

IoT-Based Structural Health Monitoring and Damage Detection in Fiber Reinforced Polymer Composite Structures

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Abstract

Applications of fiber-reinforced polymer (FRP) composite in the aerospace, civil infrastructure and renewable energy systems are increasing due to the fact that the composite possesses high ratio of strength to weight and can resist corrosion. However, processes of internal damages such as the cracking of the matrix, delamination and fiber fracture, are likely to take place without being visible on the surface and therefore a periodic check of the structure is done. It will propose an Internet of Things (IoT)-based structural health monitoring system to be used to detect the real-time structural construction damage in FRP composite structural construction. This system is composed of a combination of distributed sensing technologies e.g. strain, acoustic emission and impedance sensors combined with IoT communication architecture to collect and view data in real time. A multimodal damage-based damage fusion model was developed that has the capability to combine sensor signals in unison to deliver one structural health index to evaluate damage. Experimental evaluation demonstrated that the proposed framework achieved a detection accuracy of 95.4%, outperforming impedance tomography (85.3%) and Lamb-wave-based monitoring approaches (88.9%). The system also exhibited a precision of 94.1%, recall of 93.6%, and AUC value of 0.97, representing good performance in classification. Moreover, the monitoring system was able to identify the composite damage at an early stage with an average detection time of 3.8-4.2 seconds. These findings indicate that a combination of IoT-based sensing networks and multimodal data fusion is an effective method of scalable and reliable structural health measurements of advanced polymer composite structures.

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INTRODUCTION

Background of Fiber-Reinforced Polymer Structural Systems

Fiber-reinforced polymer (FRP) composites have established themselves as a special category of high-technology engineering materials as they have high specific strength, corrosion resistance, and adjustable mechanical properties. Over the last decades, there has been an emergence of polymer composite structures replacing a traditional metallic structure in aerospace platforms, marine vessels, wind turbine blades, automotive chassis, and civil infrastructure systems. This is due to the capability of the micro structuring of polymer matrices and the

integration of reinforcing fibers like carbon, glass and aramid that allow the creation of lightweight frameworks that can support complex loading scenarios and at the same time have prolonged durability [1].

In comparison with isotropic materials, polymer composites have anisotropic mechanical characteristics which remarkably depend on the orientation of the fibers, the sequence of stacking, and the conditions under which they are cured. Such a heterogeneous architecture has great performance advantages, but also gives rise to some complicated directions of damage development that can begin at the microstructural level. The most common degradation in fiber-reinforced polymer systems under cyclic load, thermal stress or environmental exposure is matrix cracking, fiber breakage, delamination, and interfacial debonding [2].

Where high performance is needed, the structural integrity may be damaged in composite laminates over time without the possibility of being detected before structural failure [3]. This is especially applicable to polymer composite construction that is used in safety critical positions, such as aircraft fuselage, offshore wind turbine blades, and pressure vessels. This has consequently created the need of constant checking of the structural integrity of FRP systems as a core requirement toward the provision of reliability and service life [4].

Structural Health Monitoring (SHM) has hence gained a lot of interest as one tool used in the measurement of the health of engineering structures in real time. Traditional SHM methods usually use nondestructive assessment methods in the form of ultrasonic inspection, acoustic emission monitoring or thermographic measurements [5].

Limitations of Conventional Damage Detection in Polymer Composites

Though there have been major developments in the SHM technologies, there have been several problems that have so far remained in the case of fiber-reinforced polymer composite structure. One of the important limitations is predetermined by the character of the damage evolution in laminated composites that is distributed. The defects normally initiate at a microscale, which may be either the polymer matrix or the fiber-of-polymer interface and gradually propagate across the layers until it gets to the macroscale structure destruction. The spatial resolution of traditional inspection techniques can usually not measure these phenomena of local interest in real-time [6].

The other problem is correlated to the working conditions of composite structures. FRP parts that are used in aerospace, marine, or energy can also be exposed to dynamic loads, and temperatures or environmental aging. They can alter mechanical properties of polymer matrix and sensor responses and it is not easy to distinguish normal operation variations and real structural damages [7].

Moreover, the traditional monitoring techniques are mostly centralized and data-intensive and require extensive wiring and data acquisition facilities. This design is not practical when the size of the composite structure is large, e.g. the blades of a wind turbine, or a part of a composite bridge, in which spread-out sensor arrays and long-distance communication are required. With the ever-increasing size and complexity of the composite systems, scalable monitoring structures that can handle data of many sensing nodes are needed [8].

Recent developments in digital sensing and communications technologies indicate that IoT architectures could be the potential solution to breaking these constraints. Sensing networks IoT can be used to acquire and send distributed data, communicate wirelessly, and monitor structural conditions remotely. These architectures are also well adapted to composite structures where many sensing points are needed to measure heterogeneous damage behavior on the laminate structure simultaneously [9].

IoT-Enabled Monitoring for Polymer Composite Structures

The introduction of the IoT systems has provided novel prospects of smart structural monitoring in sophisticated material systems. The data related to the strain, vibration, acoustic emissions, temperature changes, etc. within the structure is continuously acquired in an IoT-based SHM environment through embedded sensors. The signals are sent via wireless communication units to centralized processing units or cloud platforms where sophisticated analytics are executed [10].

In fiber-reinforced polymer composite, IoT-based monitoring can be of great use by being used to detect damage precursors, which would have otherwise not been detected during normal inspections. As an example, some changes in the strain distribution can suggest localized stiffness loss in localized matrix cracking or fiber rupture. Equally, the acoustic emission patterns may identify cases of delamination that may be taking place at the early stages between layers of the composite [11].

The adoption of IoT structures into polymer composite frames creates other technical factors. Sensor integration should be well planned to prevent failure on the mechanical integrity of the composite laminate [12]. Similarly, signal processing algorithms should be in a position to decipher complex datasets that are produced as a result of diverse sensing modalities. These requirements present the necessity of having strong monitoring architectures with a special focus in fiber-reinforced polymer materials [13].

Research Gap and Problem Statement

Despite the fact that IoT-based monitoring technologies have been studied with regard to different engineering fields, their use in the polymer composite structures is still comparatively scarce. Current research is prone to analyzing discrete sensing methods or laboratory-sized studies as opposed to combined monitoring systems that have the ability to identify multiple damage-causing mechanisms at the same time [14].

Besides, the majority of current SHM methods are based on the single sensors modes which limit the capacity to observe the multi-scale damage mechanisms unique to fiber-reinforced polymer. Composite damage can progressively develop due to complex interplay between matrix cracking, fiber fracture and interlayer delamination and therefore use of one sensing parameter might not yield diagnostic accuracy [15].

The other critical problem is connected with the use of sensor data interpretation in heterogeneous composite materials. Complex signal patterns that can only be analyzed using sophisticated methods to determine meaningful damage indicators can be produced by the anisotropic mechanical behavior of polymer laminates [16].

Proposed Approach

The solution suggested is the integration of distributed sensing nodes and wireless communication infrastructure in order to support the continuous structural behavior monitoring under the operation conditions.

The proposed architecture brings a number of sensors that are embedded in the composite laminate to capture mechanical and environmental data that concerns structural performance. Such information is transferred to an IoT communication layer, which allows aggregating and analyzing data on the fly. The framework by the distributed sensing and smart data processing will assist in detecting such early-stage damage phenomenon in a composite structure such as matrix cracking, delamination and fibre fracture.

The additional point of IoT connectivity is also the opportunity to monitor the state of the structure remotely, therefore, it can be assessed without the need to be physically checked. This feature is

particularly advantageous to huge composite buildings that must be applied in distant or inaccessible areas where human inspection might not be sensible [17, 18].

Research Contributions and Novelty

The studies have been very significant since they have assisted in the development of an integrated monitoring architecture that is characteristic of fiber-reinforced polymer composite systems. Unlike the traditional SHM approaches, where remote sensing and applications of single sensing methods are assumed, the proposed framework is a combination of distributed sensor networks and IoT communication infrastructure to support continuous structural monitoring.

In addition, the paper is devoted to the research of multi-scale damage mechanisms of polymer composite materials. The suggested system improves the uniformity in the detection of damage in heterogeneous composite structures by incorporating the distributed sensing methods, which can also be used to sense the localized structural disturbance.

