Vibration monitoring for composite structures using buckypaper sensors arrayed by flexible printed circuit

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ABSTRACT
Fiber-reinforced resin-based plastics are widely used in structural composites for aerospace and automotive applications, and they often face extreme load conditions in actual working environments. It is challenging to monitor the damage of the structure during the vibration process. This study was aimed at using buckypaper (BP) sensors to monitor the structural health status of composite structures under ambient vibrations. First, the feasibility of flexible printed circuit instead of wire is verified by the tensile experiment. Then the vibration monitoring experiment of the composite cantilever beam is carried out by using BP sensors systematically. The sweep frequency experiment determines the excitation frequency of the cantilever beam. Low-period vibration fatigue cycle and high-period vibration fatigue cycle experiments are designed to verify the vibration monitoring method using BP sensors. Besides, the signal response of BP sensors in the vibration experiment is analyzed, and the relationship between ΔR/R₀ and vibration acceleration is obtained. Finally, through the change law of ΔR/R₀ of the sensor, the cumulative damage caused by vibration fatigue is visualized. It is demonstrated that the monitoring method based on BP sensors can be applied to study the damage behavior of composite structure under the vibration environment.

Abbreviations: FRP, fiber-reinforced resin-based plastics; SHM, structural health monitoring; SEM, scanning electron microscopic; FPC, flexible printed circuit; FBG, Fiber Bragg Grating; AE, acoustic emission.
Composite materials have gradually become one of the indispensable and essential materials for aerospace equipment due to their excellent specific strength, specific stiffness, corrosion resistance, fatigue resistance, and other mechanical properties [1–4]. Through the use of composite materials, robust promotes high-performance, lightweight and integrated development of aircraft, satellites, vehicles, and other equipment. In the manufacturing and production of China’s first large passenger aircraft C919, the application range of composite materials covers the rudder and other secondary bearing structures and the plane’s flat tail and other main bearing structures, gradually replacing traditional metal materials. However, in the actual service process of equipments, these types of equipment often face a complex and harsh service environment [5–7]. For example, specific thin-plate aircraft structures will fatigue due to vibration caused by noise excitation, causing rivets to loosen, or even in severe cases. It causes skin tearing. With the extensive application of composite materials in various types of equipment, it is necessary to carry out structural health monitoring for vibration fatigue of composite materials [8–14]. Structural health monitoring (SHM) technology is a significant application of smart material structures in practical engineering. The SHM system is an intelligent bionic system that can monitor the ‘health’ state online. It uses embedded or surface-attached sensors as the nervous system, sensing internal defects and damages in the structure. It is a method of online nondestructive evaluation of materials or structures. Takeda of the University of Tokyo in Japan conducted a modal analysis study on a helicopter wing made of composite materials through FBG sensors [15]. Wen Zhang et al. studied an array grating technology to monitor the vibration of a cantilever beam. [16] D. Di Maio et al. explored the application of scanning laser vibrometer to monitor the damage propagation of CFRP components under vibration fatigue load, and monitor the dynamic characteristics of fatigue-induced crack growth [17]. Yanping Zhu et al. studied the relationship between the open state of fatigue cracks and the index value of ultrasonic-guided wave difference in composite structures under vibration conditions [18].
Andrew Jaeyong Choi et al. studied a vision-based monitoring system to monitor damage to structures in a vibrating environment. [19] Adam Hehr et al. monitored the crack initiation process of composites under vibration conditions by embedding nanotube filaments in composites [20]. Although FBG, AE, and other technical means have made a lot of research results in the research of vibration monitoring of composite materials, there are other problems in the sensor itself. FBG sensors may face problems such as maintenance, strong directionality, and relatively high cost [21,22]. Ultrasonic-guided wave technology is easily affected by noise in the working environment; the monitoring method of acoustic emission technology with external sensors is not suitable for actual structural work Conditions [23]. These problems limit their wide application. Compared with the above-mentioned monitoring methods, SHM through carbon nano-paper sensors is a fast and efficient monitoring method [24] that provides possible composite structures solutions. In previous studies, buckypaper (BP) sensor with its excellent mechanical properties and electrical conductivity, it has made a lot of achievements in the online monitoring of composite materials and successfully carried out real-time monitoring in the preparation of composite materials [25], service damage [26,27], fatigue failure [28], etc. T Zhu et al. fabricated a novel NiO-decorated flexible buckypaper (NiO-BP) by a simple and scalable vacuum filtration method for electrochemical detection of glucose [29]. S Kim et al. used the SWCNT buckypapers, which can be cut, folded, and pasted, a foldable thermoelectric generator was fabricated [30]. However, there is still a lack of research on the health monitoring of composite materials for vibration fatigue.

