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Real-Time Strain Monitoring in Composites Using Flat Optical Fibre Sensors – Review Paper

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Abstract
Structural health monitoring (SHM) of composite materials is critical for ensuring the reliability and longevity of high-performance engineering systems. This review comprehensively examines the advancements, challenges, and applications of flat optical fibre sensors (FOFS) for real-time strain monitoring in composite structures. Traditional electrical strain gauges and piezoelectric sensors face limitations in multiplexing, electromagnetic interference (EMI), and integration within composite layups. In contrast, FOFS offer unique advantages, including high spatial resolution, compatibility with composite manufacturing processes, and immunity to EMI. This paper analyses the working principles of FOFS, their fabrication techniques, integration methodologies, and signal interrogation systems. Case studies from aerospace, civil engineering, and renewable energy sectors underscore their practical efficacy. Challenges such as signal attenuation, temperature cross-sensitivity, and long-term durability are critically evaluated. The review concludes with future directions, including nanotechnology-enhanced sensors and machine learning-driven data analytics.

Keywords: Composite Materials, Optical Fibre Sensors, Real Time Monitoring, Strain Measurement, Structural Health Monitoring

1. Introduction
Composite materials, such as carbon fibre-reinforced polymers (CFRP) and glass fibre-reinforced polymers (GFRP), are widely used in aerospace, wind turbine blades, and automotive industries due to their high strength-to-weight ratios and corrosion resistance (Mouritz et al., 2001). However, their anisotropic nature and complex failure mechanisms—delamination, matrix cracking, and fibre breakage—necessitate robust SHM systems. Conventional non-destructive testing (NDT) methods, including ultrasonic testing and X-ray tomography, are unsuitable for real-time, in-situ monitoring [1].

Optical fibre sensors (OFS) have emerged as a transformative solution, enabling distributed or quasi-distributed strain measurements [2]. Among OFS variants, flat optical fibre sensors (FOFS) are particularly promising due to their conformability, minimal invasiveness, and compatibility with composite layup processes [3]. This review synthesises over a decade of research to evaluate FOFS as a paradigm shift in SHM.

2. Composite Materials and Failure Mechanisms
The fundamental classification of composite materials hinges significantly upon the nature of both the reinforcement phase and the matrix material employed. Typically, reinforcements manifest as either fibres or particles, each imparting distinct mechanical characteristics to the resulting composite.

Fibre reinforcement, arguably the most prevalent form in high-performance composites, involves embedding strong, stiff fibres within a matrix. These fibres can be continuous, providing exceptional strength and stiffness primarily along the fibre direction, or discontinuous (chopped fibres), which, whilst offering lower directional properties, facilitate more complex geometries and automated manufacturing processes.

Among synthetic fibre composites, Carbon Fibre Reinforced Polymers (CFRPs) and Glass Fibre Reinforced Polymers (GFRPs) stand out as the predominant choices, particularly in demanding, high-stress applications such as aerospace, automotive, and sporting goods [4]. CFRPs are prized for their exceptionally high specific stiffness and strength (stiffness-to-weight and strength-to-weight ratios), making them ideal for lightweight structural components. GFRPs, whilst having lower specific properties than CFRPs, offer a favourable balance of performance and cost-effectiveness, leading to widespread use in marine, wind energy, and infrastructure applications. Aramid fibre composites also feature, notably for their excellent toughness and impact resistance.

Moving to the matrix phase, polymer matrices are broadly categorised into thermosets and thermoplastics. Thermosetting polymers, including epoxies, polyesters, and vinyl esters, undergo an irreversible curing process to form a rigid, cross-linked network. This structure provides excellent dimensional stability, creep resistance, and good performance at elevated temperatures, making them well-suited for structural components often processed using techniques like hand lay-up, Resin Transfer Moulding (RTM), and prepreg-based manufacturing with autoclave curing. Conversely, thermoplastic matrices, such as PEEK, Polyamide (PA), and Polypropylene (PP), are polymers that can be repeatedly melted and solidified. This characteristic enables manufacturing routes like injection moulding and thermoforming, offering benefits in terms of processing speed, repairability, and potential for recycling. Thermoplastic composites generally exhibit higher toughness and impact resistance compared to thermosets, albeit often with lower stiffness.

