International Research Journal of Engineering and Technology (IRJET) **e-ISSN: 2395-0056**
Volume: 13 Issue: 03 | Mar 2026 **www.irjet.net** **p-ISSN: 2395-0072**

Low-Cost Strain-Based Early Warning System for RCC Flexural Members Using IoT

Prof. Vikas Pawar[1], Aditya Sunil Oswal[2], Aditya Sunil Gawali[3], Aditya Sanjay Lasurkar[4], Samiksha Nitin Thorat[5]

Dept. of Civil Engineering, MET BKC college, Maharashtra, India

***

Abstract - ***Structural Health Monitoring (SHM)*** *of Reinforced Cement Concrete (RCC) infrastructure is critical, as members are perpetually subjected to cyclic loading, environmental degradation, and material aging. These factors induce stochastic variations in structural response that, if undetected, compromise global stability and escalate life-cycle maintenance costs. Traditional inspection protocols primarily rely on qualitative visual assessments, which are labor-intensive and lack the precision required for proactive failure mitigation.*

This research presents a high-fidelity, cost-effective ***IoT-based strain monitoring and early warning system*** *designed for real-time autonomous observation. The hardware architecture integrates foil-type resistance strain gauges with a high-resolution signal conditioning stage and an* ***ESP32 microcontroller*** *for edge-based data acquisition. To ensure data integrity, the system establishes a calibrated baseline under ambient conditions.*

A primary challenge in SHM is the presence of signal interference; therefore, this system implements a ***confidence-based algorithmic approach*** *rather than deterministic thresholding. By analyzing temporal strain patterns and statistical consistency, the framework effectively filters transient noise and environmental fluctuations, significantly reducing the* ***False Alarm Rate (FAR)****.*

Experimental validation was executed on an RCC beam specimen to characterize the ***load-strain hysteresis*** *and verify the sensitivity of the proposed monitoring logic. The results demonstrate that the integrated system provides a scalable, low-latency, and economically viable solution for the preliminary identification of structural anomalies, offering a robust alternative to conventional intermittent inspections.*

Key Words**: Structural Health Monitoring (SHM), Internet of Things (IoT), ESP32, Reinforced Concrete, Strain Gauges, Anomaly Detection, Real-time Data Acquisition, Signal Conditioning, Predictive Maintenance, Structural Integrity, Load-Strain Hysteresis, False Alarm Rate (FAR) Reduction, Baseline Calibration, In-situ Characterization.**

1. INTRODUCTION

The global construction landscape is fundamentally anchored by **Reinforced Cement Concrete (RCC)**, particularly in the form of flexural members like beams and slabs that bear the primary structural load. While these systems are designed for durability, they exist in a state of continuous flux. From the moment of commissioning, RCC elements are subjected to a complex interplay of **cyclic loading, thermal expansion, and chemical degradation** (such as carbonation or chloride ingress). Over time, these factors lead to material fatigue and a gradual reduction in the section's moment of resistance, often manifesting as micro-cracking before any visible signs of distress appear.

The primary challenge in maintaining such infrastructure lies in the **diagnostic gap**. Traditional maintenance protocols are inherently **reactive and qualitative**, relying heavily on periodic visual inspections. However, visual observation is subjective and limited to surface-level defects; it cannot quantify the internal stress-strain distribution or identify latent structural instability. By the time a crack becomes visible to the human eye, the internal reinforcement may have already surpassed its **yield point**, leading to expensive or even impossible repairs.

The emergence of the **Internet of Things (IoT)** has introduced a paradigm shift in civil engineering through **Structural Health Monitoring (SHM)**. By embedding high-precision sensors directly onto critical members, it is now possible to transition from periodic manual checks to **continuous, real-time data acquisition**.

This project explores the development of a low-cost, automated SHM framework utilizing **strain-gauge technology and ESP32-based edge computing**. Unlike standard monitoring systems that often trigger false alarms due to environmental noise, this research proposes a **confidence-based logic** to filter transient disturbances. By establishing a digital baseline of structural response, the system aims to provide a reliable, high-fidelity early warning mechanism, ensuring that structural anomalies are flagged long before they compromise the safety of the occupants.

2. PROBLEM STATEMENT

The structural integrity of Reinforced Cement Concrete (RCC) infrastructure, specifically flexural components such as beams and slabs, is subject to continuous degradation driven by cyclic loading, environmental stressors, and material aging. These factors often lead to subtle variations in structural response that are frequently overlooked until significant, visible damage manifests, compromising safety and escalating life-cycle maintenance costs. Current diagnostic protocols rely heavily on qualitative visual inspections and manual testing, which are inherently reactive, labor-intensive, and incapable of detecting latent internal defects at an incipient stage. Furthermore, while modern Structural Health Monitoring (SHM) systems offer data-driven insights, their widespread implementation is hindered by prohibitive costs for small-scale applications and a high susceptibility to false alarms triggered by stochastic environmental noise. Consequently, there is a distinct requirement for a high-fidelity, economically viable IoT-based monitoring framework that utilizes intelligent data processing to provide reliable, real-time early warnings before structural anomalies escalate into catastrophic failure.