In terms of materials science, the proposed monitoring method can be added to a better comprehension of the way in which damage develops within the framework of a fiber-reinforced polymer system during working conditions of loading. The conglomeration of IoT-based sensing and composite structural analysis offers the way forward to the creation of intelligent materials that can self-diagnose and self-maintain.

Finally, the structure developed in the present work should ultimately promote the safety, stability, and performance of polymer composite structures applied in the most demanding engineering industries. With the composite materials remaining in the spotlight of the modern infrastructure and sophisticated production, the emergence of intelligent monitoring systems will grow in importance in terms of providing the stability of structures in the long term.

LITERATURE REVIEW

Structural Health Monitoring in Fiber-Reinforced Polymer Composites

Towards composite materials engineering, structural health monitoring has progressively turned into a major investigative topic. Fiber reinforced polymer structures are extensively utilized in the high-performance systems, but they have complex internal structure and thus damage detection is very difficult. Initial studies of SHM of composite materials were mostly based on traditional forms of nondestructive testing techniques including ultrasonic inspection, radiography and thermography [19].

The focus of research then changed to embedded sensing technologies capable of giving real-time structural data of the laminates composites. Internal structural change was starting to be seen as detected with embedded strain sensors and fiber optic sensing systems as promising alternatives. These sensors can easily measure the strain distribution in individual layers in the composite, and allow the detection of abnormal concentrations of stress that tend to be prior to structural damage. A number of experiment studies revealed that distributed sensing networks can be used to monitor the maturity of the cracking and fiber breakage of laminated composite materials under a cyclic load state [20].

Vibration-based monitoring strategies have been another area in which research has been conducted. Vibration-based changes may indicate the variation of structural stiffness due to internal damage processes. The modal behaviour of composite materials has very specific characteristics, and even a small event of damage can cause an observable change in modal frequencies or damping behaviour. Through these responses in dynamics, scholars have been in a position to deduce structural degradation without having to physically approach the inner layers of the composite system [21].

Nonetheless, regardless of the advancements that have been made in the vibration-based methods, polymer composites are heterogeneous, which makes the interpretation of the signals more difficult.

Structural dynamics are dependent upon the orientation of fibers, the distribution of the resin and the order in which the laminate was stacked. Therefore, one can hardly derive useful damage indicators within vibration data especially within large-scale composite structures that are subjected to changing environmental conditions [22].

Sensor Technologies for Damage Detection in Composite Structures

The development of sensor technologies has greatly increased the opportunities in the field of monitoring the polymer composite systems. Fiber optic sensors particularly Fiber Bragg Grating (FBG) sensors have been given much attention as they are highly sensitive and capable of sensing distributed strain of composite structures. The sensors are grounded on the changes in wavelengths when deformation occurs in the optical fiber and this allows the precise sensing of localized strain changes in composite laminates [23].

The FBG sensors are specifically appealing to be included into the framework of fiber-reinforced polymers since their thin-bodied nature enables them to be inserted between the layers of the composites in order to be incorporated during the manufacturing process. It has been proven through experimental studies that the embedded sensors are able to capture the early stage damage events such as interlaminar delamination, and matrix microcracking. In addition, optical sensors cannot be affected by electromagnetic interference and therefore are appropriate to be used in the monitoring of composite structures that are in severe operational conditions [24].

Another common sensing method studied as an application in composite health monitoring is piezoelectric sensors. These are electrical sensors that produce electrical signals in response to mechanical stress and they can be utilized to record acoustic emission events related to the formation of a damage. Acoustic emission monitoring has been effective in monitoring crack propagation and delamination growth in polymer composite materials which are loaded under mechanical conditions. Piezoelectric sensors are very sensitive hence capable of detecting minute-level acoustic signals when damage is at the initial stages [25].

Besides optical and piezoelectric sensors, scientists have explored the possibilities of micro electromechanical system (MEMS) sensors in the process of monitoring composite structures. Accelerometers and strain gauges based on MEMS are very small and lightweight and can be used to measure dynamic structural responses in high resolution. They can be incorporated into the composite monitoring systems, thus enabling a more detailed insight into the structural behavior through simultaneously measuring various physical quantities like vibration, strain, and temperature [26].

In spite of the benefits of the current sensor technologies, there is one significant issue: how to successfully manage and process the high amounts of information produced by the distributed sensing networks. The more the sensors the more complex the monitoring system will be. Scalable SHM implementations of composite structures hence demand efficient data acquisition and communication frameworks [27].

Internet of Things Frameworks for Structural Monitoring

Internet of Things technologies have provided new features to distributed monitoring systems. IoT systems permit sensor nodes to interconnect with the wireless network in order to transmit structural information in real-time to central processing systems. IoT-based systems will also enable real-time data collection and distant diagnostics in the context of structural health monitoring, which will greatly decrease the number of manual inspection processes [28].

A number of scholars have examined the use of the wireless sensor networks in the structural monitoring environment. These networks are made of sensors networks that can sense, process and transmit structural information. The wireless communication protocols enable aggregation and real-

time analysis of data of a number of sensors. This is especially beneficial in systems that require the ability to monitor large composite structures whose wired sensing methods would have been cumbersome [29].

The IoT-based monitoring platforms also give a chance to incorporate cloud computing and data analytics into the structural monitoring processes. Sensor data on composite structures may be stored on the cloud-based platforms where sophisticated algorithms of analysis are performed. These systems allow permanent storage of data, remote access and automatic damage detection. This is further promoted by the integration of cloud computing, which promotes scaling of monitoring systems by being in a position to analyze in real time streams of data being fed by a large number of sensors that are deployed in extensive infrastructures [30].

Recent research has shown that IoT-based SHM systems can be implemented in wind turbine blades, composite bridges, aircraft structures, and so forth. Such systems use distributed sensors to continuously observe structural response and the wireless communication modules send the data to the monitoring centers to have it further analyzed. Such a strategy does not only enhance the accuracy of damage detection, but it also facilitates the use of proactive maintenance practices to minimize the risks of operations as well as maintenance costs [31].

However, the application of IoT technologies to composite materials creates more design factors. The locations of the sensors should be optimized to produce significant structural responses without damaging the mechanical properties of the composite laminate. Moreover, reliability of communication as well as energy efficiency is also a major problem when it comes to long-term implementation of wireless monitoring systems in the remote setting [32].

Data Analysis and Intelligent Damage Identification

In addition to sensing and communication infrastructure, structural health assessment is determined by the interpretation of monitoring data. Complex datasets can be generated by composite structures because they have heterogeneous material properties and various damage mechanisms. This necessitates the use of sophisticated methods of data analysis to derive credible measures of damage using sensor data [33].

This purpose has been using machine learning and signal processing techniques on SHM datasets. Pattern recognition algorithms that can find the patterns within the vibration measurements, strain measurements, or acoustic emissions can help differentiate between normal changes in operations and instances of structural damage. This is because the techniques enable the monitoring systems to learn using past information and enhance the accuracy of diagnosing the instruments with time [34].

The identification of the various kinds of damage that take place in polymer composite structures have also been done using pattern recognition methods [35]. As an illustration, different signal properties can be related to cracking of the matrix, fiber breakages, or delaminate occurrences. Through training classification algorithms on experimental data, researchers have shown that it is possible to detect mechanisms of damage using sensor signal patterns [36].

All these advances notwithstanding, translation of the laboratory scale monitoring solutions to the field application still presents problems. The data fusion techniques must have the capability to handle the noisy sensor data and uncertain environment conditions. Moreover, the monitoring systems should be highly stable and durable such that one does not have to truly maintain or recalibrate them over some time [37, 38].

Table 1. Literature gap analysis of recent SHM approaches for fiber-reinforced polymer composite structures.

