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Delamination Detection in Composites Using Acoustic Signal from Fiber Bragg Grating Sensor: A Comprehensive Review

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ABSTRACT

Delamination is an important failure mode of composite materials and can cause structural failure without visible signs. Early and reliable detection is crucial, especially in safety related sectors such as aerospace, automotive or wind energy. Fiber Bragg grating (FBG) sensors have gained widespread popularity for structural health monitoring (SHM), thanks to their high sensitivity, immunity to electromagnetic interference, compactness, and multiplexing ability. This paper reviews the use of FBG sensors for acoustic signal-based delamination detection. The paper categorizes sensor configurations (embedded, surface mounted, hybrid), methods for obtaining signals estimation and extracting features. Time Frequency analysis techniques, including Short Time Fourier Transform (STFT), wavelet transforms, and Fast Fourier Transfer (FFT) are discussed together with machine learning and deep leaning techniques such as support vector machines (SVM), Convolutional Neural Networks (CNNs), long short-term memory models. Their performance of detecting and categorizing delamination events is indeed critically scrutinized. Hybrid systems between FBG and acoustic emission (AE) or piezoelectric sensors are described as a result of their improved detectability. Recent advancements are also discussed including nano enhanced coatings that aid in increasing sensor sensitivity and environmental hardiness. Environmental effects, signal loss and sensor location problems and cost of the system are considered. The review wraps up with discussion on the significant limitations that need to be addressed and suggestions for future directions, such as adaptive signal processing, integration of AI and field ready interrogation units. The extensive evaluation presented here establishes the ground for further development of FBG based SHM methods into real time delamination inspection tools for composite structures.

Keywords: Delamination detection; composite materials; Fiber Bragg Grating (FBG); acoustic signal; structural health monitoring (SHM)

INTRODUCTION

Composites such as carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP) are used extensively in aerospace, automotive industry and renewable energy due to the high strength to weight ratio along with corrosion resistance properties (Mahmood 2023). Nevertheless, these layered materials are also prone to delamination which involves the failure of neighboring plies under impact, fatigue and interlaminar stresses (de Castro Saiki & Gomes, 2024). The damage generated is commonly internally initiated, and visually hard to find that may induce structural collapse (Haddad et al. 2024). Undiscovered delamination is the cause of catastrophic failures in such critical systems as aircraft and turbines, presenting a grave threat to human lives and financial losses (Katsaprakakis et al. 2021).

Traditional nondestructive testing (NDT) methods such as ultrasonic testing, X-ray radiography, and thermography have long been used for delamination detection (Kumpati et al. 2021). These techniques, however, in general can be offline, time consuming and are not effective for internal flaws which are subsurface of complex structures (Mukherjee 2023). Their incompatibility with an online and real time monitoring makes them barely applicable to dynamic environments such as rotating turbine (Kaewniam et al. 2022). This development has given rise to the use of Structural Health Monitoring (SHM) techniques especially Fiber Bragg Grating (FBG), which offers high sensitivity, multiplexing and perfect integration with composite materials (Ahmada et al. 2025; Omenogor & Adeniran 2024).

FBG sensors, which detect strain and temperature via wavelength shifts, are immune to EMI and corrosion and support dense sensor networks (Hegde et al. 2022; Raghuwanshi et al. 2023). They can detect early stage delamination via acoustic signals and, when paired with time frequency and machine learning techniques, enhance damage characterization (Mardanshahi et al. 2025).

Acoustic frequency is an important factor in the detection of delamination because different failure modes in composites produce distinct spectral signatures. Transient AE waves are generated by growth of the interlaminar cracks during delamination with dominant frequencies from several tens to several hundred kilohertz in most cases (Ibrahim et al. 2025). Especially, three typical frequency bands are usually recognized: 60–150 kHz for matrix cracking, 200–300 kHz for interlaminar crack extension or fiber-matrix debonding and 400–500 kHz for fiber breakage. (Samborski et al. 2024). When AE waves impinge on an FBG sensor, they induce local dynamic strain that modulates both the grating period and the effective refractive index. This produces a time-varying shift in the Bragg wavelength. The ability to detect delamination-related acoustic activity is governed primarily by the interrogation system's bandwidth and demodulation rate. Unlike conventional FBG interrogators, which typically optimized for quasi-static or low-frequency strain, the delamination detection requires capturing high-frequency dynamic components, which can extend into the hundreds of kilohertz and beyond, depending on the AE content and structure. As the result, the system can only detect and track Bragg wavelength changes if their frequencies fall within the system bandwidth (Goossens et al. 2020; Smailov et al. 2024).

The acoustic frequency response is primarily determined by the inscription method and index modulation (da Silva & Webb, 2023). Type I FBG written in UV were shown to have a linear strain transfer function and low response loss, which makes them suitable for acoustic sensing. In contrast, Type II FBG inscribed by femtosecond laser have higher thermal and mechanical stability but may suffer from lower sensitivity arising from the formation of localized damage with index change (Zhang et al. 2022). Such short gauge length and π phase shifted FBG can be used to increase high frequency detection by improving the spatial resolution and bandwidth of a measurement. As such, grating design and fabrication are still important factors in controlling sensor sensitivity to the delamination induced frequencies (Wang et al. 2025).

There are still challenges to overcome such as temperature cross sensitivity, signal loss and standardized interpretation which would need to be further validated in real world scenarios (Soman et al. 2021).

The objective of this review is to fill the gap between theory and practice and provide an intensive review of FBG based acoustic signal analysis for delamination detection. Key objectives include:

1. Mechanistic insights: on how the acoustic signal features change due to the delamination in the composites.
2. Novelty: The contributions of the set-up configuration of the FBG sensor, acquisition of the acoustic signal and signal processing (the wavelet analysis and the deep learning).
3. Test Campaign: Performance benchmark of FBG systems vs classical NDT inspection sensitivity, resolution, scalability, and operational interoperability.
4. Industry Relevance: demonstrating analogies to real industrial practices in the aerospace, wind energy and automotive industrial domain to highlight short term viability and potentials for adoption.
5. Future Directions: Suggesting ways to overcome the existing technical boundaries (e.g., AI based signal recognition, multisensory Fusion, IoT based SHM infrastructure).

Based on more than 10 years of interdisciplinary research, this review not only summarizes the development of technologies, but also highlights important research directions for future studies. This paper highlights the innovation in using FBG based acoustic signal systems to enable predictive maintenance, lower lifecycle costs, and increase the overall safety and reliability of composite structures. In the context of ongoing challenges to monitor structures in real time and integrate structural data digitally, the findings provided should help move the needle in favor of structural monitoring solutions that are truly intelligent.

