analysis

Wavelength. At the early stage of the fatigue test, the wavelength is 1548 nm as shown in Fig. 9.4. Here, the original wavelength is single and does not split or shift.

As fatigue test was commenced, the wavelength moved or shifted to the left and right following the loads undergone by the workpiece. FBG data were recorded in wavelength as they simply represented the changes that happened to the workpiece's inner structure. Generally, if the workpiece material was in compression mode, then the wavelength would shift to the left. When the load was in tension mode, then the wavelength oppositely shifted to the right. Figure 9.5 illustrates selected wavelength

Fig. 9.4 Original FBG wavelength before fatigue test

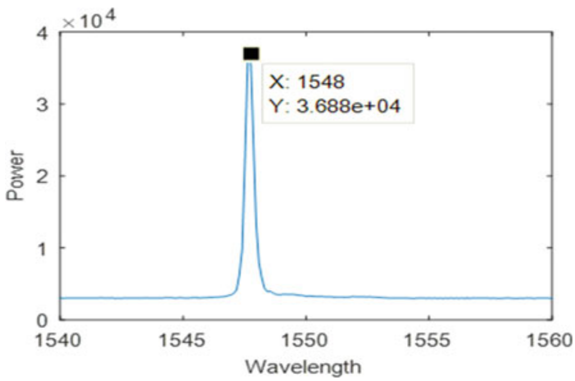
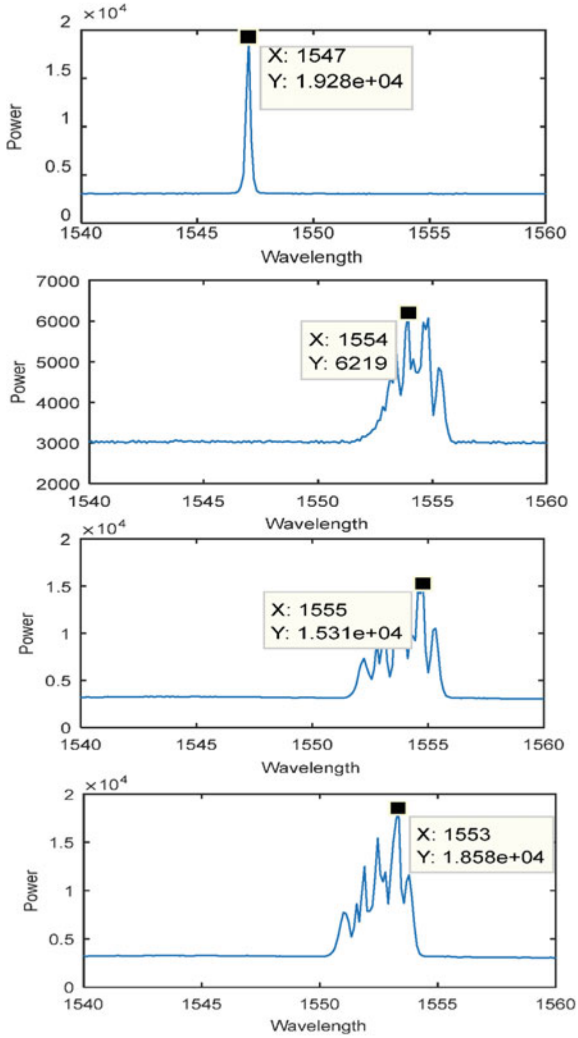


Fig. 9.5 FBG wavelength shifts of workpiece at 40% ultimate stress during a fatigue test



spectra acquired from the workpiece which experienced 40% loads from the ultimate stress by the FBG sensor during fatigue test progression. Initially, as soon as the fatigue test was started, the FBG spectra within the wavelength range of 1540 nm and 1560 nm were recorded. Figure 9.5 shows that wavelength shifts as the fatigue test progresses. These data were picked randomly after a certain duration at different intervals. However, not all figures show the complete left–right shifts of the wavelength in each data point. At an early stage of the fatigue test on the workpiece, FBG exhibited a wavelength value of 1547 nm. After a certain duration, its wavelength peaked at 1554 nm. A few peaks can be seen in this figure. At another moment during the test, the peak wavelength shifted to 1555 nm, and the last spectrum showed a

