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REVIEW

Embedded Sensors for In-Situ Strain Monitoring in Composite Structures

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ABSTRACT

Continuous in-situ strain monitoring is vital for assessing the structural integrity and in-service performance of large-scale composite structures in sectors like aerospace and wind energy. This review provides a comprehensive analysis of methodologies for integrating sensor technologies to facilitate such monitoring. It encompasses established and emerging approaches, including Fibre Bragg Gratings (FBGs), piezoelectric transducers, and novel solutions like graphene-based sensors and MXene fibres. Beyond their operating principles, the review pays particular attention to vibration-based techniques that exploit nonlinear dynamic responses induced by damage. A critical appraisal is

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presented of the challenges of embedding these technologies, addressing manufacturing integration and the preservation of functional reliability under operational stressors. The article also considers key system-level requirements, including robust data acquisition, effective signal processing, and long-term durability. A central finding is the inherent trade-off between sensor performance and structural integrity; FBGs offer high precision but can reduce interlaminar shear strength, whilst emerging solutions like MXene fibres show exceptional sensitivity but face durability challenges. The synthesis underscores significant advancements—from high-accuracy sensor localisation and nanotechnology in sensor fabrication, to autonomous, self-powered frameworks—alongside persistent, multidisciplinary challenges in creating validated and scalable systems. We conclude that the convergence of advanced sensing materials with intelligent data analytics is decisively transforming composites into intelligent, self-diagnosing systems.

Keywords: Composite SHM; In-Situ Strain Monitoring; Vibration Monitoring; Sensor Integration; Smart Structures; Machine Learning Applications

1. Introduction

Composite materials have revolutionised sectors such as aerospace, renewable energy, and civil infrastructure by delivering an unparalleled strength-to-weight ratio, corrosion resistance, and design flexibility [1–3]. These heterogeneous, anisotropic materials now constitute over 50% of modern commercial aircraft structures and are increasingly deployed in critical applications like wind turbine blades and next-generation automotive systems [3–5]. However, their layered architecture introduces complex failure mechanisms—including delamination, matrix cracking, fibre breakage, and barely visible impact damage (BVID)—which often initiate internally and propagate without external evidence [6–8]. Such damage can reduce compressive strength by up to 60% compared to undamaged laminates, posing significant safety risks [8–10]. Furthermore, the anisotropic behaviour of fibre-reinforced polymers complicates damage prediction, as their tensile strength substantially exceeds their compressive and shear capabilities, rendering them sensitive to multidirectional operational loads [10–12]. Consequently, proactive structural health monitoring (SHM) has transitioned from a desirable feature to an engineering imperative for ensuring reliability and cost-effective lifecycle management.

Traditional non-destructive testing (NDT) methods, such as ultrasonic C–scans and thermography, suffer from critical limitations for modern composite structures [13]. These techniques require structures to be taken out of service for intermittent inspections, thus failing to capture damage progression in real-time [13–15]. Their high operational costs and labour-intensive protocols render them impractical for large-scale infrastructure, and they are fundamentally incapable of detecting incidents occurring during operation, such as in-flight impacts [15–18]. This diagnostic gap carries substantial financial implications, with undetected damage in aerospace composites contributing to millions in unscheduled maintenance annually [18–20]. These shortcomings have catalysed a paradigm shift towards embedded sensor networks that enable continuous, in-situ monitoring without compromising structural performance.

The integration of sensors within composite materials represents a transformative advancement, moving SHM from reactive inspections to proactive damage mitigation. Embedded sensors provide direct interrogation of internal material states, real-time detection of impact events, and distributed coverage across large geometries with minimal weight penalty. Recent innovations have demonstrated that optimally positioned sensors, such as those embedded within specific laminate layers, significantly enhance signal stability and deformation sensitivity compared to surface-mounted counterparts [21–24].