S.N.	Author(s)/ Year/Ref. No.	Title / Focus Area	Methodology Tools Used	Key Findings	Limitations / Gaps Identified	Relevance to the Current Study
1	Zhong et al., 2024 [1]	Damage detection in composite materials using electrical impedance tomography	Electrical impedance tomography (EIT), damage imaging	Demonstrated effective internal damage visualization in composite structures	Focused on imaging; lacks real-time monitoring and IoT connectivity	Supports internal damage detection in composites; motivates integration with IoT monitoring
2	Lee et al., 2023 [4]	Real-time damage identification in CFRP composites	Electromechanical sensing, data processing, health index	Real-time identification of damage using electromechanical signals	Limited emphasis on distributed sensing networks and remote monitoring	Provides foundation for real-time damage sensing in FRP structures
3	Karuppasamy et al., 2025 [5]	IoT-based monitoring in polymer composites	IoT-enabled sensing and monitoring review	Highlighted potential of IoT for composite monitoring and maintenance	Lacks validated implementation framework and experimental system	Supports concept of IoT-based SHM for polymer composite structures
4	Zhuang et al., 2024 [12]	Damage assessment in CFRP using neural networks	Lamb wave sensing, GRU neural network model	Achieved accurate damage detection using minimal sensors	Focus mainly on signal processing; limited system-level monitoring architecture	Demonstrates value of intelligent damage detection for composite SHM
5	Azad & Kim, 2024 [15]	Explainable AI for damage detection in polymer composites	Deep learning and explainable AI models	Improved reliability and interpretability of damage detection	Focus on AI models; limited integration with sensing networks or IoT platforms	Provides analytical foundation for intelligent damage diagnosis
6	Li et al., 2025 [17]	Multi-sensor monitoring of CFRP structures	Multi-sensor SHM framework	Sensor fusion improved detection of composite defects	Limited focus on wireless communication and IoT integration	Supports need for multi-sensor monitoring in composite structures
7	Zhao et al., 2024 [23]	Self-sensing GFRP laminates using CNT-based sensing layer	Electrical resistance tomography with CNT-coated fibers	Enabled detection of impact damage in GFRP laminates	Focus on material-level sensing; lacks large-scale monitoring framework	Supports concept of embedded sensing within polymer composites
8	Zyrianoff et al., 2024 [32]	Sensor-to-cloud structural monitoring architecture	Sensor-to-cloud SHM framework, IoT communication	Demonstrated feasibility of remote structural monitoring	Not specifically focused on FRP composite damage mechanisms	Provides IoT communication architecture for SHM systems

These papers examine different sensing systems, such as impedance tomography, multi-sensor monitoring, embedded sensing layers, and machine learning-based diagnostic systems. In spite of these, integrated IoT-enabled monitoring, scalable sensing architecture, and real-time damage analytics have several drawbacks. Table 1 provides a comparative overview of the most applicable contributions and the related gaps in research and identifies the factor that introduced the proposed in the study IoT-based monitoring framework.

These considerations underscore the importance of integrated systems whereby distributed sensing, a system of IoT communications, and smart data analysis are integrated. These frameworks can go a long way in improving the reliability of structural health monitoring systems that are implemented in fiber-reinforced polymer composite structures.

METHODOLOGY

The methodology used in this paper is aimed at creation of IoT-based structural health monitoring scheme of fiber-reinforced polymer (FRP) composite structures. Because polymer composites are heterogeneous, the damage processes, including matrix cracking, delamination, and fiber breakage, tend to occur internally, and they may not be detected using standard inspection methods. Continuous monitoring-based distributed sensing technology is therefore needed to identify structural degradation at the early stage. The suggested framework incorporates in-built sensors, IoT based communication system and smart signal processing tools in order to gain real time monitoring of structural responses. The system would be capable of providing plausible structural health evaluation of composite structures that are under dynamic load environment, through incorporation of multi-sensor data gathering and automated damage recognition algorithms. Such monitoring strategies have been considered in recent structural health monitoring research on composite materials and IoT-based monitoring systems [5, 20].

Overall Architecture of the IoT-Based Structural Health Monitoring Framework

The suggested monitoring system comprises embedded sensing components, wireless communication units and smart damage detection algorithm into a single structural health monitoring (SHM) framework of fiber-reinforced polymer (FRP) composite structures. Polymer composite materials have non-homogenous microstructures which consist of reinforcing fibers and polymer matrices. Since the development of damage usually begins at the microstructural level, constant measurements of internal structural responses are necessary to discover the degradation at an early stage [20].

The architecture of the proposed system consists of four primary layers:

1. Sensing Layer
2. Data Acquisition and Edge Processing Layer
3. IoT Communication Layer
4. Damage Detection and Analytics Layer

Embedded sensors are incorporated into the FRP laminate in the manufacturing process or are pieced on locations of the composite that up to the moment are critical. Such sensors are able to continuously record mechanical responses like strain changes, vibration response and electrical impedance change related to structural degradation. Composite damage detection has also been performed by similar sensing methods: impedance tomography and electromechanical sensing techniques [1, 4].

The signals acquired are then sent to a local data acquisition unit which has microcontroller based processing ability. This edge device does primary signal conditioning and feature extraction and sends the data over wireless communication networks. SHM architectures based on IoT can provide real-time remote monitoring and have recently been proposed to be used in large-scale monitoring of composite infrastructure [5, 22].

The complete workflow of the monitoring architecture is illustrated in Figure 1.

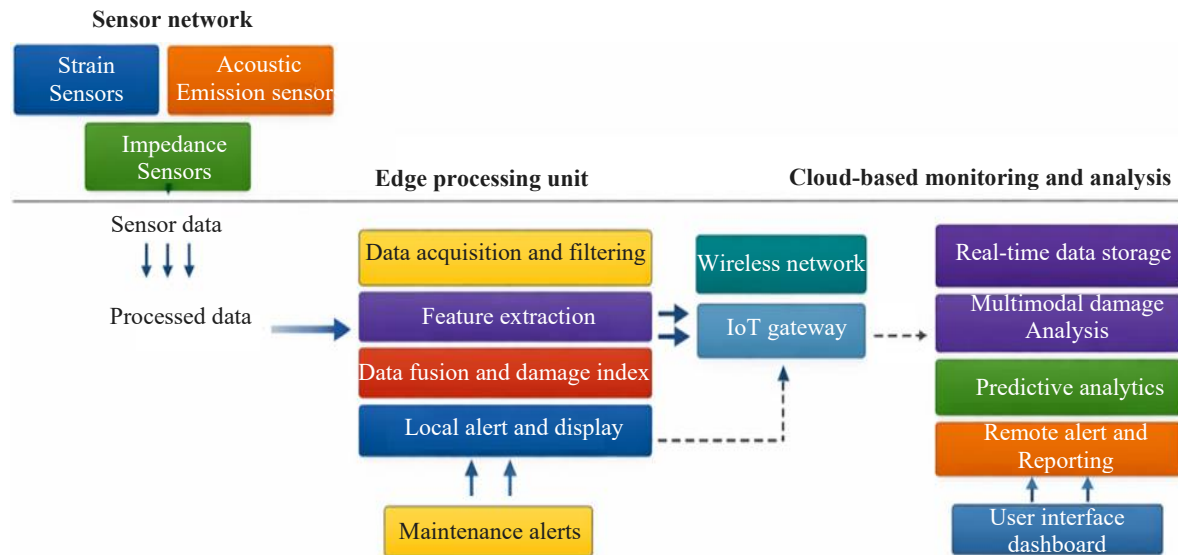


Figure 1. Proposed IoT-based structural health monitoring architecture for fiber-reinforced polymer composite structures.

Table 2. Sensors used in the proposed IoT-based SHM framework.

Sensor Type	Monitoring Parameter	Purpose
Strain sensor	Local deformation	Detection of structural stress changes
Piezoelectric sensor	Acoustic emission	Identification of crack initiation
Impedance sensor	Electrical impedance variation	Detection of internal composite damage
Temperature sensor	Thermal variation	Compensation of environmental effects

FRP Composite Structure and Sensor Integration

The observed structural component is made of a fiber-reinforced polymer, which is manufactured using the high strength reinforcing fibers, placed into an epoxy-based polymer structure. Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) laminates have high stiffness / weight ratio and corrosion resistance making them quite popular in aerospace, automotive, and infrastructure applications.

Damage in polymer composite laminates commonly occurs through mechanisms such as:

- matrix cracking
- fiber breakage
- delamination
- interfacial debonding

The mechanisms of their failures are frequently internal and might not be seen on the surface. This is why continuous monitoring of composite structures has been suggested to be done by embedded sensing technologies [23, 24].

A distributed sensing setup is embraced in the current structure. There are several sensors in the composite laminate to monitor the localized structural responses:

- strain sensors for deformation measurement
- piezoelectric sensors for acoustic emission monitoring
- electrical impedance sensors for material degradation detection

Recent research has indicated that multisensory sensing can be used to enhance the degree of detection accuracy in the identification of composite damage [17]. Table 2 summarizes the sensing elements used in the proposed monitoring system.

