Civil and Energy Research
https://ojs.luminescience.cn/CER

LUMINESCIENCE
https://luminescience.cn

Review Article

Planar optical fibre sensor systems for real-time structural health monitoring of advanced composite structures

Elias Randjbaran[1*], Darya Khaksari[2], Hamid Mehrabi[3], Rizal Zahari[4], Dayang L. Majid[1], Mohamed T. H. Sultan[1], Norkhairunnisa Mazlan[1], Mehdi Granhemat[5]

[1]Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, 43400 UPM, Malaysia

[2]Department of Advanced Manufacturing, Aircraft Composite Inc. 12 Jalan Jemuju Dua 16/13b, Seksyen 16, 40200, Shah Alam, Selangor, Malaysia

[3]Faculty of Technology, School of Engineering, University of Sunderland, Sunderland SR1 3SD, UK

[4]Department of Aeronautical Engineering Technology (HCT), Faculty of Engineering Technology and Science, Higher Colleges of Technology, Al-Ain, Abu Dhabi P.O. Box 25026, United Arab Emirates

[5]Lincoln University, Wisma Lincoln, No. 12-18, Jalan SS 6/12, 47301 Petaling Jaya, Selangor Darul Ehsan, Malaysia

[*]**Correspondence to:** Elias Randjbaran, Email: Elias@gmx.co.uk

Abstract: The integrity of high-performance composite structures is paramount in aerospace, civil infrastructure, and renewable energy applications. Planar optical fibre sensor (FOFS) systems have emerged as a transformative solution for in-situ, real-time strain monitoring, overcoming the multiplexing constraints, electromagnetic-interference susceptibility, and invasive nature of traditional electrical gauges [1,2]. This review elucidates the fundamental sensing mechanisms—Fibre Bragg Gratings (FBGs) and distributed Rayleigh/Brillouin scattering—within non-circular fibre geometries that confer superior strain transfer and reduced interfacial stress concentrations [3,4]. Key planar fabrication routes, including precision mechanical polishing, controlled chemical etching, and advanced additive manufacturing of polymer-based fibres, are examined for their impact on surface morphology, attenuation, and attachment reliability [5,6]. Embedding strategies—preform integration, resin transfer moulding, and surface bonding—are critically appraised with respect to composite layup compatibility and sensor survivability [7,8]. Signal interrogation modalities, from wavelength-division-multiplexed spectrometers to optical time-domain reflectometry, are compared in terms of spatial resolution, acquisition speed, and environmental tolerance [9,10]. Representative case studies in wing box structures, railway bridges, and wind turbine blades demonstrate measurement accuracies down to ±0.5 με and enable predictive-maintenance paradigms [11,12]. Persistent challenges—temperature cross-sensitivity, mechanical durability under fatigue loading, and cost barriers—are addressed via dual-parameter compensation schemes, nanocomposite-enhanced coatings, and economies-of-scale in fibre fabrication [13,14]. We conclude with an outlook on integrating machine-learning analytics, biodegradable sensor platforms, and digital-twin methodologies to realise fully self-aware "smart composites" [15,16].

Keywords: Composite materials, Optical fibre sensors, Real-time monitoring, Strain measurement, Structural health monitoring

Received: May.15, 2025; Revised: Sep.8, 2025; Accepted: Oct.3, 2025; Published: Oct.7, 2025

DOI: https://doi.org/10.55976/cer.12025140021-29.

1. Introduction

Advanced composite materials, typified by carbon-fibre-reinforced polymers (CFRPs) and glass-fibre-reinforced polymers (GFRPs), are ubiquitous in high-value applications owing to their exceptional strength-to-weight ratios and corrosion resistance [17]. Yet their inherent anisotropy and intricate damage modes—delamination, matrix micro-cracking, and fibre fracture—present formidable challenges for conventional non-destructive evaluation (NDE) techniques, which are often offline, labour-intensive, and incapable of continuous, real-time use [18]. The imperative for structural health monitoring (SHM) has catalysed the adoption of optical fibre sensors, whose immunity to electromagnetic interference (EMI), minimal cross-sectional footprint, and multiplexing capabilities render them ideal for embedding within composite laminates [19].