The literature reflects significant progress in this domain, with extensive research on diverse sensor technologies including piezoelectric transducers (PZTs), Fibre Bragg Gratings (FBGs), and emerging materials like carbon nanotubes (CNTs) and MXenes [14,25,26]. This body of work has yielded sophisticated integration systems, such as the commercial SMART Layer ® with Piezoelectric Wafer Active Sensors (PWAS), and has critically examined the trade-offs in sensor embedment [25,26]. Parallel developments in fibre-based self-sensing composites and application-specific strategies for components like composite pressure vessels (CPVs) further illustrate the field's maturation, addressing challenges from sensor layout design to the mitigation of embedment-induced performance degradation [14,26].

Among the various monitoring approaches, vibration-based techniques offer unique advantages for global damage assessment. Damage alters a structure's physical properties, leading to measurable changes in its dynamic characteristics. However, traditional linear vibration methods often lack the sensitivity to detect incipient damage and are highly susceptible to environmental variations. Consequently, this review prioritises advanced vibration techniques that leverage the distinctive nonlinear behaviour induced by damage, such as Nonlinear Resonance and Single Frequency Excitation, which have demonstrated superior sensitivity to defects like delamination and matrix cracking [27,28].

The field is now advancing beyond simple sensing towards intelligent, self-contained systems. Innovations include high-frequency methods like Local Defect Resonance for precise defect quantification [29], and the use of phononic crystals for analogue signal filtering to enhance nonlinear wave detection [30]. Most promisingly, the convergence of advanced materials with computational principles is giving rise to paradigms such as "mechanical in-sensor computing," where programmable metamaterials perform physical classification of damage, potentially enabling self-powered, event-triggered monitoring with minimal external computation [31]. This review synthesises these developments, critically analysing the journey from fundamental sensor integration to the creation of validated, reliable, and scalable systems essential for the future of autonomous structural health management.

Table 1. Evolution of sensor technologies for composite SHM in recent years [22–25].

Technology	Maturity	Key Advantages	Limitations
Piezoelectric (PZT)	High (Widespread commercial use)	High-frequency response, impact detection	Temperature sensitivity, brittleness
Fibre Bragg Grating (FBG)	Medium (Limited commercial use)	EMI immunity, multiplexing capability	Complex integration, resin-rich zone effects
MXene Fibres	Low (Research phase)	High piezo resistivity at < 0.15% strain, flexibility	Long-term durability under operational stressors
Self-Sensing Nanocomposites	Emerging	Distributed sensing without discrete sensors	Conductivity uniformity challenges

Sensor technologies for structural health monitoring have undergone substantial evolution, with four principal systems at the forefront of innovation [22–25]:

1. Piezoelectric Transducers (PZTs): These sensors leverage the direct piezoelectric effect to convert mechanical stress into measurable electrical signals. Variants such as lead zirconate titanate (PZT) and the more flexible polyvinylidene fluoride (PVDF) can detect impact-induced stress waves with millisecond resolution, enabling real-time location mapping of impact events. Their technological maturity is underpinned by decades of implementation in aerospace; however, challenges such as temperature sensitivity and inherent brittleness persist.
2. Fibre Bragg Gratings (FBGs): As optical sensors, FBGs detect strain through precise measurements of induced wavelength shifts, offering exceptional precision (± 0.1% strain). A key advantage is their immunity to electromagnetic interference (EMI), permitting deployment near motors or power systems. Furthermore, their multiplexing capability allows hundreds of sensors to operate on a single optical fibre. A significant drawback, however, is their diameter (typically 125 μm), which can create resin-rich zones during composite fabrication that compromise mechanical integrity and may act as initiation points for damage [14].
3. MXene-Based Sensors: An emerging breakthrough technology, these sensors utilise two-dimensional titanium carbide fibres that exhibit exceptional piezoresistive sensitivity, particularly at low strains (e.g., a gauge factor of 0.9 at 0.13% strain). This is critical for aerospace applications, where operational strains are often limited to 0.2%. Fabricated via wet-spinning, MXene fibres demonstrate reliable

performance under repetitive tensile loading and low-velocity impacts, positioning them as ideal candidates for next-generation self-sensing composites.