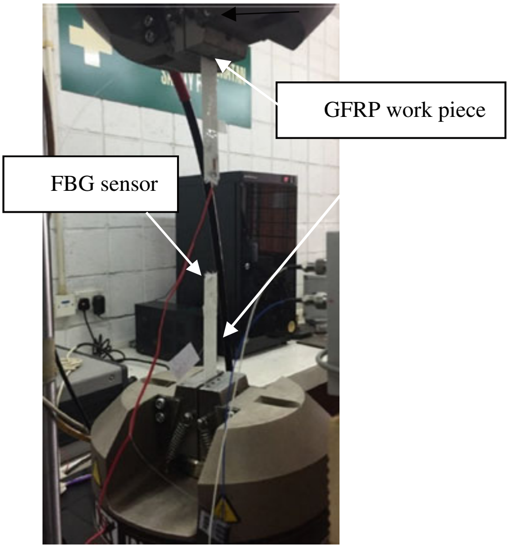


Fig. 9.6 Fractured workpiece after fatigue test with FBG sensor still intact

wavelength of 1553 nm. A perfect bonding between the FBG sensor and the workpiece surface can produce a smooth spectrum without any spectrum splitting. Xue et al. [27] supported this finding. Even though a few peaks appeared that could possibly be due to a slight decrease in bonding between the FBG sensor and surface of the composite workpiece during the cyclic loading, the wavelength shift is still noticeable. The FBG sensor was still intact and attached to the workpiece for the entire test duration and even after the workpiece already fractured as in Fig. 9.6. This finding exhibits successful fatigue damage sensing capability with a considerably wide sensor positioning which is about 10 cm from the exact failure location.

Data Analysis. The FBG wavelength spectrum was recorded multiple times during the fatigue test to monitor the condition of the FBG sensor when subjected to high-cycle fatigue loads. The result is illustrated in Fig. 9.5, where the x-axis represents the increment of the number of data, *n*. Such a recording was purposely carried out to understand the characteristics of FBG signal under fatigue loading. The integrity of the FBG obviously remains for the entire test duration. The spectra became more intense as the specimen approached fatigue failure with the increased loading cycle. More wavelengths of the same length or intensity were observed at the close time intervals. This phenomenon can be seen in Fig. 9.5 which clearly shows that the FBG sensor can detect the changes that occurred in the specimen structures and translate them into wavelength changes.

Upon commencing the fatigue test on the workpiece, the FBG wavelength was recorded simultaneously. Figure 9.7 shows the distribution of the wavelength shift or spectrum during fatigue test progression. Each dot in the figure represents a spectrum that has a wavelength value at a specific time. This wavelength value varies along the time duration depending on the loads given during the cyclic fatigue test. Figure 9.7 clearly illustrates that the FBG sensor recorded the condition of what was happening

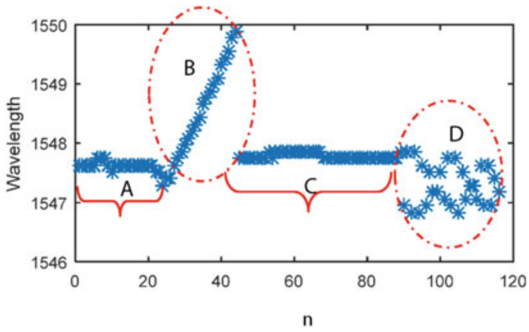


Fig. 9.7 Intensity of FBG wavelength for workpiece that undergone 40% of ultimate strength load during fatigue test

to the workpiece for the entire fatigue test. This result is consistent with the findings in [26]. FBG can monitor the structural health over quite a long duration by recording the changes experienced by the structure. The wavelength originated at less than 1548 nm then shifted to a higher wavelength of more than 1548 to 1550 nm at $n = 45$. After that, the wavelength shifted to the lower value that was close to 1457.5 nm for a certain duration and lastly distributed at less than 1547 nm before the workpiece failed.