3. RESEARCH OBJECTIVES

The primary goal of this research is to develop an autonomous, cost-effective monitoring framework for infrastructure safety. To achieve this, the project is directed toward the following technical objectives:

[1] **To investigate the mechanical response** and strain distribution profiles of Reinforced Cement Concrete (RCC) flexural members under various loading scenarios.

[2] **To architect an economically viable sensing framework** utilizing high-sensitivity resistive foil-type strain gauges for the precise quantification of micro-strains.

[3] **To engineer a robust, IoT-integrated Data Acquisition (DAQ) node** leveraging the ESP32 microcontroller for real-time edge processing and wireless telemetry.

[4] **To implement analytical algorithms** for characterizing temporal strain signatures and identifying stochastic deviations from established structural baselines.

[5] **To develop a confidence-based Early Warning System (EWS)** designed to provide proactive alerts for incipient structural anomalies while minimizing the False Alarm Rate (FAR).

[6] **To formulate a comprehensive experimental protocol** for validating the system's sensitivity through controlled loading of instrumented RCC beam specimens.

4. PROPOSED METHODOLOGY

The **Proposed Methodology** for this research is structured into a systematic engineering workflow, transitioning from hardware architecture design to the implementation of the analytical warning logic. The process is divided into the following technical phases:

[1] Sensor Integration and Signal Conditioning

The initial phase involves a comprehensive evaluation of strain measurement techniques to select high-sensitivity, foil-type resistive strain gauges. To translate minute mechanical deformations into measurable electrical signals, a precision signal conditioning circuit is designed using a **Wheatstone Bridge** configuration. This analog output is then interfaced with a 24-bit **HX711 analog-to-digital converter (ADC)**, which provides the high-resolution amplification required to capture micro-strain variations.

[2] IoT Data Acquisition (DAQ) and Firmware Development

The hardware core utilizes an **ESP32 microcontroller**, selected for its dual-core processing capabilities and integrated Wi-Fi stack. Firmware is developed to establish a robust Data Acquisition (DAQ) pipeline that samples sensor data at calibrated intervals. This system is programmed to establish a **digital structural baseline** by recording strain signatures under ambient, "zero-load" conditions, providing a reference for future anomaly detection.

[3] Analytical Framework and Warning Logic

A primary focus of the methodology is the development of a **confidence-based detection algorithm**. Unlike conventional systems that use simple thresholding, this framework continuously analyzes temporal strain trends and statistical consistency. The logic evaluates four critical parameters: **Trend (T), Sudden Jumps (J), Baseline Shifts (B), and Persistence (P)**. A warning signal is only dispatched once the cumulative confidence score exceeds a predefined limit, effectively filtering out stochastic environmental noise and transient loading disturbances.

[4] Experimental Validation Protocol

To verify system efficacy, a controlled experimental plan is formulated using an instrumented RCC beam specimen. The specimen is subjected to incremental flexural loading in a **Universal Testing Machine**

(UTM) to characterize the load-strain hysteresis and observe specific failure modes, such as crack initiation and steel yielding. The data collected during these tests serves to calibrate the warning thresholds and validate the real-time response of the IoT node.

5. PROPOSED METHODOLOGY

The operational framework of the proposed system is engineered to provide continuous, real-time telemetry of structural deformation through a multi-stage data processing pipeline.

[1] Signal Acquisition and Processing

The system initiates with the detection of micro-strains in flexural members using high-sensitivity resistance strain gauges. These analog signals are routed through a bridge circuit to a 24-bit **HX711 signal conditioning unit**, which amplifies and digitizes the data for processing by the **ESP32 microcontroller**. A digital reference baseline is established under ambient loading conditions to serve as the structural "signature" for normal behavior.

[2] Confidence-Based Detection Framework

To mitigate the high **False Alarm Rate (FAR)** typical of single-threshold systems, this research implements a multi-parameter evaluation logic. The system calculates a cumulative **Confidence Score (C)** by monitoring four distinct structural indicators:

- **Trend Variation (T):** Quantifies a progressive increase in the strain-to-load ratio, signaling a loss of sectional stiffness.
- **Sudden Jump (J):** Identifies instantaneous spikes in strain values without corresponding load increments, typically associated with micro-crack initiation.
- **Baseline Shift (B):** Detects permanent residual deformation or "creep" that persists even after the removal of transient loads.
- **Persistence (P):** Evaluates the temporal stability and repetition of abnormal readings to ensure they are not caused by stochastic sensor noise.