COMPOSITE MATERIALS AND DELAMINATION

COMPOSITE MATERIAL FUNDAMENTALS

Composite materials are products of at least two constituent materials with disposed physical or chemical properties, and the characteristics of the composite material reach advanced performance, which is impossible for a single constituent material (Bhong et al. 2023). Fibre reinforced polymers (FRPs), such as carbon fibre reinforced polymers (CFRPs) and glass fibre reinforced polymers (GFRPs), have been used in industrial applications owing to their outstanding strength to weight ratio, corrosion resistance, and fatigue properties. They are mainly composed of fibres exhibiting high strength (such as carbon, glass, or aramid) encased in a polymer matrix (such as epoxy or polyester) (Rajak et al. 2021). The layering architecture of composites, the so called manufacturing process (e.g. autoclave curing, resin transfer molding, or filament winding), can offer customized mechanical performances to suit the required load bearing applications (Phiri et al. 2024). However, this anisotropic behavior may also create high sensitivities, particularly at ply level interlaminar interfaces, where stress concentration can cause damage (Ogunleye et al. 2024).

DELAMINATION MECHANISMS

Delamination, defined as the splitting of neighboring composite layers, is one of the most important failure modes in laminated composites (Deng et al. 2023). Interlaminar stresses developed due to several reasons are responsible for it (de Castro Saiki & Gomes 2024; Deng et al. 2023). Low velocity tool drop or bird strike impact loadings create local stress points which drive the initiation of mid plane delamination in metal matrix composite, MMCs (de Souza 2022). Furthermore, cyclic loading from repeated mechanical or thermal loading slowly reduces the strength of the interface and results in fatigue delamination (Malekinejad et al. 2023). Therefore, manufacturing imperfections such as voids, resin rich sections, or under curing can induce local intrinsic defects which alter the strength and performance of composites (Talreja 2024). Moreover, environmental effects such as moisture, thermal cycling, and chemical attack may intensify interface debonding, leading to a fast delaminating process (de Castro Saiki & Gomes 2024; Tian et al. 2024).

Delamination is usually initiated as micro cracks at the matrix/fiber interface and continues under sustained loading until the micro cracks propagate and begin to grow coalesced macro cracks (Behvar et al. 2024; Farahmand, 2025; Yan et al. 2024). The propagation of this damage is typically classified into three fracture modes using fracture mechanics (Wang et al. 2021). Mode I (opening mode) is generated by tensile stresses that develop normal to the crack plane, resulting in the separation between layers. Meanwhile, Mode II (sliding mode), is initiated when the in-plane shear stresses cause two neighboring layers to slide with respect to each other. Lastly, Mode III or tearing mode, is an interfacial mode that involves out of plane shear stresses resulting in the twisting or tearing along the interface (J. Chen et al. 2024; Jin et al. 2022; Jin et al. 2023). The various types of delamination are illustrated in figure 1. A clear understanding of such failure modes is necessary when developing more damage tolerant composite structures and increasing their resistance against delamination.

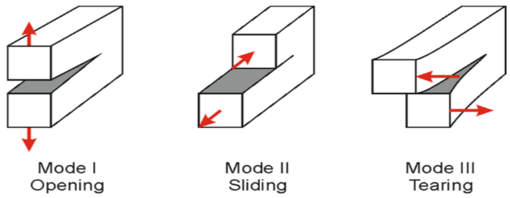

FIGURE 1. Different mode of delamination (a) Mode I Opening (b) Mode II Sliding (c) Mode III Tearing

IMPACT ON STRUCTURAL PERFORMANCE

Delamination severely compromises the structural integrity of composite materials by weakening their mechanical properties and increasing susceptibility to failure (Huang & Bobyr 2023). This contributes to breakage and loss of load carrying capacity (de Castro Saiki & Gomes, 2024). Such a redistribution of effective stress creates localized weak regions, making the structure more prone to failure under operational loads. Moreover, delamination particularly within compressively loaded sub-laminate layers, can trigger sub-laminate buckling, which accelerates structural degradation and may ultimately lead to collapse (Zou et al. 2023). On the one hand, regions where delamination occurs are stress concentrators, where crack tips amplify local stresses and initiate secondary damage modes, such as fiber breakage and additional matrix cracking (de Castro Saiki & Gomes 2024; Huang & Bobyr 2023; Mohammadi et al. 2024). As a result, delamination not only initiates failure but also worsens the overall degradation of composite structures, making early detection and mitigation essential for ensuring long term reliability and safety (Hassani et al. 2021).

As an example for aerospace applications, bond line delamination in wing skins or fuselage panels may reduce their fatigue life by up to 60% threatening mid-flight catastrophic failures (Pollock et al. 2021; Russo et al. 2023). Similarly, wind turbine blades with undetected delamination may fracture under operational loads, leading to costly repairs and downtime (Kong et al. 2023). The hidden nature of delamination often subsurface and invisible to visual inspection underscores the need for advanced detection methods.

TRADITIONAL DETECTION CHALLENGES

Traditional NDT techniques may be inefficient and unreliable for complex composites (Gupta et al. 2022). Ultrasonic inspection is effective for sub-surface defects, but can be difficult to implement for deeply buried structures and complex geometries that require a coupling gel and may be hard to interpret by lay people (Ensminger & Bond 2024; Yang et al. 2023). X-ray radiography has poor contrast for polymer composites, is hazardous due to radiation, and does not detect planar defects when parallel with the beam (Chen et al. 2022). The shallow depth sensitivity of thermography, as well as low delamination resolution and its vulnerability to environmental thermal noise limit the use of this technique (Riaz et al. 2023). Finally, tap testing is a subjective process requiring substantial time and is not practical for mass or automatic inspection (Chen et al. 2022; Han et al. 2024; Nasimi et al. 2021). Therefore, the need for Fiber Bragg Grating (FBG) sensing is consequently increasing, offering high accuracy, real-time and flexible monitoring in complex structures (Theodosiou, 2024). Table 1 show the summarize comparison of conventional NDT with FBG based sensing for delamination detection.

These techniques are limited because they are typically performed offline and after damage has occurred, providing no early warning during in-service operation. Moreover, they often lack the sensitivity required to detect early-stage delamination (often < 1 mm) and are not readily integrated into structural health monitoring (SHM) systems for real-time inspection (Hassani & Dackermann 2023).