Beyond these established synthetic systems, natural fibre composites are gaining significant traction, driven by the imperative for more sustainable engineering solutions [5]. Utilising fibres derived from plants, such as flax, hemp, jute, and bamboo, these composites offer-appealing attributes including low density, biodegradability, and cost competitiveness. While considerations regarding moisture absorption and inherent variability need careful engineering, their potential for reducing environmental footprint and lifecycle impact is considerable, leading to increasing adoption in less load-bearing or interior applications across various industries.

Particle-reinforced composites, whilst less prevalent in advanced structural applications compared to their fibre counterparts, are nonetheless valuable. They involve dispersing particulate fillers within a matrix, typically polymers or metals. These particles (e.g., ceramics, carbides, or even simpler fillers like carbon black) are often used to modify specific properties, such as enhancing stiffness, improving wear resistance, altering thermal or electrical conductivity, or simply to reduce overall material cost. Their behaviour is generally isotropic, unlike the anisotropic nature of many fibre composites.

Understanding these various combinations of reinforcement and matrix materials is crucial, as the specific properties of a composite are meticulously engineered based on the intended application, required performance criteria, manufacturing feasibility, and cost constraints. The continued development in both constituent materials and processing techniques presents exciting opportunities for tailoring composite properties to meet increasingly stringent engineering demands.

Composite materials, engineered combinations of reinforcements like carbon or glass fibres embedded within a matrix of thermoset or thermoplastic polymers, are revolutionizing industries demanding high strength-to-weight ratios, with Carbon Fibber Reinforced Polymers (CFRP) and Glass Fibber Reinforced Polymers (GFRP) becoming staples in aerospace, automotive, and sporting goods due to their superior performance in high-stress scenarios, while the burgeoning field of sustainable engineering explores natural fibre composites as eco-friendly alternatives; however, these materials are susceptible to unique failure modes, including delamination, the insidious separation of layers caused by impact or fatigue, matrix cracking, initiated by thermal cycling or mechanical overload, and catastrophic fibre breakage, a sudden tensile failure, necessitating advanced monitoring techniques; therefore, the integration of Fibre Optic Sensors (FOS) provides a powerful solution for real-time detection of these defects, leveraging their high sensitivity and spatial resolution to detect early signs of damage before they escalate into structural failures, thus enhancing the safety and longevity of composite structures [4-9].

2.1. Optical Fibre Sensors: An Overview

Optical fibre sensors offer a robust alternative to traditional electrical sensors by leveraging the principles of optics; instead of electrical signals, they modulate light properties such as intensity or wavelength within a fibre optic cable, effectively turning the fibre itself into a sensing element, providing immunity to electromagnetic interference (EMI) [10]. This allows for real-time monitoring of physical parameters like strain or temperature. Fibre Bragg Gratings (FBGs), for example, act as precise wavelength filters, shifting their reflected wavelength proportionally to applied strain, offering a localized measurement much like a strain gauge, while Long-Period Fibre Gratings (LPFGs) can be employed to sense bending and temperature variations [11,12]. Furthermore, distributed sensing techniques exploit light scattering phenomena along the entire fibre length, such as Rayleigh, Brillouin, or Raman scattering, to provide continuous monitoring over extended structures, making them invaluable for applications where EMI is a concern, or where large numbers of sensors need to be multiplexed efficiently along a single cable, such as in structural health monitoring of bridges or pipelines, and particularly benefiting from their corrosion resistance and inherent longevity in harsh environments [13-15].

