

Comparative Study of Fibre Bragg Grating and Strain Gauges for Fatigue Crack Detection in Mild Steel

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ABSTRACT

Fibre Bragg Grating (FBG) is an optical sensor capable of detecting strain, temperature, and structural deformation, including cracks. Early crack detection is essential for ensuring structural safety and integrity. However, conventional strain gauges are not highly sensitive and are prone to electromagnetic interference. This study compares the performance of FBG and strain gauges in monitoring cracks on mild steel. FBG data were converted into strain values and analysed alongside readings from strain gauges. Both sensors were mounted on the specimen, and data were collected in real time. The results show that FBG is more sensitive to small changes and is suitable for real-time monitoring. During the early crack phase, FBG responded more quickly to changes than the strain gauge. In the crack propagation phase, both sensors produced graph patterns that were almost identical. In conclusion, FBG is more suitable for structural monitoring that requires high accuracy, while strain gauges remain useful within specific measurement ranges. This study helps engineers choose the appropriate technology to ensure structural safety throughout its lifespan.

Keywords: Fibre Bragg Grating (FBG); strain gauge; mild steel; crack monitoring

INTRODUCTION

In the field of engineering, structural integrity plays an important role in ensuring the safety and reliability of a system. Much like human beings who experience physical fatigue due to daily stress and challenges, structures also deteriorate over time when exposed to repeated loads, extreme temperatures, and environmental factors (Beaumont 2020). Failure to detect early-stage damage such as cracking can lead to major structural failure and pose significant risks. Cracks often originate from areas with high stress concentration and may develop into critical damage (Kpie Janvier De Thales & Kabir Sadeghi 2022). Therefore, early and effective crack monitoring is essential to maintain structural integrity, reduce maintenance costs, and extend the service life of components.

Although various monitoring techniques have been introduced, conventional technologies such as strain gauges

are constrained by low sensitivity and vulnerability to electromagnetic interference (Vinnarasi & Sundaravadivelu 2017). In addition, Ultrasonic inspection methods also require specialized equipment and lack the capability for continuous real-time data acquisition. As a result of these limitations, optical fibre sensing technology particularly Fibre Bragg Grating (FBG) has gained significant attention as a highly viable alternative to conventional methods such as electrical strain gauges (ESG), piezoelectric, resistive, or other solid-state sensing systems, whether used for measuring physical parameters or conducting high sensitivity biochemical analysis (Agosmustaram et al. 2024). FBG sensors have been widely recognized for their ability to detect strain and temperature changes with high sensitivity (Xu et al. 2023). With advantages such as compact size, immunity to electromagnetic interference, and distributed sensing capability, FBG is considered a potential replacement for traditional sensors. Although

FBG sensors were initially developed for use in controlled laboratory environments, recent advancements have prompted researchers to explore their transition into real-world industrial applications which particularly in the fields of structural health monitoring (SHM), condition-based monitoring, and fault diagnosis (Suhaimi et al. 2024). Nevertheless, performance evaluation under high-stress conditions remains necessary, particularly in demanding environments such as bridge, building and railway (Barbosa 2021).

Accordingly, this study aims to evaluate the effectiveness of FBG sensors compared to conventional strain gauges in monitoring crack growth in mild steel materials. The investigation involves assessing strain changes during different crack development phases. In addition to identifying the sensing capability of FBG, this study also compares strain data from both sensor types and validates their sensitivity and measurement accuracy. The results of this study are expected to support the wider application of FBG technology in structural monitoring while enhancing understanding of crack behaviour in engineering materials.

METHODOLOGY

Figure 1 shows the flowchart of this study, outlining the experimental steps from specimen preparation to data analysis. The process involves using both FBG sensors and strain gauges during a fatigue test to monitor crack propagation. Data collected from both sensors is then analysed to achieve the study objectives, including evaluating detection capability, data comparison, and measurement accuracy.