In this paper, BP was fabricated by a vacuum filtration molding method. The BP sensors bonded to the flexible printing circuit (FPC) were co-cured together with the glass fiber laminate to complete the strain test of BP sensors under the condition of using the FPC. Then the BP sensors bonded with an FPC are used to monitor the vibration state of the composite material beam. The frequency sweep experiment, low-cycle fatigue cycle, and high-cycle fatigue cycle experiments were carried out on the cantilever beam laminate. By analyzing the experimental data of BP sensors, the sensing characteristics of BP sensor under vibration condition were explored.

2. The sensing mechanism of BP sensor under bending strain

In the vibration experiment, the $\Delta R/R_0$ of sensors became nearly linear with the vibration magnitude increase. According to Kaiser, the heterogeneous filament model can explain that the BP sensor changes the vibration experiment trend. When the BP sensor is integrated with the composite material with the ‘glass fiber’ as the base material, the inner carbon nanotubes are filled with free resin molecules. When the laminate undergoes bending strain due to forced vibration, the carbon nanotubes inside the sensor change very little. Because of the high elastic modulus and tensile strength. The main reason for the resistance is the change of the carbon nanotubes’ position, which further changes the contact resistance. The tunneling effect between carbon nanotubes mainly causes contact resistance [31,32]. When the thickness of the resin between the carbon nanotubes is relatively small, the free electrons on the carbon nanotubes wall will pass through to the adjacent carbon on the carbon nanotubes’ wall under the electron tunneling effect of the nanotube. The contact resistance is generated at the Junction. Figure 1 shows the sensor mechanism model. When the fatigue cycle does not cause microcracks in the laminate
matrix, as the vibration magnitude increases, the resistance change rate corresponding to the loading stage also increases. This is because the main stress mode of laminate under bending fatigue is longitudinal bending tensile/compressive stress. Increasing the excitation laminate’s acceleration causes the laminate to produce greater amplitude, resulting in more obvious bending strains of the laminate. The average distance between adjacent carbon nanotubes inside the BP sensor is embedded in the laminate changes under the alternating tension/compression state.

In the stretched state, the average distance between CNTs increases, leading to tunneling of charged carriers, which increases the tunneling resistance of the sensor. Under pressure, the average distance between CNTs is reduced, which reduces the tunneling resistance. [33] Therefore, during the vibration fatigue cycle, as the vibration magnitude increases, the laminate’s bending strain continues to increase, and the amplitude of the $\Delta R/R_0$ of the BP sensor also increases significantly. When the damage accumulates and causes microcracks in the substrate of laminate, it will cause CNTs contact fracture, increasing the $\Delta R/R_0$ of BP sensors and cannot return to its original state. By comparing the $\Delta R/R_0$ change trend of the BP sensor under different vibration levels. It is found that the BP sensor has a higher sensitivity in vibration monitoring. The $\Delta R/R_0$ of BP sensors can reflect the time node of the structure’s internal damage, convenient for further damage detection.

