Research in Emerging and Applied Technologies
https://reatjournal.com

Strain Detection in Aerospace Composite Panels under Photonic Sensing Modules and Damage Accumulation

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Abstract

The integration of structural health monitoring systems within aerospace structures represents a crucial paradigm shift toward predictive maintenance and enhanced operational safety. This paper presents a detailed investigation into the deployment of photonic sensing modules, specifically embedded and surface-mounted Fiber Bragg Grating sensors, for real-time strain tracking and damage accumulation characterization in advanced carbon fiber reinforced polymer composite panels. Through systematic experimental validation and theoretical modeling, we examine how microstructural degradation, including matrix cracking, delamination, and fiber breakage, alters the strain fields within the composite laminate. The photonic modules capture these localized disturbances via characteristic modifications in the reflected optical spectra, such as peak wavelength shifting, spectral broadening, and birefringence-induced peak splitting. By correlating these optical signatures with progressive mechanical loading, a high-fidelity mapping of damage propagation is achieved. The results demonstrate that photonic sensing not only offers superior spatial and temporal resolution compared to conventional resistive strain gauges but also provides critical early-warning indicators of structural failure prior to visible macroscopic degradation. Ultimately, this research establishes a robust methodology for the online assessment of aerospace structural integrity, laying the groundwork for self-sensing composite architectures in future aerospace platforms.

Keywords: Photonic Sensing; Structural Health Monitoring; Composite Panels; Damage Accumulation; Strain Detection

1. Introduction

1.1 Structural Health Monitoring in Modern Aerospace Applications

The design and maintenance of modern aerospace vehicles are undergoing a fundamental transformation characterized by the widespread adoption of advanced composite materials. Carbon fiber reinforced polymer composites have largely replaced traditional metallic alloys in primary load-bearing structures, such as commercial transport fuselages, wing boxes, and empennages. This shift is driven by the outstanding specific strength, exceptional fatigue resistance, and high stiffness-to-weight ratios that composite laminates exhibit. Despite these superior mechanical properties, the structural complexity of laminated composites introduces distinct vulnerabilities. Unlike ductile metals, which typically deform plastically prior to failure, composite materials exhibit complex, progressive, and often subsurface damage modes. These damage mechanisms, which include matrix cracking, fiber-matrix debonding, interlaminar delamination, and fiber fracture, often propagate deep within the laminate without leaving visible indications on the external surface [1].

To mitigate the risks associated with undetected damage propagation and to reduce the reliance on conservative design margins, the aerospace industry has prioritized the development of structural health monitoring technologies. Structural health monitoring involves the continuous or periodic assessment of structural integrity through permanently integrated sensing networks [2]. By capturing real-time physical parameters such as strain, vibration, temperature, and acoustic emissions, these networks enable a transition from traditional schedule-based maintenance inspections to more efficient, cost-effective, and safe condition-based maintenance protocols.

1.2 Limitations of Conventional Strain Sensing Technologies

For decades, electrical resistance strain gauges have served as the industry standard for strain measurement in both experimental mechanics and aerospace structural testing. These sensors operate on the principle of piezoresistivity, where mechanical deformation of a metallic foil element yields a corresponding change in its electrical resistance. While electrical strain gauges are mature and relatively inexpensive, they exhibit severe performance limitations when deployed for long-term, continuous monitoring in demanding aerospace environments. A primary drawback is their high susceptibility to electromagnetic interference, which can arise from onboard avionics, power distribution systems, lightning strikes, or external atmospheric disturbances. Such interference introduces significant noise into the strain signals, potentially masking subtle changes associated with structural degradation [3].

Furthermore, conventional foil strain gauges require extensive coaxial cabling to transmit electrical signals from the sensing nodes to central data acquisition units. In a large-scale commercial aircraft, the aggregate weight of this wiring network can negate a substantial portion of the weight savings gained by utilizing composite materials. Electrical systems also present inherent safety risks in aviation environments, particularly when integrated near composite fuel tanks or dry bays, where spark generation must be avoided under all operating conditions. From an integration standpoint, foil gauges are strictly limited to surface-mounted configurations. They cannot be embedded within the composite laminates without creating significant geometry discontinuities and stress concentrations, which compromises the local mechanical performance of the host structure. Consequently, conventional electrical strain gauges are ill-suited for capturing the internal, through-thickness strain fields and localized damage progression that characterize composite degradation.