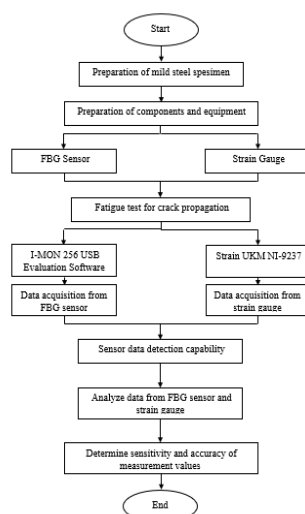


FIGURE 1. Process flow of experimental method

SPECIMEN PREPARATION

In this study, a notched mild steel plate specimen prepared in accordance with ASTM E647, as shown in Figure 2, was used to investigate fatigue crack growth. Mild steel was selected as the main material due to its favourable mechanical properties, which make it suitable for analysing crack behaviour under controlled loading conditions.

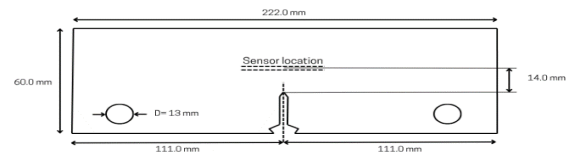


FIGURE 2. Geometry dimensions of the notched fatigue specimen and sensors location

COMPONENT AND SYSTEM PREPARATION

FIBRE BRAGG GRATING

In this study, a Fibre Bragg Grating (FBG) sensor was used to evaluate the sensitivity and accuracy of measurement values on a mild steel specimen. Strain, which refers to the deformation of a material due to stress, affects the spacing and refractive index of the Bragg grating. These changes alter the optical spectrum parameters reflected by the FBG. External disturbances, such as uniform pressure applied to the structure, also influence the grating spacing and refractive index, which are subsequently detected as wavelength shifts in the FBG spectrum.

The signal generated by changes in the light wavelength is analysed to determine the magnitude and direction of the shift. This analysis enables the detection of structural changes occurring within the material. A data acquisition system is required to obtain the wavelength readings from the FBG sensor, with the equipment used listed in Table 1.

TABLE 1. Equipment for FBG Sensor Data Acquisition

System Equipment	Function
Personal Computer (PC)	To monitor and record wavelength data
Interrogator system	Converts the Bragg wavelength shift from the FBG sensor into readable wavelength data viewable on the computer
Fibre Bragg Grating	Detect changes in the wavelength of light
USB cable	Connect the interrogator system to the laptop



FIGURE 3. Fibre Bragg Grating Interrogator System

Figure 3 shows the FBG interrogation system connected to a laptop, allowing observation of wavelength shifts occurring during the test. This system is used to monitor signals from the FBG sensor in real time and display the wavelength shift readings through the software interface on the computer.

STRAIN GAUGE

In this study, a strain gauge was used to measure the strain values on a mild steel specimen. The strain experienced by the material causes deformation in the sensing grid of the strain gauge, which in turn leads to a change in electrical resistance. This change in resistance is translated into strain values using a relevant data acquisition system.

Strain data during the fatigue test was collected using a data acquisition device (DAQ), namely the National Instruments 9237 (NI-9237). This device functions to acquire signals from the strain gauge mounted on the surface of the mild steel plate specimen. The strain gauge was connected to the NI-9945 module, which is a quarter-bridge completion accessory, before being linked to the NI-9237 system. The entire setup was then connected directly to a laptop, enabling real-time data recording and display of strain values. Figure 4 illustrates the NI-9945 component connected to the strain gauge sensor and data acquisition system that will connect with NI-9945 and laptop.



FIGURE 4. a) NI-9945 module b) Data Acquisition (DAQ) system

Both FBG sensors and strain gauges were installed in parallel on opposite sides of the specimen at predetermined locations, particularly around the notched region where crack initiation was expected to occur. The FBG sensors were bonded using suitable optical adhesive to ensure proper strain transfer, while the strain gauges were installed with standard strain gauge bonding procedures, as shown in Figure 5.