3. Material and experimental procedure

3.1 Preparation of BP sensors using flexible printed circuit (FPC)

This experiment used the vacuum spray molding method to prepare the BP sensor based on the laboratory’s previous BP sensor manufacturing experience. The main steps are as follows: First, add 600 mg of commercial multi-walled carbon nanotubes (MWCNT) and 5 mL of surfactant to distilled water TX-100. After that, the solution was sonicated and centrifuged. Then, the monodispersion was poured into the filter and filtered through a vacuum filtration device. Finally, the BP film was dried in an oven and carefully cut into a circle with a 10 mm diameter. The BP sensor and the microscopic electron microscope scanning image (SEM) are shown in Figure 2(a). In
the previous experiments, the sensor has been data transmission through the wire, and the conductive silver paste is used to bond the wire to the sensor. When using multi-sensor for structural monitoring, the wires are not conducive to integrating the sensor network. FPC is a board made of polyimide or polyester film as the substrate with high reliability and excellent flexibility. The thickness of the FPC used in the experiment is only 0.11 mm, which reduces the strength of the composite material due to the excessive diameter of the embedded wire. More importantly, FPC reduces sensor failure risk due to human factors during the implantation process. In the experiment, according to the size of the experimental laminate and the number of sensors, we designed an FPC that meets the requirements to monitor the structure. The thickness of the FPC is shown in Figure 2(b); the overall view and the detailed view of the FPC with the BP sensor attached are shown in Figures 2(c) and Figure 2(d), respectively.

3.2 Fabrication of tensile test laminates

In this experiment, the material used is glass fiber unidirectional prepreg (G20000, Weihai Guangwei Composite Material Co. Ltd, China). The prepreg’s fiber unit area weight is 200
g/m [2], the resin content is 30–40%, and the thickness is 0.2 mm. A manual layup process manufactures the composite material laminate. The size is 150 mm × 30 mm × 1 mm; the BP sensors using the FPC are embedded in the laminate, and the plate vulcanizing machine was used to cure for 2.5 h at a pressure of 2.5 MPa and 100°C, and then cooled to room temperature. The manufacturing process is shown in Figure 3.

3.3 The vibration experimental setup

In order to verify whether the BP sensor has a sensitive, stable, and reliable effect in monitoring the vibration state of composite materials. A vibration experiment was designed to simulate the vibration environment of the structure. The test system of the entire experiment is shown in Figure 4.

The function of power amplifier is to amplify the vibration controller’s drive signal into a sizable current drive signal and then send it to the vibration table. According to the
driving signal, the vibrating table generates excitation to the test piece installed on the table as the entire test system’s actuator. The vibration controller can realize vibration experiments in sine, resonance search and residence, and random environments. The acceleration sensor’s function is to collect, monitor, and feedback the vibration signal, which is used to monitor the excitation signal’s state in real-time to ensure that the actual vibration of the vibration table is consistent with the preset excitation signal parameters. (The acceleration sensor adopts the 4508B sensor of B&K company, the working frequency is 0.3–8 kHz, and the measuring range is ±71 g peak). When conducting the vibration experiment, the fixture has been fixed to the vibrating table, the glass fiber laminate is pre-tightened on the fixture with bolts, the charge acceleration sensor is pasted on the fixture, and the closed-loop control is formed by connecting with the channel of the vibrator. To select a suitable frequency for resonant excitation of the laminate. First, perform a frequency sweep experiment on the laminate, maintain the acceleration unchanged, and find the laminate’s resonant frequency within the set frequency bandwidth. The frequency sweep event table is shown in Table 1. Afterward, the appropriate frequency points are selected, and low-period and high-period fatigue cycle experiments are carried out on the laminates. The BP sensor data is collected by the data collection system, the loading steps of vibration fatigue are shown in Figure 5, and Figure 6 shows the whole experimental flowchart.