1.3 Objectives and Scope of the Study

To overcome the inherent constraints of electrical sensing technologies, photonic sensing modules have emerged as a highly promising alternative for aerospace structural health monitoring. Among various optical sensing modalities, Fiber Bragg Grating sensors offer significant advantages, including absolute measurement capabilities, immunity to electromagnetic interference, lightweight profiles, low signal attenuation over long transmission distances, and high multiplexing potential. Because optical fibers are fabricated from high-strength silica glass and feature diameters comparable to individual composite reinforcement plies, they can be seamlessly integrated directly between the composite laminates during the fabrication process, facilitating true in situ structural health monitoring [4].

The objective of this study is to provide a comprehensive explanation of strain detection using integrated photonic sensing modules and to analyze its correlation with progressive damage accumulation in aerospace composite panels. This paper details the physical principles of optical wave propagation in deformed waveguides, the mechanics of strain transfer between the composite matrix and the embedded optical fiber, and the unique optical spectral signatures associated with different stages of damage progression. Through systematic experimental testing under cyclic and monotonic loading conditions, this research demonstrates how specific changes in the reflected optical spectra, including spectral shifting, peak distortion, and birefringence-induced splitting, can be leveraged to locate, identify, and quantify damage states within the composite panels.

2. Theoretical Background of Photonic Sensing and Wave Propagation

2.1 Principles of Fiber Bragg Grating and Optical Interrogation

The operational foundation of a Fiber Bragg Grating sensor is based on the periodic modulation of the refractive index along the core of a single-mode silica optical fiber. This periodic structure is typically written into the fiber core using a high-intensity ultraviolet laser beam and an interferometric phase mask. When a broadband optical spectrum is launched into the optical fiber, it propagates through the core until it encounters the grating zone. At this location, a narrow band of wavelengths is reflected back toward the light source, while the remaining optical spectrum is transmitted through the grating without significant attenuation [5]. The central wavelength of the reflected light, known as the Bragg wavelength, is governed by a fundamental phasematching condition. Specifically, the Bragg wavelength is equal to two times the effective refractive index of the fiber core multiplied by the physical grating period.

When the optical fiber experiences mechanical deformation or temperature changes, both the effective refractive index and the physical grating period are modified. This alters the reflected Bragg wavelength. Under a purely axial tensile strain, the optical fiber is physically elongated, which increases the grating period. Concurrently, the radial contraction of the fiber core, driven by Poisson effects, alters the density of the glass structure and changes its refractive index through the photoelastic effect. The combination of these two phenomena results in a highly linear shift of the Bragg wavelength toward longer wavelengths. Under uniform thermal loading, the thermal expansion of the silica glass alters the grating period, while the thermo-optic effect modifies the effective refractive index, causing a similar spectral shift. Modern optoelectronic interrogation systems resolve these minute wavelength variations with high precision, typically employing swept-wavelength tunable lasers or spectrometer-based configurations to convert optical spectral shifts into real-time strain data.

2.2 Waveguide Mechanics and Optical-Thermal-Mechanical Coupling

The quantitative analysis of strain using embedded optical fibers requires a deep understanding of the strain transfer mechanics between the host composite laminate and the glass core of the sensor. Since the optical fiber is an elastic inclusion embedded within an anisotropic, layered composite structure, the strain field of the host material is not directly experienced by the fiber core. Instead, the strain is transferred through the protective polyimide coating, which acts as an intermediate shear-lag layer. The efficiency of this strain transfer is dictated by the shear modulus and thickness of the protective coating, the bonding quality at the fiber-matrix interface, and the embedment length of the grating. Analytical shear-lag formulations indicate that a high-modulus, ultra-thin coating maximizes strain transfer efficiency, allowing the optical fiber to accurately register the strain states of the surrounding composite material [6].