The shortcomings associated with current nondestructive testing (NDT) methods have driven the incorporation of embedded sensor technology such as FBG systems that can perform in situ monitoring for delamination in real time (Hassani & Dackermann, 2023; Theodosiou, 2024). In contrast to traditional procedures, FBG sensors can record high frequency acoustic signatures related with the initial stage of delamination phenomena, i.e., interlaminar stress waves and microstructural damages. This could provide early damage notifications and structural diagnosis under actual utilization (Ibrahim et al. 2025; Mieloszyk 2021). The subsequent sections explore how acoustic signal analysis based on FBG technique is developed to tackle these problems, by means of the improvement of sensitivity, signal processing integration and system scalability between laboratory research and industry.

TABLE 1. Comparison of conventional NDT with FBG based sensing for delamination detection

Criteria	Ultrasonic Testing	X-ray Radiography	Thermography	Tap Testing	FBG Based Sensing
Detection Type	Subsurface	Subsurface	Surface/ subsurface (limited)	Surface (local response)	Subsurface + Incipient delamination
Sensitivity to Small Defects	Moderate (≥ few mm)	Low (poor contrast in polymers)	Low (surface focused)	Low (subjective)	High (detects <1 mm delamination via Acoustics signal)
Effectiveness on Complex Geometry	Limited	Limited	Limited	Moderate	High (fiber integration into any shape)
Real Time Monitoring	No	No	No	No	Yes
Integration into SHM Systems	Difficult	Not possible	Not practical	Not possible	Yes (full integration)
Environmental Interference	Low	Radiation hazards	High (thermal noise)	Moderate	Very Low (immune to EMI and thermal noise)
Operator Dependence	High (requires expertise)	Moderate	Moderate	High (subjective assessment)	Low (automated data interpretation)
Practicality for Large Structures	Moderate (manual scanning required)	Low (logistical constraints, radiation safety)	Low (affected by environment)	Low (labor intensive)	High (continuous embedded monitoring)
Early Damage Detection Capability	Low	Low	Low	Very Low	High (detects acoustic signal at initiation stage)

Source: (Caliskan et al. 2022; C. Chen et al. 2024; Gu et al. 2020; Hellier, 2003; Matveenko et al. 2021)

FUNDAMENTALS OF FIBER BRAGG GRATING (FBG) SENSORS

WORKING PRINCIPLE

The working principle of a FBG sensor relies on detecting changes in the physical environment such as stress, strain, and temperature which alter the grating period or the refractive index of the fiber core (Theodosiou 2024). These changes causes a corresponding shift of the Bragg grating central wavelength (Shojaei Khatouni et al. 2024). By developing a mathematical model of cervical strain and stress that relates the measured parameters to the Bragg (central) wavelength shift, changes in stress or strain can be determined accurately (Sahota et al. 2024).

When a broadband ASE is coupled to the FBG, as illustrated by Figure 2, an equivalent portion of the light is reflected at the Bragg wavelength because of the periodic change in the refractive index, leaving the rest of the light to be transmitted down the fibre (Song et al. 2025; Vaddadi et al. 2022). This filter mechanism makes it possible to use the FBG as wavelength selective reflector (Theodosiou 2024). Based on the fiber coupled mode theory, the reflection wavelength of the Bragg grating can be expressed as equation (1):

$$\lambda_B = n_{eff}\Lambda \qquad (1)$$

where λ_B is Bragg wavelength, n_{eff} is refractive index and Λ is Bragg period.

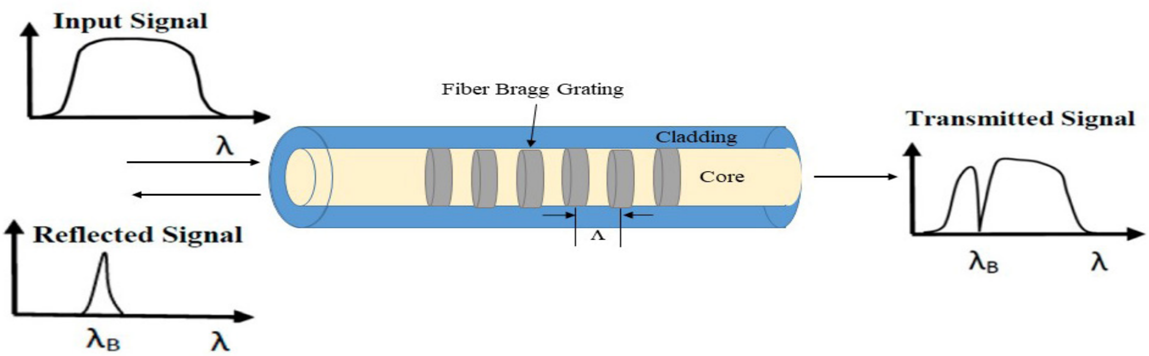

FIGURE 2. Working principle of FBG

The wavelength-shift scale in Figure 2 has been intentionally magnified to clearly illustrate the qualitative relationship between applied strain and the Bragg wavelength variation. In practical applications, the absolute wavelength shift is typically on the order of picometers. Finally, the optical fiber shown is a schematic representation; in practice, FBG sensors are generally inscribed in single-mode fibers to ensure stable Bragg reflection and accurate wavelength interrogation.

The Bragg center wavelength is mainly affected by temperature and strain (Tan et al. 2021). This relationship can be mathematically expressed by the following equation (2):

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon + (\alpha + \xi)\Delta T \qquad (2)$$

where $\Delta\lambda_B$ represents the Bragg wavelength shift, P_e is the photo elastic coefficient of the fiber core material, ε denotes the longitudinal strain, α is the thermal expansion coefficient of the optical fiber, ξ is the thermo optic coefficient, and ΔT is the temperature variation (Musa et al. 2023; Suhaimia et al. 2024).

If the experiment is conducted under constant temperature conditions, equation (2) can be simplified as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon \qquad (3)$$

It can be seen that the Bragg wavelength shift is linear with strain without considering the effect of temperature.

ADVANTAGES OVER CONVENTIONAL SENSORS

DURABILITY

While silica fibers are inherently brittle, FBG sensors exhibit superior durability in harsh environments compared to piezoelectric and resistive sensors. This durability is attributed to the high chemical inertness of silica and the application of specialized polymer or metallic coatings (e.g., polyimide or acrylate), which protect the fiber from mechanical abrasion and environmental degradation. Unlike electrical sensors, FBG are immune to electromagnetic interference (EMI) and signal drift caused by insulation breakdown at high temperatures (Yassin et al. 2024). In case of coating and embedding into composite laminates, effective strain sharing leads to the reduction in localized stress and fiber failure (Gabardi et al. 2023). Moreover, FBG operate very well above 300°C and type II FBG extends this operation range in order to eliminate the overheating, signal drift and insulation failures that constrain electric sensors under high temperature (Walker et al. 2025).