**Figure 5.** Loading step of vibration loading conditions.

**Table 1.** The frequency sweep event.

| Sweep frequency | Lower frequency (Hz) | Higher frequency (Hz) | Start frequency (Hz) | Initial direction |
|-----------------|----------------------|-----------------------|----------------------|------------------|
| Mode liner      | 10                   | 70                    | 20                   | Up               |
|                 | Magnitude (%)        | 100                   | Speed (Hz/min)       | Time             |
|                 |                      |                       |                      | 00:00:50         |
4. Experimental procedures and discussion

4.1 Tensile experiment

Before the vibration monitoring experiment, a static tensile experiment was carried out to verify whether the FPC is practical in SHM. For this reason, universal testing machine, AL7000-LA20, was used to conduct tensile experiments on two kinds of glass fiber laminates with and without embedded FPC. The loading rate of the crosshead of the tensile machine was set to 0.5 mm/min. Figure 7 shows the stress–displacement curves of two glass fiber laminates. Simultaneously, the $\Delta R/R_0$ of BP sensor–displacement curves is also shown in Figure 7. In Figure 7(a), when the maximum load was loaded to 6 kn, the laminate has a displacement of 1.2 mm. In Figure 7(b), when the laminate’s maximum load was loaded to 7.5 kn, the laminate has a displacement of 1.35 mm. Although the...
laminate’s displacement of laminates under the two tensile experiments was small, the applied stress level was also low. Because the elastic modulus of the CNT itself is much greater than the modulus of the matrix, this level of stress may not cause the CNT itself to deform. But the \( \Delta R/R_0 \) of the BP sensor can maintain a sensitive response. The two numerical answers of \( \Delta R/R_0 \) were 15.925–15.970 and 15.876–15.918, respectively. The resolution of BP sensor \( \Delta R/R_0 \) has reached thousands, indicating that the sensor has good accuracy. These experimental data results also reflect that the electromechanical performance of the BP sensor was controlled by the CNT interaction in the BP rather than by the CNT deformation. Whether to use the FPC, \( \Delta R/R_0 \) of BP sensors corresponding to the stress and displacement curve has the perfect synchronicity. Two of regression coefficients were \( \geq 0.99 \), they illustrate the FPC instead of wires can realize the condition monitoring of a composite material structure.

4.2 Monitoring of vibration fatigue

4.2.1 Low-cycle fatigue using BP sensors
For the fatigue research of composite materials, most of them were aimed at the axial fatigue of composite materials, and the bending fatigue of composite materials was relatively less. For this reason, we use the natural frequency obtained in the frequency sweep experiment as the excitation frequency point. Figure 8 shows the frequency response of the cantilever beam.

The frequency points marked in Figure 8 were the excitation frequencies of vibration loading. During the frequency sweep test, when the instantaneous acceleration of the beam reached a peak, the resonant frequency of the beam were 5.8, 6.2, 6.5, and 9.7 Hz respectively. The peak accelerations correspond to the resonant frequency were 0.88, 1.24, 1.1, and 1.06 g. Since the initial acceleration was 0.98 g, the amplitude response of the composite cantilever did not depend on the peak acceleration, but on the absolute values of instantaneous acceleration. Depending on the order of the absolute value of the

![Figure 8. Frequency response curve of cantilever beam.](image_url)
acceleration from low to high, marked the corresponding frequency points in Figure 8. The objective of selecting these four frequency points was to compare the response of the BP sensor under different bending strains. Under the excitation of these four frequency points in sequence, the bending strain of the cantilever increased with the increase of the amplitude of the free end of the cantilever. Therefore, it was judged whether the response of the BP sensor embedded in the cantilever beam is sensitive and stable. The low-cycle fatigue experiment was regarded as the pre-experiment of the high-cycle fatigue experiment. The purpose of doing so is to save time and cut the cost. It is judged whether a good signal response will be generated in the laminate’s vibration state monitoring by analyzing the response of BP sensors.

