*Wasit Journal of Engineering Sciences*
Journal homepage: https://ejuow.uowasit.edu.iq
Vol. 14 No. 3 September 2026, pp.167-182
https://doi.org/10.31185/ejuow.v14i3.988

ISSN 2305-6932
*Original Research*

# A Cost-Effective Sensor System for Structural Health Monitoring: Design and Experimental Evaluation

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Received Jun. 14, 2026 Revised Jul. 2, 2026 Accepted Jul. 4, 2026 Online Sep. 1, 2026

## ABSTRACT

Structural health monitoring (SHM) is an essential part of disaster prevention and can reduce human deaths and material losses. On the other hand, common SHM systems tend to be limited because of their high cost and difficult installation. In this research, the SHM device is used to measure deflections and bending of the composite steel-concrete beam, and the stress sensors are used to collect data from the device. The device described in this research is low-cost. Researchers wanted to investigate the behavior of a composite steel-concrete beam under various loading scenarios using a testing machine that measured the concrete's strength and stress. The results of experimental dynamic characterization have been used to verify the reliability and good response of the proposed low-cost system. The Nash-Sutcliffe efficiency (NSE), normalized root mean square error (NRMSE) and Mean Absolute Error (MAE) were used. Each proposed model exhibits very high predictive power, with NSE=99.1%, NRMSE=2.66%, and MAE=496.05με, indicating excellent alignment between observed and simulated values within the range of experimental measurements at higher resolution. The proposed system is cost-effective, efficient, and innovative, while leveraging existing monitoring systems without compromising the quality or specificity of the output.

**Keywords**: Structural health monitoring; Low-cost system sensing system; Strains gauge; Composite steel-concrete beam.

## 1. INTRODUCTION

Civil infrastructure such as buildings and bridges is always subjected to aging, adverse environmental conditions, overloads, earthquakes and other external factors, which, over time, cause a decrease in the structural performance of the infrastructure during its service life [1]. Although these changes are not necessarily detected early on, they are likely to progress to serious structural changes. They also result in unpredictable failures, significant financial losses and potential safety risks to the public [2].

Therefore, maintaining the safety, reliability, and serviceability of civil structures has become an essential requirement for sustainable infrastructure management. In this context, SHM has emerged as an effective engineering approach for continuously evaluating structural conditions through integrated sensing, data acquisition, and data analysis, enabling early damage detection, condition assessment, and timely maintenance planning [3].

In recent years, technological advances have greatly improved the capabilities of SHM, enabled by artificial intelligence [4], wireless communication and the Internet of Things [5], cloud computing, and digital engineering technologies [6]. These developments have expanded to improve the efficiency of maintenance activities and support decision-making with a higher level of accuracy. They are not limited to intelligent data processing, continuous real-time monitoring, and the remote management of infrastructure. Despite the significant operational benefits provided by (SHM) systems, their implementation faces numerous challenges. The most notable of these include the high cost of sensing devices and commercial data acquisition systems, the complexity of installation procedures, the need for a large number of cables, and the requirements for long-term maintenance [7].

In addition, traditional inspection methods still rely heavily on visual inspection and manual procedures, making the evaluation of structural conditions a time-consuming process that depends on subjective judgment. Therefore, these methods are not suitable for continuous monitoring. Although many indicators are used to assess structural integrity, the most common are strain, displacement, crack propagation, and vibration [8].

Strain measurement provides direct information about structural deformation and the redistribution of stresses within the structure. Therefore, it is considered one of the most reliable methods for the early detection of damage. Furthermore, crack monitoring is an important indicator of structural deterioration, as the initiation and propagation of cracks are among the earliest visible signs of deterioration [9].

The accuracy of structural inspection and damage detection has improved significantly in recent years due to advances in modern sensing technologies and image processing techniques [10]. Nevertheless, practical challenges still limit the widespread adoption of (SHM) systems [11].

The limitations of many existing monitoring systems include the use of complex hardware, specialized sensor components, or costly commercial products, which are not appropriate for large-scale civil engineering applications or projects with limited funds [12].

Furthermore, high measurement accuracy in a simple hardware configuration with low implementation cost is one of the key issues in developing apractical and reliable monitoring system [10]. This end, there is an ongoing demand for low-cost sensing platforms that can deliver accurate and reliable measurements without adding complexity or cost to the system [13].

To address these issues, this study proposes a new cost-effective SHM system that uses conventional electrical strain gauges and an STM32 microcontroller for continuous strain measurements. The proposed system was tested experimentally by comparing its direct response to that of a commercial data acquisition system under progressive compression loading, and different stages of the structural response were tested. The proposed system cannot only be employed to continuously monitor the strain of structural elements in a practical, economical, and reliable manner but also keep the hardware configuration simple and the implementation cost low. Moreover, it provides a future-proof base for further integration with smart damage diagnosis techniques and wireless communication technologies for applications in smart structural health monitoring.

## 2. Materials and Methods

Comparative testing was performed on a classical SHM system to verify the feasibility of an alternative, low-cost, simple SHM system. In addition to testing the timing of the system's response and some potential operational limitations as a function of varying environmental conditions, the tests also evaluated the overall monitoring performance to confirm the system can provide a level of measurement quality acceptable to.

### 2.1. Structural Integrity Monitoring Systems

Advanced SHM technologies continuously monitor the state of structures and detect damage in its early phases, which is vital to the protection and maintenance of structural integrity. Not only are these systems designed to be affordable and easy to implement, but they also utilize low-cost sensors and technology solutions that are easily accessible to all, without the need for expensive and complicated devices.

### 2.2. Low-Cost Structural Integrity Monitoring System

The measurement system in this paper has greater capability for acquiring strain signatures with higher resolution and repeatability. As shown in Figure 1, the system uses strain gauges wired in a pair of resistances to form one-half of a Wheatstone bridge circuit that produces a differential voltage output due to small mechanical deformations. The bridge is powered by a stable 50 mA current source, assuring that the measurement conditions are stable during the acquisition time. The output signal is then passed through a DC shift and offset calibration stage to remove the unwanted offset components and set the baseline level. In addition, the conditioned signal is filtered with a 10th-order low-pass filter with a high-frequency cutoff to reduce high-frequency noise. Since the bridge output signal is only a few mV, a high-precision amplifier with a fixed gain of 10 is used to buffer the signal, and an adjustable gain in the 100–1000 range is kept meeting the different measurement needs. The amplifier output is then offset with a 1.65 V reference voltage so that it falls within the ADC's acceptable input range. Not only does this conditioning step help to preserve signal integrity before digitization, but it also optimizes the dynamic range of the acquired data. The conditioned analog signal is then digitized by the microcontroller STM32F103C8T6, which acquires, processes, and communicates the measured values to the computer monitoring system for further processing and storage.