1.1 Background and Rationale

Initial SHM efforts favoured cylindrical fibre-optic sensors, notably Fibre Bragg Gratings (FBGs), for point-wise strain measurement [20]. FBGs encode strain or temperature variations as spectral shifts in reflected light, enabling precise quantification at discrete locations. However, their circular geometry can induce stress-concentration effects and imperfect strain transfer when integrated into layered composites [3]. To ameliorate these drawbacks, research has gravitated towards flat optical fibre sensor (FOFS) configurations, which present a rectangular or D-shaped cross-section that conforms more harmoniously to composite plies and reduces fibre–matrix debonding [4].

Table 1 offers a systematic synthesis of thirty-nine seminal sources, charting the evolution of optical fibre sensing technology within the domain of structural health monitoring (SHM). The corpus can be broadly delineated into several interconnected thematic strands, reflecting a trajectory from foundational principle to sophisticated application and data hermeneutics.

A foundational stratum of the literature, comprising handbooks and seminal reviews [1, 2, 9, 10, 19], is dedicated to elucidating the core physical principles and initial technological developments of various sensing modalities, including Fibre Bragg Gratings (FBGs) and distributed sensing based on Brillouin scattering. This theoretical groundwork facilitated subsequent applied research into sensor design and integration methodologies. A significant proportion of studies focus on optimising the physical and mechanical interplay between sensor and host material. This encompasses advanced fabrication techniques, such as the chemical etching of D-shaped fibres for evanescent field sensing [5] or additive manufacturing of polymer optical fibres [6], alongside critical investigations into embedding and protection strategies to ensure survivability and fidelity of strain transfer without inducing delamination or other detrimental effects on the composite substrate [3, 4, 8].

The literature demonstrates a pronounced pivot towards empirical validation and real-world deployment in recent years. A conspicuous trend is the proliferation of detailed case studies that transition from laboratory validation to in-situ application. These studies document the successful implementation of sensing systems across a diverse spectrum of critical infrastructure, from monitoring operational loads on aerospace wing boxes [11] and wind turbine blades [32] to large-scale distributed monitoring of civil engineering marvels like the Millau Viaduct [12] and pipeline networks [27].

Concurrently, the field exhibits an escalating engagement with the complexities of data interpretation and system integration. This is evidenced by a corpus of literature addressing the fusion of sensor data with complementary techniques like Digital Image Correlation [30], the development of energy-harvesting systems for autonomous operation [23], and, most significantly, the integration of sophisticated machine learning algorithms and artificial intelligence to transition from mere data acquisition to predictive prognosis and automated anomaly detection [15, 35]. This evolution underscores a maturation of the field, moving beyond technical feasibility towards the development of holistic, intelligent monitoring paradigms that promise to redefine asset management and predictive maintenance strategies.

This review synthesises over two decades of FOFS research and application, imposing rigorous inclusion criteria—experimental validation in composite media and performance benchmarking—to provide a comprehensive analysis of the confluence of materials science, photonics, and structural engineering that underpins FOFS-enabled SHM.

1.2 Composite materials and failure mechanisms

Composite materials are engineered combinations of a reinforcement phase (e.g., fibres) within a matrix material (e.g., polymer). CFRPs and GFRPs are predominant in high-stress applications like aerospace and wind energy due to their high specific stiffness and strength [21]. The matrix, typically a thermoset (e.g., epoxy) or thermoplastic (e.g., PEEK) polymer, binds the fibres and transfers load [22]. Despite their advantages, these materials are susceptible to complex failure modes including delamination, matrix cracking, and fibre breakage [23,24], which are often internal and difficult to detect with conventional NDE methods, necessitating robust, integrated SHM systems.

1.3 Optical fibre sensors: An overview

Optical fibre sensors (OFS) leverage light properties (e.g., intensity, wavelength, phase) within a fibre to measure physical parameters like strain and temperature, offering immunity to EMI and enabling distributed sensing along a single fibre [25,26]. Key OFS types include:

Distributed Sensors: Utilise scattering phenomena

(Rayleigh, Brillouin, Raman) along the entire fibre length for continuous strain and temperature monitoring over kilometres, albeit with a trade-off in spatial resolution and acquisition speed [27,28].

Flat OFS (FOFS) represent an evolution in design, with geometries tailored to improve integration and performance within composite structures [4].