In complex aerospace structures, the strain field is rarely uniaxial or uniform. When an embedded optical fiber is subjected to multi-axial mechanical loading, the transverse stress components alter the isotropic nature of the silica core, inducing optical anisotropy. This phenomenon, known as the photoelastic or photo-elastic effect, causes the refractive index of the core to split into two distinct, orthogonal directions corresponding to the principal stress axes. This stress-induced birefringence splits the reflected Bragg wavelength into two separate peaks. By monitoring the separation distance between these split peaks, researchers can isolate and measure the transverse strain components acting on the fiber, which provides vital clues regarding matrix cracking and interlaminar shear strain accumulation in the surrounding laminate.

3. Damage Accumulation Mechanisms in Carbon Fiber Reinforced Polymers

3.1 Microstructural Degradation and Matrix Cracking

The mechanical degradation of carbon fiber reinforced polymer composite panels under applied tensile or fatigue loading begins at the microscopic level. The initial stage of damage accumulation is characterized by the formation of microcracks within the polymer matrix, particularly in the off-axis plies where the fiber orientation is transverse to the principal loading direction. These matrix cracks are driven by local stress concentrations at the fiber-matrix interface and propagate parallel to the reinforcement fibers. As the applied load increases, the density of these matrix cracks rises, eventually reaching a characteristic damage state where the crack spacing stabilizes. While individual matrix cracks do not immediately compromise the structural integrity of the panel, they act as initiation sites for more severe damage modes, such as interlaminar delamination [7].

The presence of a matrix crack near an embedded Fiber Bragg Grating sensor introduces a highly localized stress concentration and a non-uniform strain field along the length of the grating. When a crack propagates adjacent to the sensor, the localized strain field exhibits a sharp gradient, with the portion of the grating closest to the crack experiencing a high tensile strain, while the remainder of the grating remains under nominal strain. This non-uniform strain distribution disrupts the periodic phase condition of the grating. Instead of a simple shift in the reflected Bragg wavelength, the reflected spectrum undergoes significant distortion, manifesting as spectral broadening, asymmetry, and peak splitting. By analyzing these spectral distortions, the initiation and local density of matrix cracks can be detected well before they cause macroscopic structural failure.

3.2 Delamination Propagation and Impact Damage Dynamics

Delamination, which is the separation of adjacent ply layers within a composite laminate, represents one of the most critical and insidious damage modes in aerospace structures. Delamination can be initiated by out-of-plane loading, high interlaminar shear stresses, or low-velocity impacts, such as tool drops during maintenance or runway debris strikes during takeoff and landing. This type of damage is particularly dangerous because it significantly reduces the compressive strength and buckling resistance of the panel, while remaining largely undetectable during routine visual inspections. Consequently, this is often referred to as barely visible impact damage [8].

When an impact event occurs, it generates a complex wave propagation field and leaves a localized residual strain field in the affected region. Photonic sensing modules are uniquely suited for detecting and tracking delamination propagation due to their high spatial sensitivity. As a delamination front approaches an embedded optical fiber sensor, the local interlaminar shear stress transfer is interrupted, causing a distinct drop in the axial strain transmitted to the fiber core. Additionally, the opening of the delamination crack alters the local bending compliance of the laminate plies, leading to localized bending and transverse compression of the optical fiber. This mechanical state results in clear optical signatures, including significant birefringence-induced peak splitting and a marked decrease in the intensity of the reflected spectrum. By distributing a network of multiplexed Fiber Bragg Gratings across the composite panel, the position, boundary, and growth of the delamination zone can be continuously mapped in real time.

4. Experimental Setup and Photonic Module Integration

4.1 Panel Fabrication and Sensor Embedding Process

To validate the theoretical capabilities of photonic sensing modules for damage detection, an experimental study was conducted using carbon fiber reinforced polymer composite panels. The composite panels were fabricated using high-strength carbon fiber epoxy prepreg tapes with a quasi-isotropic layup configuration of [0/45/-45/90]s, resulting in an eight-ply laminate with a nominal thickness of 1.0 millimeter. During the manual layup process, single-mode optical fibers featuring polyimide coatings and containing written Fiber Bragg Grating sensors were carefully integrated within the mid-plane of the composite laminate. Polyimide coatings were specifically selected over standard acrylate coatings due to their thin profile and high temperature resistance, which prevents thermal degradation during the composite curing process.