In Fig. 9.7, the wavelength is plotted versus n, where n is the summation of n_i for $i = 0$ to N, and N is the number of data. n_0 is the number of data before the fatigue test was started at $t = 0$ s, and n_N is referred to the final second of the fatigue test. As soon as the fatigue test started at A, the wavelengths were shifting the higher and lower values within the range of 1547–1548 nm. This might represent that the FBG was exhibiting the tension and compression experienced by the workpiece when fatigue loading was applied. However, the wavelength shifts were tremendously increasing without going back to their original intensity at B. This might imply that the plastic deformation started to happen where the FBG wavelength was deformed like the workpiece where it was bonded to. The FBG wavelength then went back to the normal wavelength. At this section, it did not deform the workpiece because, at this time, the workpiece might have lost its elasticity. Lastly at D, the workpiece experienced pre-failure where the FBG started to crack and finally failed. The FBG sensor was still in good condition and did not damage or break even after the test was completed. This result demonstrates the robustness of applying FBG in the structural health monitoring system, specifically one that involves an extreme environment.

Based on the presented FBG graphical wavelength historical data, the proposed monitoring approach is feasible for the various structural health monitoring systems. This is because the level of failure and respective prevention strategies varies between dynamic systems. Prevention of any plastic deformation may be regarded as crucial for a particular system. Where in other structural components, the similar warning requirement could be extended until crack initiated before a total failure occurred.

9.5 Conclusion

This study reveals that the FBG sensor is capable of detecting physical changes inside composite components. The workpiece under tension and compression loadings are reflected in the FBG wavelength shifts. It was proven by the data acquired on the GFRP workpieces that had undergone fatigue test. Although the wavelength shifts did not directly address fatigue failure in this study, it may be possible if further analysis is performed. The research objective is achieved successfully as the results clearly show the connection between the FBG wavelength shifts and cyclic loading applied to the composite plate workpieces along the fatigue test. The after test check-up demonstrates that the FBG remained on the composite workpieces and mostly did not degrade. Since the indication of the fatigue crack initiation is not clear until the crack size reaches a critical limit, this monitoring approach offers early fatigue damage detection. The critical level should be avoided because of the rapid crack propagation until a complete fracture is often too late for any preventive action. A more interesting part to be highlighted is this monitoring approach's capability in fatigue failure indication for the studied brittle material.

References

1. Gude M, Hufenbach W, Koch I, Koschichowa R, Schulte K, Knoll J (2013) Fatigue testing of carbon fibre reinforced polymers under VHCF loading. Proc Mater Sci 2:18–24
2. Adam TJ, Horst P (2014) Experimental investigation of the very high cycle fatigue of GFRP [90/0]s cross-ply specimens subjected to high-frequency four-point bending. Compos Sci Technol 101:62–70
3. Gardyński L, Caban J, Barta D (2018) Research of composite materials used in the construction of vehicle bodywork. Adv Sci Technol Res J 12(3)
4. Patel M, Pardhi B, Chopara S, Pal M (2018) Lightweight composite materials for automotive-a review. Int Res J Eng Technol (IRJET) 5(11)
5. Suresh S (2001) Fatigue of materials, 2nd edn. Cambridge University Press
6. Ferdous W, Manalo A, Peauril J, Salih C, Reddy KR, Yu P, Schubel P, Heyer T (2020) Test and modelling the fatigue behavior of GFRPR. Composites–effect of stress level, stress concentration and frequency. Eng Sci Technol Int J 23(5):1223–1232
7. Tanimoto T, Amijima S (1975) Progressive nature of fatigue damage of glass fiber reinforced plastics. J Compos Mater 9:380–390
8. Kocaman ES, Akay E, Yilmaz C, Turkmen HS, Misirlioglu IB, Suleman A, Yildiz MT (2017) Monitoring the damage state of fiber reinforced composites using an FBG network for failure prediction. Materials 10(32):1–19
9. Glisic B, Chen J, Hubbell D, Streicker B (2011) A comparison between Bragg-gratings long-gauge strain and temperature sensors and Brillouin scattering-based distributed strain and temperature sensors. In: Proceedings of SPIE 7981. https://doi.org/10.1117/12.881818
10. Garcea SC, Spearing SM, Sinclair I (2012) Exploring the fundamental of fatigue in composites: opportunities using x-ray computed tomography imaging. Air Force Research Laboratory annual report, University of Southampton, United Kingdom
11. Mouritz AP, Townsend C, Shah Khan MZ (2000) Non-destructive detection of fatigue damage in thick composites by pulse-echo ultrasonics-ultrasonic and SEM evaluations. Compos Sci Technol 60(1):23–32