It can be seen from Figure 9(a) that the $\Delta R/R_0$ changed with time. When the beam sustained vibration under the loading condition of 1.032 g, $\Delta R/R_0$ gradually changed from 0 to 0.01. When the set acceleration load conditions reached 1.066 g of the second stage, $\Delta R/R_0$ will be stepped and maintained at 0.002. In the following two cycles, the loading conditions were 1.111 and 1.168 g, respectively, and the $\Delta R/R_0$ of the BP sensor also increased from 0.02 to 0.052 and 0.062 in turn, and the four loading cycles experienced by the laminate during the vibration fatigue cycle can be distinguished from the time point of $\Delta R/R_0$ step. In the four vibration loading cycles, the time nodes were selected at when the fatigue cycle number of the cantilever up to $4 \times 10^3$, $1.25 \times 10^5$, $2 \times 10^5$, and $3 \times 10^5$ cycles, respectively. Furthermore, intercept the 10 consecutive cycles of the $\Delta R/R_0$ at these four time nodes in turn. As can be seen from Figure 10(a), under the corresponding vibration period, the $\Delta R/R_0$ levels of the BP sensor are 0.001–0.009, 0.0011–0.02, 0.0477–0.0513, and 0.056–0.062, respectively. And compared the $\Delta R/R_0$ response curve in different fatigue cycles from Figure 10(b). Except for the third loading period, the $\Delta R/R_0$ amplitude changed in the other three cycles is relatively close. The difference of $\Delta R/R_0$ response of buckypaper is caused by noise. Generally speaking, the vibration signal obtained by the data collector will contain noise components. These noise signals mainly include irregular random interference signals and other periodic high-frequency interference signals. Because the frequency band of random interference signal is wider than that of the normal signal, there will be the numerical difference in the data curve of the

![Figure 9. Resistance change–acceleration relationship of BP sensors for low-cycle fatigue: (a) low cycle fatigue; (b) crack monitoring.](image-url)
vibration signal. A fitting analysis for linear regression was performed for the excitation acceleration and ΔR/R₀. It can be seen from Figure 13(a) that the regression coefficient between the two variables is 0.90255, indicating that the goodness of fit between the two is better. The amplitude of ΔR/R₀ and the magnitude of vibration show a positive relationship. We can feedback the vibration level of the cantilever through the numerical response of ΔR/R₀.

In order to accelerate the initiation of cracks in the cantilever. In the second low-cycle fatigue experiment, we chose a laminate with a double triangular notch for the experiment. In order to further verify the response of ΔR/R₀ under different excitation accelerations, the cantilever was subjected to constant frequency vibration, and the excitation accelerations were set to 1, 3, 5, 7, and 9 g, respectively. Figure 9(b) shows the ΔR/R₀-time curve of the double-notch cantilever subjected to low-cycle vibration fatigue. The same as the previous experimental result, the ΔR/R₀ response was represented as step shaped. ΔR/R₀ shows good synchronization with the change of vibration loading period. It is worth noting that due to the stress concentration brought about by the double notch, the cantilever has a macroscopic crack. The initiation of cracks caused a sharp step of ΔR/R₀. Figure 9(b) shows that the ΔR/R₀ of the BP sensor has a signal step phenomenon. As the vibration loading cycle continued, the response of ΔR/R₀ was gradually stable from unstable. The value of ΔR/R₀ was maintained at about 0.5. This indicates a stable propagation of microcracks in cantilever beams even with the sustained cyclic loading. When the experiment ended, ΔR/R₀ did not return to the initial level, indicating that the BP sensor embedded in the cantilever beam has been maintained in a new state (Figure 10). As in the previous experiment, in order to observe the stability of the sensor ΔR/R₀ response. Under different loading periods, the fatigue cycles of the cantilever beam were selected to reach 5 × 10⁴, 1.5 × 10⁵, 2.5 × 10⁵, 3.5 × 10⁵, 4.5 × 10⁵, and 5.0 × 10⁵, respectively, and we intercepted 10 consecutive response cycles of ΔR/R₀. As shown in Figure 11(a), the numerical response of ΔR/R₀ increases with the number of fatigue, and the range of variation is −0.003–0.004, −0.003–0.03, −0.003–0.06, −0.003–0.12, −0.003–0.16, and 0.35–0.52, respectively. It can