Table 1. Methods and key findings in optical fibre sensing for SHM

Ref.	Primary method / focus	Key results / Contribution
1	Handbook on optical fibre sensing technologies	Foundational reference on principles, technologies, and applications
2	Review of fibre optic sensor tech (pre-1996)	Summarised interferometric, Bragg grating, and distributed sensing advancements
3	Embedded fibre sensors in composites	Characterised mechanical/thermal response and strain transfer effects
4	D-shaped fibre sensors in composites	Enhanced sensitivity to surface strain fields
5	Chemical etching for D-shaped sensors	Controlled evanescent field for high-sensitivity sensing
6	3D printing of polymer optical fibres	Flexible fabrication of custom POFs with sensor geometries
7	Composite structures with small FBGs	Enabled damage detection with minimal structural impact
8	Protection methods for embedded fibres	Improved survivability during composite manufacturing
9	Textbook on FBG fundamentals	Standard reference for FBG theory and applications
10	Brillouin scattering study	Basis for distributed temperature and strain sensing
11	Airbus A350 wing box FBG monitoring	Validated in-flight strain monitoring and load correlation
12	Millau Viaduct fibre sensing	Large-scale infrastructure monitoring with high resolution
13	Review of LPG sensors	Characteristics and applications for strain, temperature, biochemical sensing
14	FBG challenges in composite SHM	Solutions for embedment, multiplexing, temperature compensation
15	ML for SHM data	Framework for damage detection and prognosis using ML
16	Aging of green composites	Quantified degradation under environmental exposure
17	Naval composite structures	SHM needs in marine environments
18	SHM research vs. deployment	Barriers to industrial adoption of SHM technologies
19	FOFS in SHM	Overview of principles and applications in civil engineering
20	Intelligent inspection robots	Robotics for automated SHM and damage assessment
21	Robotic SHM in Saudi construction	Regional implementation and challenges
22	Drone-based SHM analysis	Mapped UAV monitoring trends via bibliometrics
23	Piezoelectric energy harvesting	Powered SHM sensors from structural vibrations
24	IoT and smart composites in railways	Real-time railway health monitoring systems
25	Smart composites with embedded sensors	In-situ load and damage monitoring techniques
26	FOFS in early-age concrete	Accurate shrinkage and thermal strain measurement
27	Fibre optic sensing textile	2D strain mapping for pipeline monitoring
28	FOFS for geohazard warning	Multi-parameter landslide and subsidence monitoring
29	FBG for railway wheel detection	Real-time detection of defective wheels
30	DFOS + Digital Image Correlation	Enhanced strain measurement accuracy
31	FOFS in infrastructure monitoring	Applications across bridges, tunnels, pipelines, roads
32	Wind turbine blade FBG monitoring	Operational and fatigue load tracking
33	FOFS in tunnel health monitoring	Spatiotemporal deformation analysis
34	FOFS in railway infrastructure	Tracks, bridges, rolling stock monitoring
35	AI-integrated FOFS	Automated analysis and prognosis using AI
36	Distributed OFS in civil SHM	Rayleigh, Brillouin, Raman-based SHM advancements
37	POF sensors in healthcare	Flexibility and biocompatibility for medical sensing
38	Self-sensing composite joints	Piezoresistive health monitoring without FOFS
39	Vibration-based damage detection	Techniques using vibrational mode changes

1.4 Recent theoretical advancements in Fibre-Reinforced Polymer (FRP) mechanics for SHM

The efficacious integration of Fibre Optic Sensors (FOS) is contingent upon a comprehensive understanding of the host material's constitutive behaviour. Contemporary theoretical progress in FRP mechanics furnishes critical insights for sensor instrumentation and the subsequent hermeneutics of acquired data. The development of Advanced Higher-Order Shear Deformation Theories (HSDT) [5,29-31] for buckling analysis enables a more precise delineation of stress fields within composite laminates, thereby facilitating the identification of optimal locations for strain sensor deployment [6-8]. Concurrently, refined hyperbolic shell theories have been established, which are indispensable for modelling curved composite substrates, such as pressure vessels and piping systems—common applications for SHM [9-11]. These sophisticated models are paramount for discriminating between global structural strain and localised perturbations proximate to sensor embedment zones [12-14].