2.2. Flat Optical Fibre Sensors: Design and Fabrication

Considering the practicalities of embedding sensors within composites, Flat Optical Fibre Sensors (FOFS) represent a significant design evolution aiming to mitigate some of the integration challenges associated with standard cylindrical fibres. Their distinct Structural Configuration, typically featuring a rectangular or D-shaped cross-section as opposed to the conventional circular profile, is specifically engineered to reduce stress concentrations at the composite-sensor interface during curing and subsequent loading, thereby minimising the risk of localised damage or delamination that can compromise sensor performance and structural integrity in real-world applications [16]. This geometry also subtly enhances light-matter interaction, contributing to improved sensing sensitivity for parameters like strain. Achieving this non-circular profile necessitates specific Fabrication Techniques, including established methods like Mechanical Polishing using abrasive processes to flatten standard fibres (Zhou et al.,), more advanced approaches like 3D Printing for additive manufacturing of polymer-based flat fibres suitable for complex geometries or dynamic environments (Zhang et al.,), and Etching via chemical processes to precisely control the removal of cladding material each offering different trade-offs in terms of precision, cost, and material compatibility [17]. Furthermore, Material Considerations are paramount; traditional Silica Fibres offer high durability and performance under static loads and high temperatures but are inherently brittle and susceptible to bending losses, making them less ideal for highly dynamic or tightly curved applications [18], whilst Polymer Optical Fibres (POF), though typically less sensitive and with higher attenuation, provide superior flexibility, are lightweight, and more robust under mechanical stresses, making them particularly well-suited for monitoring structures experiencing large deformations or dynamic loading where bending is a concern[19]. The selection of flat FOFS design, fabrication method, and material is a pragmatic engineering decision driven by the specific performance requirements, manufacturing constraints, and operational environment of the target composite structure.

2.3. Integration of FOFS into Composites

Integrating Fibre Optic Fibre Sensors (FOFS) effectively into composite structures is a critical step for realising reliable Structural Health Monitoring, and this process involves specific embedding techniques and overcoming notable technical challenges in a real-world manufacturing environment. Two prominent embedding methods are widely employed: Preform Integration, where the delicate optical fibres are meticulously positioned and secured alongside the reinforcing fibres prior to matrix infusion or consolidation, often manually during the fibre layup process, which allows precise sensor placement but requires careful handling to avoid damage and embedding during Resin Transfer Moulding (RTM) or similar liquid moulding processes, where the sensors are placed within the dry preform mould before resin is injected under pressure, necessitating sensor protection and ensuring the resin flow front doesn't damage or displace the fibres [20,21]. However, regardless of the technique chosen, practical challenges persist: Adhesion Issues can arise if the resin matrix does not bond sufficiently to the sensor's protective coating or the fibre itself, potentially creating a localised mechanical decoupling which leads to inaccurate strain transfer and problematic signal drift under load cycles furthermore, Thermal Mismatch between the silica optical fibre (and its coating) and the surrounding composite matrix and fibres can induce internal stresses during temperature changes or curing, potentially leading to localised delamination or micro-buckling, ultimately compromising sensor integrity and measurement accuracy, particularly in applications experiencing significant thermal cycling [22,23]. Successfully addressing these integration challenges through appropriate sensor coatings, robust packaging, and refined manufacturing processes is essential for ensuring the long-term reliability and performance of embedded FOFS within composite structures.

2.4. Real-Time Strain Monitoring Systems

2.4.1. Signal Interrogation Methods

-Right then, extracting meaningful and actionable data from embedded Fibre Optic Fibre Sensors (FOFS) is critically dependent on the chosen signal interrogation method, the technique used to translate the optical signals within the fibre into quantifiable engineering parameters like strain or temperature. Two principal methods are widely employed in real-world applications. Firstly, Spectrometric Detection, particularly prevalent in Fibre Bragg Grating (FBG)-based systems, relies on monitoring the precise wavelength of light reflected by the gratings. As strain or temperature changes, the FBG's grating period shifts, causing a corresponding shift in the reflected wavelength, which is then detected and measured by a spectrometer or interrogator. Utilizing Wavelength Division Multiplexing (WDM), engineers can effectively interrogate multiple FBGs spaced along a single optical fibre simultaneously, providing point-sensing capabilities at numerous discrete, pre-defined locations within a structure, which is invaluable for monitoring critical areas or known stress concentrations [24]. Conversely, for applications demanding continuous monitoring over longer lengths rather than at specific points, Optical Time-Domain Reflectometry (OTDR) techniques are frequently employed. OTDR systems inject pulses of light into the fibre and analyse the characteristics (intensity, timing) of the light that is backscattered from intrinsic scattering sites along the fibre's entire length. By meticulously measuring the time it takes for the backscattered signal to return, the system can map out strain or temperature profiles and, crucially, detect and precisely localise events such as breaks, micro-cracks, or significant strain changes anywhere along the fibre run [25]. The selection between these methods is a key engineering decision, driven by the specific requirements of the monitoring task, whether it necessitates high-precision measurement at defined points or continuous, distributed coverage over large or complex geometries.