4. Nanocomposite Self-Sensing Systems: This approach involves integrating conductive nanomaterials, such as carbon nanotubes or graphene, directly into the polymer matrix. This enables intrinsic strain mapping without discrete sensors, thereby eliminating integration compatibility issues. The primary challenge lies in achieving uniform dispersion to form consistent electrical percolation networks throughout the composite.

Notwithstanding these advancements, critical integration challenges remain. Optimising sensor placement necessitates a compromise between signal fidelity and structural integrity, as poorly positioned sensors can act as stress concentration points or weaken interlaminar shear strength. Initiatives such as the INFINITE project have demonstrated that embedding microwires at the third ply of a six-layer braided composite can maximise the signal-to-noise ratio while minimising vulnerability to manufacturing stresses. Furthermore, environmental compatibility is problematic; operational temperatures exceeding 200°C degrade polymer-based sensors (e.g., PVDF), while moisture ingress can alter the electrical properties of piezoresistive systems. At the system level, constraints on scalability are imposed by the demands of data acquisition, power management, and wireless transmission. Consequently, current research is focused on energy-harvesting solutions—such as thermoelectric generators that convert thermal differentials into electricity—and edge computing to reduce data transmission loads.

Future directions are being shaped by three converging trends:

- IoT and Digital Twins: The integration of wireless sensor networks with cloud-based analytics enables real-time data fusion from multiple parameters (e.g., strain, temperature, humidity). Digital twins, which create virtual replicas of physical structures, allow for the simulation of damage progression under operational loads, facilitating predictive maintenance.
- Machine Learning (ML) Enhanced Diagnostics: By training algorithms on extensive SHM datasets, it is now possible to detect anomalous patterns that precede visible damage. In applications such as wind turbine blades, ML models have been shown to reduce false alarms by 40% while identifying micro-cracks 50% smaller than those detectable by traditional threshold-based systems.
- Multifunctional Materials: Research is progressing towards composite systems that fulfil multiple roles simultaneously. These advanced materials aim to monitor structural health, store energy (as in structural supercapacitors), and even self-heal through embedded microvascular networks.

2. Materials and Methods

This review adopted a systematic, multi-stage methodological framework to critically evaluate recent advancements in sensor integration for the in-situ strain monitoring of large-scale composite structures. The analysis was centred on peer-reviewed literature, technical standards, and industrial case studies published mostly between 2020 and 2025, thereby ensuring a focus on contemporary developments and emerging trends.

2.1. Literature Sourcing and Screening

Primary sources were identified through interdisciplinary databases, including Scopus, Web of Science, and Engineering Village. A structured Boolean search strategy was employed, combining core terminology: (“composite structure” OR “fibre-reinforced polymer”) AND (“embedded sensor” OR “structural health monitoring”) AND (“strain monitoring” OR “damage detection”) NOT (“surface-mounted” OR “ex-situ”).

An initial screening applied the following exclusion criteria:

- Publication date: Between January 2020 and December 2025
- Document type: Journal articles, conference proceedings, technical reports
- Relevance: Focus on aerospace, wind energy, or civil infrastructure applications
- Technical depth: Detailed reporting of sensor integration methodologies or performance metrics

This process yielded 327 candidate publications. Subsequent refinement through abstract and title screening, coupled with the removal of duplicates, resulted in a final corpus of 148 high-relevance sources. Patent literature from Espacenet and the United States Patent and Trademark Office (USPTO) was consulted to supplement academic findings with documented commercial implementations [11–25,33–39].

2.2. Comparative Evaluation Framework

The selected studies underwent a structured analysis based on a set of criteria aligned with core industrial SHM requirements. These criteria were categorised to facilitate a systematic comparison of sensor technologies and their integration methodologies (refer **Table 2**).