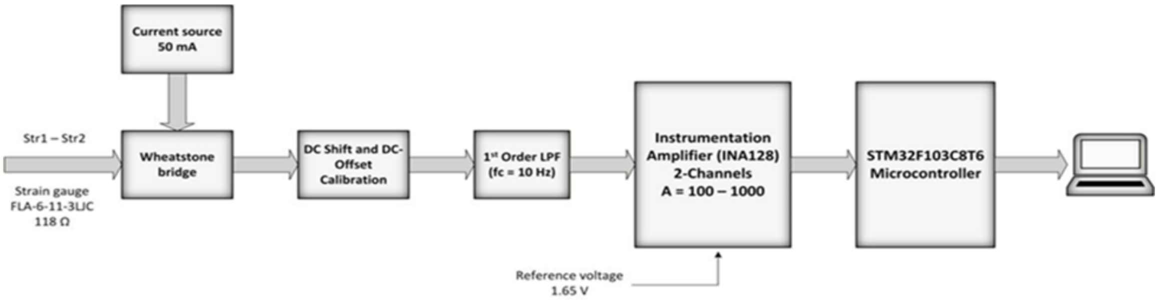


Figure 1. System Block diagram.

A micro-analog signal-conditioning circuit for interfacing low-level sensor signals with the microcontroller (STM32F103C8T6) is shown in Figure 2 [14]. In addition to the proposed circuit architecture, the circuit includes operational amplifiers, passive filtering elements, dedicated micro-amplifiers, and tunable reference networks, all of which provide signal-processing stability, immunity to noise and common-mode interference, and ensure high measurement accuracy [15],[16].

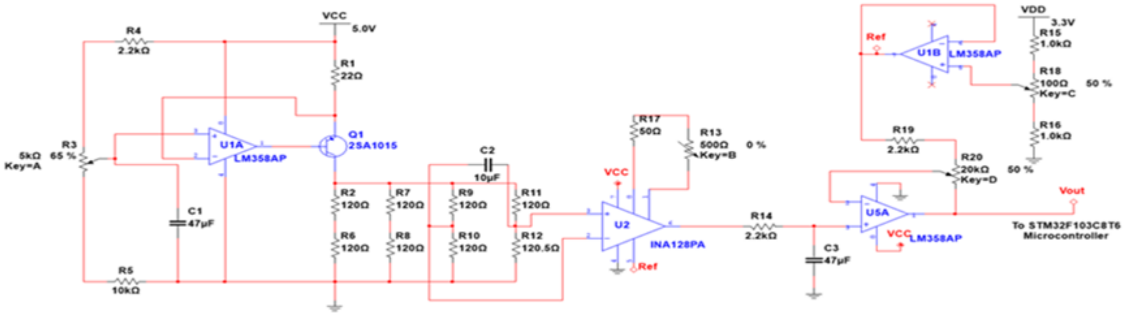


Figure 2. Schematic diagram of the proposed strain gauge signal-conditioning circuit and data acquisition interface.

The sensor and analog signal-conditioning circuit provide low-frequency filtering and amplification.

### 2.3. Signal Conditioning and Pre-Amplification

The signal conditioning stage uses an LM358 operational amplifier with a 5V power supply. Resistors R3 and R5 form a variable resistor network to fine-tune the input bias and adjust gain to suit different sensor sensitivities. Capacitor C1 (47 µF) is added to remove low-frequency noise and to provide DC operating-point stability. In addition, the next pre-conditioning stage is a PNP transistor (2SA1015) that raises the voltage high enough to allow sufficient current to flow through the chain of transistors to keep the output voltage constant. The amplifier configuration, established by the resistors R1-R4, guarantees linear operation and thermal stability during the measurement process.

### 2.4. Differential Signaling and Noise Rejection

A balanced resistor network (R2–R12) is used to convert the processed signal into a differential signal. This is done to greatly reduce common-mode noise. This configuration not only makes the component less susceptible to displacement interference, but also helps to resist electromagnetic interference (EMI), which is common in industrial environments and integrated circuits [17].

In addition, capacitor C2 (10 µF) smooths the DC voltage by shunting the high-frequency ripple components to ground, which helps reduce the ripple reaching the instrumentation amplifier stage [18].

### 2.5. Amplifier Stage

The INA128 instrumentation amplifier was used to amplify the differential signal [19]. The same resistor values were used throughout all parts of the circuit, while the amplifier gain was adjusted by changing the value of resistor R13 to match the sensitivity of the sensor.

The INA128 amplifier is characterized by a high common-mode rejection ratio (CMRR), a low input offset voltage, in addition to excellent thermal stability, which ensures optimal performance when amplifying low-level signals. The input voltage at the reference terminal of the INA128 amplifier is adjusted in order to achieve the best utilization of the differential input range, so that it falls within the allowable range of the single-ended analog-to-digital converter (ADC) input of the microcontroller (MCU).

In addition, the output calibration and filtering stage uses another LM358 operational amplifier equipped with a continuously adjustable trim potentiometer and a low-pass filter to calibrate the amplified signal.

Resistors R14, R19, and R20 form a network responsible for controlling the output voltage adjustment. To reduce high-frequency noise and transient disturbances, capacitor C3 (47 µF) was added.

Furthermore, resistors R15, R16, and R18 form a precision voltage reference network that provides accurate adjustment of the output voltage offset and contributes to preventing saturation of the analog-to-digital converter (ADC) input, thereby maintaining the output signal within the allowable operating range of the ADC of the STM32F103C8T6 microcontroller, which ranges from 0 to 3.3 V.

Also, before the conditioned output voltage (Vout) is converted into a digital signal by the STM32F103C8T6 microcontroller, the signal passes through different signal conditioning stages, as shown in Figure (2).

This design is characterized by low output impedance, high noise immunity, while maintaining a stable output voltage, which is considered very important for ensuring accurate digital sampling of the signal and achieving reliable data acquisition. Figure 3 shows the block diagram of the entire data acquisition system.