SCALABILITY

As analogue devices, FBG are broadband and can be multiplexed in wavelength (WDM) or time domain (TDM) (Yuan et al. 2024). These approaches can be used to read out multiple gratings on a single fiber with a common light source (Theodosiou, 2024). The wavelength shifts produced are read out as digital counts by optical interrogators, which allows for extensive sensor networks. The ability of multiplexing will greatly reduce cabling complexity and weight of system compared to the electronic sensors, and therefore FBG based monitoring systems are very suited for large scale composite structures such as wind turbine blades, aircraft wings, civil infrastructures (Gui et al. 2023).

INTEGRATION WITH IOT SYSTEMS

FBG sensors can be readily integrated with contemporary IoT systems to enable real-time, remote structural health monitoring (SHM). Their optical signals can be transmitted over long distances with low loss, then converted into digital data by interrogators and streamed directly to cloud-based platforms for analysis. This allows the possibility for predictive maintenance by applying machine learning algorithms that recognize initial stages of delamination in composites (Kinet et al. 2014). For example, smart city infrastructure such as FBG networks in composite buildings or bridges supply strain and temperature readings to warn engineers of forthcoming failures. Classical sensors, working with analog signals, typically demand signal conditioning and are not compatible with wireless IoT protocols (Kok et al. 2024). The digital native design of FBG sensors lends itself to scalable, automated SHM solutions conducive to the trend in Industry 4.0 toward networked, data informed decision making.

PRINCIPLE OF ACOUSTIC SIGNAL DETECTION USING FBG SENSOR

Figure 3 illustrates the signal transduction pathway, from delamination-induced AE to optical wavelength modulation and, ultimately, to digital signals, at a conceptual level rather than as a detailed system architecture.

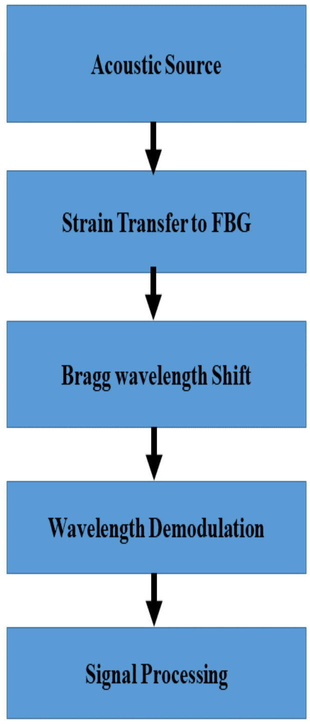

FIGURE 3. Acoustic signal detection workflow

INTERACTION OF ACOUSTIC WAVES WITH THE FBG

The basic principle of acoustic wave detection with FBG sensors is the effective transference of mechanical vibrations from the external material to the optical fiber. The acoustic wave passing through the material generates local pressure perturbations and mechanical deformation as a result of impulsion, fatigue or structural stress in the material (Yassin et al. 2024). If an FBG sensor is directly bonded or embedded in the structure, the acoustic vibrations mechanically couple to the fibre. The acoustic energy causes a time scheduled micro strains along the fibre, which continuously stretches and compresses the grating region in one phase with the wavefront. This mechanical coupling is essential for the FBG to act as a transducer for the acoustic vibration through conversion into Bragg wavelength shifts, which are monitored by optical interrogators (Alias et al. 2024).

STRAIN TRANSFER EFFICIENCY

High-sensitivity acoustic sensing with FBG sensors is based on strain transfer from the host matrix to the fibre core, which translates into measurable variations of optical wavelengths due to mechanical oscillations (Hu et al. 2024). The coupling efficiency is determined by bond stiffness, bond quality, sensor package and acoustic impedance between the structure and fiber (Floris et al. 2021).

Loose coupling caused by compliant adhesives, air gaps, or mismatched material properties, can attenuate and distort strain waves as they propagate to the FBG, thereby degrading signal quality. This problem is more pronounced at the higher frequencies, because even small signal losses cause large frequency and amplitude errors (Bado & Casas, 2021). A weak mechanical interface can lead to fiber stress localization and poor harmonic response, constraining the broadband dynamic strain transfer. Therefore, the optimal strain transfer efficiency is crucial in achieving high resolution, sensitivity and reliability of FBG based AUMS for aerospace, automotive and offshore applications (Markom et al.).

STRAIN INDUCED CHANGES IN THE FBG

As acoustic waves propagate along the optical fiber, they generate a time-varying (dynamic) strain that periodically stretches and contracts the FBG region. This cyclic deformation modifies the grating period Λ, defined as the spacing between adjacent grating planes. Simultaneously, the strained environment affects the refractive index (n) of the grating via photo elastic effect, a phenomenon where mechanical stress gives rise to alterations in the optical properties of materials. Both responses from mechanics and optics make FBG extremely sensitive to short lived disturbances such as sound waves. (Cusano et al. 2004; Honglin Zhang et al. 2023).

The overall shift in the Bragg wavelength due to dynamic strain is given by equation (3). Under small-strain conditions, the strain wavelength relationship is effectively linear, enabling FBG sensors to capture low amplitude, high frequency vibration responses relevant to acoustic measurements. A strain increment of 1 $\mu\varepsilon$ typically yields a wavelength shift of approximately 1.2pm, providing the sensitivity needed to detect small structural perturbations (Dey et al. 2021).

Although Equations (1)–(3) express the Bragg condition, their function in delamination detection is attributed to time dependent strain perturbations resulting from acoustic waves (Ibrahim et al. 2025). Temperature effects are virtually absent thanks to the short event duration; hence the Bragg wavelength shifts are primarily strain driven. High frequency acoustic waves result in micro second scale strain modulations, which demands high speed interrogation and dynamic effects of strain transfer as well as band width limitations over static strain sensing (Jalil, 2023).

Temperature changes on Bragg wavelength due to thermal expansion and refractive index modification are also studied. But, for acoustic signal detection, short time measurements are driven predominantly by dynamic rather than thermal strain. In order for us to isolate acoustic signals, taking advantages of high frequency filtering or dual FBG setups with temperature compensation is effective (Chen et al. 2023). Such wavelength modulation induced by strain enables FBG sensor to provide real time acoustic monitoring in industrial environment such as aerospace, electric vehicles (EV), and offshore platform with the advantages of high sensitivity, electromagnetic immunity, and structural integration (Jinachandran & Rajan 2021).