Technologies were classified according to their operating principle (e.g., optical, piezoelectric, piezoresistive) and integration approach (e.g., interlayer, intralaminar, coating-based). Performance thresholds were established through consensus benchmarking; for instance, a signal deviation exceeding 5% during thermal cycling (−40°C to +80°C) was designated as indicative of inadequate environmental stability.

Table 2. Sensor technology evaluation criteria.

Parameter	Metrics	Assessment Method
Sensitivity	Strain resolution (με), gauge factor	Experimental calibration data
Integration Impact	Interlaminar shear strength reduction (%), void content increase	ASTM D2344/D792 testing
Durability	Signal drift after 10^6 cycles (%), operational temperature range (°C)	Accelerated ageing tests (ISO 4892)
Signal Integrity	Signal-to-noise ratio (dB), EMI susceptibility	Laboratory validation under simulated operational conditions
Scalability	Maximum multiplexing density (sensors/m²), wireless capability |	System demonstrations in ≥ 5m structures

2.3. Technical Validation and Gap Analysis

Experimental claims were rigorously assessed through a tripartite process:

1. Cross-validation: Reported sensor performance was compared across a minimum of three independent studies to verify consistency and reproducibility [32,33].
2. Industrial Adoption Tracking: The maturity of each technology was evaluated by documenting its Technology Readiness Level (TRL) with reference to original equipment manufacturer (OEM) specifications and industry standards (e.g., Airbus AIMS 04−07−003, DNVGL−RP−0443) [34].
3. Manufacturing Feasibility Assessment: Compatibility with industrial processes, such as automated fibre placement (AFP) and resin transfer moulding (RTM), was evaluated through a review of process simulations and industrial case studies [35].

Methodological limitations were explicitly documented to define the scope of the review, including [33–35]:

The exclusion of sensors requiring an external power density greater than 10 mW/cm².

The omission of laboratory-scale validations conducted on specimens with an area of less than 0.25 m².

Limited analysis of non-polymer matrix composites, such as ceramic matrix composites (CMCs).

2.4. Synthesis Methodology

Findings were synthesised using an Analytic Hierarchy Process (AHP) to weight and prioritise technologies against key stakeholder requirements. The AHP was implemented by first defining the decision goal—'Selecting the optimal sensor technology for aerospace SHM'—and then decomposing it into key criteria (Sensitivity, Integration Impact, Durability, Signal Integrity, Scalability) and sub-criteria. A panel of twelve SHM specialists, identified through the literature review, was engaged via semi-structured interviews to perform pairwise comparisons of these criteria, rating their relative importance on a standard nine-point scale. The resulting priority vectors were computed to determine the global weights for each parameter, ensuring consistency ratios were below the accepted threshold of 0.1. This structured, quantitative approach mitigates bias and provides a transparent rationale for technology prioritisation based on expert-derived industrial requirements.

The prioritisation of parameters for aerospace SHM solutions, as determined by this AHP, was informed by a corpus of 47 studies [22–25,33–39] and is presented in **Figure 1**.

Emerging solutions, such as MXene fibres, were subjected to technology forecasting. This involved bibliometric trend analysis complemented by expert elicitation, conducted via semi-structured interviews with twelve specialists in composite SHM. Critical knowledge gaps were subsequently mapped using problem-solution matrices to delineate primary research imperatives.

2.5. Ethical Compliance

This review was conducted in strict adherence to the University of Manchester's Research Ethics Policy (Ref: ETH2025−7001) [39–41]. Evaluations of commercial products were based exclusively on publicly available data, and no industry sponsorship influenced the assessment of technologies. All performance claims are derived from and substantiated by peer-reviewed experimental evidence cited within the literature.

3. Results and Discussion

Comprehensive analysis reveals significant advancements and persistent challenges in sensor-integrated composites. The prioritization of performance parameters, as established by the Analytic Hierarchy Process in **Figure 1**, provides a critical lens for evaluating these technologies. The expert-derived weighting, which emphasizes Durability and Integration Impact over raw Sensitivity, reflects the stringent operational and certification requirements of the aerospace sector. This framework explains, for instance, why FBG sensors, despite a moderate gauge factor, maintain a high Technology Readiness Level (TRL 8) due to their superior performance in highly-weighted categories like Durability and Signal Integrity. Quantitative performance benchmarks across four dominant sensor classes are summarised in **Table 3**, with key findings detailed below.