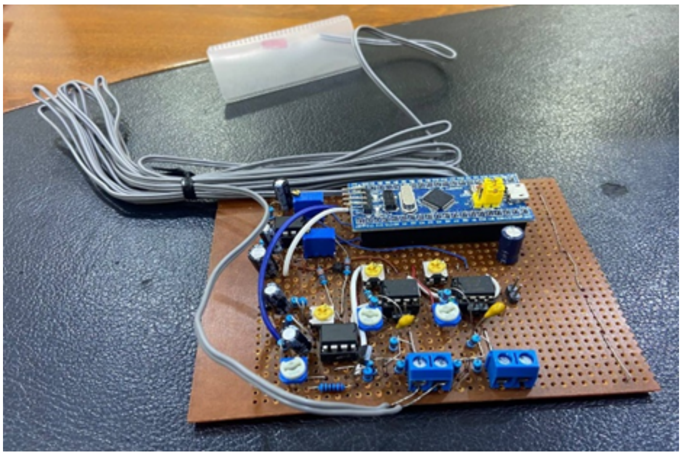

Figure 3. The SHM system setup: (a) connection to the computer; (b) the STM32 microcontroller circuit.

A dedicated graphical user interface (GUI) based on a PC was designed to provide real-time visualization of the results of measurements and to allow the user to save and archive the measured data for later analysis, as shown in Figure 4. Besides, the analog signals are converted to digital by the microcontroller STM32, and sent digitally to the monitoring system for processing. The proposed platform not only shows low noise sensitivity and appropriate measurement accuracy but also provides a solid basis for its use as a mechanical testing platform in SHM scenarios.

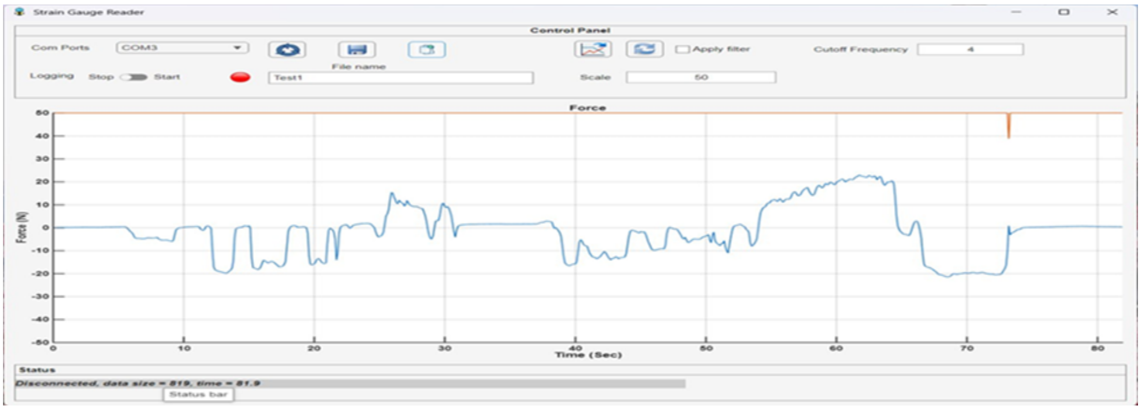


Figure 4. MATLAB Program Execution.

### 2.6. Theoretical Framework and Measurement Principles

One of the key concepts of structural load monitoring systems is high measurement accuracy, which underpins the safe and reliable physical modeling of the long-term safety and operational condition of engineering structures. Correct strain measurement can not only provide valuable data on structural deformation but also be used to evaluate the behavior of materials under permanent loads. The difference between the final length L of the specimen and the initial length $L_0$ is called the elongation ΔL and is written as[20]:

$$\varepsilon = \Delta L / L_0 \tag{1}$$

SHM systems are usually used at a relatively low level of stress, so strain is often referred to in microstrain (με) units, which is equal to ($\mu\varepsilon = 10^6$ m). Microstrain units can be used not only for accurate characterization of the structural response but also to quantify material behavior under in-service loading conditions.

### 2.7. Measurement of Electrical Resistance Strain

A strain gauge is a device that converts mechanical strain into a change in electrical resistance proportional to the strain. The sensitivity of the strain gauge is not only described by the Gauge Factor (GF), but also formally defined as the ratio of the relative change in electrical resistance to the applied mechanical strain [21] as shown in equation (2):

$$GF = (\Delta R/R) / \varepsilon \quad (2)$$

The relative change in electrical resistance ΔR/R is plotted against mechanical strain ε.
The strain can be calculated by rearranging Equation (2) using the measured change in resistance and the known value of the Gauge Factor.
In general, a GF of 2.08 means that a foil-based strain gauge has linear or quasi-linear behavior only in the elastic deformation regime. Traditional foil-based strain gauges are widely used in SHM applications because of their higher stability and reproducibility, even though piezoelectric sensors based on novel structures and advanced materials have shown significantly improved sensitivity compared to conventional strain gauges. In addition, the Wheatstone bridge circuit is used to measure very small changes in the strain gauge's resistance. The basic Wheatstone bridge not only contains four arms of resistance driven by a Wheatstone bridge excitation voltage Vex, but it can also be used to detect the strain behavior of one of the arms when the arm is placed under load by measuring the bridge output differential voltage Vo. For applications in a quarter-bridge, the active sensing element is one arm; the other three arms are constant resistors. If the deformations are small, the output voltage can be written as equation (3):

$$Vo \approx Vex/4 \times GF \times \varepsilon \quad (3)$$

Rearranging equation (3), we obtain equation (4):

$$\varepsilon = 4Vo / (Vex \times GF) \quad (4)$$

This equation provides a direct correlation between the applied mechanical stress and the measured electrical output, and it is a generalized equation that can be used for any empirical strain measurement system, such as structural stress monitoring applications. The precision measurement amplifier not only improves signal fidelity but also, by leveraging advanced analog front-end signal processing technology, greatly enhances the accuracy of the actual sensing and data acquisition system.

## 3. Experimental Program

The experimental program investigated the flexural behavior of a composite steel-concrete beam and measured the accuracy of the proposed low- cost monitoring system compared with a high-accuracy commercial monitoring system (Data Taker DT85G). In addition, the laboratory specimen was built to a size of one-third of the full-scale model, which meets established engineering slenderness requirements such as ASTM and Eurocode requirements.