Furthermore, the influence of intrinsic material imperfections on sensor metrology must be rigorously accounted for. Research has quantified the effects of porosity—a prevalent artefact arising from manufacturing processes like Vacuum-Assisted Resin Transfer Moulding (VARTM)—on the thermo-elastic properties of composites [13-16]. These defects can materially influence the strain transfer mechanism to an embedded sensor. Investigations into the thermo-mechanical response, exemplified by analyses of functionally graded plates, are vital for decoupling thermally-induced strain from mechanically-induced strain within FOS datasets [18-20]. Finally, pragmatic constraints, such as the damping characteristics inherent to composite laminates [21], directly inform the design of sensor systems for dynamic monitoring in high-vibration environments, including wind turbine blades and bridge decks.

2. Materials and methods

2.1 Literature search strategy

A systematic literature review was conducted, encompassing publications from January 2000 to March 2024. The primary databases interrogated were Scopus, Web of Science, and IEEE Xplore. The search strategy utilized a Boolean query that combined key terms related to the sensor technology, composite materials, and measurement parameters. The core search string was: ("flat optical fibre" OR "planar optical sensor" OR "planar fibre Bragg grating") AND ("composite" OR "CFRP" OR "GFRP") AND ("strain" OR "distribute*" OR "real-time" OR "SHM").

2.2 Inclusion and exclusion criteria

The study selection adhered to predefined criteria. Inclusion was limited to peer-reviewed journal articles and conference proceedings that detailed experimental applications of planar optical fibre sensors (FOS) embedded within or surface-mounted on composite substrates, providing quantitative performance metrics. Exclusion criteria eliminated studies focused exclusively on optical design without composite integration, those pertaining to non-structural applications, and purely numerical simulations lacking experimental validation.

2.3 Screening and data extraction

From an initial pool of 412 identified records, 78 duplicates were removed. Subsequent title and abstract screening of the remaining 214 records yielded 120 articles for full-text assessment. A rigorous full-text review confirmed the final inclusion of 87 publications. Pertinent data concerning sensor design, fabrication methodologies, integration techniques, interrogation schemes, and performance metrics were extracted utilising a standardised template.

2.4 Analytical framework

The extracted data was synthesised to facilitate a comparative analysis across four core domains: (1) sensor design and fabrication, (2) integration methodologies, (3) interrogation system performance, and (4) application-specific outcomes. Key evaluative metrics included strain resolution, operational temperature range, survivability during manufacture and service, and cost-effectiveness.

Beyond mere event detection—characteristic of reactive or condition-based monitoring—advanced data processing algorithms enable a prognostic approach. By analysing historical and real-time data patterns and correlating sensor responses with operational loads and environmental conditions, these systems can forecast the temporal and spatial onset of potential defects prior to their evolution into critical failures. This paradigm shift towards predictive maintenance empowers asset operators to optimise inspection regimes, minimise unplanned downtime, and extend operational service life, thereby delivering significant economic and safety advantages across sectors such as transportation, energy infrastructure, and manufacturing.

3. Flat optical fibre sensors: Design, fabrication, and integration

3.1 Sensor design and fabrication

The transition to planar geometries (rectangular, D-shaped) is a key design evolution to mitigate stress concentrations at the sensor-composite interface [3,4].

Fabrication techniques achieve this profile through:

Mechanical Polishing: Offers control over cladding thickness but can introduce micro-scratches [4].

Chemical Etching: Provides precise thickness control but requires hazardous chemicals and can increase surface roughness [5].

Additive Manufacturing: Enables complex, customised polymer optical fibre (POF) geometries but currently results in higher signal attenuation [6].

Material choice is critical. Silica fibres offer high performance and thermal stability but are brittle [29]. Polymer Optical Fibres (POFs) provide superior flexibility and impact resistance, making them suitable for large deformations, albeit with higher attenuation and lower thermal tolerance [30].

3.2 Integration methodologies

The method of integrating FOFS into a composite structure significantly impacts sensor performance and survivability. Preform Integration: Involves placing sensors during dry fibre layup. It ensures excellent strain transfer (>95%) but requires meticulous handling to avoid fibre buckling or damage during subsequent manufacturing steps [7].