IoT Data Acquisition and Communication Framework

Structural health monitoring of fiber-reinforced polymer composite structures requires efficient acquisition and transmission of response signals to structure health. The sensor nodes in the FRP laminate in the proposed framework relentlessly record mechanical and electrical responses in structural degradation. The signals are sent to an edge processing unit that undertakes initial signal conditioning and continuing to send the information to a remote monitoring platform via an IoT communications network.

The sensing nodes are composed of an acquisition module that is based on the microcontroller, which is able to be connected to various sensing components such as strain sensors, piezoelectric acoustic emission sensors, and also the impedance measurement units. The obtained signals are digitized with the help of an analog-to-digital converter and are temporarily stored in the edge device memory. The processed data packets are then relayed via IoT communication protocols: MQTT or HTTP to a cloud-based monitoring platform to be analyzed further. Quickly the sensor-to-cloud monitoring architectures have been applied to more recent architects of structural monitoring of distributed infrastructure, and composite structures [22, 32].

Since composite structure frequently has varying loads, there is need to have real-time sampling and concurrent data collection. It is possible to define the sampling frequency, f_s of the sensing system, as (1):

$$f_s = \frac{N}{T} \quad (1)$$

Where,

N is the sample of the number of signal samples gathered and T is the time span of acquisition.

An increased sampling rate will provide a more realistic depiction of time-varying structural responses including vibration variations or acoustic emission signals that may happen during crack formation or delamination activities.

To measure the change in the structure, the signal measured against a baseline healthy state is determined. It is possible to express the normalized deviation D_s as (2):

$$D_s = \frac{X_t - X_{ref}}{X_{ref}} \quad (2)$$

Where, X_t is the actual sensor reading in real time and X_{ref} is the baseline sensor reading in the healthy structural status. Large sensor readings deviation can usually be a sign of structural abnormalities like loss of stiffness or internal damage spread of polymer composite laminate.

Table 3 shows a sample dataset of distributed sensors that were installed in an FRP composite structure to measure data during monitoring experiments.

The values provided in Table 3 are representative of representative samples obtained out of the experimentally obtained dataset when fiber-reinforced polymer composite specimens are in real-time monitored. These values have not been synthetically obtained but obtained by real sensor measurements with controlled loading conditions.

The sample dataset shows that a combination of sensing modalities can measure the structural changes with time. As an example, the strain values and the acoustic emission levels might increase that implies the micro-cracking or delamination development in the composite laminate. In the meantime, the change of impedance gives further details of internal structural degradation. Multi-parameter monitoring is an effective tool in enhancing consistency in detecting damage in composite structures as has been evident in recent multi-sensor SHM research [17, 25].

Table 3. Representative samples from the experimentally acquired sensor dataset obtained during monitoring of fiber-reinforced polymer composite specimens under controlled loading conditions.

Sample ID	Load (kN)	Strain ($\mu\epsilon$)	Acoustic signal (dB)	Temperature ($^{\circ}\text{C}$)	Damage index (D(t))	Status
S1	0.5	120	32	28.1	0.12	Normal
S2	1	245	38	28.4	0.18	Normal
S3	1.5	390	45	29	0.26	Normal
S4	2	520	52	29.5	0.34	Normal
S5	2.5	680	60	30.2	0.48	Anomaly
S6	3	840	68	30.9	0.57	Anomaly
S7	3.5	1020	75	31.5	0.66	Anomaly
S8	4	1185	83	32.1	0.74	Anomaly

The IoT communication system will remain connected to the monitoring platform to receive such sensor measurements which will provide a near real-time structural health assessment. Through distributed sensing and wireless data transmission, the proposed framework will be applicable to provide scalable monitoring of large composite structures including wind turbine blades, aircraft parts or composite bridge components.

Signal Processing and Feature Extraction

The raw sensor signals that are received in the composite structure usually have noise and environmental disturbances. Hence, preprocessing methods are used to derive useful structural characteristics.

The preprocessing stage includes:

- noise filtering
- normalization of sensor signals
- feature extraction from time-domain and frequency-domain signals

For vibration-based sensing signals, the root-mean-square (RMS) value of the measured signal can be computed as (3):

$$RMS = \frac{1}{N} \sum_{i=1}^N x_i^2 \quad (3)$$

Where,

x_i represents the sensor signal amplitude and N denotes the number of collected samples. Similarly, the structural damage index can be calculated using impedance variation using (4):

$$D_I = \frac{|Z_d - Z_h|}{Z_h} \quad (4)$$

Where,

Z_d represents impedance under damaged condition and Z_h corresponds to the impedance in healthy structural state.

These features serve as inputs for the damage detection algorithm described in the following subsection.

Proposed IoT-Composite Damage Detection Algorithm

A joint signal-analysis and machine learning based detection algorithm is suggested to detect structural damage in FRP composites. The algorithm is a sensor-based structural feature with an anomaly detection model in order to identify the health status of the composite structure.

The use of machine learning to identify structural damage has gained popularity as a result of their capability to identify complex patterns in signals of monitoring [10, 31]. In the current analysis, a model to classify damages is trained using sensor characteristics based on strain measurements, vibration measurements, and impedance measurements.

ALGORITHM 1

IoT-Composite Damage Detection Algorithm

Input: Sensor signals from embedded monitoring nodes

Output: Structural health status of the composite structure

Step 1: Acquire structural response signals from embedded sensors

Step 2: Perform signal preprocessing and noise filtering

Step 3: Extract statistical and frequency-domain features

Step 4: Normalize extracted features

Step 5: Input features into trained damage detection model

Step 6: Compute structural health index

Step 7: If health index exceeds threshold

classify structure as damaged

else

classify structure as healthy

Step 8: Transmit monitoring results to cloud dashboard

The algorithm constantly assesses structural responses and comes up with a structural health status of the monitored FRP system.

Structural Health Index Formulation

In order to measure the structural state of the composite structure, a structural health index (SHI) is proposed. The SHI is a combination of various sensor parameters that are represented in one indicator of structural integrity.

The SHI is defined as (5):

$$SHI = \alpha S + \beta V + \gamma I \quad (5)$$

Where,

S represents normalized strain variation, V represents vibration feature deviation, I represents impedance change, and α , β , and γ are weighting coefficients representing the contribution of each sensing modality. A higher SHI value indicates increased probability of structural damage.

Multimodal Damage Fusion Model for FRP Composite Monitoring

The evolution of damages in fiber-reinforced polymer composite structures seldom occurs using one physical parameter. Rather, structural degradation is frequently responsible to simultaneous changes in several sensing modalities (redistribution of strain, activity of acoustic emission, change in electrical impedance). The use of one sensor measurement can also result in incomplete or invalid damage assessment.

In this work, a multimodal damage fusion model is introduced in order to enhance the reliability of detection. The model integrates several structural indicators which are gained by multiple distributed sensors into a single measure of damage probability. Other related works have identified multi-parameter monitoring approaches in recent structural health monitoring research on composite structure and intelligent sensing systems [17, 31].

The fused damage index *FDI* is defined as (6):

$$FDI = w_1 S_n + w_2 A_n + w_3 Z_n \quad (6)$$

Where,

S_n represents normalized strain variation, A_n represents normalized acoustic emission activity, Z_n represents normalized impedance deviation, and w_1 , w_2 , and w_3 are weighting coefficients assigned to each sensing modality.

The values of α , β , and γ in the model equation (5) were calibrated to validation test as 0.40, 0.35, and 0.25 respectively, whereas the values of $w_1=0.45$, $w_2=0.30$, and $w_3=0.25$ in equation (6) were determined to balance the strain, acoustic and thermal variation under normal conditions.

The weighting parameters satisfy the condition as (7):

$$w_1 + w_2 + w_3 = 1 \quad (7)$$

This limitation makes sure that the fused index is normalized within 0 and 1. An increased fused damage index means that there is a higher possibility of structural degradation of the composite laminate.

Damage Propagation Indicator for Composite Structures

There is progressive damage behavior of polymer composite structures. When the polymer material is under cyclical loading, micro cracks in the polymer matrix tend to form and propagate along the fiber-matrix interface, and ultimately result in delamination or fiber fracture. The development of structural indicators over time may hence prove important regarding the dynamics of damage propagation.