The optical fibers were aligned parallel to the carbon reinforcement fibers of the surrounding plies to minimize the formation of resin-rich pockets, which can act as microstructural defects and initiate early delamination. The ingress and egress points, where the optical fibers exit the edges of the composite panel, were protected using specialized polytetrafluoroethylene tubing. This tubing prevents the fragile glass fibers from shearing at the panel boundaries during handling and testing. The consolidated prepreg assembly was then placed in an autoclave and subjected to a standard cure cycle, which involved ramped heating to 180 degrees Celsius under a constant pressure of 0.6 megapascals, followed by a controlled cooling phase. This fabrication procedure ensured high-quality consolidation with minimal void content and excellent bonding at the interface between the composite matrix and the embedded optical fibers [9].

4.1.1 Summary of Specimen and Sensor Parameters

To provide a clear reference for the experimental parameters, the material properties of the composite laminate and the geometric characteristics of the integrated optical fiber sensors are summarized in Table 1.

Table 1: Material Properties and Optoelectronic Sensing Parameters

Parameter Type	Parameter Name	Measured Value
Composite Material	Carbon Fiber Prepreg Elastic Modulus	135 Gigapascals
Composite Material	Ply Thickness	0.125 Millimeters
Optical Sensor	Cladding Diameter	125 Micrometers
Optical Sensor	Polyimide Coating Thickness	15 Micrometers
Optical Sensor	Initial Bragg Wavelength	1550.2 Nanometers
Optical Sensor	Strain Sensitivity Coefficient	1.2 Picometers per Microstrain

The selected parameters represent typical values for aerospace-grade materials, ensuring that the findings of this study are directly applicable to industrial applications.

4.2 Optoelectronic Interrogation and Loading Configuration

The experimental testing program was designed to subject the fabricated composite panels to controlled mechanical loading while continuously monitoring their optical spectral responses. Tensile testing was performed using a computer-controlled, servo-hydraulic fatigue testing machine equipped with high-capacity hydraulic grips. To prevent premature slip or failure at the gripping zones, glass-epoxy bevel tabs were bonded to the ends of the composite specimens using a high-strength adhesive. The mechanical tests included both monotonic tensile tests to failure and tension-tension cyclic fatigue tests, designed to induce progressive damage accumulation.

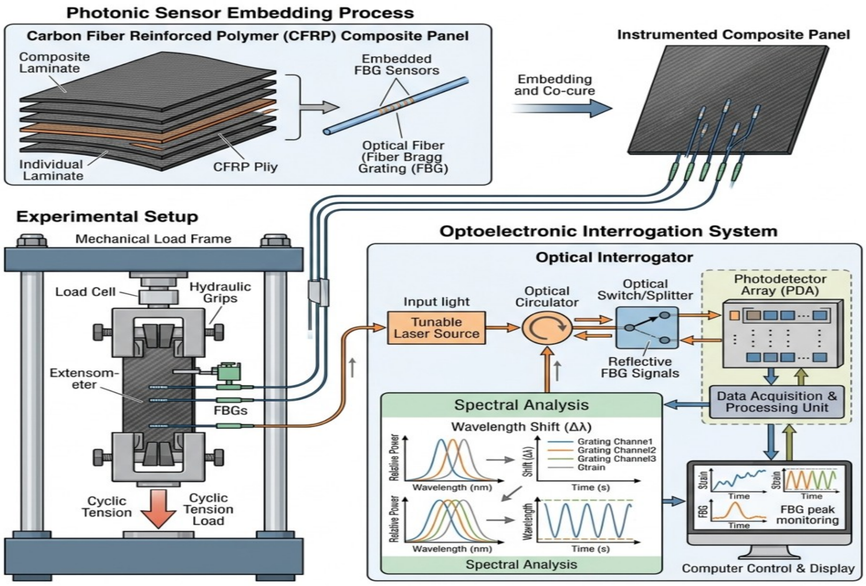

Figure 1: Comprehensive Schematic of Photonic Sensing Integration and Experimental Optoelectronic Interrogation System for Aerospace Composite Panels

The integrated Fiber Bragg Grating sensors were connected to a high-speed optical interrogation system capable of tracking wavelength shifts with a resolution of 0.1 picometers. This system utilizes a swept-wavelength tunable laser source operating in the 1550 nanometer telecom band and an array of high-speed photodetectors to record the reflected optical spectra at a sampling frequency of 1 kilohertz [10]. This high sampling rate allowed the system to capture transient strain variations and dynamic damage events during mechanical loading. Digital image correlation was employed as an independent, non-contact full-field strain measurement technique to validate the strain data acquired by the embedded photonic sensors.