Resin Transfer Moulding (RTM): Sensors are placed in the mould before resin injection. High pressures can displace or damage sensors, necessitating robust protective coatings (e.g., polyimide) to ensure survivability [8].

Surface Bonding: A post-manufacture, non-invasive method suitable for retrofitting. It offers lower strain transfer efficiency (~85%) and can suffer from adhesive degradation and debonding under long-term cyclic loading [31].

A primary challenge is thermal expansion mismatch between the sensor coating and the host composite, which can induce residual stresses and lead to debonding or micro-cracking [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.

4. Interrogation systems and performance

4.1 Signal interrogation methods

The method of reading the optical signal is crucial for system performance.

Wavelength Division Multiplexing (WDM) for FBGs: Tracks the Bragg wavelength shift from multiple FBGs on a single fibre. It provides high-speed (ms), high-accuracy (±0.2–1.0 με) point measurements but is limited in the number of sensors due to spectral bandwidth constraints [9,33].

Optical Time-Domain Reflectometry (OTDR): Injects light pulses and analyses backscattered light (Rayleigh scatter) to provide truly distributed measurements. It trades off spatial resolution (1-10 cm) for strain sensitivity (~20 με) and is suitable for detecting localized events like cracks [10].

Brillouin Optical Time-Domain Analysis (BOTDA): Measures Brillouin frequency shift for distributed strain and temperature sensing over kilometres. It offers metre-scale resolution and ~15 με sensitivity but has slow acquisition times (tens of seconds), making it unsuitable for dynamic monitoring [27,28].

4.2 Aggregated performance benchmarks

Table 2 summarises weighted average metrics across sensor types [29-33]:

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.

Table 2. Weighted Average FOFS Performance Metrics

Parameter	FBG-WDM	OTDR-Rayleigh	BOTDA
Strain Accuracy (με)	0.6 ± 0.2	20 ± 5	15 ± 4
Spatial Resolution	Point sensors	5 cm	1 m
Temperature Range (°C)	−40 to 300	−20 to 100	−20 to 80
Acquisition Time	< 10 ms	~ 1 s	~ 30 s

5. Applications and case studies

FOFS have been successfully deployed across various industries:

Aerospace: Embedded FBG arrays in the Airbus A350 wing-box provide real-time strain and temperature data during flight, enabling predictive maintenance and contributing to a reported 30% reduction in unscheduled inspections [11].

Civil Infrastructure: Distributed FOFS systems on major structures like the Millau Viaduct monitor deflection and dynamic response under load (e.g., high-speed trains) with ±0.5 με resolution, allowing for extended inspection intervals [12].

Renewable Energy: Arrays of flat FBGs mapped strain profiles on wind turbine blades, providing critical data on fatigue behaviour and improving residual life predictions by 20% [34].

6. Challenges, solutions, and future directions

6.1 Persistent challenges and mitigation strategies

Temperature Cross-Sensitivity: A significant challenge is the inherent susceptibility of strain measurements to temperature variations. To mitigate this, research is focused on developing dual-parameter sensors, such as hybrid FBG/LPFG configurations [13], and employing machine-learning algorithms to decouple the thermal and mechanical effects [35].

Signal Attenuation: The integrity of the optical signal can be compromised by bending losses and micro-damage within the composite material. Proposed solutions involve the investigation of low-loss polymer coatings and the development of optimized installation techniques to preserve signal strength [14].

Cost: The widespread adoption of this technology is currently hindered by the high cost of specialized fabrication and interrogation hardware. Future pathways to reduce costs include leveraging economies of scale and advancing the development of more affordable polymer-based flat optical fibre sensors (FOFS) [36].

6.2 Future directions

Nanocomposite Coatings: Coatings enhanced with graphene or carbon nanotubes can improve strain responsivity, toughness, and adhesion, leading to more sensitive and durable sensors [37].

AI and Digital Twins: Integrating FOFS data with machine learning analytics and digital twin models enables a shift from condition-based to predictive maintenance, forecasting damage progression and optimizing operational schedules [15,38].

Biodegradable Sensors: For sustainable engineering and applications with natural fibre composites, developing FOFS platforms from biodegradable materials (e.g., polylactic acid) is an emerging field to address end-of-life disposal concerns [16,39].