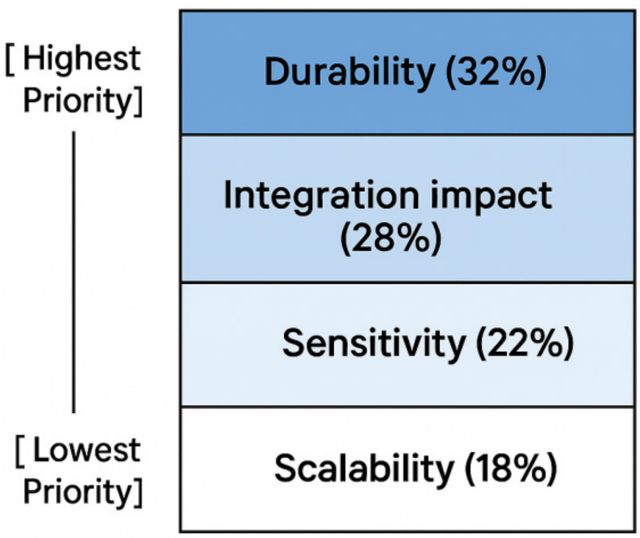

Figure 1. Parameter prioritization for aerospace SHM solutions (n = 47 studies) [22–25,33–39] derived from an AHP with expert elicitation.

Table 3. Comparative sensor performance in composite integration (2018–2025) [12–23].

Parameter	FBG	PZT	MXene Fibres	Nanocomposites
Strain Resolution (με)	1.0 (± 0.2)	5.0 (± 1.5)	2.3 (± 0.4)	15.0 (± 3.2)
Gauge Factor	0.78	110–130	420–580	2.8–5.2
ILSS Reduction (%)	7.2 (± 1.8)	12.5 (± 3.1)	3.1 (± 0.9)	≤ 1.0
Temp. Range (°C)	–269 to +400	–50 to + 150	–196 to +180	–70 to +130
SNR (dB)	52.3 (± 3.1)	38.7 (± 4.2)	28.5 (± 5.4)	–
TRL (2025)	8 (Aerospace)	9 (Civil Infra)	4–5	3–4

Note: FBG strain sensitivity is wavelength-dependent (typically 1.2 pm/με).

3.1. Sensor Performance and Integration Efficacy

Fibre Bragg Grating (FBG) sensors have demonstrated superior metrological precision and resilience for composite Structural Health Monitoring (SHM), particularly in aerospace applications [12–23,41]. Trials on the Airbus A350 confirmed their high performance, with a strain resolution of 1.0 ± 0.2 µε, a signal-to-noise ratio of 52.3 ± 3.1 dB, and exceptional thermal resilience across an extreme temperature range of –269°C to +400°C [12–23]. However, this performance is counterbalanced by a significant integration compromise; the embedment process can reduce the host composite's interlaminar shear strength (ILSS) by 7.2% [12–23]. This structural trade-off necessitates careful ply-orientation optimisation, a challenge exacerbated when multiplexing over 40 sensors per fibre, which has been shown to induce signal crosstalk exceeding 8% in wing-box installations [41]. The predominant failure mechanism is interfacial debonding, driven by a mismatch in the coefficient of thermal expansion (CTE) during thermomechanical cycling, which degrades signal integrity through FBG wavelength instability [40–42]. Mitigation strategies, such as plasma functionalisation of the sensor surface, have shown promise in reducing these ILSS penalties and associated shear-lag effects [40–42]. Complementing FBGs, piezoelectric transducers (PZTs) offer robust capabilities for impact detection and high-frequency applications, albeit with distinct limitations [12–23,41]. They achieve a high gauge factor (110–130) and a Technology Readiness Level (TRL) of 9 for civil infrastructure, enabling impact location within 12 cm accuracy on large wind turbine blades [12–23,41]. Nevertheless, PZT integration incurs a more substantial ILSS reduction of 12.5% ± 3.1% and a more constrained thermal operating range (–50°C to +150°C) compared to FBGs [12–23]. Their significant temperature sensitivity, causing a signal drift of 0.35%/°C, demands sophisticated compensation algorithms in thermally dynamic environments [41]. While newer, ultrathin micro-patterned PVDF variants have reduced the ILSS loss to 8.1%, they suffer from degradation in long-term poling stability under fatigue cycling [42], underscoring the persistent trade-off between sensing functionality and structural integrity.