The total score is derived using the following relation:

$$C = T + J + B + P$$

[3] C. Alert Thresholds and System Response

Table 1: System responses are categorized based on the severity of the calculated confidence score:

Confidence Score	Structural Condition	System Action
0 – 3	Safe	Ambient monitoring and data logging.
4 – 7	Warning	Generation of proactive alerts indicating potential distress.
7 – 10	Danger	Emergency trigger; immediate structural assessment required.

This hierarchical approach ensures that temporary noise or transient environmental disturbances do not trigger unnecessary alarms, focusing instead on stable, repeated deviations that signify genuine structural anomalies

6. ADVANTAGES AND DISADVANTAGES

[1] Advantages

- Economic Scalability: The use of off-the-shelf IoT components provides an affordable alternative to industrial-grade SHM hardware.
- High Signal-to-Noise Ratio (SNR): The confidence-based logic effectively filters environmental interference and electrical noise.
- Autonomous Monitoring: Enables 24/7 real-time structural observation without manual intervention.

[2] Constraints and Limitations

- Laboratory Scale: The current prototype is validated under controlled experimental conditions.
- Maintenance Requirements: Periodic calibration of the strain gauges is necessary to maintain long-term accuracy.
- Installation Precision: The system's sensitivity is highly dependent on the quality of the sensor adhesive and placement

7. EXPERIMENTAL INVESTIGATION AND RESULTS

To evaluate the efficacy of the proposed Structural Health Monitoring (SHM) framework, a controlled flexural test was conducted on an instrumented Reinforced Cement Concrete (RCC) specimen. The objective was to correlate real-time strain acquisition with physical failure modes and validate the confidence-based warning logic.

[1] Experimental Setup and Instrumentation

To evaluate the system's efficacy, a simply supported Reinforced Cement Concrete (RCC) beam was subjected to a central point load using a Universal Testing Machine (UTM).

- **Specimen Dimensions:** The beam featured a span length of 0.6 m with a cross-sectional area of 150 mm x 150 mm.
- **Material Grades:** Concrete of grade M25 and steel of grade Fe500 were utilized for the specimen.
- **Sensing Architecture:** A foil-type resistance strain gauge was bonded to the tension face of the beam and interfaced with a signal conditioning unit and an ESP32 microcontroller for real-time data acquisition.

[2] Characterization of Load-Strain Behavior

The experimental results identified several distinct phases in the structural response of the beam:

- **Linear Elastic Region**: Initially, the strain increased proportionally with the applied load, indicating that the beam was operating within its elastic limits. At a load of 14.1 kN, the system recorded a strain of 148 micro-strain.
- **Crack Initiation (The "Jump" Event):** At approximately 16.1 kN, a sudden and significant increase in strain was detected, jumping from 166 to 242 micro-strain. This indicated the onset of micro-cracking in the tension zone and the subsequent transfer of stress to the reinforcement.
- **Steel Yielding:** As loading continued, the stiffness of the section reduced, leading to rapid strain growth. Yielding of the steel reinforcement was observed at 44.5 kN, where the strain reached 2483 micro-strain.
- **Ultimate Capacity and Failure:** The beam reached its ultimate load capacity of 53.2 kN at 6893 micro-strain. Beyond this peak, the beam exhibited softening behavior, eventually leading to catastrophic structural failure at a maximum strain of 13,193 micro-strain.

Table -2: Key Load-Strain Milestones

Load (kN)	Strain (με)	behavior
0.0	0	Initial condition
3.8	32	Linear elastic behaviour
8.8	93	Elastic bending continuous
14.1	148	Pre-cracking stage
15.8	166	Micro-cracking stage
16.1	242	Sudden transfer to steel
19.5	469	Crack elastic behaviour
25.5	854	Crack propagation
29.9	1153	High strain under load
30	1185	Baseline shift during load
39.5	1963	Rapid strain growth
44.5	2483	Steel yielding begins
46.8	4013	Strain hardening phase
51.5	5993	Plastic hinge formation

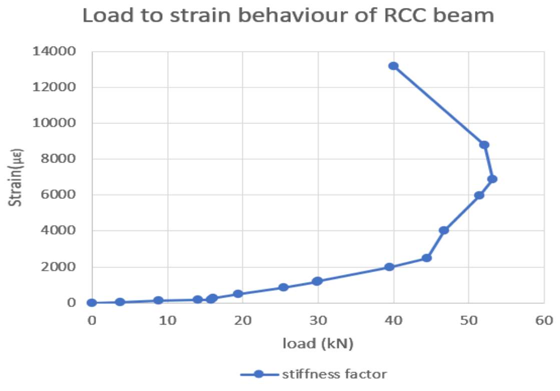

Chart -1: loss of stiffness factor.