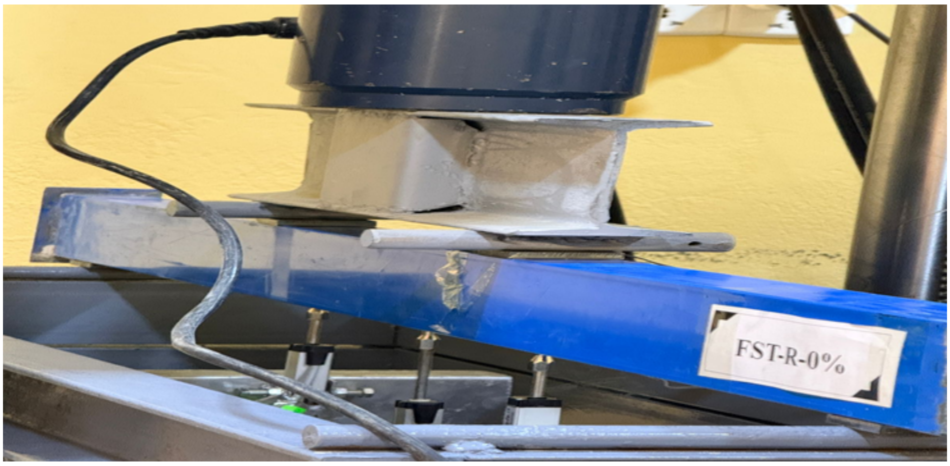


Figure 5. Composite steel-concrete beam.

The cross-sectional slenderness ratios (b/t, D/t) were checked to ensure the cross-section was within the prescribed design limits. The beam tested was 50 mm × 100 mm × 1350 mm. Moreover, the steel section was concreted, cast, and cured according to standard laboratory procedures to ensure the best quality of the materials. The beam was then mounted on a loading machine for bending tests, in which loads were applied progressively, and the corresponding structural response was measured with strain gauges, as shown in Figure 6.

In addition, a single strain gauge (GF=2.08) was mounted at the midspan of the top surface of the specimen to monitor the strain response throughout the loading process.

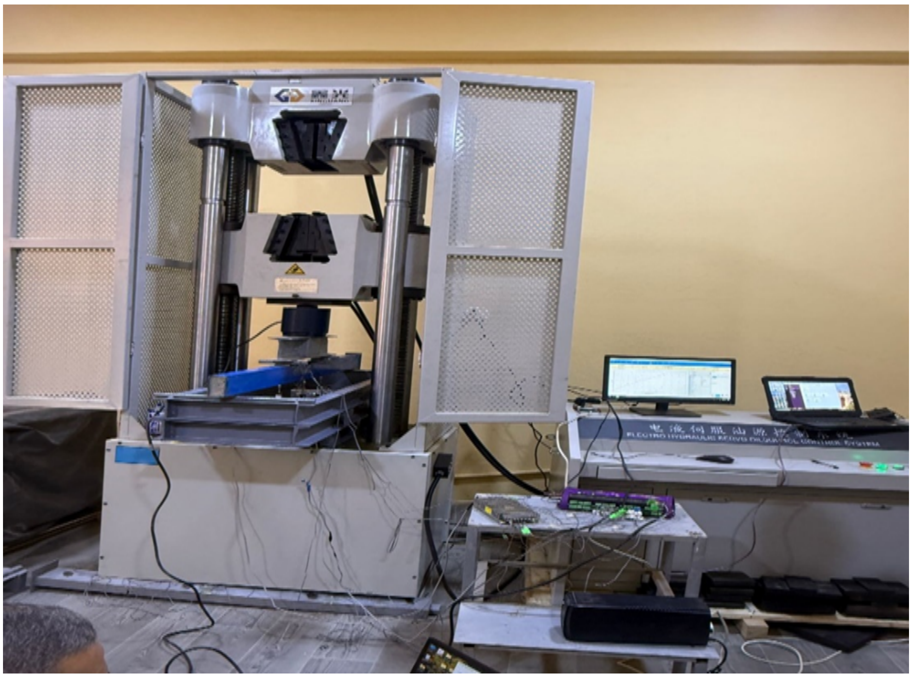

Figure 6. Compression Testing of Composite steel-concrete beam.

In this study, two different measuring devices were used: a low -cost conventional sensing system, and a high-precision commercial reference instrument, allowing the direct comparative evaluation of the results obtained by both systems as shown in Figure 7.

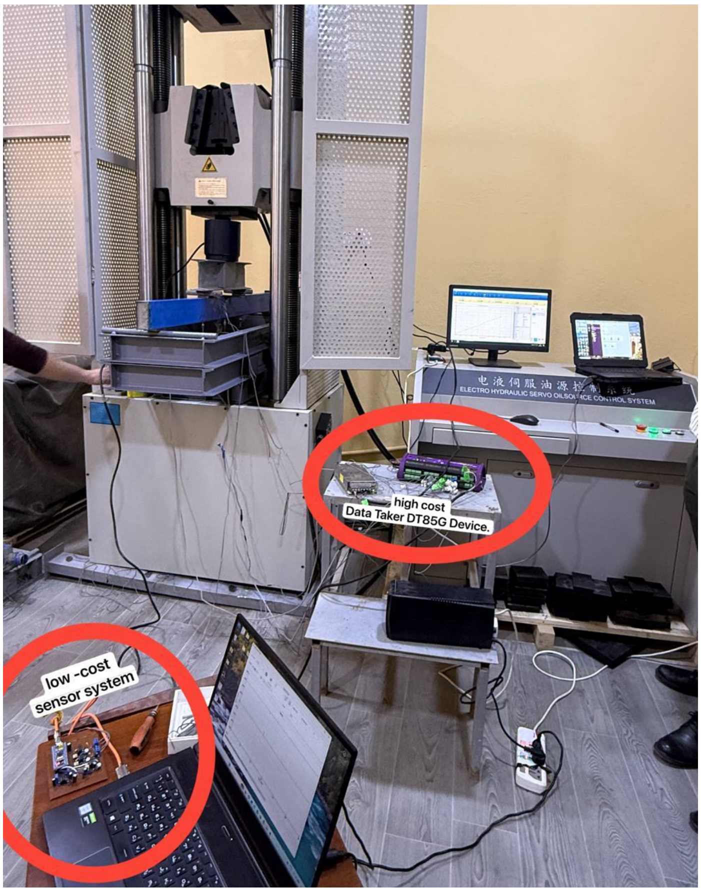


Figure 7. Experimental Setup and Instrumentation System for Composite steel -concrete beam.

### 3.1. Reference Data Recorded

For comparative evaluation of the proposed low-cost IoT-based measurement system, the high-performance commercial Data Acquisition system DT85G Geo Data Logger, shown in Figure 8, was used in this study. In addition to being a multi-channel stand-alone data logger with a full range of features and capabilities for scientific and engineering applications, the Data Taker DT85G is a powerful data acquisition and measurement solution in harsh environments where multi-channel data acquisition and high accuracy are critical. The system offers measurement accuracy up to 18-bit resolution and supports a variety of sensing elements such as strain gauges, differential linear displacement transducers, and thermocouples for precise signal processing in structural integrity monitoring and geotechnical measurements.