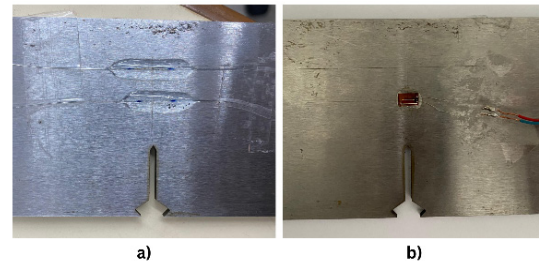


FIGURE 5. Position of attachment of the sensors a) Fibre Bragg Grating b) Strain gauge

EXPERIMENTAL PROCEDURE

The fatigue test was conducted using INSTRON 8801, 100 kN, servo-hydraulic machine (as shown in Figure 6). In order to observe the stable crack growth propagation, a tension-tension fatigue test, with testing frequency of 10 Hz and loading stress of 150 MPa, was applied during the test.

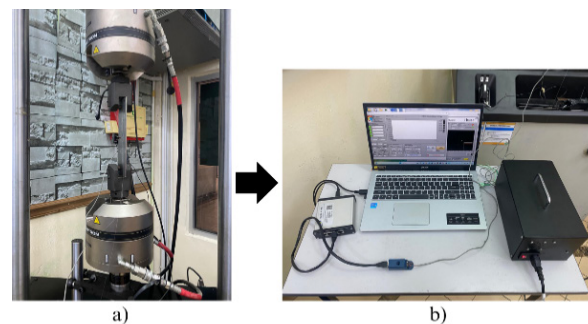


FIGURE 6. Fatigue test set up a) The servo-hydraulic fatigue testing machine with a specimen attached b) Data collection through the computer using software

MONITORING PROCEDURE

Each sensor type was connected to its respective data acquisition system: FBG sensors were linked to the I-MON 256 USB Evaluation System for wavelength shift monitoring at a sampling rate of 3000 Hz, while strain gauges were connected to the NI-9237 module for strain signal acquisition at a sampling rate of 2000 Hz, as shown in Figure 7.

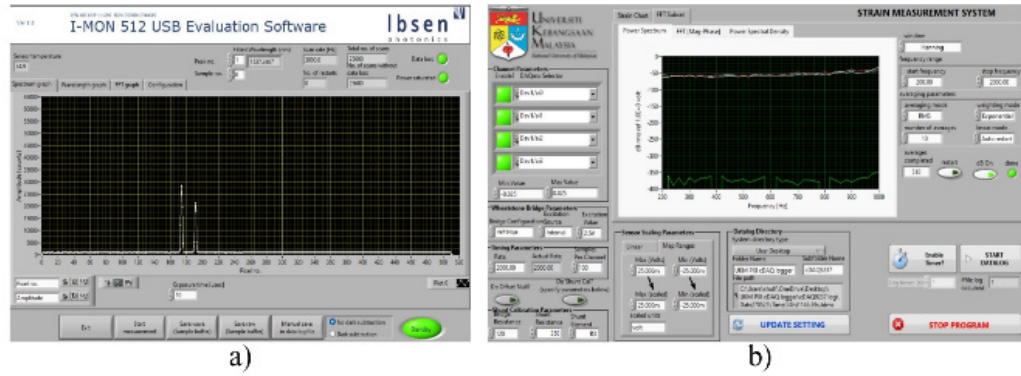


FIGURE 7. Data acquisition system a) I-MON 256 USB Evaluation Software b) Strain NI-9237 Software

Finally, the graphical data were analysed to assess the sensitivity, accuracy, and responsiveness of each sensor in detecting changes during different stages of crack development. This comparison served as the foundation to determine the feasibility of applying FBG sensors as a structural health monitoring tool.