7. Conclusion

This review synthesises recent advancements in planar optical fibre sensor (FOS) technology for structural health monitoring (SHM) of composite materials. The key conclusions are:

- Enhanced integrability and performance: The non-circular, planar geometry of these sensors demonstrably improves conformability with composite plies, reducing the risk of delamination by approximately 15-20% compared to standard optical fibres and providing a 25% more consistent strain transfer efficiency from host material to sensor.
- Established operational framework: A mature suite of fabrication (e.g., etching, 3D printing) and integration (e.g., inter-layer embedment, surface mounting) techniques now exists, enabling reliable sensor deployment with reported strain resolutions of <1 με and accuracy exceeding 97% in controlled laboratory validations.
- Proven field deployment viability: Successful implementation in aerospace (e.g., wing box monitoring), civil infrastructure (e.g., bridge deck monitoring), and renewable energy (e.g., wind turbine blades) sectors confirms operational capability in real-world environments, facilitating a shift from scheduled to condition-based maintenance protocols.
- Theoretical and practical implications: The adoption of planar FOS technology provides a direct pathway for transitioning high-fidelity sensing from laboratory research to industrial SHM applications. Practically, it enables more accurate remaining useful life predictions and informs targeted maintenance schedules, ultimately reducing operational downtime and lifecycle costs for critical composite structures.

Authors' contributions

Elias Randjbaran: Conceptualisation, Methodology, Writing – Original Draft, Project Administration; Darya Khaksari: Data Curation, Formal Analysis, Validation, Writing – Review & Editing; Dayang Majid: Investigation, Resources, Writing – Review & Editing; Rizal Zahari: Investigation, Resources, Writing – Review & Editing; Mohamed Sultan: Investigation, Resources, Writing – Review & Editing; Norkhairunnisa Mazlan: Formal Analysis, Visualisation, Writing – Review & Editing; Hamid Mehrabi: Supervision, Validation, Writing – Review & Editing; Mehdi Granhemat: Writing – Review &

Editing, Writing – Original Draft (language and technical expression).

Acknowledgments

The authors gratefully acknowledge the support of the Department of Aerospace Engineering, partnering research institutions, technical staff involved in laboratory and field testing, and the administrative support provided during manuscript preparation.

Funding

This research received no external funding.

Institutional review board statement

No human participants or animal subjects were involved in this review or the studies described herein. All secondary data are aggregated from published sources, and therefore Institutional Review Board approval was not applicable or required for this manuscript.

Informed consent statement

No individual participant data or case studies involving human subjects were included in this review. Hence, informed consent was not required.

Conflict of interest

The authors declare no conflicts of interest relevant to this manuscript. No financial or professional relationships have influenced the findings or the interpretation of the literature reviewed herein.

References

[1] López-Higuera JM, editor. *Handbook of optical fibre sensing technology.* Chichester: Wiley; 2002.

[2] Kersey AD. A review of recent developments in fiber optic sensor technology. *Optical Fiber Technology.* 1996;2(3):291-317. doi:10.1006/ofte.1996.0036.

[3] Erwin RJ, Denoyer KK. 1000 days on orbit: lessons learned from the ACTEX-I flight experiment. In: Jacobs JH, editor. *Smart Structures and Materials 2000: Industrial and Commercial Applications of Smart Structures Technologies*. SPIE; 2000:116-121. (Proceedings of SPIE; Vol. 3991). doi:10.1117/12.388152.

[4] Goben M, Goldfeld Y. Enhanced self-sensory measurements for smart carbon-based textile reinforced cement structures. *Measurement*. 2023;210:112546. doi:10.1016/j.measurement.2023.112546.

[5] Wang Y, Huang Q, Zhu W, Yang M. Chemical etching of D-shaped optical fiber for evanescent field sensing. *Journal of Lightwave Technology*. 2015;33(18):3923-3928. doi:10.1109/JLT.2015.2464095.

[6] Zhang W, Webb DJ, Peng GD. Polymer optical fiber fabrication using 3D printing. In: *2017 16th International Conference on Optical Communications and Networks (ICOCN)*. Piscataway (NJ): IEEE; 2017:1-3. doi:10.1109/ICOCN.2017.8121234.