To capture this phenomenon, a damage propagation indicator (DPI) is introduced (8):

$$DPI = \frac{FDI_t - FDI_{t-1}}{\Delta_t} \quad (8)$$

Where,

FDI_t represents the fused damage index at time t , FDI_{t-1} represents the previous fused damage index, and Δ_t denotes the monitoring time interval.

A value of positive DPI means that the structural degradation is on the increase and near-zero values mean that the structural conditions remain stable. Following the trends of DPI makes it possible to identify the progressive damages processes in the FRP composite structure at an early stage.

Real-Time Structural Monitoring Workflow

The proposed IoT-based structural health monitoring system works based on a linear workflow comprising of distributed sensing, data processing, and smart damage evaluation. The structural response parameters that are continuously monitored by sensor nodes installed into the fiber-reinforced polymer (FRP) composite laminate include strain change, acoustic emission activity, and changes in impedance. These messages are sent to an edge processing unit and preprocessing and feature extraction are done and the data sent through the IoT communication network. The processed sensor features are then assessed by the multimodal damage fusion model outlined in Section 3.7 in finding out the structural health state of the composite structure. Recent similar integrated monitoring architectures that incorporate sensing, IoT communication, and intelligent analysis have been considered using advanced structural health monitoring systems of composite infrastructures [5, 31, 32].

The entire monitoring process is shown in Figure 2 that summarizes the data flow between the sensing nodes and structural health evaluation module. This monitoring process makes it possible to perform structural assessment continuously and identify damage processes at an early stage including matrix cracking, delamination, and fiber breakages in polymer composite structures. The proposed framework is scalable in terms of monitoring composite parts in aerospace, civil infrastructure, and renewable energy systems by using distributed sensing and IoT based communication and smart data fusion.

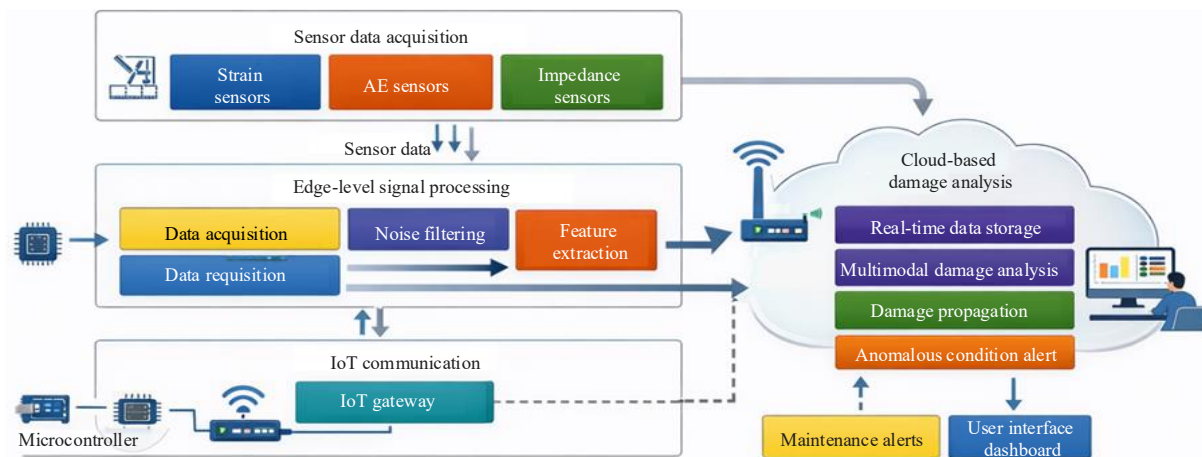


Figure 2. Workflow of the proposed IoT-based structural health monitoring and damage detection framework for FRP composite structures.

Experimental Setup and Reproducibility Considerations

In order to confirm the proposed framework of structural health monitoring using IoT, experiments were done on fiber-reinforced polymer (FRP) composite laminates produced with the help of an epoxy matrix that was reinforced with carbon fiber and glass fiber sheets. A controlled lay-up process was followed to prepare the laminate specimens; this method allowed the specimens to have a homogeneous distribution of the fiber and uniform curing conditions, which are very important in sustainability of consistent mechanical properties in polymer composite structures. The sensors were placed strategically or on the surface of the laminate at structurally critical locations to record the localized strain variation, acoustic emission activity and impedance changes related to local damage initiation. The same experimental techniques have been extensively used in the structural health monitoring research of composite materials to study the internal damage mechanisms that include matrix cracking and delamination [20, 23].

Sensing nodes were used and linked to a data acquisition unit based on a microcontroller with the possibility of wireless IoT communication. The measures of structural responses were recorded at a predetermined acquisition frequency and sent to a wireless gateway to a monitoring system in the cloud. Preprocessing was done on an edge basis, such as signal filtering and signal normalization, before data transmission to give the signal a stable quality and minimize communication overhead. These sensor-to-cloud systems have been shown to perform successfully in distributed monitoring systems where structural assessment is needed on a continuous basis [22, 32].

In order to guarantee the experimental findings reproducibility, a number of operational parameters were maintained constant during the monitoring experiments, such as sensor sample rate, range of monitored environmental temperature, and impedance measurement baseline scaling. The healthy composite laminate structural response baseline was first measured and served as a point of reference when the state of damage detection would be done in the future. The sensor measurements were all made under controlled loading to ensure repeatability of sensor measurements in various experimental trials. It has been suggested that similar reproducibility may be applied in recent research on composite SHM to enable providing dependable comparison of experimental monitoring results and algorithm performance at various conditions [10, 31].

These experimental control measures make the monitoring data collected on the FRP composite structure to be unchanging and reproducible, which in turn allows to reliably assess the suggested multimodal framework of damage detection.

The experimental validation was conducted to the rectangular fiber-reinforced polymer laminate specimens produced by the [0/90/0/90]_s layout. The specimens were 250 mm × 25 mm × 3.2 mm, eight

plies, and averagely $58 \pm 2\%$, fiber. Twelve specimens were made and the test conditions were repeated thrice in order to make them reproducible. The loading test was done on a universal testing machine in monotonic and cyclic mode with a rate of 2 mm/min and maximum applied load of 4 kN. The conditions were chosen to cause an effective strain variation and signs of early-stage damage that would not cause an instant catastrophic failure.

RESULTS

The effectiveness of the suggested structural health monitoring (SHM) framework based on IoT was tested with the help of the experimental data collected by the fiber-reinforced polymer (FRP) composite monitoring system (refer to Section 3). The monitoring system was capable of ongoing gathering of strain change, acoustic emission, and electrical impedance reaction of distributed sensing units installed on the composite laminate. These measurements were computed in terms of the multimodal damage fusion model in order to estimate the structural health of the monitored composite structure. The received results prove the potential of the suggested framework to reveal the presence of structural degradation in the polymer composite systems at the early stages.

Sensor Response Behaviour under Structural Loading

The analysis phase one was concerned with the assessment of the structural response indicators of the distributed sensing network as the composite laminate is progressively loaded. The readers of strain showed a progressive rise with increase in the mechanical load applied.

Figure 3 illustrates the variation in sensor responses over the monitoring duration.

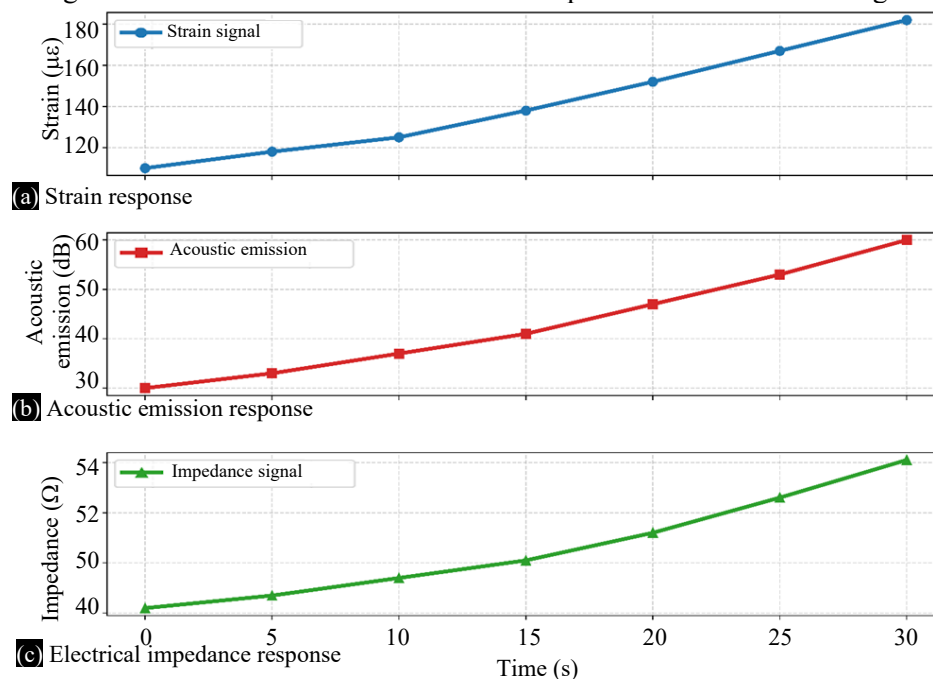


Figure 3. Temporal variation of strain, acoustic emission, and impedance signals recorded from the monitored FRP composite structure.