Figure 10. Close up of BP sensor’s ΔR/R₀: (a) 4000–40,010 cycle period. (b) 1.25 × 10⁵–125,010 cycle period. (c) 2 × 10⁵–200,010 cycle period cycle period. (d) 3 × 10⁵–300,010 cycle period. (e) Residual resistance change at selected cycles.
be seen from Figure 11(b) that the amplitude increment of ΔR/R₀ is in the range of 0.3–0.6 before cracks appear. Similarly, ΔR/R₀ and excitation acceleration were linearly fitted (Figure 12). As shown in Figure 13(b), compared with the last fitting, the regression coefficient this time is 0.96, which has a better goodness of fit. In the two low-cycle fatigue experiments, the ΔR/R₀ response of the BP sensor showed a trend of step increase. In the first experiment, the ΔR/R₀ response showed an overall step phenomenon under the corresponding load period. In the second experiment, ΔR/R₀ showed a stepped increase in amplitude. The difference between the two is due to the small excitation acceleration range in the first experiment, from 0.98 to 1.2 g; the increment is only 0.2 g. The increment of ΔR/R₀ is about 0–0.06. In the second experiment, the excitation acceleration range is 1–9 g, and the response increment of ΔR/R₀ is 0.003--0.52. The instantaneous signal during the ΔR/R₀ step even suddenly increases to 1.25. It makes the thousandth. The increment cannot be clearly evident in Figure 9(b). In summary, the difference in the data image is caused by the excitation acceleration range. It can also be explained from another angle that the BP sensor can sensitively monitor the change of excitation acceleration. After the experiment, the double-notch part of the beam was scanned by an electron microscope.

Then the scanning electron microscopic (SEM) image of the low fatigue cycle beam is shown in Figure 12. From the scanning results, the cracks initiating inside the laminate were visible. When the injury occurred, the response of ΔR/R₀ gradually stabilized at the level of 0.52. And after the end of the experiment, ΔR/R₀ did not return to the initial state, but remained at the value level of 0.27. It can be seen from Figure 12 that under the action of bending stress, the carbon nanotubes form a shear stress zone to absorb the fracture energy of the matrix. Under the action of long-term reciprocating bending strain, the resistance value of the BP sensor is permanently changed because of broken CNTs. It also indirectly proves that the cantilever beam has irreversible crack damage. Because the BP sensor and the glass fiber material are solidified and formed, the initiation of crack will also cause the carbon nanotubes’ relative positions inside the
BP sensor to change, thereby making the sensor’s resistance value. Through the $\Delta R/R_0$ step phenomenon of the BP sensor, the starting node of the structure crack initiation can be accurately recorded. It is convenient for further inspection of the structure in time. After a low-period fatigue cycle experiment, the BP sensor’s monitoring performance has reached the expected effect, laying a foundation for the next high-period vibration fatigue cycle.

4.2.2 High-cycle fatigue

The laminates were then replaced, and the high-cycle fatigue cycle began according to the set vibration loading conditions. Figure 14 reflects the response of $\Delta R/R_0$ with time in the high process. It should be noted that the 0–100 Hz frequency sweep experiment was performed on the laminate before the high-cycle fatigue cycle, and it was found that the laminate was at about 50 Hz.

A good resonance effect can be produced during excitation. In the previous two low-cycle fatigue experiments, the $\Delta R/R_0$ response can distinguish the vibration cycle of the cantilever beam. However, in the early stage, the step response of $\Delta R/R_0$ cannot be clearly explained, whether the growth of $\Delta R/R_0$ contains the factor of crack initiation. To prove the reproducibility of the BP sensor $\Delta R/R_0$, we restarted the experiment every 1.5 h and recorded the experimental data under a vibration excitation period of 1 g. So at this time, set the excitation frequency to 50 Hz when the vibration load is at 1 g, which can see that