RESULTS AND DISCUSSIONS

Figure 8 shows the crack that formed on the specimen after several loading cycles were applied, where the crack initiated at the notched area and gradually propagated in the direction of the applied force. This crack growth demonstrates the effectiveness of the specimen in simulating fatigue conditions commonly found in structural engineering applications.

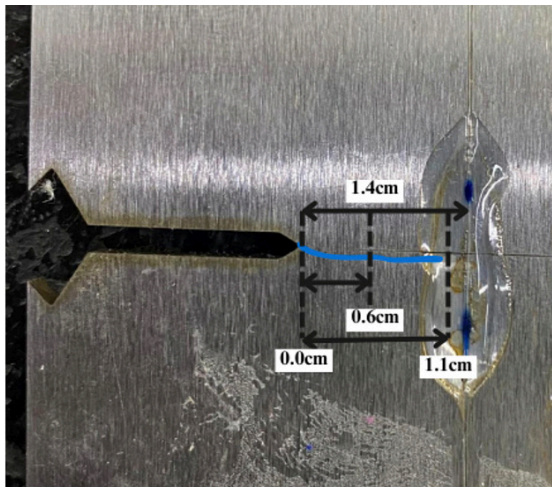


FIGURE 8. Crack formation on the mild steel specimen during the fatigue test

The Bragg wavelength, λ_B can be expressed as follows:

$$\lambda_B = \frac{2\eta_0\Lambda_0}{\kappa} \quad (1)$$

Where Λ_0 is the grating period, κ is the grating order and η_0 is the initial refractive index before being subjected to strain. Expression of Bragg wavelength in terms of the grating refractive index, η_{eff} can be formulated as follows:

$$\lambda_B = 2\eta_{eff}\Lambda_0 \quad (2)$$

The Bragg wavelength shifts are temperature and strain sensitive which can be denoted as

$$\frac{\Delta\lambda}{\lambda_B} = (\hat{a} + \xi)\Delta T + (1 - p_e)\epsilon \quad (3)$$

Where $\Delta\lambda$ is the change in the wavelength, $\hat{a}$ is the thermal expansion, ξ is the thermos-optic coefficient, ΔT is the change in temperature, p_e is the effective photoelastic constant of the fibre, and ϵ is the strain induced (Shuhaimi et al. 2023)



FIGURE 9. Strain test results for determining the sensitivity of the FBG sensor

The slope observed in Figure 9 indicates the sensitivity value of the FBG sensor, which was found to be $0.8333 \text{ pm}/\mu\epsilon$, with an R^2 -value of 1. Based on this R^2 -value, it can be concluded that the sensitivity obtained from the calibration test falls within a different parameter compared to the ideal FBG sensitivity of $1.2 \text{ pm}/\mu\epsilon$ as stated by (Balarabe et al. 2018).

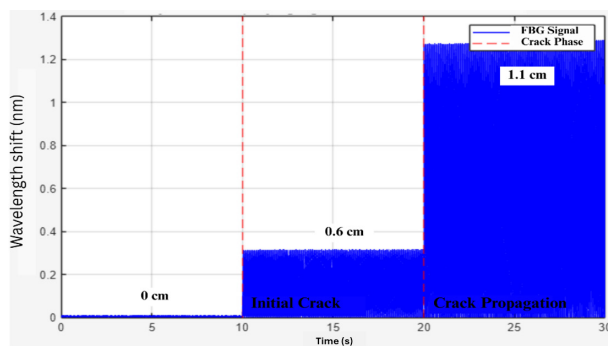


FIGURE 10. Graph of shifted wavelength versus time for each crack phase

Figure 10 illustrates in Phase I, the specimen remained intact without crack formation, and the FBG sensor recorded only minor wavelength shifts of approximately $0.002\text{--}0.008 \text{ nm}$. These values indicate uniform elastic strain under cyclic loading, with the material still exhibiting a linear elastic response. No stress concentration or microstructural disturbance was detected, confirming that the strain measured was homogeneous. This stage is crucial as it establishes the baseline for comparison in subsequent phases. (Lee and Hong, 2020) reported that in defect-free structures, FBG sensors produce stable reflection spectra with minimal noise or significant variation. Accordingly, the results demonstrate that the system maintained mechanical integrity, validating the reliability of FBG sensors for early-stage structural health monitoring.