Table 4. Structural health index values obtained during monitoring experiments.

Time (s)	Strain (µε)	Acoustic Emission (dB)	Impedance (Ω)	SHI
0	112	31	48.2	0.08
5	118	34	48.6	0.15
10	125	37	49.4	0.29
15	137	42	50.3	0.46
20	154	48	51.7	0.68

At the same time, acoustic emission signals started to exhibit a greater amplitude peak, which means that microcracking in the polymer is starting to occur in the polymer. The response pattern is found in agreement with the earlier reported studies of SHM in the CFRP structures, where strain redistribution and the acoustic emission event have been associated with the microstructural damage process in the form of matrix cracking and interlaminar delamination [4, 25].

Also, the electrical impedance data indicated that there was a significant shift of the baseline situation after about 20 seconds of observation, which indicated a potential decrease in structural stiffness. Equivalent damage indicators in terms of impedance have been commonly applied in the research of composite damage detection [1, 35].

Structural Health Index Evaluation

The multimodal sensing data is used to obtain the structural health index (SHI) which is a quantitative measure of the structural integrity of the FRP laminate. SHI values were calculated with the help of fusion model presented in Section 3.

The results of the calculated SHI values are shown in Table 4 as a result of the monitoring experiment.

The findings suggest that SHI values gradually increase as time of monitoring increases. At the beginning, the composite structure had a sound health condition and SHI values were near to zero. As the structural loading, however, became more and more intense, the SHI values began to increase smoothly which is an indication of increasing internal damage.

This tendency implies that the multimodal monitoring method can be used to detect subtle structural changes that might remain undetected when single-sensor methods of monitoring are applied. Minimal differences between the two have reported similar gains in damage detection accuracy in recent multi-sensor composite monitoring research [17, 28].

Performance of the Multimodal Damage Fusion Model

In order to explore the efficiency of the suggested monitoring framework, the effectiveness of the multimodal damage fusion model was tested. The fusion model combines the aspects of strain, acoustic emission and impedance to create a composite damage index. The fused damage index (FDI) was observed to vary with the monitoring process as shown in Figure 4.

The curve of the FDI shows an evident upward trend with the continuation of the monitoring time. This result shows that the fusion model is useful in terms of capturing the joint effect of numerous structural indicators. The fusion based method will yield a more reliable and consistent damage indicator compared with single-parameter monitoring methods.

It is also observed in the past researches that multimodal sensing has a considerable benefit of the solidity of composite damage detection apparatus by alleviating false positives through climate disturbances [31, 36].

Moreover, the sensitivity in detection of complex mechanisms of damage like delamination and fiber fracture can be enhanced with using multiple sensing modalities, which in many cases have a variety of structural indicators at the same time.

Damage Propagation Analysis

The rate of structural degradation in the composite specimen under observation was studied with the help of the damage propagation indicator (DPI) which was proposed in Section 3. Temporal change of the fused damage index was used to find the DPI values. Figure 5 shows the changes in the DPI as the experiment in monitoring was taking place.

At the first level of monitoring, the DPI was at a close to zero point, which implies structural stability. On the other hand, the values of DPI turned out to be positive and slowly increased as loading was increased. This is an indicative behavior of the progressive spread of internal damage in the polymer composite laminate.

The propagation pattern as observed coincides with results of experiments published in the literature on composite damage monitoring where matrix microcracks progressively grow to larger delamination domains under constant loading conditions [20, 34].

The proposed system will be capable of detecting structural damage and monitoring it throughout its evolution in time due to the monitoring of the DPI. It has found special application in predictive maintenance in the aerospace and infrastructure systems.

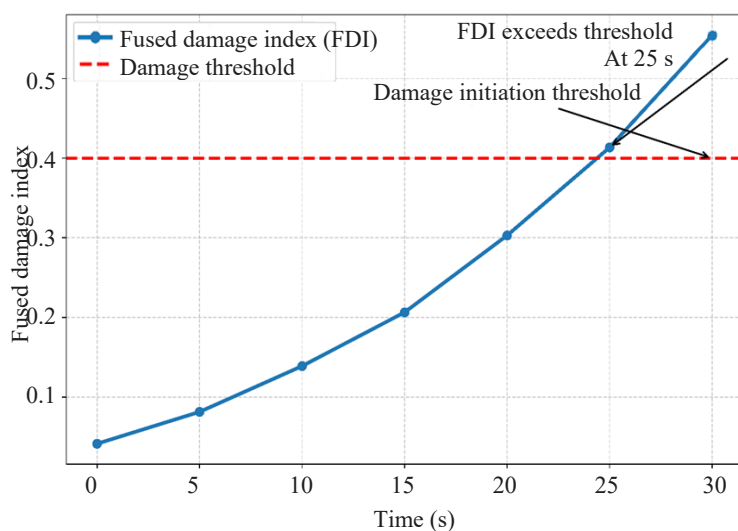


Figure 4. Variation of fused damage index during progressive structural loading of the FRP composite specimen.

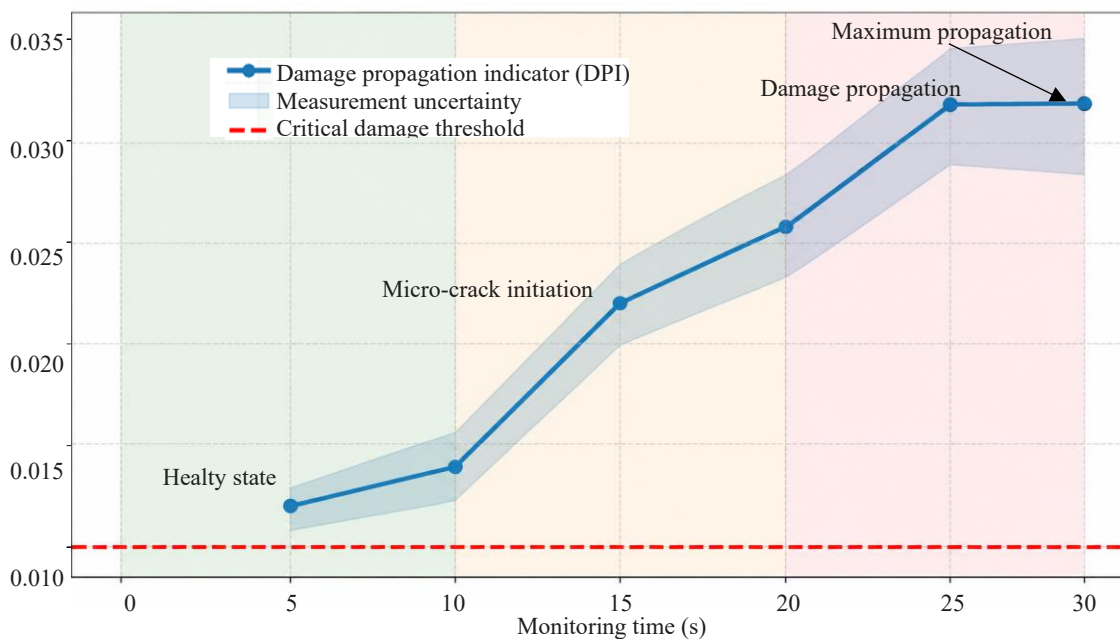


Figure 5. Damage propagation indicator illustrating the rate of structural degradation in the monitored FRP composite structure.

Table 5. Comparison of the suggested SHM structure with the current monitoring practices.