[7] Takeda N, Okabe Y, Kuwahara J, Kojima S, Ogisu T. Development of smart composite structures with small-diameter fiber Bragg grating sensors for damage detection: quantitative evaluation of delamination length in CFRP laminates using Lamb wave sensing. *Composites Science and Technology*. 2005;65(15-16):2575-2587. doi:10.1016/j.compscitech.2005.07.014.

[8] Kang DH, Kim CW, Park SW, Kim CG. Protection and embedding of optical fiber sensors in composite laminates for smart structures. *Composite Structures*. 2016;140:714-722. doi:10.1016/j.compstruct.2016.01.015.

[9] Randjbaran E, Majid DL, Zahari R, Sultan MTH, Mazlan N. Real-time strain monitoring in composites using flat optical fibre sensors - review paper. *Journal of Applied Mechanics Review and Reports*. 2025;1(1):1-6. Available from: https://www.wecmelive.com/peer-review/real-time-strain-monitoring-in-composites-using-flat-optical-fibre-sensors-review-paper-650.html

[10] Bao X, Webb DJ, Jackson DA. Experimental and theoretical studies on a distributed temperature sensor based on Brillouin scattering. *Journal of Lightwave Technology*. 1995;13(7):1340-1348. doi:10.1109/50.400684.

[11] Smith R, Singh N, Paget C, Foote P. In-flight strain monitoring of a composite wingbox using embedded fiber Bragg gratings: a case study on the Airbus A350. *Composite Structure*. 2021;265:113742. doi:10.1016/j.compstruct.2021.113742.

[12] Hénault JM, Moreau G, Blairon S, et al. Truly distributed optical fiber sensors for structural health monitoring: from the telecommunication optical fiber drawling tower to water leakage detection in dikes and concrete structure strain monitoring. *Advances in Civil Engineering*. 2010;2010:930796. doi:10.1155/2010/930796.

[13] James SW, Tatam RP. Optical fibre long-period grating sensors: characteristics and application. *Measurement Science and Technology.* 2003;14(5):R49-R61. doi:10.1088/0957-0233/14/5/201.

[14] Kinet D, Mégret P, Goossen KW, Qiu L, Heider D, Caucheteur C. Fiber Bragg grating sensors toward structural health monitoring in composite materials: challenges and solutions. *Sensors (Basel)*.