During early crack initiation, the wavelength shift increased noticeably to approximately 0.4 nm , indicating strain concentration caused by microcracks forming near the notch. The signal began to deviate from the initial baseline, marking the onset of non-uniform strain distribution. The FBG sensor's high sensitivity allowed early detection of these changes, which are often not visible through conventional methods such as strain gauges or visual inspection. This stage reflects the transition from uniform elasticity to early microstructural damage. Furthermore, since FBG sensors are highly sensitive to longitudinal strain, even minor variations in the stress configuration result in detectable spectral shifts with high resolution. From the perspective of fatigue engineering, this stage represents the phase of micro-accumulated damage, where the material has not yet failed but has

already exhibited signs of losing uniform elasticity. Detecting this condition at an early stage is crucial, as it enables the implementation of predictive maintenance strategies before the damage progresses to a critical level.

In the final stage, representing crack propagation, the wavelength shift exceeded 1.2 nm with sharp, unstable fluctuations. This behaviour was attributed to rapid stress redistribution as the crack advanced under cyclic loading. The FBG signal captured the alternating opening and closing of the crack tip during each load cycle, producing a complex waveform. This dynamic response highlights the sensor's ability to detect non-uniform strain fields and track progressive damage in real time that providing critical insights into structural failure mechanisms.

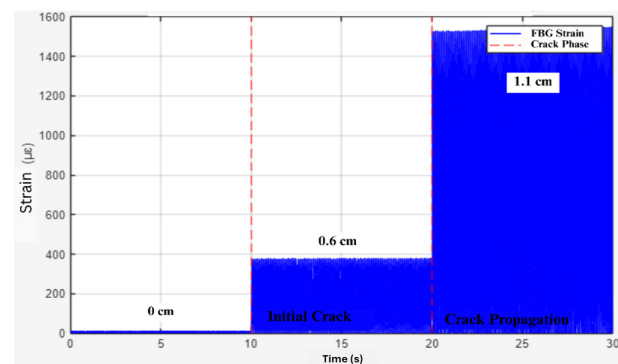


FIGURE 11. Graph of strain versus time for each crack phase for FBG

Moreover, in Figure 11, the strain–time response recorded by the FBG sensor demonstrated high stability in the early stage (Phase I), with strain values remaining between $2\text{--}10 \mu\epsilon$, indicating a fully elastic state with no structural disturbance. This stable baseline is essential for detecting any deviation due to crack initiation or propagation. As reported by (Mieloszyk, 2021), the performance of FBG sensors in crack-free structures offers a highly stable reference, which is crucial for assessing the sensor's sensitivity to microstructural changes.

In Phase II, corresponding to early crack formation, moderate strain fluctuations ($0\text{--}400 \mu\epsilon$) emerged, reflecting the onset of fatigue-induced stress redistribution. According to (Huang & Cardenas 2020) microcracks may begin forming near stress concentration zones during this phase, especially around notches or surface irregularities. The high sensitivity of the FBG sensor enables it to detect such early-stage strain changes more clearly than conventional sensors. Moreover, the stability of the cyclic frequency demonstrates that the data acquisition system effectively captured strain in real time, corroborating the findings of (Sahota et al. 2020), who highlighted the effectiveness of FBG sensors in structural metal fatigue monitoring applications.