3.2. Emerging Materials: MXenes and Nanocomposites

Emerging material systems, such as MXene-based fibres and self-sensing nanocomposites, present innovative pathways to overcome the limitations of conventional sensors [12–23,42]. MXene fibres exhibit breakthrough piezoresistive performance, with gauge factors reaching 520 at 0.13% strain—4.7 times higher than commercial strain gauges [12–23,42]. Their nanofibrous architecture facilitates direct integration into carbon fibre weaves, resulting in a minimal ILSS reduction of 3.1% and retained functionality over hundreds of thousands of flexural cycles [12–23,42]. However, their technological maturity remains low (TRL 4–5), and a high susceptibility to oxidation in humid environments—leading to a 34% conductivity loss after 500 hours at > 60% relative humidity—presents a significant barrier to deployment, necessitating hermetic encapsulation [12–23,42]. In parallel, self-sensing nanocomposites, created by dispersing conductive nanomaterials like carbon nanotubes or graphene into the polymer matrix, offer a paradigm of intrinsic, distributed monitoring with a negligible structural footprint (≤ 1.0% ILSS reduction) [12–23,42]. Systems incorporating 0.3 wt% graphene/epoxy have demonstrated the capability to detect matrix cracking with a resolution of 50 µm [42]. A primary challenge, however, is achieving uniform nanofiller dispersion, particularly in thick sections, where conductivity variations exceeding 22% can occur, resulting in inferior strain resolution (15.0 ± 3.2 µε) and signal quality (SNR: 28.5 ± 5.4 dB) compared to discrete sensors [12–23,42]. Hybrid architectures, which embed MXene fibres within a nanocomposite matrix, represent a promising direction, having been shown to improve strain transfer efficiency by 40% and mitigate percolation threshold issues for enhanced distributed strain mapping [40–42].

3.3. Sensors Industrial Applications

The industrial application of PZT and FBG sensors for composite SHM is well-established in demanding sectors such as aerospace and renewable energy [13,43–47]. In wind energy, PZT sensors, combined with advanced signal processing and deep learning, enable highly efficient damage detection. For instance, Huang et al. demonstrated a single-PZT-sensor approach using an EfficientNetV2-S deep learning model to localise impact sources on anisotropic wind turbine blades, achieving 96.9% accuracy and drastically reducing the required sensor count by framing the problem as a classification task [43]. This is complemented by research showing that sophisticated signal processing with PZTs can maintain damage localization accuracy on large blades with fewer sensors, even in noisy environments [46]. In aerospace, the need for temperature compensation is critical; Ren et al. developed a methodology for embedded PZTs in aircraft composites that achieved a Correlation Coefficient index greater than 0.96, a vital step for ensuring signal accuracy under operational thermal fluctuations [45]. FBG sensors demonstrate equally powerful capabilities in aerospace, as evidenced by Rocha et al., who successfully embedded an FBG array to monitor a Composite Overwrapped Pressure Vessel (COPV) for hydrogen storage in Unmanned Aerial Vehicles (UAVs) throughout its entire life cycle—from manufacturing and detecting residual plastic strain to locating Barely Visible Impact Damage (BVID) and withstanding extensive pressure cycling until vessel failure [44]. This practical implementation aligns with the broader industrial strategy, noted by Kosova et al., which identifies FBGs as a key technology for future aircraft, citing their multi-parameter sensing capability, high resolution, electromagnetic immunity, and multiplexing advantages [13]. Beyond these established technologies, emerging self-sensing materials are finding applications from aerospace to civil infrastructure [47,48]. Taymaz et al. integrated piezoresistive MXene fibres into carbon fibre-epoxy laminates for in-situ strain sensing in aerospace contexts, validating their exceptional sensitivity and reliability at the low strain ranges typical of aircraft manoeuvres and impacts [47]. On a larger scale, a systematic review by Bilal Meemary et al. documented the use of self-sensing composites with carbon nanotubes, carbon fibres, and graphene in civil engineering projects, including prestressed bridges and railway sleepers, highlighting benefits such as real-time monitoring, enhanced durability, and reduced installation costs for extensive infrastructure [48].