Moreover, commercially available data loggers such as the DT85G are widely used in experimental studies to ensure the technical stability and accuracy of measurements for system validation and performance evaluation. While these systems are more expensive to acquire than other measurement systems, the higher cost reflects their greater accuracy, durability, and compliance with industry measurement requirements. The DT85G has built-in Ethernet connectivity and supports popular communication protocols such as Modbus and FTP, enhancing data integrity and remote access for ongoing structural monitoring applications.

Figure 8. Data Taker DT85G Device.

### 3.2. Economic Evaluation of the Proposed System Compared with the Commercial Data Acquisition Systems

Table 1 shows that the proposed system also results in significant cost savings during implementation compared with commercial data acquisition systems, while maintaining a satisfactory level of measurement accuracy. This is a significant cost advantage that demonstrates the proposed system's potential as an economical alternative to conventional commercial systems, especially for cost-sensitive projects where conventional systems are not economical.

**Table 1**. Approximate Cost Comparison between the Proposed System and Commercial Data Acquisition Systems.

| System | Approximate Cost (USD) |
|---|---|
| Data Taker DT85G | ≈ 5,100$ |
| HBK Quantum X MX840B | ≈ 6,000$ |
| **Proposed Low-Cost SHM System** | **100$** |

## 4. Results and Discussion

Data on load-strain response and its validation results for the proposed low-cost sensing system are presented in the next section. To examine the performance of the proposed low-cost SHM system, comprehensive validation was conducted in terms of measurement accuracy, reliability, and precision under gradually increasing static loading. In addition, the strain response results obtained with the developed system were directly compared with those from a commercially available reference laboratory data acquisition system. In addition to being performed under controlled laboratory conditions, the validation test used a composite steel-concrete beam (i.e., a steel beam filled with concrete) as the main test object, ensuring a representative structural configuration for the experimental validation process.

### 4.1. Flexural Characterization and Deformation States at the Interfaces

The load-strain relationship of the composite steel-concrete section was investigated by comparing simultaneous measurements from the commercial reference system and the proposed low-cost measuring system. The experimental curves for both systems showed an excellent match at all load levels and proved the ability of the proposed low-cost system to effectively track the structural response over the entire range of loading, as shown in Figure 9.

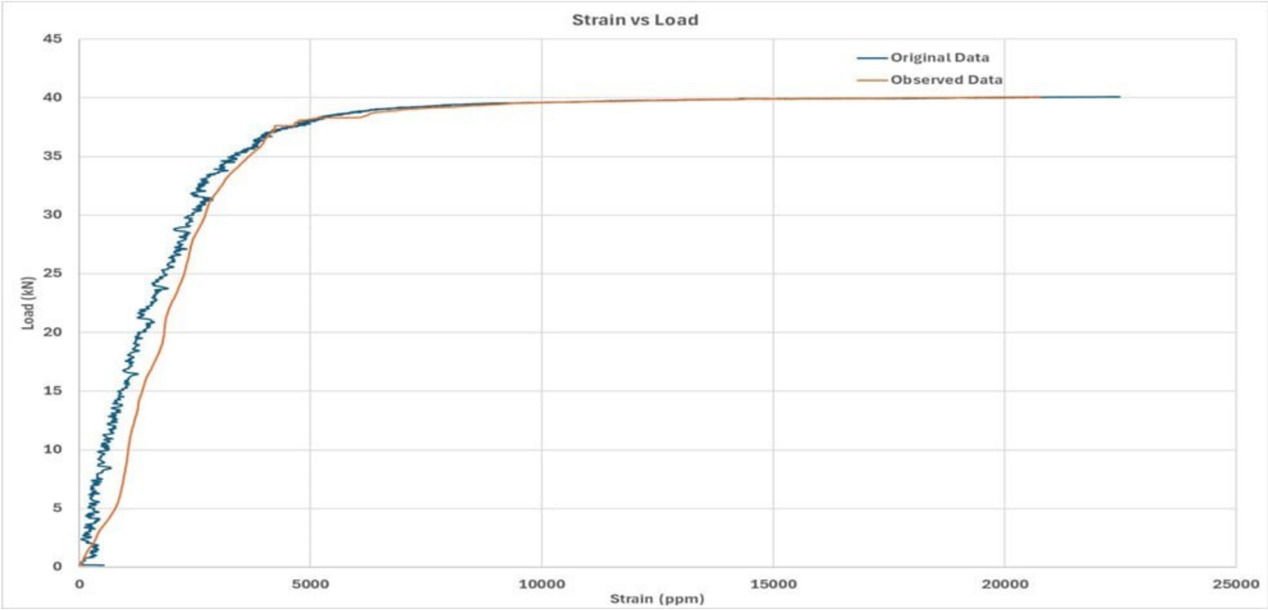

Figure 9. Comparison between reference and low-cost sensor load-strain curves from experimental raw data.

### 4.2. Structural Response Analysis: Three Mechanical Stages

The structural response is expressed as a data-driven explanation based on test results, assuming complete composite action between layers, and is divided into three mechanical stages.

**Stage 1: Elastic Phase (0–30 kN):**
The composite section was linearly elastic under loading up to about 30 kN. The measured flexural strain increased linearly with applied load, reaching a maximum of ~2500 με at 30 kN. The structural response was mainly elastic, with no permanent deformation observed. In addition, the readings from the high-accuracy reference system were almost indistinguishable from those of the low-cost sensor during this phase, indicating little experimental noise or variance in the measurements.

**Stage 2: Elastic-Plastic Transition (30-37kN):**
The structure transitioned into the elastic-plastic phase between 30 kN, and 37 kN. In this state, not only did the load-strain curve increasingly deviate from linearity, but the strain measured also increased towards 4500 με at 37 kN, indicating that the composite section was experiencing partial yielding and full bending deformation. The range of this transition was nonlinear relative to the structural response, but the difference between the two measurement systems was negligible throughout the transition, as shown in Figure 10.

**Stage 3 is the stage of full plastic yield, and ultimate condition (37-40 kN).** This is because the applied load increment after 37 kN was rather small, but after passing the 37 kN mark, the composite beam entered the full nonlinear plastic stage (between point A and B in the load-strain curve).
This stage not only marked the point at which full plastic yielding had occurred but also indicated that a small increase in load (10 N) produced large, disproportionate changes in the measured strain, as shown in Figure 10.