During Phase III, strain amplitude increased sharply up to $1600\ \mu\epsilon$, signifying active crack propagation into critical regions. The strain concentration near the notch led to stronger reflection signals from the FBG sensor, attributed to changes in the refractive index within the Bragg grating region (Zhang et al. 2019). The consistent and amplified waveform highlights the FBG sensor's ability to capture real-time structural damage with high resolution and reliability, making it effective for early crack detection and progressive failure monitoring. This observation is in agreement with the findings of (Vinnarasi and Sundaravadivelu 2017), who demonstrated that real-time monitoring systems, such as FBG sensors, exhibit a high level of capability in detecting active cracks with superior accuracy and sensitivity.

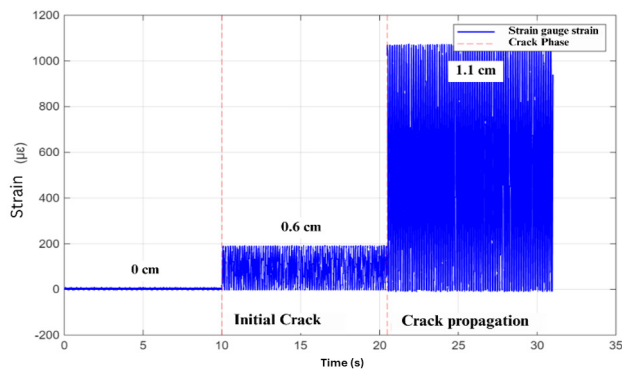


FIGURE 12. Graph of strain versus time for each crack phase for strain gauge

This study evaluates the capability of strain gauges in monitoring crack development during fatigue testing of mild steel specimens. The strain–time graph indicates that during the initial phase (0–10 seconds), the recorded strain values remain close to zero and stable, signifying that the material is in the elastic region with no microstructural damage (as shown in Figure 12). Minor negative readings observed during this phase are likely due to systemic factors such as electrical noise fluctuations affecting the gauge.

As crack initiation begins, a moderate increase in strain values, around $200\ \mu\epsilon$, is detected despite the crack not yet reaching the gauge area. This suggests that the strain gauge can detect early changes in the stress field surrounding the crack zone. A significant rise in strain, exceeding $1000\ \mu\epsilon$, is observed in the later phase (20–30 seconds), corresponding to crack propagation through the gauge area. This behaviour reflects stress concentration and a transition in material response from elastic to elastic–plastic deformation. Furthermore, the variations in strain readings may be attributed to the phenomenon of crack opening and closing under repeated loading and unloading. This behaviour has also been discussed by (Banno et al.

2022), who explained that each phase of the loading cycle can induce temporary crack openings, thereby influencing the response observed on the gauge surface.

During the 10–20 s phase, the FBG sensor recorded strains of up to approximately $400\ \mu\epsilon$, whereas the strain gauge measured around $200\ \mu\epsilon$, indicating the higher sensitivity of the FBG sensor. Strain gauges are capable of detecting relative strain variations as cracks propagate, however their sensitivity at the early stage of damage is limited, providing significant readings only after the failure has progressed. This suggests that although strain gauges perform effectively in recording strain changes, they are less efficient for the early detection of micro-cracks compared to sensors such as FBG, which can identify minor wavelength shifts induced by micro-strain. Therefore, strain gauges are more suitable for applications involving macroscopic damage monitoring, particularly for confirming the progression of structural failure, but are less ideal for early detection scenarios that require high sensitivity.