12. Colombo C, Libonati F, Vergani L (2012) Fatigue damage in GFRP. Int J Struct Integr 3(4):424–440
13. Wang P, Takagia T, Takenob T, Miki H (2013) Early fatigue damage detecting sensors—a review and prospects. Sens Actuators A Phys 198:46–60
14. Karimian SF, Modarres M, Bruck HA (2020) A new method for detecting fatigue crack initiation in aluminum alloy using acoustic emission waveform information entropy. Eng Fract Mech 223(106771):1–12
15. Papazian JM, Nardiello J, Silberstein RP, Welsh G, Grundy D, Craven C, Evans L, Goldfine N, Michaels JE, Michaels TE, Li Y, Laird C (2007) Sensors for monitoring early stage fatigue cracking. Int J Fatigue 29:1668–1680
16. Belhouideg S, Lagache M (2018) Effect of embedded strain gage on the mechanical behavior of composite structures. J Modern Mater 5(1):1–7
17. Liu B, Zhang S, Jianping HE (2019) Deformation measurement of glass structure using FBG sensor. Photonic Sens 9(6)
18. Guo X, Wang B, Ma Z, Wang Z (2019) Testing mechanical properties of rock bolt under different supports using fiber bragg grating technology. Sensors 19(4098). https://doi.org/10.3390/s19194098
19. Claire D, Silvia T, Ivan G, James K, Travis N (2012) High-strain fiber bragg gratings for structural fatigue testing of military aircraft. Photonic Sens 2(3):215–224
20. Arena M, Viscardi M (2020) Strain state detection in composite structures: review and new challenges. J Compos Sci 4(60). https://doi.org/10.3390/jcs4020060
21. Sahota JK, Gupta N, Dhawan D (2020) Fiber Bragg Grating sensor for monitoring of physical parameters: a comprehensive review. Opt Eng 59(6):060901–060935
22. Werneck MM, Allil RCSB, Ribeiro BA, de Nazaré FVB (2013) A Guide to fiber bragg grating sensors, current trends in short and long-period fiber gratings. In: Cuadrado-Laborde C (ed) IntechOpen, pp 1–24
23. Rao MB, Bhat MR, Murthy CRL, Madhav KV, Asokan S (2006) Structural health monitoring (SHM) using strain gauges, PVDF film and fiber bragg grating (FBG) sensors: a comparative study. In: Proceedings of national seminar on non-destructive evaluation,7–9 Dec, Hyderabad
24. ASTM D3479/D3479M-19 (2019) Standard test method for tension-tension fatigue of polymer matrix composite materials. ASTM International, West Conshohocken, PA
25. Xue G, Fang X, Hu X, Gong L (2018) Measurement accuracy if FBG used as a surface-bonded strain sensor installed by adhesive, 57(11):2939–2946
26. Keulen CJ, Akay E, Melemez FF, Kocaman ES, Deniz A, Yilmaz C, Boz T, Yildiz M, Turkmen HS, Suleman A (2016) Prediction of fatigue response of composite structures by monitoring the strain energy release rate with embedded fiber Bragg gratings. J Intell Mater Syst Struct 27(1):17–27
27. Kocaman ES, Akay E, Yilmaz C, Turkmen HS, Misirlioglu IB, Suleman A, Yildiz M (2017) Monitoring the damage state of fiber reinforced composites using an FBG network for failure prediction. Materials 10(32):1–19