5. Quantitative Analysis and Strain-Damage Characterization

5.1 Optical Spectrum Shifts and Strain Reconstruction

During the initial elastic loading phase of the composite panels, the embedded Fiber Bragg Grating sensors exhibited a highly linear, uniform shift in their reflected Bragg wavelengths. Under these conditions, the strain field along the length of the grating remains uniform, and the shape of the reflected spectrum is preserved. This response confirms that the sensor behaves as a high-fidelity strain transducer in the absence of local structural defects. The linear relationship between the wavelength shift and the axial strain was used to reconstruct the strain history of the panel, showing excellent agreement with the surface strain measurements obtained via digital image correlation [11].

As the applied tensile load increased and microstructural damage began to accumulate, the reflected optical spectra departed from this uniform behavior. The initiation of matrix cracking in adjacent off-axis plies generated local, high-frequency strain perturbations along the grating length. These localized strain variations caused a non-uniform shift in the reflection spectrum, which manifested as a gradual broadening of the spectral peak and a reduction in peak reflectivity. To quantify these changes, a spectral reconstruction algorithm was developed. This algorithm solves the inverse problem of optical wave propagation in non-uniform gratings, mapping the distorted spectral shape back to the underlying axial strain distribution [12]. Through this technique, the local strain gradients induced by individual matrix cracks were resolved, providing a direct optical measurement of microstructural damage initiation.

5.1.1 Spectral Degradation Over Cyclic Loading

To illustrate the relationship between mechanical degradation and optical response, the evolution of the reflected spectrum parameters over progressive fatigue cycles is presented in Table 2.

Table 2: Spectral Parameter Performance Under Cumulative Load Cycles

Fatigue Cycles	Peak Wavelength Shift	Full Width at Half Maximum	Reflection Intensity Loss
0 Cycles	0.0 Picometers	0.15 Nanometers	0.0 Decibels
100000 Cycles	240.5 Picometers	0.16 Nanometers	0.2 Decibels
250000 Cycles	485.2 Picometers	0.19 Nanometers	0.7 Decibels
500000 Cycles	720.1 Picometers	0.28 Nanometers	1.8 Decibels
750000 Cycles	910.4 Picometers	0.45 Nanometers	3.5 Decibels
1000000 Cycles	1050.8 Picometers	0.62 Nanometers	5.4 Decibels

As shown in Table 2, the progressive accumulation of damage leads to a non-linear increase in the full width at half maximum of the peak, accompanied by an increasing loss of reflection intensity, which serves as a metric for internal structural degradation.

5.2 Birefringence Effects and Multi-Axial Damage Evaluation

A key advantage of embedded photonic sensing modules is their ability to resolve multi-axial strain states through the analysis of stress-induced birefringence. In a pristine, undamaged composite laminate subjected to uniaxial tension, the transverse stresses acting on the embedded optical fiber are relatively minor, and the reflected optical spectrum retains a single, well-defined peak. However, as cyclic fatigue loading progresses, the accumulation of matrix cracks and the onset of localized delamination create a complex, multi-axial stress field surrounding the sensor. This multi-axial state generates significant transverse stresses perpendicular to the longitudinal axis of the optical fiber.

These transverse stresses break the radial symmetry of the fiber core, inducing birefringence. As a result, the optical fiber propagates two orthogonal polarization modes at slightly different velocities, causing the single Bragg reflection peak to split into two separate peaks [13]. The wavelength separation between these split peaks is directly proportional to the difference between the principal transverse stresses.