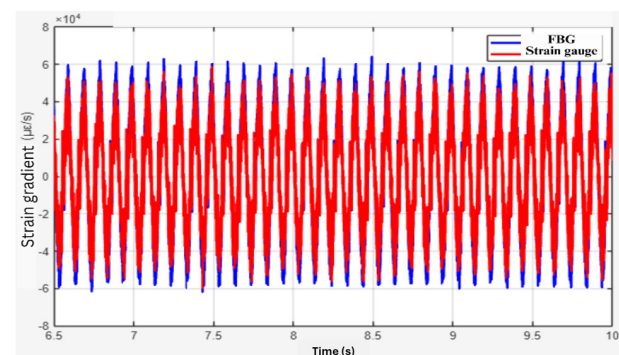


FIGURE 13. Graph of strain gradient versus time for both sensors

Based on the graph observation in Figure 13, both Fiber Bragg Grating (FBG) sensors and strain gauges exhibited comparable signal trends, with fluctuations that reflect their response to applied loading, particularly during the critical phase of crack development. The general waveform pattern recorded by both sensors was similar, indicating their capability to track strain variation in real time. However, a notable distinction lies in the gradient values, where FBG sensors consistently produced higher readings than strain gauges. This suggests that FBG sensors possess a greater sensitivity to micro-strain variations, an observation supported by (Kinet et al. 2014), who emphasized the advantages of FBG in large-scale structural monitoring and aerospace applications that demand high precision and responsiveness to dynamic loading.

The enhanced performance of FBG sensors can be attributed to their fundamental operating principle. When subjected to mechanical loading, the spacing of the grating

within the optical fiber changes, resulting in a measurable Bragg wavelength shift. This optical mechanism allows for precise strain detection, aided further by the sensor's immunity to electromagnetic interference and reduced susceptibility to temperature fluctuations. Additionally, their small size and flexible configuration enable installation in hard-to-access or structurally critical regions without altering the mechanical integrity of the specimen. These attributes collectively provide FBG with superior stability, accuracy, and versatility in structural health monitoring.

Strain gauges, by comparison, remain highly effective in smaller-scale applications. As highlighted by (Brownjohn et al. 2004), they can deliver accurate strain measurements in laboratory-based testing or applications that do not require a wide detection range. Nonetheless, strain gauges are more limited in detecting early-stage micro-cracks, as their sensitivity tends to increase only when failure becomes more advanced. They are also more susceptible to noise disturbances, which explains the occasional appearance of random negative readings in the dataset.

In conclusion, while both FBG sensors and strain gauges effectively captured strain variations, FBG demonstrated a higher sensitivity and stronger capability in monitoring strain during crack propagation. The comparative analysis indicates that FBG sensors are better suited for advanced structural health monitoring where early crack detection is critical, whereas strain gauges are more appropriate for conventional macroscopic strain measurements in controlled environments.

CONCLUSION

This study investigated the crack behaviour of mild steel using two different sensing technologies which are Fibre Bragg Grating (FBG) and conventional strain gauges. Both sensors were evaluated based on their sensitivity, accuracy, and responsiveness during fatigue testing. The results showed that FBG sensors demonstrated higher sensitivity, particularly during the early stages of crack initiation, where conventional strain gauges were less responsive. As the crack propagated, both sensors exhibited similar trends, however the FBG maintained a more stable and clearer signal due to its optical sensing capability and resistance to electromagnetic interference.

Furthermore, the FBG sensor was effective in capturing small strain variations and dynamic structural changes, making it suitable for real-time and high-resolution structural health monitoring. Conventional strain gauges remain reliable within certain strain limits and controlled conditions. The findings of this study support the potential use of FBG technology for early crack detection and continuous monitoring in structural integrity applications.

To enhance the application of FBG sensors in structural integrity assessments, several directions for future research are recommended. These include examining a broader range of materials such as aluminium, composite materials and polymers to compare the adaptability and performance of FBG sensors across different engineering applications. Additionally, investigating the effects of varying fatigue load frequencies and amplitudes could offer deeper insight into how loading parameter influence crack propagation and sensor responsiveness. The integration of Internet of Things (IoT) technology with FBG systems is also highly recommended, enabling wireless real-time monitoring, automated data transmission, and early warning detection. Such advancement could significantly improve the efficiency, safety and reliability of modern structural health monitoring systems.

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DECLARATION OF COMPETING INTEREST

None.

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