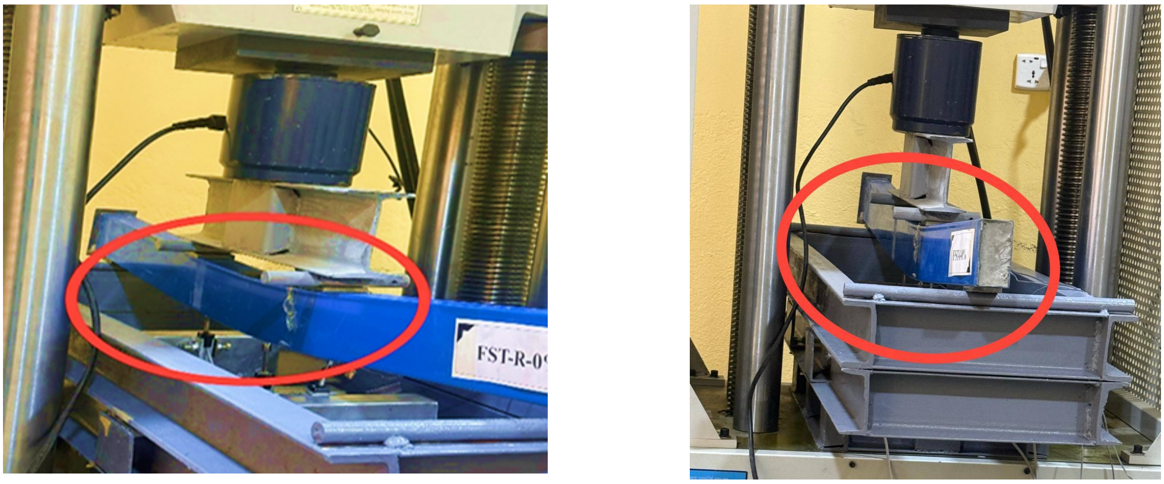

Figure 10. Experimental Load-Strain Response: Reference vs. Low-Cost Sensor System.

The horizontal plateau at the 40 kN load level defines the fully plastic region, which represents the maximum structural capacity of the composite section. Moreover, a long ductile plateau was maintained at strains well above 20,000 με up to the onset of structural failure at ~22,500 με. The outer steel portion exhibits strong ductile behavior and can confine the concrete core and maintain the integrity of the cross-section throughout the loading range up to the ultimate capacity. A full set of statistical performance criteria was used to objectively validate the reference system's agreement with the proposed low-cost system within an advanced structural engineering evaluation framework. In addition to the NSE, NRMSE, and MAE used as performance indicators, the (r) and $R^2$ were also introduced to gain a multi-dimensional statistical assessment.

The following high-precision performance parameters were obtained from the quantitative analysis. The NSE value of 0.991 confirms the appropriateness of the proposed system for evaluating measurement conformity, with strain measurements from the low-cost sensor close to those of the reference system, with only slight differences noted in the elastic slope and the broad plastic plateau region.

In addition, the NRMSE of 2.66% remains below the accepted 5% threshold for accurate measurements in experimental structural mechanics, and the MAE of 496.05 με attests to the proposed sensor's reliable performance in the presence of signal noise and geometric variation. The values (r = 0.9967) and ($R^2$ = 0.9934) indicated that the two measurement systems were not only well linearly aligned but also showed good agreement in both the linear elastic and nonlinear plastic regions. While these metrics were calculated separately, their close agreement suggests that the proposed monitoring framework can explain 99.34% of the strain variation observed in the composite experiment.

All statistical indices confirming the performance of the proposed system is summarized in a table, that is, Table 2.

**Table 2.** Statistical Performance Evaluation of the Proposed Low-Cost Sensor System.

| **Evaluation Metric** | **Statistical Value (Actual data)** | **Target Threshold** | **Performance Assessment** |
|---|---|---|---|
| Nash-Sutcliffe Efficiency (NSE) | 0.991 | ≥0.90 | Excellent Predictive accuracy and tracking |
| Normalized RMSE (NRMSE) | 2.66% | ≤5.00% | Highly precise with minimal residual error |
| Pearson's Correlation (r) | 0.9967 | 1.00 | Robust and strong linear relationship |
| Coefficient of Determination ($R^2$) | 0.9934 | 1.00 | 99.34% of data variance successfully explained |

| | | | |
|---|---|---|---|
| Mean Absolute Error (MAE) | 496.05 με | - | Low average absolute error, indicating good agreement with the reference system |

## 5. Comparison with Recent Related Studies

To further clarify the contribution of the proposed low-cost sensor system, its performance was compared with that of three recent studies on low-cost data acquisition and wireless SHM systems.

Abazeed et al [22] developed an ultra-low-cost wireless data acquisition system for strain and deflection monitoring. Not only was their system based on commonly available electronic components, and open-source software, but it was also designed at an estimated cost of approximately USD 20, making it a highly economical solution. The system was experimentally evaluated through displacement measurements, aluminum beam testing under static and dynamic conditions, and reinforced-concrete beam bending tests. Although the developed system demonstrated reliable performance, its results indicated that it could measure displacement with a root mean square error (RMSE) of approximately 0.1 mm and capture strain values within a few microstrains.

While **Abazeed et al.** [22] and the present system aim to provide a low-cost alternative for monitoring structural response, the present system was directly validated against a high-end commercial data acquisition system when compression loading was applied. These statistical indicators obtained from the model are: NSE = 0.991, $R^2$ = 0.9934, r = 0.9967, and NRMSE = 2.66%, indicating excellent agreement with the reference system.

In contrast to **Abazeed et al.** [22], who computed accuracy in terms of RMSE for displacement and strain measurements, the present study provides a more comprehensive statistical analysis of the agreement between the low-cost and commercial reference systems.

**Nilnoree et al** [23] designed a low-cost wireless sensor network framework for SHM based on mimic broadcasting using TCP/IP socket programming. They used a Raspberry Pi 4 as a gateway, a Raspberry Pi Zero 2W as sensor nodes, ADXL345 MEMS accelerometers, and DS3231 real-time clock modules. The study was not only about time synchronization among multiple low-cost Wireless Sensing Nodes (WSNs), but also about synchronizing acceleration signals using Dynamic Time Warping (DTW) for frequency-domain analysis.

They found small drifts on the order of a millisecond in their experimental results prior to signal alignment, and they used DTW to correct the timing of the low-cost sensor signals.