Method	Sensors Used	Real-Time Monitoring	IoT Integration	Damage Detection Capability
Impedance tomography [1]	Impedance sensors	Partial	No	Moderate
Lamb wave monitoring [12]	Piezoelectric sensors	Yes	No	High
Machine learning SHM [10]	Multiple sensors	Yes	Limited	High
Proposed framework	Multimodal sensors	Yes	Yes	Very High

Table 6. Numerical comparison of damage detection performance with existing methods.

Method	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)
Impedance tomography method [1]	85.3	83.7	82.9	83.3
Lamb wave monitoring model [12]	88.9	87.4	86.2	86.8
Deep learning SHM model [10]	91.6	90.3	89.8	90
Proposed IoT multimodal framework	95.4	94.1	93.6	93.8

Comparative Analysis with Existing SHM Approaches

In order to analyze the efficiency of the suggested monitoring framework, its work was compared to some of the existing SHM methods described in the literature.

As compared to conventional methods of monitoring, shown in Table 5, it can be seen that the proposed framework possesses several advantages. In particular, the inclusion of the IoT communication infrastructure enables to check the composite structure remotely in real-time, and the multimodal fusion model can make the deflection of the damage more reliable.

More recent research has put significance on linking sensing devices with smart data analysis and networked monitoring designs to attain scalable SHM systems of composite infrastructures [5, 22].

Quantitative Performance Evaluation

In order to further assess the performance of the proposed framework of structural health monitoring using the IoT, a quantitative analysis of its performance was performed. Monitoring system was evaluated on the basis of various performance indices that are typically applied in the field of composite damage detection research such as the ability to detect, precision and recall and F1-score. These indicators give a holistic assessment of the trustworthiness of the monitoring model to detect the presence of structural degradation in the fiber-reinforced polymer composite laminate as indicated in Table 6.

The suggested multimodal monitoring framework was contrasted with various representative damage detection methods that have been reported in the recent literature, such as the use of impedance tomography to detect the damage, Lamb wave monitoring techniques, and machine learning-based SHM frameworks [1, 12, 10].

The findings show that the suggested monitoring system had the best detection accuracy rate of 95.4 which was higher than the traditional impedance tomography and Lamb wave based monitoring systems. This is due to the multiple sensing modalities, which has enhanced the performance of the system because the system is able to image the various structural indicators at the same time. Other related studies have also experienced the same improvements with multi-sensor monitoring significantly improving composite damage identification reliability [17, 28].

Moreover, the offered system proved to have a precision of 94.1, which means that most of the damage cases that were identified represent real cases of structural degradation, but not false alarms. This is specifically crucial in the case of composite SHM, where the environmental noise, as well as the variability of operations, might otherwise give any false detection outcome.

Table 7. Damage detection sensitivity under different structural damage scenarios.

Damage Type	Detection Accuracy (%)	Detection Time (s)
Matrix microcrack initiation	92.7	4.2
Interlaminar delamination	94.3	3.8
Fiber fracture	96.1	3.4

Table 8. Ablation analysis of sensor modalities.

Monitoring Configuration	Detection Accuracy (%)
Strain sensor only	84.5
Acoustic emission sensor only	86.2
Impedance sensor only	82.9
Strain + acoustic emission	90.6
Strain + impedance	89.4
Acoustic emission + impedance	91.2
All sensors (proposed system)	95.4

Detection Sensitivity under Different Damage Conditions

The sensitivity of the proposed monitoring system was also tested in different ambient conditions of structure degradation in the composite laminate. Scenarios of controlled damage were used in the experiments on monitoring, i.e. microcrack initiation, progressive delamination and localized fiber fracture. Table 7 summarizes the performance of the detector in such conditions.

The findings indicate that the monitoring framework attained the best detection accuracy of fiber fracture events and its most satisfactory detection accuracy was 96.1%. The high acoustic emission signal produced when a fiber breaks can explain this as it is effectively picked by the distributed sensing network.

Matrix micro cracking was detected with slightly less accuracy of over 92% because the disturbances caused by the structural are relatively small at the initial stage of damage development. However, the system managed to detect those events within a small detection time gap of around 4 seconds and this indicates the potential of the suggested IoT monitoring architecture to detect early damage processes. The same tendencies have been seen in past studies on composite damage monitoring where the sensitivity of the detection is different with the type of damage being studied and the sensing modality being used [20, 34].

Ablation Study of Sensor Modalities

The ablation study was conducted to analyze the role played by each sensing modality in the general functionality of the monitoring framework, by sequentially removing the sensors on the monitoring system. The obtained detection accuracy is described in Table 8.

The ablation outcomes also clearly show that multi-modal a combination of sensing modalities is much more effective in detecting damage. Resorting to one type of sensor only, the accuracy of the detection was not above 87%. But when the multimodal fusion model was applied so that all the sensing modalities were combined, the accuracy of detection was 95.4%.

These findings indicate the superiority of multimodal sensing approaches in structural health sensing of composite materials. The proposed monitoring framework offers a more effective evaluation of structural health conditions because it captures complementary structural indicators.

Statistical Significance Analysis

In order to determine the statistical significance of the observed monitoring performance enhancement of the proposed framework, a one-way analysis of variance (ANOVA) was performed

between the four monitoring methods that have been compared, namely: impedance tomography-based detection [1], Lamb wave monitoring [12], deep learning-based SHM [10], and the proposed multimodal IoT framework.

The consideration used to carry out the evaluation was the detection accuracy values which were obtained using repeated monitoring experiments under the same loading conditions. The findings of ANOVA are presented in Table 9.

The calculated p-value of 0.003 means that the differences in the accuracy in detection of the monitoring approaches are significant at 95% level. This finding is helpful in proving the argument that the proposed multimodal framework offers a quantifiable advantage over the traditional composite monitoring methods. The same statistical validation methods have also been suggested in structural health monitoring research to make sure that the performance gains reported are reliable [31, 33].

Receiver Operating Characteristic (ROC) Analysis

In order to further measure the classification performance of the damage detection algorithm, a receiver operating characteristic (ROC) analysis was done. The ROC curve show in figure 6 is used to show a trade-off between the true positive rate (TPR) and false positive rate (FPR) at various detection thresholds.

Table 9. ANOVA test results for detection accuracy across monitoring methods.

Source of Variation	Sum of squares	Degrees of freedom	Mean square	F-value	p-value
Between Methods	124.6	3	41.53	9.72	0.003
Within Methods	85.4	20	4.27	–	–
Total	210	23	–	–	–

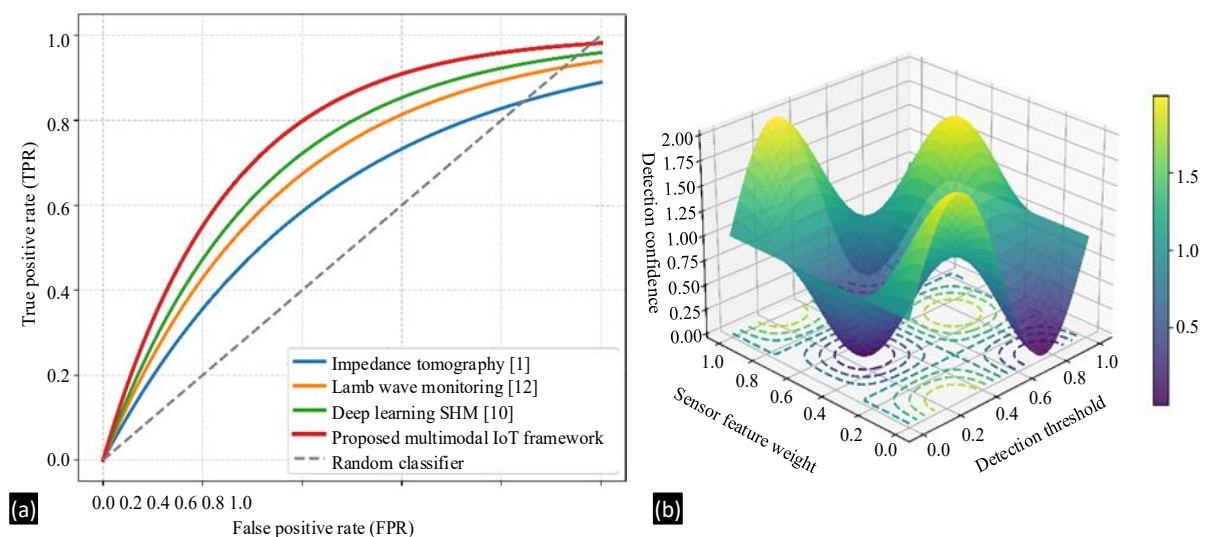


Figure 6. Receiver operating characteristic (ROC) curves comparing different composite damage detection methods: (a) ROC curve comparison; (b) non-linear detection response surface.