DEMODULATION OF THE WAVELENGTH SHIFT

FBG sensors operate on the principle of sensing minute changes in Bragg wavelength due to strain, such as that induced by sound waves. Since these shifts are in the optical, they cannot be understood without the proper demodulation. Demodulation translates the fluctuations in optical wavelength into detectable electrical signals, commonly variations of voltage or intensity, providing a method to measure, display and analyze its response with standard data acquisition. In previous acoustic sensing work, two major demodulation methods have been practiced: interferometric detection and wavelength based detection with the necessary optical systems (Wu et al. 2021).

Optical interrogators serve as the hardware interface that implements these demodulation techniques by tracking Bragg wavelength shifts with high temporal resolution (Dey et al. 2025). Common interrogator designs include wavelength scanning tunable laser systems, edge filter based intensity demodulation, interferometric interrogation methods and spectrometer based detection reported in the literature (Wang et al. 2022). High speed interrogators that usually sample at rates of over 1 MHz are necessary to accurately record short duration, high frequency strain transients for AE monitoring and delamination detection. As a result, the optical interrogator determines directly the sensitivity, bandwidth, and cost of FBG based acoustic sensing systems (Wong et al. 2020).

INTERFEROMETRIC DETECTION

Interferometric detection approaches measure the time varying strain and convert a phase dynamic to intensity changes that is measured by the optical path length difference. In Michelson or Mach–Zehnder, Fabry–Perot interferometer setups light is divided into a reference and sensing arm and one arm produces strain induced phase shifts leading to intensity modulation by interference upon recombination (Zhu et al. 2022). These methods are highly phase sensitive and capable of sensing high frequency acoustic signals in the kHz–MHz range at a resolution of nano strain. Interferometric systems, in contrast, are sensitive to environmental perturbations and need accurate phase control as well as shape of their demodulation signal which makes them less robust for practical application (Ibrahim et al. 2025). Interferometric approaches are hence frequently implemented in the optical interrogation unit of FBG based sensing systems to improve the wavelength resolution without losing the robustness and multiplexing potential of FBG sensors.

WAVELENGTH DEMODULATION

The demodulation of the Bragg wavelength is based on monitoring it directly which has been translated into electrical signals by means of intensity modulation or spectral analysis. One of popular schemes is the edge filter used method where an optical filter linear to wavelength is used and strain induced changing in wavelengths are converted into intensity variation sensed by a photo detector. This method is especially interesting for low to medium frequency signals such as vibrations or impact events (Silveira et al. 2021). Spectral interrogation systems in which the wavelength can be detected using techniques such as tuning laser, arrayed waveguide grating (AWG), or Fabry–Perot filter, are of high spectral resolution but yet require a slow response time. Therefore, these structures are more suitable for stable multi sample and multi point detection (Silveira et al. 2021; Yuan et al. 2021).

Each method has tradeoffs: interferometric devices have high resolution for the highest frequency acoustic events, and wavelength demodulation-based sensors provide a straightforward technique with relatively low cost for long term monitoring. Hybrid systems are emerging as they combine some of these approaches in efforts to optimize speed, sensitivity, and scalability for broad spectrum acoustic monitoring (Y. Li et al. 2021).

SIGNAL PROCESSING AND CORRELATION

The process and analysis of demodulated optical signals is a critical part of the FBG ultrasonic sensing. After the exchange between Bragg wavelength shifts and electronic signals by using interferometric or demodulation technology, the acoustic information will be extracted therein. Sensor data acquisition has to be done in real time, especially for structural health monitoring (SHM) to detect the fault at early stage and it is possible with fast photodetector and high speed DAQ systems (Wu et al. 2021).

Among the most important parameters are frequency and amplitude. The frequency content given by FFT, STFT or Wavelet Transform is able to identify not only resonant modes but also transient phenomena such as delamination or matrix cracking (Silik et al. 2021). Amplitude represents acoustic strain intensity, and it should be calibrated using known strain levels to calculate absolute strain or energy defects (Theodosiou, 2024; Tosi, 2017; Zhou et al. 2024). However, performance may be diminished due to environmental noise, signal drift and interference. Sophisticated techniques such as lock in amplifiers enhance SNR, and digital filters (low pass, band pass, and adaptive) attenuate background noise without distorting relevant acoustic signals (Silik et al. 2021; Yassin et al. 2024).

Combining such instruments provides high resolution acoustic sensing in aerospace, automotive and offshore contexts. When combined with machine learning strategies, predictive maintenance is enabled through automatic fault classification and long term condition monitoring (Nayak et al. 2025).

Even though optical intensity is usually measured by photodetectors, rather than wavelength itself in (distributed) FBG systems, wavelength changes are typically transformed into intensity variations using wavelength selective components like tunable filters, interferometers, or spectrometers. Figure 4 provides a simplified overview of the process, emphasizing the functional signal flow rather than the internal optical conversion mechanisms.

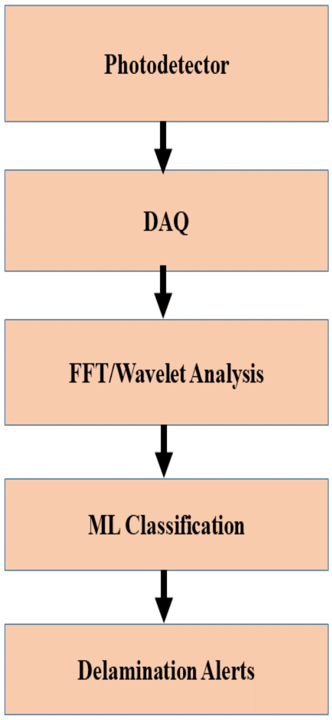

FIGURE 4. Signal processing pipeline

KEY PARAMETERS AFFECTING ACOUSTIC DETECTION

The sensitivity and accuracy of the FBG acoustic detection system are seriously affected by physical and environmental parameters. According to (Yassin et al. 2024) values of these parameters significantly affect the quality of SHM algorithms, especially for the detection and characterization of input-output data..

The FBG length is a basic design parameter which affects spectral response and mechanical resonant frequencies. Short grating lengths (1–10 mm) are optimized for higher frequency short-range signals, as they possess higher intrinsic resonant frequencies and higher strain resolution over a small sensing area (Shekar et al. 2021). This property makes them suitable for analyzing ultrasonic signals (typically 60 kHz to 500 kHz) corresponding to delamination initiation. In contrast, long gratings provide broader reflectivity spectra, but they can function as low-pass filters for the reflected spectral data and introduce interference noise (Soman et al. 2024; Willberry et al. 2020).