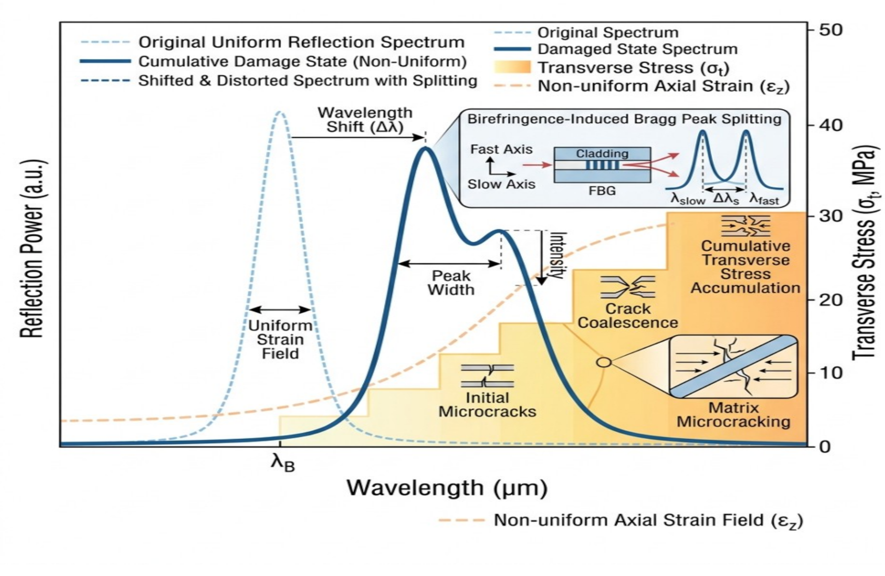

Figure 2: Spectral Response Characteristics and Birefringence Induced Bragg Peak Splitting Under Cumulative Damage State

By monitoring the onset and magnitude of this peak splitting, the growth of transverse microcracks and the propagation of interlaminar delaminations can be monitored. This capability enables the detection of multi-axial stress fields and subsurface damage modes that are difficult to resolve using conventional surface-mounted strain sensors.

6. Discussion and Future Outlook

6.1 Reliability and Practical Implementation Challenges

While the experimental results demonstrate the high sensitivity and diagnostic power of integrated photonic sensing modules, several challenges must be addressed before this technology can be widely adopted in commercial aviation and aerospace operations. A key concern is the long-term durability of embedded optical fibers under the harsh operating conditions typical of aerospace platforms, which include high-amplitude vibrations, cyclic mechanical loading, thermal cycling from minus fifty-five to over eighty degrees Celsius, and exposure to moisture and aviation fluids. Long-term studies are needed to ensure that the presence of the embedded glass fiber does not compromise the fatigue life of the composite laminate, and that the fiber-matrix bond remains stable over decades of service [14].

Another practical challenge lies in the design of robust, reliable connectivities at the boundaries of the composite panels. The ingress and egress points, where the delicate glass optical fibers exit the cured composite structure, are highly vulnerable to mechanical damage during assembly, maintenance, and operation. Developing ruggedized, low-profile optical connectors that can be integrated directly into the edges of composite panels without adding significant weight or aerodynamic drag is essential. Additionally, further research is required to resolve the temperature-strain cross-sensitivity inherent to Fiber Bragg Grating sensors. This issue is typically addressed by deploying collocated reference gratings that are mechanically isolated from the host structure, allowing thermal wavelength shifts to be isolated and subtracted from the total spectral response.

6.2 Concluding Remarks and Future Research Horizons

This study demonstrates that integrated photonic sensing modules, specifically embedded Fiber Bragg Grating sensors, provide an effective and reliable method for real-time strain tracking and damage accumulation characterization in aerospace composite panels. By capturing localized strain gradients and transverse stress fields, these sensors resolve microstructural damage modes, such as matrix cracking and delamination, via clear signatures in their reflected optical spectra. This capability enables the detection of subsurface defects well before they manifest as visible macroscopic damage, offering a valuable tool for structural health monitoring in advanced aerospace vehicles [15].

Looking forward, the next phase of research will focus on transitioning from point-based sensing to fully distributed optical sensing networks. By utilizing high-resolution optical frequency domain reflectometry and Rayleigh backscattering, continuous strain profiles can be measured along the entire length of an unmodified optical fiber with sub-millimeter spatial resolution. This approach would eliminate the need to write individual gratings into the fiber, enabling the continuous monitoring of entire composite structures. Additionally, integrating these advanced sensing networks with machine learning and pattern recognition algorithms will allow for the automated interpretation of complex spectral distortions. This integration will enable real-time damage classification, localization, and residual life estimation, paving the way for self-sensing, intelligent composite architectures in next-generation aerospace systems.

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