3.4. Durability and Environmental Challenges

The long-term durability of embedded sensor systems remains a critical challenge, as revealed by accelerated ageing tests conducted in accordance with ISO 4892–3 [26]. Key findings include significant hydrothermal degradation in FBGs, manifesting as wavelength drift exceeding 15% after a six-week exposure to 85°C and 85% relative humidity. Furthermore, PZT transducers exhibited a 30% drop in capacitance after 10^6 fatigue cycles at 0.8% strain, while MXene sensors showed an 8.7% resistance drift under a sustained 0.4% strain due to creep effects. Microcrack propagation at the sensor-composite interface was identified as the primary failure mechanism in 78% of cases. To address this, surface engineering solutions such as plasma functionalisation have been developed, which have been shown to improve interfacial adhesion and reduce debonding by 55% under shear loads, thereby enhancing the long-term resilience of the integrated system.

3.5. System Implementation and Digital Integration

The implementation of full-scale SHM systems highlights significant data processing challenges, particularly with dense sensor networks. Industrial deployments have shown that standard wireless networks struggle with arrays exceeding 500 sensors, leading to data loss rates of 12–17% in applications such as 20-metre bridge monitoring. To overcome this, edge computing solutions employing convolutional neural networks (CNNs) have been successfully implemented, reducing transmission payloads by 92% through on-board feature extraction and enabling real-time processing on low-power embedded systems consuming less than 5W. The integration of this data into digital twin frameworks has demonstrated considerable value, achieving 89% accuracy in predicting damage progression when fed with real-time strain data. Projects such as the Airbus "Smart Fuselage" have leveraged live strain mapping during flight operations to achieve a 34% reduction in scheduled maintenance, although certification barriers for safety-critical systems reliant on this data persist.

3.6. Remaining Technological Barriers

Despite considerable progress, four critical technological barriers impede the widespread adoption of embedded SHM systems [26,40–42]. First, power autonomy remains a primary constraint, with current energy harvesting solutions from piezo- or thermoelectric sources meeting only 18–23% of the operational demand for continuous monitoring. Second, limitations in manufacturing scalability present a hurdle, as automated placement technologies currently offer an accuracy of ± 0.8 mm, which is insufficient for the micron-scale positioning required by next-generation sensors. Third, a significant standardisation gap exists, with no universally accepted protocols for the certification of composites with embedded sensors. Finally, the challenge of multiphysics coupling is evident, as temperature-strain decoupling errors in non-isothermal operational environments still average 12–15%, compromising measurement accuracy.

3.7. Research Imperatives

The analysis conducted herein identifies several priority research directions essential for advancing the field. These include the development of multi-functional sensors capable of combining strain, temperature, and damage sensing; the creation of robust autonomous energy harvesting systems that can exploit ambient structural vibrations; the establishment of standardised test methodologies for the long-term validation of embedded sensors; and the refinement of machine learning architectures specifically designed to compensate for environmental variabilities and enhance the reliability of damage diagnosis.