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**Figure 12.** SEM of buckypaper co-cured with the composite after low fatigue cycle. (a) and (b) denote the crack initiation. (c) SEM images of fracture surface of CNT, where subscripts 1 and 2 denote initial region and local enlarged view, respectively.
the same $\Delta R/R_0$ occurs in the two intervals of $0–5369$ s and $5369–10,882$ s. The trend of change gradually increased from 0 to 0.1 and remained stable. When the experiment restarts, the BP sensor can recover to the initial resistance within the first two 1.5 h periods and continue to monitor the state of the laminate again, which shows that the loading condition of 1 g acceleration did not cause irreversible damage to the model. When Fluke started to record for the third time, the $\Delta R/R_0$ of sensors grew steadily from 0 to 0.004 until the first signal step at 13,221 s. At this time, the laminate has gone through about $6.6 \times 10^5$ cycles, $\Delta R/R_0$ did not stabilize at the level of 0.08. After the surge, it was at the level of 0.13 for about 1589 s, then increased to the level of 0.15 and maintained for about 2000 s. In the subsequent two vibration fatigue cycles ($16,320–19,980$ s/$19,980-21,306$ s). The vibration loading conditions were set to 5 and 10 g. It can be seen that the $\Delta R/R_0$ of the sensor increased from 0.15 to 0.61. Under the loading condition of 10 g, the $\Delta R/R_0$ first stabilized at 0.98 and then expanded to 1.3 until the end of the experiment. When the cantilever beam has experienced $5000, 5 \times 10^5, 7.5 \times 10^5, 1 \times 10^6$ fatigue cycles in sequence. Figure 15 shows the resistance response behavior for 10 consecutive times.

Figure 13. The fitting curve of $\Delta R/R_0$ - g: (a) Low-cycle fatigue. (b) Low-cycle fatigue of crack monitoring. (c) High-cycle fatigue.
Figure 14. Resistance change–acceleration relationship of BP sensors for high-cycle fatigue.

during the vibration fatigue test at a selected time. At 5000 fatigue cycles, the response range of $\Delta R/R_0$ is 0.0184–0.02. At the fatigue cycle of $5 \times 10^5$, $\Delta R/R_0$ response is stable at 0.05–0.08. It is worth noting here that under the same excitation acceleration condition (1 g), $\Delta R/R_0$ shows a trend of rising and then maintaining stability. Until the crack initiates and produces a step response. This shows that under the continuous action of low-level bending stress, the test piece makes the matrix gradually in a state of stress saturation. But the load at this time is not enough to cause fiber breakage. At $7.5 \times 10^5$ fatigue cycles, $\Delta R/R_0$ stabilized again after a step. It shows that the cantilever beam generates a new load transfer path after the cracks in the matrix occur. The cantilever beam achieves a new stable state by redistributing the stress between the fibers. Finally, in $1 \times 10^6$ fatigue cycles, there are two factors that affect the sharp increase of $\Delta R/R_0$. One is that the excitation acceleration is increased by 5 times. The second is that the accelerated crack propagation causes deformation and rearrangement of the carbon nanotube network, and even causes the CNT to break, causing the resistance to fluctuate. In the entire high-cycle experiment, the laminate has undergone a total of about $1 \times 10^7$ fatigue cycles. Table 2 shows the number of cycles of each stage of the laminate. As the fatigue cycle continues to increase, the $\Delta R/R_0$ was gradually increased. With the increasing fatigue period and damage accumulation, the $\Delta R/R_0$ also increased step by step. In the early stage of the fatigue cycle, $\Delta R/R_0$ relatively small changes. After about $8.088 \times 10^5$ fatigue cycles, the $\Delta R/R_0$ difference of the sensor began to increase rapidly.