Acoustic coupling efficiency further governs how elastic wave energy transfers from the host structure to the fiber core. Successful detection relies on high-quality bonding at the fiber-adhesive interface; poor contact attenuates strain waves and degrades signal quality, particularly at higher frequencies (Kim et al. 2021; Wang & Dai, 2019). These waves are detected by the FBG with axial strain (and thus change in grating period) as well as transverse strain-mediated refractive index alteration through the photo elastic effect. The peak sensitivity is obtained when FBG is parallel to the major strain direction from the acoustic source. (Willberry et al. 2020).

Temperature compensation is ultimately relied on for all the FBG sensor systems, particularly when temperature changes as in the case where there are variations in environmental temperature. Since Bragg wavelength is sensitive to both temperature and strain, temperature induced shifts may overlap or mimic the acoustic signals, resulting in incorrect conclusions (Kashyap, 2009). One common remedy to this issue is using dual FBG configurations in which one sensor head relies on both temperature and strain as cross sensitivity factors, and the second (stain isolated) reference FBG can be used for temperature only sensing application. The difference between the two signals provides a true strain effect. Or, advanced signal processing methods and machine learning techniques could be utilized to separate the temperature effect and strain effect online, further improving reliability of acoustic signal detection (Gupta et al. 2024; Zhang et al. 2019).

These parameters grating length, acoustic coupling and temperature control must be optimally balanced during the design and implementation of FBG based acoustic systems (Yassin et al. 2024). Such devices, once tuned, allow high resolution monitoring of dynamic structural activity and thus pave the way to the exploitation of FBG as effective acoustic monitors for applications that range from automotive industry up to aeronautics with the naval and civil engineering sectors in between. (Theodosiou, 2024).

WHY FBG EXCEL IN ACOUSTIC SENSING

FBG sensors have a very competitive edge over traditional acoustic sensors due to its high strain sensitivity, immune to EMI, multiple sensing and embeddable in the composite structures. In contrast with piezoelectric sensors, FBG allow to distribute the sensing along a single fiber with subsequent ease of the cabling for delamination localization without compromise on long term reliability in a harsh environment requirement (Alhussein et al. 2025).

One of their main characteristics is their high sensitivity to small strain changes, which can be as low as nano strain (~1 $n\varepsilon/\sqrt{Hz}$) (Yassin et al. 2024). This capability is important to record weak acoustic vibrations in the early stage of delamination, micro cracking or pressure vessel leaks, where low-amplitude high-frequency signals (~kHz) are considered as the primary signs of initiation failure (Rito et al. 2021; Hanqi Zhang et al. 2023). Additionally, the optical operation gives immunity to EMI otherwise often encountered by resistive or piezoelectric sensors in electrically noisy environments (Zhou et al. 2025).

Moreover, FBG sensors can support a wide detection bandwidth, ranging from low-frequency structural vibrations to high-frequency damage-related signatures. As noted in the Introduction, three representative AE frequency bands are often reported for composite materials: 60–150 kHz, 200–300 kHz, and 400–500 kHz. These bands are commonly associated with matrix cracking; interlaminar crack propagation or fibre–matrix debonding; and fibre breakage or pull-out, respectively (Willberry, 2022). This enables the surveillance of various dynamic events such as impacts, fatigue and elastic waves induced by interlaminar damage (Samborski & Korzec, 2023).

Another advantage is the `multiplexing' feature which applies to the concept of FBG technology. With the aid of WDM and TDM, tens of FBG can be inscribed into one optical fiber, each with a unique Bragg wavelength (Hou et al. 2025). This allows distributed acoustic sensing (DAS) to be performed over large structures with lightweight, low cabling profile (C. Li et al. 2021). Multiplexing of a large number of FBG into one system also enables the simultaneous monitoring of different physical quantities (e.g., 3D strain, temperature and pressure), enhancing the applicability of the system (Wright et al. 2019).

These combined attributes of high sensitivity, broad bandwidth, and multiplexing capability make FBG the preferred choice for data-centered real time SHM. Recent experimental advancement of FBG-based AE sensing systems for damage detection is reviewed in the following sections.

REVIEW OF EXISTING METHODS AND ADVANCES IN DELAMINATION DETECTION USING FBG SENSOR

METHODOLOGICAL APPROACHES

Several available methodologies have been examined through which delamination can be identified in composites by employing FBG sensors, and yet variations exist concerning sensor location, signal processing technique and application domain. For instance, incorporated FBG in the CFRP laminates attained a maximum of 95% detection capability for 2mm delamination during impact loading (J. Li et al. 2021), but surface mounted FBG on the GFRP beams under fatigue loading exhibited relatively lower accuracy (~90%) (Loman & Zohari, 2020). The signal resolution of embedded systems is improved since strain transfer occurs directly from the host material to the sensor core. However, on board sensors are inconvenient for installation and must be situated at specific positions in the fabrication process (Kakei et al. 2019).

Hybrid approaches further improve performance. Zhang et al. (2023) inserted an array of FBG along with piezoelectric transducers, obtaining ±3 mm localization accuracy on aerospace use composites. This achieved better performance in terms of robustness, and sensitivity than single mode systems. Likewise, Hafizi et al. (2023) merged FBG and AE (acoustic emission) spectral data to increase delamination detection rate. However, such heterogeneous approaches where additional low-cost sensors are integrated can introduce practical challenges, particularly in calibration and data fusion. The implementation of advanced signal processing methods such as STFT, FFT and matched filtering were commonly used for better feature extraction of acoustic signals. For example, Soman et al. (Soman et al. 2025) showed that the matched FBG filters can provide a significant improvement over conventional edge filter techniques in the presence of noise and temperature drift. It is this last advantage that is of utmost significance in any real world setting where temperature changes and other environmental condition tend to have a large impact on signal to noise ratio.

A critical comparison further reveals that methods using only curvature derived indexes such as (Wildy et al. 2021) are more likely to be influenced by environmental noise. By contrast, signal driven approaches such as STFT and machine learning based pipelines are more robust for load and operating conditions (Kahandawa et al. 2024; Li et al. 2025). Deep learning approaches, such as the Deep Residual Shrinkage Networks (DRSN) are integrated and impressive improvements in performance have been reported with delamination classification accuracies of up to 97.98% (Li et al. 2025). Table 2 presents a summary of relevant studies in methodology, materials and performance metrics.