Unlike this work, the present study's main interest is not in wireless time synchronization or modal analysis. It simply tests the accuracy of a low-cost load-strain sensor system in compression.

The two studies are complementary: **Nilnoree et al.** [23] showed how synchronized low-cost wireless sensing networks can be made feasible; the present study showed how a low-cost sensing system can reliably measure structural response using strain measurements, with strong statistical agreement with a commercial reference system.

A multi-sensor system for SHM using WSN was developed by **Dagsever et al** [24]. In their system, they included a PZT sensor, a strain gauge, an accelerometer, and an environmental sensor on a very small, flexible PCB (3 cm × 3 cm). The system was designed to be lightweight and scalable for SHM applications, and used Bluetooth low energy for wireless communication.

**Dagsever et al** [24], validated the proposed multi-sensor system by comparing it to the commercial instruments. The PZT response was compared with that of a commercial oscilloscope, and strain and acceleration results were compared with those of a commercial DAQ system. They revealed that the proposed system was in good agreement with the commercial devices both in terms of wave profile and peak and decay characteristics. Overall performance was satisfactory, but there were some minor sampling variations due to delays in wireless transmission. The proposed system in the present work presented a similar level of agreement with a commercial reference system with NSE = 0.991, $R^2$ = 0.9934, r = 0.9967, NRMSE = 2.66%, and MAE (496.05) με. While **Dagsever et al** [24], were interested in multi-sensor platform for aerospace related SHM applications, the present study is aimed at strain monitoring of compression loaded structural members. Moreover, an evaluation of the proposed system was accomplished by analyzing the various loading stages such as elastic stage, elastic-plastic transition, and full plastic yielding, which gave a detailed analysis of the performance of the system under progressive structural deformation.

In summary, the proposed low-cost sensor system achieves accuracy comparable to recent low-cost SHM systems reported in the literature. The use of several statistical indicators in the present study, and the fact that the only difference with the proposed system is that the system is directly validated with a high-end commercial data acquisition system, and not just based on visual agreement or on just one error indicator, are other objectives that have been incorporated into the present study. The high values of NSE, $R^2$, and Pearson's correlation coefficient, together with a low NRMSE, are used to validate the reliability of the proposed system for tracking the load-strain behavior. Thus, it is concluded that the proposed system is a practical and economical approach for SHM applications, particularly when conventional commercial data acquisition systems are cost-prohibitive.

**Table 3.** Comparison of the Proposed Low-Cost Sensor System with Recent Related Studies.

| Study | System Type | Reported Results | Comparison with Present Study |
|---|---|---|---|
| Abazeed et al. (2025) | Ultra-low-cost wireless strain/deflection DAQ | Cost ≈ USD 20; RMSE ≈ 0.1 mm; strain within few microstrains | Our system achieved NSE = 0.991, $R^2$ = 0.9934, r = 0.9967, NRMSE = 2.66% , MAE (496.05) με |
| Nilnoree et al. (2024) | Low-cost WSN using Raspberry Pi and MEMS accelerometers | Improved alignment of acceleration signals after millisecond-level drift | Our work focuses on load-strain accuracy rather than synchronization |
| Dagsever et al. (2025) | Multi-sensor WSN: PZT, strain gauge, accelerometer, environmental sensor | Similar waveforms, peaks, and decay patterns; minor wireless delay | Our system also matches commercial DAQ, with quantified statistical accuracy |

## 6. Conclusion

An inexpensive SHM system has been developed and tested to monitor the strain of a steel-concrete composite beam under bending loads in real time. The results showed that the proposed system was able to track the structural response during the loading process: the linear-elastic stage, the elastic-plastic transition stage, and the approach to the maximum applied load.

The developed monitoring system not only provided measurements that agreed well with those obtained by the commercial reference data acquisition system (DT85G), but also yielded an NSE of 0.991, an NRMSE of 2.66%, and an MAE of 496.05, indicating that the three measurements were highly consistent.

In this paper, an initial laboratory-based experimental validation is presented, and the results show that the proposed low-cost system has potential as an effective tool for SHM applications.

Additionally, it is suggested that more specimens, load cases, and long-term monitoring studies be conducted to fully assess the system's performance and applicability.

Finally, the proposed framework provides a viable and cost-effective solution for real-time structural monitoring, with measurement results comparable to the commercial reference system.

## Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

## Funding Information

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

## Author Contributions

Dina HAIDER: Conceptualization, methodology, hardware design, software development, experimental investigation, data acquisition, formal analysis, writing – original draft. Manaf K. HUSSEIN: Supervision, methodology review, validation of experimental results, manuscript review and editing. Riyadh A. ABBAS: Supervision, technical guidance, data interpretation, manuscript review, and final approval of the submitted version. All authors read and approved the final version of the manuscript.

## Acknowledgments

The authors would like to thank the Department of Civil Engineering and the Department of Electrical Engineering at the College of Engineering, Wasit University, Iraq, for providing the facilities and technical support required to complete this research.

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## Notation List

| Abbreviation/Symbol | Meaning |
|---|---|
| SHM | Structural Health Monitoring |
| GF | Gauge Facto |
| ADC | Analog-to-Digital Converte |
| MCU | Microcontroller Unit |
| GUI | Graphical User Interface |
| STM32 | STM32F103C8T6 Microcontroller |
| INA128 | Instrumentation Amplifier |
| DAQ | Data Acquisition |
| DT85G | Commercial Data Acquisition System |
| WSN | Wireless Sensor Network |
| PZT | Piezoelectric Transducer |
| MEMS | Micro-Electro-Mechanical Systems |
| DTW | Dynamic Time Warping |
| PCB | Printed Circuit Board |
| IoT | Internet of Things |
| AI | Artificial Intelligence |
| Vex | Excitation Voltage |
| Vo | Bridge Output Voltage |

| | |
|---|---|
| E | Mechanical Strain |
| ΔL | Elongation (Change in Length) |
| L0 | Initial Gauge Length |
| L | Final Gauge Length |
| ΔR | Change in Electrical Resistance |
| R | Initial Electrical Resistance |
| ΔR/R | Relative Change in Resistance |
| CMRR | Common-Mode Rejection Ratio |
| NRMSE | Normalized Root Mean Square Error |
| MAE | Mean Absolute Error |
| NSE | Nash–Sutcliffe Efficiency |
| R^2 | Coefficient of Determination |
| R | Pearson Correlation Coefficient |
| με | Microstrain |