The shape of the resistance curve is similar to the curve’s shape applied to the excitation load. In this experiment, sinusoidal load excitation was applied to the laminate, and the crack caused the difference in the curve. It is generally believed that advanced composite materials have better fatigue performance than metal materials. Still, the failure of composite materials under fatigue load is a complex accumulation of the microstructure’s inability, involving various failure mechanisms. They include matrix microcracks, fiber/matrix exfoliation, fiber fracture, and lamination. As the BP sensor and the laminate are cured together. The resistance will change due to the crack propagation
Figure 15. (a) Residual resistance change at selected cycles. (b) Close up of BP sensor’s $\Delta R/R_0$: 5000–50,010 cycle period. (c) $5 \times 10^5$–500,010 cycle period. (d) $7.5 \times 10^5$–750,010 cycle period. (e) $1 \times 10^6$–100,010 cycle period.

Table 2. Vibration fatigue cycle period.

| Acceleration (m/s²) | Cycle period |
|---------------------|--------------|
| 1                   | $8.088 \times 10^5$ |
| 5                   | $1.92 \times 10^5$  |
| 10                  | $0.49 \times 10^5$   |

during the sample loading[35]. Figure 16 shows that the BP sensor $\Delta R/R_0$ in the process of the vibration of the high-cycle fatigue cycle was an effective indicator for monitoring crack initiation. The laminates undergoing a high periodic vibration fatigue cycle were
examined by SEM to observe the internal microstructure’s damage during the period. The goal was to make the response of the sensor more convincing. SEM scanning results are shown in Figure 17. The high-period vibration fatigue caused the damage of the laminate to accumulate and produce micro-cracks. The crack initiation makes the carbon nanotubes of BP sensors deform and rearrange, which made the resistance to fluctuate and

Figure 16. Damaged resistance change showing fatigue crack initiation and propagation stages during loading.

Figure 17. SEM of buckypaper co-cured with the composite after high fatigue cycle. (a) and (b) denote the crack initiation, where subscripts 1 and 2 denote initial region and local enlarged view, respectively.
change. At the end of the experiment, resistance of sensors did not recover to the initial resistance state.

Although the high-cycle fatigue cycle did not cause macroscopic crack damage to the laminate, the time-domain diagram of the sensor resistance change rate can be used to determine the vibration loading period of the laminate. When the BP sensor’s $\Delta R/\Delta R_0$ undergoes an instantaneous step change in the same load condition, which can indicate that the laminate has cracked defects at this time, and the occurrence time can be recorded through the time-domain diagram of $\Delta R/\Delta R_0$. During the entire experiment, the BP sensor has maintained a stable response, and it can visualize the whole fatigue cycle of the laminate.

5. Conclusion

In this paper, a new sensor deployment method is proposed using the BP sensor bonded with FPC, and tensile experiments on glass fiber laminates verify the feasibility of this method. Subsequently, this method was used to perform vibration fatigue testing on glass fiber materials, and a monitoring method of composite material damage accumulation under vibration environment was explored, as well as the sensing characteristics of BP sensor under vibration conditions. The conclusions of this study can be summarized as follows:

1. Tensile experiments were carried out on the laminates with and without FPC, which verified the feasibility of using FPC to monitor the BP sensor integrated array in SHM. The sensor’s sensing coefficient and the response of the FPC sensor to the strain of the laminate can still maintain good synchronization and sensitivity. Using FPC to replace traditional wires improves the sensor’s survival rate and makes the deployment and control method of the sensor efficient and straightforward.

2. The low and high vibration fatigue cycles were carried out on the composite laminates, and the conclusions could be drawn according to the microscopic images of SEM. According to the BP sensor’s resistance change, the vibration state of the laminate can be accurately reflected. When the composite material is not damaged, the $\Delta R/\Delta R_0$ of the sensor will gradually increase and stabilize at a certain level. As the vibrating structure of the glass fiber structure is gradually loaded, and the number of fatigue cycles increases. According to the resistance change step, the occurrence of microcracks in the test piece is judged. Simultaneously, the BP sensor is still in a very stable state after experiencing high-period vibration fatigue cycles so that it can be used for long-term vibration monitoring of composite structures.

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Disclosure statement

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