Current methods are not standardized in terms of sensor configurations, and their positioning strategies remain empirical. Most experimental configurations are limited to laboratory scale and cannot simulate real world conditions such as thermal cycling, humidity, or structural ageing. Moreover, the extension of these techniques to different composites layups or geometry is not well understood.

Next efforts should compare detection based on the benchmark across standardized composite coupons with different delamination modes. Studies are needed to develop field deployable systems based on adaptive signal processing and explainable AI. In addition, "plug and play" FBG packages with pre-validated strain transfer models for different composites are also necessary.

However, real world deployment faces environmental limitations such as thermal drift, mechanical vibration, and signal attenuation, especially in thick composites. These issues necessitate careful sensor positioning and advanced denoising techniques to ensure reliable signal acquisition in operational settings (Jinachandran & Rajan 2021; Yan et al. 2023).

TABLE 2. Summary of Key Studies (Methodology, Materials, Results)

Author, Year	Methodology	Materials	Key Results	Quantitative Performance Indicators
(Soman et al. 2025)	Matched FBG filters for guided wave detection; simulations and experiments	Composite plates	Robust under varying temperatures; superior to edge filtering	SNR improvement of ~10.5–20 dB; Localization error margin < 8 mm; thermal range of -20°C to +80°C
(Kahandawa et al. 2024)	Combined spectral analysis with AE data.	Composite laminates	Improved accuracy; enhanced delamination detection	Localization error ±3 mm
(Li et al. 2025)	Deep learning (DRSN) via patch-type fsFBG sensors	Carbon fiber composites	97.98% accuracy in delamination classification	Accuracy 97.98%; multi class delamination
(Wildy et al. 2021)	Compared scanning laser Doppler vibrometry (SLDV) with FBG using curvature damage index	Composite laminate beams	FBG less noise-sensitive; optimal detection near sensor surface	0.583:1 depth to thickness ratio for peak detection;
(Rito et al. 2021)	Embedded chirped FBG sensors for strain & fatigue monitoring	Hybrid composite patches	Real-time tracking of delamination initiation & progression	Strain resolution < 1 με; early crack detection
(Arena & Viscardi, 2020)	Reviewed FBG in SHM; analyzed complex strain challenges	Various composite structures	Improved sensor placement needed; EMI robustness highlighted	Density: 100 pts/fiber; >90% FEA correlation.

SIGNAL PROCESSING AND FEATURE EXTRACTION

The signal processing and feature extraction is a critical element in determining the effectiveness of a FBG based detection system. In composite material applications, the signals generated by FBG sensors are often complex, non-stationary, and easily contaminated by environmental noise. Traditional methods that rely on time domain analysis or thresholding are found to be inadequate for interpreting damage in structural components subjected to dynamic loads. Accordingly, research is now shifting drastically towards time-frequency analysis and artificial intelligence (AI) based feature extraction techniques to improve the robustness and automation of structural health monitoring (SHM) systems.

Time-frequency analysis using Wavelet Transform, Short Time Fourier Transform (STFT) and Fast Fourier Transform (FFT) have become increasingly popular. Zhang et al. detected impact-induced delamination in CFRP laminates using embedded FBG. They used a hybrid STFT-FFT method and were able to achieve detection accuracy of over 95%. The hybrid approach allows for better detection of transient acoustic emissions by increasing the signal resolution in both the time and frequency domains. Similarly, Hafizi et al. (Hafizi et al. 2023) used STFT and a support vector machine (SVM) classifier to analyze the spectral shift of FBG sensors under delamination stress. This helped reduce false positives to less than 5%.

Signal transformation to the time-frequency domain also serves as a critical data preparation step for deep learning models. For example, used STFT to convert ultrasonic signals into time frequency spectral images (spectrograms). This image-based strategy improves the robustness of the model to signal variance. This shows that this STFT-CNN framework is highly adaptable to detect delamination in composite materials. For time series data, feature extraction needs to retain temporal continuity in order to recognize delayed or intermittent delamination, which are commonly missed by static classification (Safwan Mahmood et al. 2023)

However, the quality of FBG signals is often compromised in extreme operating environments such as aerospace engines. Study by (Q. Wu et al. 2018) highlighted the challenge of frequency overlap where engine vibrations (10–1000 Hz) can interfere with delamination signals that are in the range of 20–500 kHz. The use of Wavelet denoising and hybrid sensing integration (such as FBG and piezoelectric data fusion) emerge as technical solutions to separate the real damage signal from thermal and mechanical noise. Although classical feature extraction techniques such as SVM or Random Forest are easier to implement with minimal data requirements, they often fail to handle overlapping signal features in real-world structures. Therefore, automating feature extraction through deeper neural network architectures is an urgent need to improve the reliability of real-time diagnostics systems.

DEEP LEARNING AND FEATURE CLASSIFICATION

Deep learning techniques have transformed the way acoustic data from FBG sensors are processed for delamination detection. Deep learning enables automatic feature extraction from complex time-frequency data while the traditional technique relies heavily on hand-crafted features. Li and friends (Li et al. 2025) has achieved 97.t% accuracy in identifying various delamination patterns by using Deep Residue Shrinkage Networks (DRSN) to classify strain signals from FBG. The model is able to denoise and capture key frequency domain features that conventional thresholds cannot isolate well.

The ability of neural networks to handle signal variance is further enhanced through Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM). Dang et al. (Dang et al. 2022) demonstrated that an image based strategy using CNNs improves the robustness of models to signal variations, especially in identifying defect patterns in complex structures. However, since CNNs often ignore temporal continuity, Safwan et al. (Safwan Mahmood et al. 2023) applied LSTM models to FBG time-series data. This approach successfully detected delayed or intermittent delamination, which are usually difficult to classify by static models.

Despite their great performance, deep learning models suffer from “black-box” problems that damage trust in important industries like aerospace. The less transparent nature of the model and the requirement for large training datasets have make it difficult to apply such models in uncertain real-world situations. To overcome these limitations, the integration of explainable AI (XAI) methods such as Grad-CAM (Gradient-weighted Class Activation Mapping) or SHAP (SHapley Additive exPlanations) values is needed to enhance the interpretability of model decisions.

In addition, recent studies have started to explore hybriarchitecturees that combine the spatial advantages of CNN and the temporal capabilities of LSTM for more holistic detection. The use of AI has also been extended to decoupling algorithms for temperature strain separation (L. Wu et al. 2018). This technique allows the actual delamination signal to be separated from thermal disturbances, thereby improving the accuracy of real-time diagnostics in structural health monitoring systems.