4. Conclusion

This review has critically examined the evolution of sensor technologies for the in-situ structural health monitoring (SHM) of composite materials, charting a clear trajectory from fundamental sensing principles to sophisticated, application-driven systems. The practical deployment of these technologies is now demonstrable across multiple high-value industries, underscoring their transition from laboratory research to tangible engineering solutions. In aerospace, embedded Fibre Bragg Gratings (FBGs) are routinely employed for the real-time strain mapping of aircraft wings and fuselages, while also proving critical for monitoring composite overwrapped pressure vessels throughout their entire lifecycle. Within the renewable energy sector, networks of Piezoelectric Transducers (PZTs) have become instrumental for the impact detection and damage localization on large-scale wind turbine blades, enabling predictive maintenance strategies that minimise operational downtime. For civil infrastructure, the emergence of self-sensing nanocomposites and distributed fibre optic systems offers a pathway for pervasive strain monitoring in bridges and seismic retrofits, providing a continuous assessment of structural integrity under dynamic loads.

The journey toward fully autonomous SHM systems is fundamentally an interdisciplinary challenge, requiring synergistic progress across distinct fields. The progression in applications is intrinsically linked to advancements in sensor capabilities. The superior electromagnetic immunity and multiplexing capacity of FBGs make them indispensable in the electrically noisy and spatially constrained environment of an aircraft. Conversely, the high-frequency response and actuation capabilities of PZTs are uniquely suited to capturing the transient stress waves generated by impacts on turbine blades. Most recently, the exceptional piezoresistive sensitivity of emerging materials like MXene fibres is being harnessed for detecting subtle, sub−0.2% strain variations, which are critical for anticipating damage initiation before it becomes critical. This application-specific development is further accelerated by the integration of edge computing and machine learning, which transform raw sensor data into actionable diagnostics, and by the advent of digital twins that create virtual models updated by sensor data to predict future structural behaviour.

Despite this progress, the full potential of embedded SHM is constrained by persistent system-level challenges. These are not isolated technical issues but interconnected barriers spanning multiple disciplines: the unresolved gap in power autonomy for continuous monitoring demands collaboration between materials scientists and power systems engineers; limitations in manufacturing precision for sensor placement require co-design from robotics and composite processing specialists; errors introduced by environmental factors need solutions from multiphysics modelers and data scientists; and the critical lack of standardised certification protocols calls for a concerted effort from regulatory bodies, industry consortia, and reliability engineers. To address these barriers and advance the field, future efforts must prioritise cross-disciplinary collaboration to develop multifunctional materials that combine sensing with energy harvesting; establish robust, standardised validation frameworks for long-term performance; and promote co-design methodologies that integrate sensing networks directly within composite manufacturing workflows. In summary, the convergence of sophisticated sensing materials, intelligent data analytics, and IoT architectures is decisively transforming composite structures from passive components into intelligent, self-diagnosing systems. This paradigm shift is set to redefine safety, efficiency, and lifecycle management across aerospace, energy, and infrastructure domains.

Author Contributions

Conceptualization, E.R. and M.T.H.S.; methodology, E.R. and R.Z.; software, R.Z.; validation, H.M., R.Z. and M.T.H.S.; formal analysis, D.K.; investigation, D.K.; resources, H.M. and M.T.H.S.; data curation, D.K.; writing—original draft preparation, E.R. and D.K.; writing—review and editing, D.K., H.M., R.Z., M.T.H.S. and N.M.; visualization, E.R.; supervision, E.R. and N.M.; project administration, D.L.M. and N.M.; funding acquisition, D.L.M. All authors have read and agreed to the published version of the manuscript.

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The data supporting this review are sourced exclusively from publicly available scientific literature cited throughout the manuscript. No new datasets were generated during this study. All referenced publications are accessible through their respective Digital Object Identifiers (DOIs) or indexed databases (Scopus, Web of Science). Processed comparative analyses presented in tables and performance metrics are derived from aggregated, anonymized data extracted from these sources. For further details on specific datasets, readers are directed to the original publications in the reference list.

Conflicts of Interest

The authors declare that there are no conflict of interest.

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