C. Validation of Confidence-Based Warning Logic

A critical test of the system was conducted by holding a constant load of 30 kN to observe "Baseline Shift," which represents permanent residual deformation.

Table 3: Baseline Shift Observation at Constant Load (30 kN)

53.2	6893	Ultimate load reached
52.1	8793	Post peak softening
40.1	13193	Structural failure
0.0	9993	Residual deformation

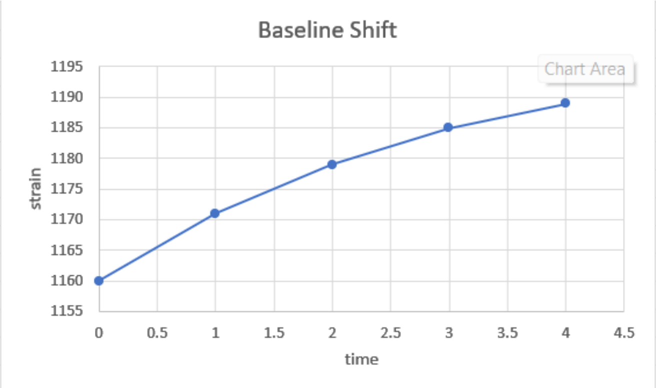

Chart -2: Baseline Shift

During this phase, the system checked four parameters—Trend (T), Jump (J), Baseline (B), and Repetition (P). By scoring each parameter as two based on the observed severity, the system generated a cumulative confidence score. For this specific case, a confidence index score of 5 was calculated, correctly triggering a "Warning" level alert to indicate possible structural damage without generating a false alarm from temporary noise.

8. FUTURE SCOPE

The current research serves as a foundational framework for low-cost structural monitoring, with several avenues for future technical expansion:

[1] **Network Scalability:** Future iterations aim to transition from a single-sensor prototype to a distributed wireless sensor network (WSN) to facilitate comprehensive monitoring of large-scale infrastructure such as bridges and multi-story buildings.

[2] **Cloud-Integrated Telemetry:** Integrating the ESP32 node with cloud-based IoT platforms would enable centralized data management, allowing engineers to access structural health metrics remotely from any location.

[3] **Mobile Interface Development:** The development of dedicated mobile applications can provide real-time push notifications and dashboard visualizations for immediate stakeholder alerts during critical structural events.

[4] **Advanced Analytics:** Incorporating machine learning algorithms and advanced data analysis techniques could improve the system's ability to perform long-term predictive maintenance and fatigue life estimation.

[5] **Long-Term Durability Studies:** Future work will focus on the performance and calibration stability of the sensing nodes over extended periods in diverse environmental conditions

9. CONCLUSIONS

This research successfully demonstrates the development and validation of a cost-effective, IoT-based Structural Health Monitoring (SHM) system designed for RCC flexural members. Unlike traditional inspection methods that are qualitative and reactive, the proposed framework provides a quantitative, real-time assessment of structural response.

The integration of **confidence-based warning logic** represents a significant technical improvement over standard thresholding systems, as it effectively filters stochastic environmental noise and transient disturbances to minimize the False Alarm Rate (FAR). Experimental testing on an RCC beam specimen confirmed the system's high sensitivity to critical mechanical transitions, including micro-crack initiation at 16.1 kN and the onset of steel yielding at 44.5 kN. Furthermore, the system accurately identified permanent residual deformation through baseline shift analysis, triggering proactive alerts as intended.
Ultimately, the developed system offers a reliable, simple, and economically viable solution for preliminary structural assessment, providing a robust tool for enhancing the safety and longevity of modern civil infrastructure.

Time(min)	Strain (με)
0	1160
1	1171
2	1179
3	1185
4	1189

10.REFERENCES

[1] Anjuna, S., Radhakrishnan, N., & George, G. (2025). Internet of Things (IoT)-based strain monitoring system for large engineering structures. Innovative Infrastructure Solutions, 10, Article 40. SpringerNature.

[2] Ferreira, R., Silva, P., & Rocha, J. (2022). Use of IoT for structural health monitoring of civil engineering structures. Sensors, 22(23), 8320. MDPI.

[3] Rahita, A. C., Zaki, A., Nugroho, G., & Yadi, S. (2024). Internet of Things (IoT) in Structural Health Monitoring: A decade of research trends. Instrumentation Mesure Metrologie, 23(2), 123-139.

[4] Shukla, M. D., & Joshi, S. (2025). Structural health monitoring of RCC structure by Internet of Things. International Journal of Environmental Sciences, 11(22), 581-588.

[5] Zhang, B., Ren, Y., He, S., Gao, Z., Li, B., & Song, J. (2025). A review of methods and applications in structural health monitoring (SHM) for bridges. Measurement, 245, 116575. Elsevier.