## REFERENCES


[1] M. Zhang, Z. Liu, C. Shen, J. Wu, and A. Zhao, "A review of radio frequency identification sensing systems for structural health monitoring," Materials (Basel)., vol. 15, no. 21, p. 7851, 2022. https://doi.org/10.3390/ma15217851

[2] Y.-J. Cha, R. Ali, J. Lewis, and O. Buyukozturk, "Deep learning-based structural health monitoring," Autom. Constr., vol. 161, p. 105328, 2024. https://doi.org/10.1016/j.autcon.2024.105328

[3] C. A. Tokognon, B. Gao, G. Y. Tian, and Y. Yan, "Structural health monitoring framework based on Internet of Things: A survey," IEEE Internet Things J., vol. 4, no. 3, pp. 619-635, 2017. https://doi.org/10.1109/JIOT.2017.2664072

[4] V. Plevris and G. Papazafeiropoulos, "AI in structural health monitoring for infrastructure maintenance and safety," Infrastructures, vol. 9, no. 12, p. 225, 2024. https://doi.org/10.3390/infrastructures9120225

[5] A. C. Rahita, A. Zaki, G. Nugroho, and S. Yadi, "Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends," Instrumentation, Mes. Metrologies, vol. 23, no. 2, 2024.https://doi.org/10.18280/i2m.230205

[6] Z. Sun, S. Jayasinghe, A. Sidiq, F. Shahrivar, M. Mahmoodian, and S. Setunge, "Approach towards the development of digital twin for structural health monitoring of civil infrastructure: A comprehensive review," Sensors, vol. 25, no. 1, p. 59, 2024.https://doi.org/10.3390/s25010059

[7] M. Abdulkarem, K. Samsudin, F. Z. Rokhani, and M. F. A Rasid, "Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction," Struct. Heal. Monit., vol. 19, no. 3, pp. 693-735, 2020.https://doi.org/10.1177/1475921719854528

[8] A. Elsisi, A. Zamrawi, and S. Emad, "A Comprehensive Review of Structural Health Monitoring for Steel Bridges: Technologies, Data Analytics, and Future Directions," Appl. Sci., vol. 15, no. 22, p. 12090, 2025. https://doi.org/10.3390/app152212090

[9] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, M. Gabbouj, and D. J. Inman, "A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications," Mech. Syst. Signal Process., vol. 147, p. 107077, 2021. https://doi.org/10.1016/j.ymssp.2020.107077

[10] A. Meoni, A. D'Alessandro, M. Mancinelli, and F. Ubertini, "A multichannel strain measurement technique for nanomodified smart cement-based sensors in reinforced concrete structures," Sensors, vol. 21, no. 16, p. 5633, 2021.https://doi.org/10.3390/s21165633

[11] V. P. Golding, Z. Gharineiat, H. S. Munawar, and F. Ullah, "Crack detection in concrete structures using deep learning," Sustainability, vol. 14, no. 13, p. 8117, 2022. https://doi.org/10.3390/su14138117

[12] J. Olivera, M. Gonzalez, J. V. Fuente, R. Varga, A. Zhukov, and J. J. Anaya, "An embedded stress sensor for concrete SHM based on amorphous ferromagnetic microwires," Sensors, vol. 14, no. 11, pp. 19963-19978, 2014. https://doi.org/10.3390/s141119963

[13] Z. Jia et al., "Development of a novel adaptive range strain sensor for structural crack monitoring," J. Mar. Sci. Eng., vol. 10, no. 11, p. 1710, 2022. https://doi.org/10.3390/jmse10111710
[14] R. Gao, "A Comparative Study of an STM32F103C8T6-Based FreeRTOS Smart Home System for Environmental Monitoring and Control," Informatica, vol. 49, no. 24, 2025. https://doi.org/10.31449/inf.v49i24.11427
[15] Y. Wang, D. Li, Q. Ma, and G. Wang, "Design and simulation analysis of smart home storage robot system based on STM32," in 2025 International Conference on Intelligent Robotics and Automatic Control (IRAC), IEEE, 2025, pp. 54-58. https://doi.org/10.1109/IRAC67707.2025.11381033
[16] A. F. H. Dhrubo and M. A. Qayum, "STM32-based IoT framework for real-time environmental monitoring and wireless node synchronization," arXiv Preprint arXiv2506.17295, 2025. https://doi.org/10.48550/arXiv.2506.17295
[17] L. Zhu and J. Lu, "Differential Signal Integrity Analysis in High-Speed Circuits," in Proceedings of the 2nd International Symposium on Integrated Circuit Design and Integrated Systems, 2025, pp. 236-244. https://doi.org/10.1145/3772326.3774738
[18] Z. Yu and B. Zhang, "The art of noise modeling and mitigation on power line communication in distributed energy system," IEEE Trans. Instrum. Meas., 2025. https://doi.org/10.1109/TIM.2025.3552456
[19] L. E. Bengtsson, "A microcontroller-based lock-in amplifier for sub-milliohm resistance measurements," Rev. Sci. Instrum., vol. 83, no. 7, 2012. https://doi.org/10.1063/1.4731683
[20] X. Kang et al., "A concise review of state-of-the-art sensing technologies for bridge structural health monitoring," Sensors, vol. 25, no. 17, p. 5460, 2025. https://doi.org/10.3390/s25175460
[21] S. Zike and L. P. Mikkelsen, "Correction of gauge factor for strain gauges used in polymer composite testing," Exp. Mech., vol. 54, no. 3, pp. 393-403, 2014.https://doi.org/10.1007/s11340-013-9813-7
[22] A. Abazeed, M. Abdelshakor, A. Othman, K. F. Tee, and A. Lorenzana, "Development of an ultra-low-cost wireless data acquisition system for monitoring strain and deflection," J. strain Anal. Eng. Des., vol. 60, no. 3, pp. 196-207, 2025. https://doi.org/10.1177/03093247241293865
[23] S. Nilnoree, A. Taparugssanagorn, K. Kaemarungsi, and T. Mizutani, "Enhancing Wireless Sensor Network in Structural Health Monitoring through TCP/IP Socket Programming-Based Mimic Broadcasting: Experimental Validation," Appl. Sci., vol. 14, no. 8, p. 3494, 2024. https://doi.org/10.3390/app14083494
[24] F. Dagsever, Z. Sharif Khodaei, and M. H. F. Aliabadi, "WSN-Based Multi-Sensor System for Structural Health Monitoring," Sensors, vol. 25, no. 14, p. 4407, 2025. https://doi.org/10.3390/s25144407