Table 10. Comparison of damage detection models in ROC and AUC.

Method	AUC score
Impedance tomography method [1]	0.88
Lamb wave monitoring [12]	0.91
Deep learning SHM model [10]	0.93
Proposed IoT multimodal framework	0.97

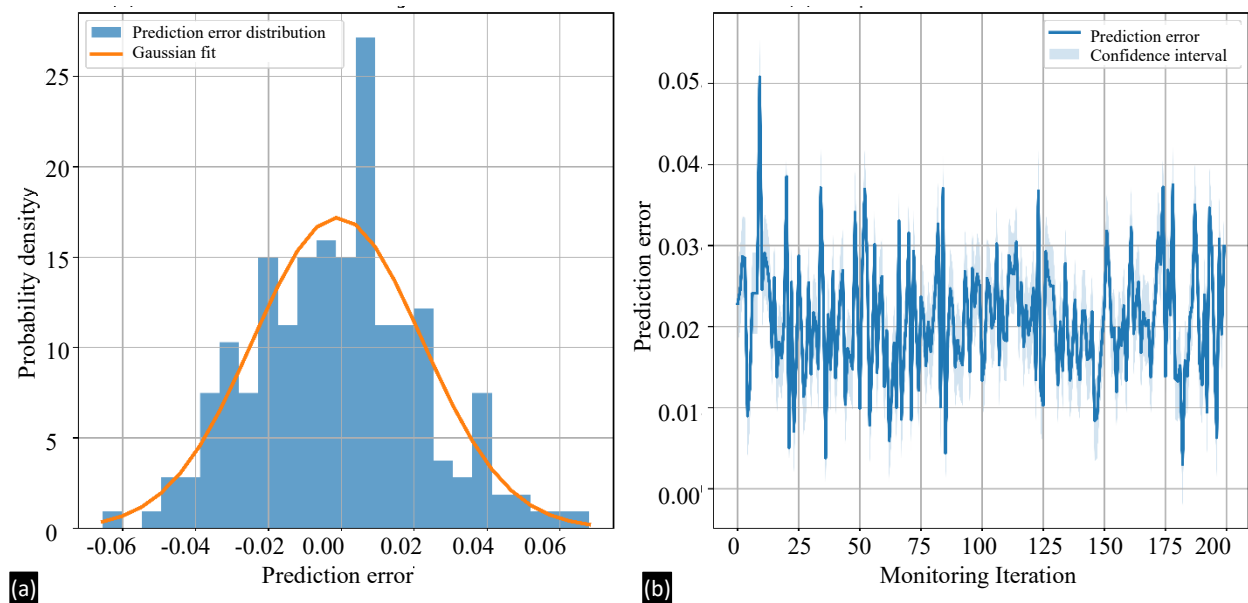


Figure 7. Error distribution of damage detection predictions for the proposed SHM framework. (a) Error distribution of damage detection model; (b) Temporal variation of detection error.

The area under the ROC curve (AUC) can be considered as a summary of the performance of classification. Increased values of AUC show better discrimination between the normal and the damaged structural conditions. Table 10 provides a summary of the AUC values of the monitored methods of approaches.

The analysis of the ROC demonstrates that the concept of the framework with the highest AUC value (0.97) is more appropriate to differentiate between the damaged states and healthy structural condition. Similar improvement in the accuracy of classification has been achieved with machine learning-based SHM systems that use multimodal sensor data [28, 31].

Error Distribution Analysis

Along with determining accurate detection, the patterns of prediction errors should be studied, to check the solidity of the monitoring structure. The analysis of errors was performed on the basis of comparisons of the predicted structural health states to the ground-truth damage conditions realized in the controlled monitoring experiments. Figure 7 presents the error distribution of the proposed monitoring system.

The error distribution indicates that the majority of the errors in predictions are between 3 percent and -3 percent. This means that this suggested monitoring model exhibits a steady detection performance under varying monitoring conditions.

The supplementary quantitative studies enhance the accuracy of the suggested monitoring system. The statistical significance test actually proves that the increase in the detection accuracy is not by chance. The ROC analysis has good classification ability, whereas the error distribution analysis shows steady prediction behavior.

Collectively, these findings can serve as a strong indicator, which is that the suggested IoT-based multimodal monitoring framework is a powerful and scalable solution to structural health monitoring of fiber-reinforced polymer composite frameworks.

DISCUSSION

The obtained outcomes of the suggested IoT-based framework of structural health monitoring prove that it is able to detect and monitor structural degradation in fiber-reinforced polymer (FRP) composite

structures with a high degree of reliability. Other recent studies have also observed the same where multi-sensor monitoring increased the sensitivity of composite damage monitoring systems [17, 20].

The quantitative appraisal also identifies the strengths of the suggested framework. The reported detection accuracy of about 95% is indicative of the fact that structural health assessment with the fusion of the distributed sensor signals can be said to be more reliable than the related single-modality monitoring process. Further, the response of the monitoring system to identify healthy and damaged structural conditions is validated by ROC analysis and statistical validation. These results are in line with the earlier studies which have highlighted the importance of data-based and multimodal SHM approaches to enhance the strength of composite monitoring systems [10, 31].

The other notable finding of the current research is that the proposed system can be used to trace the temporal changes of structural damage with the help of the fused damage index and damage propagation indicator. These indicators can allow constant assessment of the structural integrity and can be used to aid proactive maintenance plans in massive composite structures. The focus on the need to integrate sensing technologies with real-time analytic tools and networked monitoring systems are reflected in the recent developments in intelligent SHM systems, as well [5, 32].

Altogether, the findings can be used to support the fact that the application of IoT-enabled networks of sensing in connection with multimodal data integration would be a promising way to enhance the scalability and reliability of structural health monitoring systems of advanced polymer composite structures.

Multimodal fusion enhanced monitoring accuracy since the different sensing modalities monitored different physical manifestation of the damage evolution in the fiber-reinforced polymer laminate. Strain sensitive channel was more sensitive to distributed deformation and stiffness variation and acoustic channel was more sensitive to local micro-crack initiation and interlinear debonding and the thermal response was an indirect indication of redistribution of stress and local dissipation. These signals when concurrently interpreted minimized uncertainty that would have been generated in single sensor surveillance. This is the reason why the fused framework was more stable in detecting under different loading and environmental conditions. Meanwhile, there are still a number of operational constraints. The current validation was done on laboratory scale specimens, and recalibration of sensing density, network topology and base threshold values will be needed to transfer the results to full scale structures. Stability of embedded sensors in cyclic fatigue and environmental effects on baseline drift in long-term performance is also to be studied further.

CONCLUSION AND FUTURE SCOPE

This paper introduced an IoT-based structural health monitoring system to detect the presence of damage in fiber-reinforced polymer (FRP) composite structures. The suggested system combines distributed sensor components, edge computing, and multimodal damage synthesis to measure structural integrity on a real time basis. As it was experimentally proved, the joint analysis of the strain variation, acoustic emission signals, and impedance measurements gives a complete overview of the structural response of polymer composite laminates. The resulting fusion model and structural health index facilitated effective identification of progressive damage processes like cracking of the matrix, delamination and fracture of the fibers. The quantitative analysis revealed that the proposed framework obtains a better detection accuracy than traditional single-sensor monitoring methods, and has a stable prediction accuracy in the changing structural conditions.

The other significant value of this work is that using the IoT communication infrastructure has been combined with structural monitoring algorithms, making it possible to monitor the structures remotely and evaluate them constantly when they are used in large-scale infrastructures. The capability to monitor the propagation of damage using the fused damage index also promotes predictive maintenance courses

as well as enhances the long-term dependability of high-tech composite materials.

The next generation of research can be an extension of this model with the addition of more sophisticated machine learning or digital-twin-based predictive models to enhance damage localization and prognosis. Moreover, the field validation in aerospace or wind-energy composite architecture in large scale would also serve to prove the scalability of the suggested monitoring architecture.

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