2.5. Case Studies

Practical deployment and rigorous testing in demanding operational environments are crucial for validating advanced Structural Health Monitoring technologies like Fibre Optic Fibre Sensors (FOFS), and several key case studies demonstrate their efficacy in critical composite structures. In the aerospace sector, a prime example is the integration of embedded FBG-FOFS within the Airbus A350 wingbox [26]. This application is particularly noteworthy as the wingbox is a primary load-bearing component subjected to complex stresses during flight, and the continuous, real-time strain and temperature data provided by the FOFS network is essential for detailed structural analysis, informing predictive maintenance strategies, and ensuring long-term airworthiness. Similarly, in the renewable energy industry, FOFS have been successfully utilised for strain mapping in wind turbine rotor blades [17]. Wind turbine blades operate under immense and constantly varying cyclic loading, making them susceptible to fatigue damage; the ability of embedded FOFS to precisely monitor distributed strain across these large, flexible composite structures under operational conditions provides vital insights into their mechanical behaviour, aids in optimising performance, and supports condition-based or predictive maintenance planning to maximise asset lifespan and reliability. These examples collectively underscore the capability of FOFS to deliver essential high-fidelity data for managing the integrity and performance of complex composite structures in critical engineering applications.

2.6. Challenges and Limitations

Despite the significant advantages offered by Fibre Optic Fibre Sensors (FOFS) for Structural Health Monitoring, their practical deployment in real-world engineering applications is accompanied by several persistent challenges that require careful consideration. A primary concern is temperature cross-sensitivity, where temperature fluctuations can significantly influence the measured strain readings, potentially leading to inaccurate interpretations of structural behaviour if not accounted for. Engineers typically address this through compensation techniques or, more robustly, by employing dual-parameter sensors, such as hybrid Fibre Bragg Grating and Long Period Fibre Grating (FBG-LPFG) configurations, which allow for simultaneous strain and temperature measurement, enabling effective decoupling of the two effects [27]. Furthermore, signal attenuation poses a technical hurdle, as light signals travelling through the embedded optical fibres can weaken due to bending, micro-cracks, or material interfaces within the composite structure. While this limits the maximum length of sensing arrays and the density of sensors, ongoing research into advanced polymer coatings and meticulous installation procedures offers promising avenues for mitigating these losses and ensuring sufficient signal integrity over long distances [28]. Finally, a significant barrier to widespread adoption remains the inherent cost associated with FOFS systems; the high-precision fabrication required for the optical fibres, coupled with the specialised equipment and skilled labour needed for embedding and interrogation, renders initial implementation relatively expensive compared to conventional sensor technologies [29]. Whilst economies of scale and technological advancements are steadily reducing these costs, they still represent a substantial factor in the feasibility assessment for many engineering projects, particularly those outside high-value sectors like aerospace. Addressing these limitations is paramount for transitioning FOFS from research laboratories to routine industrial practice, demanding continued focus on robust sensor design, installation methodology, and cost reduction strategies.

2.7. Future Directions

Looking ahead, the trajectory for advancing FOFS-based SHM systems is incredibly promising, driven by innovation across several key fronts. These developments aim to push the boundaries of sensitivity, data interpretation, and environmental sustainability, crucial for deploying these technologies in increasingly complex and demanding engineering applications.

Nanocomposite Coatings for Enhanced Sensitivity: One particularly exciting avenue involves leveraging advanced materials to augment the fundamental sensing capabilities of the optical fibres. The application of nanocomposite coatings, notably those incorporating materials like graphene, holds significant potential here. Graphene's exceptional mechanical and electrical properties, combined with its high surface area, allow for a more pronounced interaction with minute strain changes or subtle variations in environmental parameters like temperature or humidity. By coating the fibre with such materials, researchers are developing graphene-enhanced FOFS that promise significantly higher sensitivity. In real-world terms, this translates to the ability to detect much smaller micro-cracks, localised delaminations, or subtle changes in stress distribution at a far earlier stage than currently possible [30]. This enhanced fidelity is critical for proactive maintenance and ensuring the long-term integrity of highly loaded or safety-critical structures like aircraft components, wind turbine blades, and bridge decks.