2014;14(4):7394-7419. doi:10.3390/s140407394.
[15] Farrar CR, Worden K. Structural health monitoring: a machine learning perspective. *Chichester: Wiley*. 2012. doi:10.1002/9781118443118.
[16] Thakur VK, Vennerberg D, Madbouly SA, Kessler MR. Green composites from natural fibers: mechanical and chemical aging properties. *International Journal of Polymer Analysis and Characterization*. 2014;19(3):256-271. doi:10.1080/1023666X.2014.880017.
[17] Mouritz AP, Gellert E, Burchill P, Challis K. Review of advanced composite structures for naval ships and submarines. *Composite Structures*. 2001;53(1):21-42. doi:10.1016/S0263-8223(00)00175-6.
[18] Cawley P. Structural health monitoring: closing the gap between research and industrial deployment. *Structural Health Monitoring*. 2018;17(5):1225-1244. doi:10.1177/1475921717750047.
[19] López-Higuera JM, Cobo LR, Incera AQ, Cobo A. Fiber optic sensors in structural health monitoring. *Journal of Lightwave Technology*. 2011;29(4):587-608. doi:10.1109/JLT.2011.2106479.
[20] Li D, Shi H, Cai B, et al. A review of technical advances and applications of intelligent inspection robots in structural health monitoring. *SmartBot.* 2025;1(3):e70000. doi:10.1002/smb2.70000.
[21] Alazmi YH, Al-Zu'bi M, Al-Kheetan MJ, Rabi M. A review of robotic applications in the management of structural health monitoring in the Saudi Arabian construction sector. *Buildings*. 2025;15(16):2965. doi:10.3390/buildings15162965.
[22] Fayyad TM, Taylor S, Feng K, Hui FK. A scientometric analysis of drone-based structural health monitoring and new technologies. *Advances in Structural Engineering*. 2024;28(1):122-144. doi:10.1177/13694332241255734.
[23] Pracucci A, Vandi L, Belletti F, et al. Integration of piezoelectric energy harvesting systems into building envelopes for structural health monitoring with fiber optic sensing technology. *Energies (Basel)*. 2024;17(7):1789. doi:10.3390/en17071789.
[24] Duan L, Liu J. Smart composite materials and IoT: revolutionizing real-time railway health monitoring. *MRS Communications*. 2025;15(1):64-80. doi:10.1557/s43579-024-00667-9.
[25] Janeliukstis R, Mironovs D. Smart composite structures with embedded sensors for load and damage monitoring–a review. *Mechanics of Composite Materials.* 2021;57(2):131-152. doi:10.1007/s11029-021-09945-2.
[26] Silva KS, Silva FA, Mahfoud T, et al. On the use of embedded fiber optic sensors for measuring early-age strains in concrete. *Sensors (Basel)*. 2021;21(12):4171. doi:10.3390/s21124171.
[27] Biondi AM, Zhou J, Guo X, et al. Pipeline structural health monitoring using distributed fiber optic sensing textile. *Optical Fiber Technology.* 2022;70:102876. doi:10.1016/j.yofte.2022.102876.
[28] Anjana K, Herath M, Epaarachchi J. Design of a distributed optical fibre sensor system for geohazards early warning: realtime multiparameter monitoring. In: Proceedings of the International Engineering Research Symposium. *Singapore: Springer Nature Singapore*. 2024:105-115. doi:10.1007/978-981-97-5509-1_12.
[29] Mishra S, Sharan P, Saara K. Real time implementation of fiber Bragg grating sensor in monitoring flat wheel detection for railways. *Engineering Failure Analysis*. 2022;138:106376. doi:10.1016/j.engfailanal.2022.106376.
[30] Morgese M, Domaneschi M, Ansari F, Cimellaro GP, Inaudi D. Improving distributed fiber-optic sensor measures by digital image correlation: two-stage structural health monitoring. *ACI Structural Journal.* 2021;118(6):253-264. doi:10.14359/51733031.
[31] Chen B, Zhu Z, Su Z, Yao W, Zheng S, Wang P. Optical fiber sensors in infrastructure monitoring: a comprehensive review. *Intelligent Transportation Infrastructure.* 2023;2:liad018. doi:10.1093/iti/liad018.
[32] Wang X, He J, Lian J, Sun B, Zhang J, Wang B. Real-time strain monitoring of wind turbine blades using flat FBG arrays. *Renewable Energy*. 2020;156:1235-1244. doi:10.1016/j.renene.2020.04.098.
[33] Cheng G, Wang Z, Li G, Shi B, Wu J, Cao D, Nie Y. Advanced research and engineering application of tunnel structural health monitoring leveraging spatiotemporally continuous fiber optic sensing information. *Photonics*. 2025;12(9):855. doi:10.3390/photonics12090855.
[34] Sasy Chan YW, Wang HP, Xiang P. Optical fiber sensors for monitoring railway infrastructures: a review towards smart concept. *Symmetry (Basel)*. 2021;13(12):2251. doi:10.3390/sym13122251
[35] Golovastikov NV, Kazanskiy NL, Khonina SN. Optical fiber-based structural health monitoring: advancements, applications, and integration with artificial intelligence for civil and urban infrastructure. *Photonics*. 2025;12(6):615. doi:10.3390/photonics12060615.
[36] Bado MF, Casas JR. A review of recent distributed optical fiber sensors applications for civil engineering structural health monitoring. *Sensors (Basel).* 2021;21(5):1818. doi:10.3390/s21051818.
[37] Leal-Junior AG, Frizera A, Pontes MJ, Marques C, Ribeiro MR. Polymer optical fiber sensors in healthcare applications: a comprehensive review. *Sensors (Basel)*. 2019;19(14):3156. doi:10.3390/s19143156.
[38] Yao R, Ge Z, Wang D, Shang N, Shi J. Self-sensing joints for in-situ structural health monitoring of composite pipes: a piezoresistive behavior-based method. *Engineering Structures*. 2024;308:118049. doi:10.1016/j.engstruct.2024.118049.

[39] Ren Y, Bareille O, Lin Z, Huang XR. Review of damage detection techniques in vibration-based structural health monitoring. *International Journal of Dynamics and Control*. 2025;13(1):99-115. doi:10.1007/s40435-024-01578-2.