CRITICAL COMPARISON OF RESEARCH APPROACHES

The comparison of the literature presents important tradeoffs in techniques for delamination detection by FBG. Embedded FBG display better sensitivity due to the direct embedding of composite layers, demonstrated by Zhang et al. (Hanqi Zhang et al. 2023) and Li et al. (J. Li et al. 2021). However, their methods are tedious in set up and not retrofittable. By contrast, surface mounted sensors are easier to deploy but may have lower signal quality (Loman & Zohari 2020).

In terms of classification methodology, classical machine learning algorithms and deep learning methods still differ significantly in performance. Using conventional methods, such as Support Vector Machine (SVM) and Random Forest (RF), is usually simpler and requires less training data. But their effectiveness really depends on how well the features were manually extracted. To distinguish small damage mechanisms, classical algorithms often face difficulties. This is especially true when signals overlap in real structural environments (Hafizi et al. 2023; Liu, 2021). Deep learning models such as CNN and LSTM, which can extract features automatically, are not capable of doing this. Deep learning models, on the other hand, are better at classifying complex delamination patterns (Li et al. 2025). However, these models are more expensive to run and need more technical knowledge, especially when it comes to making the model understandable, which is often seen as a “black box.”

Despite variations in experimental conditions, representative quantitative benchmarks can be identified across reported studies. FBG based acoustic delamination detection systems commonly achieve detection accuracies of 90–98% for delamination on the order of 2–5 mm (Ahmada et al. 2025; Mardanshahi et al. 2025). Delamination related acoustic emissions are typically observed within 20 kHz to 1 MHz, with higher sensitivity above 100 kHz for localized damage (Ibrahim et al. 2025; Samborski et al. 2024). In hybrid FBG based systems, localization errors are generally within ±2-5 mm, depending on sensor spacing and signal processing methods (C. Chen et al. 2024; Matveenko et al. 2021). Although direct normalization remains challenging, these ranges provide a practical reference for comparative performance evaluation.

Furthermore, comparisons by industry show that monitoring strategies have different priorities. The aerospace industry is more likely to spend a lot of money on embedded systems and deep learning models that can detect microscopic delamination for safety reasons (Kahandawa et al. 2024; Hanqi Zhang et al. 2023). In contrast, the wind energy industry prioritizes efficiency by using the multiplexing feature of FBG sensors to cover large areas, such as turbine blades, without the need for complex AI architectures (Bang et al. 2012).This difference suggests that no single delamination diagnostic solution is right for everyone.

Now, many research discussions regarding the use of hybrid sensing systems are beginning to dominate as a way to overcome the limitations of single sensors. The integration of data from FBG with other modalities, such as piezoelectric sensors, offers advantages in terms of more precise damage localization (Hafizi et al. 2023). However, from a system comparison perspective, this hybrid approach introduces a new challenge, namely the need for much more sophisticated data fusion algorithms. This creates a critical balance between increased diagnostic accuracy and increased signal decoding burden, the validation of which is still limited to laboratory parameters compared to field conditions with multiple damage scenarios.

CHALLENGES, LIMITATIONS AND FUTURE OUTLOOK

Although FBG sensing technology has shown excellent performance in laboratory tests, its transition to large-scale industrial applications still faces significant economic and technical constraints. The main challenge that often limits widespread use is the very expensive cost of high-resolution optical interrogators (Shah 2023). In addition to cost, the issue of signal degradation due to excessively long fiber arrangements on large structures such as bridges or aircraft wings can cause critical signal attenuation (Muller et al. 2009).This requires a more complex signal compensation system, which is rarely discussed in studies that focus only on small laboratory specimens.

Another significant technical constraint is cross-sensitivity to temperature. Although AI algorithms have been proposed for temperature-strain separation, real time implementation remains difficult because a temperature change as small as 1°C can trigger drastic reading errors of up to 10 $\mu\varepsilon$ events (Q. Wu et al. 2018). Failure to address this issue in operating environments with extreme temperature fluctuations will compromise the reliability of delamination early warning. In addition, long term exposure to environmental factors such as humidity and continuous mechanical vibration raises questions about the durability of the sensor and the need for more robust mounting methods (Berghmans et al. 2009; Yassin et al. 2024).

The future direction of research is now beginning to shift towards the integration of Digital Twins and polymer sensing technologies. In contrast, the use of polymer-based FBG (POF) sensors offers greater flexibility for curved structures (Torzoni et al. 2024). It is expected that integration with cloud platforms will support more efficient predictive maintenance systems and automate diagnostic processes (Chethana et al. 2023). Accelerating the commercialization of these FBG-based SHM systems worldwide will be aided by harmonization efforts through international standards such as ASTM and ISO (Bhatta & Dang 2024; Murphy 2022; Nayak 2024; Soman et al. 2021).

CONCLUSION

This review paper comprehensively covered the features and developments of FBG sensors for composite delamination monitoring based on acoustic signal detection. FBG sensors have several significant advantage compared with the traditional non-destructive testing (NDT) techniques, such as immune to EMI, high sensitivity, multiplexing property, and the ability of real-time detection. These properties make FBG particularly appropriate for embedded advanced smart composites and complex structural applications

The review pointed out that when FBG sensors are embedded in composites they offer the capability for precise recording of strain and acoustic emission signals associated with delamination phenomena. STFT and wavelet transforms are common signal processing techniques used for feature extraction. It is important to note that the incorporation of recent breakthroughs in machine learning and deep learning methods, such as Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM) networks, Deep Residual Shrinkage Networks (DRSN), has changed the way damage characteristics are interpreted. Recent studies utilizing these AI-driven pipelines have reported delamination classification accuracies as high as 97.98%, while hybrid approaches using Support Vector Machines (SVM) have successfully reduced false positive rates to less than 5%. The hybrid sensing integrated systems of FBG transducers and AE (or piezoelectric) transducers enhance detection accuracy and spatial resolution, with precision errors of only a few millimeters.

However, many obstacles remain before they may be universally adopted. Environmental influences including temperature and humidity changes and signal loss in thick composite laminate indeed still are major restricting factors. Recent studies on nano modified FBG coatings and adaptive calibration methods look very promising to solve these problems.

In summary, FBG-based acoustic sensing system is a promising candidate for SHM with high-density, high-spatial resolution in aerospace, wind energy and automotive industries. To achieve successful widespread deployment, future work needs to emphasize the design of standardized installation procedures, AI recognition algorithms which are both robust and explainable and an economical series of interrogation systems. With further development, FBG technology could become a key component of predicting the remaining life of composite structures.

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DECLARATION OF COMPETING INTEREST

None.

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