AI-Driven Analytics for Predictive Maintenance: As FOFS deployments generate increasingly vast and complex datasets, the paradigm is shifting from simple rule-based anomaly detection towards sophisticated, AI-driven analytics. The application of machine learning algorithms to these continuous streams of strain, temperature, and vibration data is set to revolutionise maintenance strategies [31]. Instead of merely identifying that something has happened (reactive or condition-based monitoring), these algorithms can analyse patterns, correlate sensor responses with operational loads and environmental factors, and ultimately predict when and where potential issues are likely to occur before they become critical failures. This move towards truly predictive maintenance enables engineering operators to optimise inspection schedules, minimise costly unplanned downtime, and extend the useful life of assets, providing tangible economic and operational benefits across industries such as transport, energy infrastructure, and manufacturing.

Biodegradable Sensors for Sustainable Engineering: With a growing global emphasis on sustainability and the circular economy, the materials used in SHM systems are also coming under scrutiny. For certain applications, particularly those involving natural fibre composites or structures with defined service lives, the development of biodegradable sensors is gaining significant traction [32]. This involves exploring sensor designs and constituent materials that can safely and effectively degrade at the end of the composite's operational life cycle. This is particularly pertinent for less load-bearing or short-to-medium lifespan composite applications where traditional sensor materials might pose recycling or disposal challenges. Integrating biodegradable FOFS, or at least biodegradable components within the sensor system, aligns seamlessly with the principles of green engineering, reducing environmental burden and simplifying end-of-life management processes for composite structures.

These interconnected areas of research and development collectively point towards a future where SHM systems based on FOFS are not only more sensitive and intelligent but also contribute positively to the overall sustainability of engineering structures, driving forward the capabilities of smart, durable, and environmentally conscious composite applications.

In summary, Fibre Optic Fibre Sensors (FOFS) represent a truly significant and indeed, ground breaking advancement within the critical field of Structural Health Monitoring (SHM). Their inherent nature offers unparalleled capabilities for real-time, distributed strain monitoring directly within composite structures, a capability previously challenging to achieve effectively and reliably. This real-time insight is crucial for assessing structural integrity, predicting potential failures in situ, and ultimately optimising maintenance programmes, thereby extending operational lifespan, and enhancing safety margins.

Naturally, as with any innovative technology, the widespread implementation and long-term deployment of FOFS within complex composite systems present certain technical and practical challenges. These typically encompass considerations around seamless integration during the manufacturing process without compromising structural performance, ensuring robust long-term durability and survivability in diverse and often harsh operational environments, and the subsequent requirement for sophisticated signal processing techniques to interpret the vast amounts of sensor data generated accurately.

However, the promising path forward lies unequivocally in concerted interdisciplinary innovation. Crucially, ongoing advances in materials science are proving vital for developing bespoke sensor packaging and embedding techniques that ensure both the survivability of the sensitive optical fibres during demanding composite fabrication processes and their reliable, consistent performance over decades in the field. Concurrently, the rapid evolution in data analytics, machine learning algorithms, and artificial intelligence is essential for transforming raw sensor data into actionable intelligence, enabling automated damage detection, characterisation, and informed prognostic decision-making [33].
These combined efforts are genuinely heralding a new era in 'smart composites'. This is an era where composite structures are not merely passive load-bearing components, but active, self-aware systems capable of continuously sensing, analysing, and reporting their own condition. Such advanced capabilities will undoubtedly revolutionise the design, certification processes, deployment strategies, and asset management of composite structures across numerous critical sectors, from aerospace and civil infrastructure to renewable energy and transport. Whilst further rigorous validation, standardisation, and robust economic models are necessary to fully realise this potential on a grand scale, the fundamental benefits and transformative impact of integrating FOFS into composite SHM systems are undeniably clear and compelling from an engineering perspective.

3. Conclusion

FOFS represent a ground breaking advancement in SHM, offering unparalleled real-time strain monitoring capabilities. While challenges persist, interdisciplinary innovations in materials science and data analytics promise to overcome these barriers, heralding a new era in smart composites.

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