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Structural Health Monitoring Of RCC Structure By Internet Of Things

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Abstract: *. This research explores the integration of Internet of Things (IoT) technology with structural health monitoring (SHM) in a laboratory environment and RCC structure. Combining sensors such as accelerometers, strain gauges, and environmental monitors with Arduino-based and ESP8266 microcontroller platforms, this study demonstrates real-time, wireless monitoring of structural models under various loads and environmental exposures. The results validate the effectiveness of IoT-based approaches in achieving accurate, cost-efficient, and scalable monitoring solutions for the assessment and maintenance of civil structures.*

Keywords: *SHM, Accelerometer, Sensor, IoT, Bridge, Wooden bridge, Steel Scale, Concrete cube, Sensors*

INTRODUCTION

The safety and durability of civil infrastructure are of paramount importance in ensuring the functionality and reliability of modern society. Reinforced concrete (RC) structures such as bridges, water tanks, retaining walls, and buildings are expected to serve for decades with minimal maintenance. However, numerous instances of premature deterioration and even structural failure have highlighted the urgent need for continuous assessment and maintenance strategies. This has led to the emergence of Structural Health Monitoring (SHM) as a critical field of study and application within civil engineering. SHM refers to the process of implementing a damage detection and characterization system for engineering structures. It involves continuous or periodic monitoring using sensors, data acquisition systems, and analytical tools to assess the performance and integrity of a structure. Traditional methods of structural inspection—such as visual inspection or occasional testing—are labor-intensive, time-consuming, and often inadequate to detect early-stage damage or predict potential failure. Therefore, there is a growing demand for intelligent and automated systems capable of providing real-time insights into structural conditions.

The integration of the Internet of Things (IoT) with SHM has opened new possibilities for cost-effective, scalable, and high-resolution monitoring solutions. IoT refers to a network of interconnected physical devices equipped with sensors, software, and communication technologies that enable data collection, transmission, and analysis in real time. When applied to SHM, IoT technologies allow for the remote monitoring of structural parameters such as strain, displacement, acceleration, temperature, and humidity. The data collected can be processed using cloud computing platforms and analyzed to detect anomalies, predict failures, and schedule maintenance proactively.

The advancement of low-cost microcontrollers like the Node MCU ESP8266, combined with sensors such as MPU6050 (accelerometer), strain gauges, and DHT11 (temperature and humidity sensor), makes it feasible to create compact, affordable, and efficient SHM systems. These devices can be deployed on lab-scale or real-life structural models to simulate and study various loading conditions, environmental effects, and damage scenarios. By building an experimental lab-scale model embedded with these sensors, researchers can validate the effectiveness of IoT-based SHM approaches before applying them to full-scale structures.

In this study, an experimental lab-scale RC model is instrumented with multiple sensors and monitored through an IoT framework. The primary aim is to assess the structural behavior under controlled conditions and evaluate the feasibility of remote monitoring for real-time damage detection and service life estimation. The study focuses on the integration of sensing hardware, data acquisition using wireless

communication, and interpretation of sensor outputs through data analytics. Emphasis is placed on understanding the dynamic behavior of the model under simulated loads, and how environmental parameters influence the readings.
Moreover, the significance of this study extends beyond academic curiosity. The increasing frequency of structural collapses, particularly in rapidly urbanizing regions, underlines the importance of timely diagnosis and preventive action. IoT-based SHM systems, when optimized and validated, can serve as a backbone for smart infrastructure management in developing and developed regions alike. The insights derived from this lab-scale investigation can be scaled up and adapted for use in real-time monitoring of bridges, buildings, dams, and other vital structures.

A. IoT-based SHM Technologies

IoT-enabled Structural Health Monitoring (SHM) systems are generally composed of three essential elements: sensing devices, communication infrastructure, and data processing mechanisms. The sensing components are responsible for capturing critical structural parameters such as deformation, vibrations, thermal variations, and mechanical stress. These sensors are strategically installed on the structure to continuously gather real-time data reflecting its condition. Once the data is collected, it is transmitted wirelessly using communication protocols like Wi-Fi, mobile networks, or satellite links to a remote data hub. At this stage, advanced computational tools—ranging from data analytics platforms to artificial intelligence and visualization software—are employed to interpret the incoming data. These tools help in identifying trends, anomalies, or early signs of structural deterioration, thereby enabling timely maintenance and decision-making.

B. IoT Sensors for SHM

IoT-based Structural Health Monitoring systems utilize a range of sensors tailored to the type of structure and the specific parameters under observation. Commonly implemented sensors include those that measure strain, vibration, temperature, displacement, and pressure. These devices can either be embedded within the structural elements during construction or externally mounted using adhesive materials or mechanical clamps. The selection and placement of sensors are critical, as they ensure accurate detection of structural behavior and potential signs of deterioration over time.

C. Challenges and Opportunities

Challenges- Deploying an IoT-based Structural Health Monitoring (SHM) system, even on a lab-scale model, presents several hurdles. One of the main difficulties lies in maintaining the accuracy and stability of sensor outputs, especially when using affordable electronic components prone to interference or drift. In addition, real-time wireless communication can be unreliable due to connectivity issues, potentially leading to incomplete or delayed data transmission. Ensuring uninterrupted power to all components— especially during extended testing periods—is another technical challenge. Moreover, integrating diverse sensors and ensuring seamless data flow from collection to cloud storage requires careful system design. Translating findings from controlled laboratory experiments to actual large-scale structures also involves dealing with environmental unpredictability and more complex load conditions.
Opportunities - On the other hand, the use of IoT in SHM creates a wide range of possibilities. Laboratory models offer an accessible platform to experiment with advanced monitoring technologies at a relatively low cost. They enable real-time observation of structural responses under various loading or environmental conditions, which is valuable for early damage detection and maintenance planning. Such experimental setups also serve as educational tools, fostering interdisciplinary learning between structural engineering, electronics, and data science. Additionally, integrating cloud services and visualization tools allows for remote access to structural data, making monitoring more flexible and efficient. These developments lay the foundation for more intelligent infrastructure systems capable of self-monitoring and adaptive response in real-world applications.

LITERATURE REVIEW

Structural Health Monitoring (SHM) has evolved significantly over the years, especially with the integration of Internet of Things (IoT) technologies. Traditional SHM techniques involved manual inspections and wired sensor systems, which were often costly and limited in scope. The introduction of wireless sensor networks improved flexibility, but challenges related to data transmission and scalability remained. With the rise of IoT, modern SHM systems now utilize microcontrollers like NodeMCU and Arduino, paired with sensors such as strain gauges, accelerometers, and temperature sensors, to enable real-time monitoring of structural conditions.

Several researchers have demonstrated the effectiveness of IoT-based SHM on small-scale experimental models. These studies show that lab-scale setups allow for safe, low-cost testing of sensor integration, wireless data collection, and structural behavior under controlled loading. Platforms like ThingSpeak and Blynk have also been used for remote data visualization and storage. However, challenges such as sensor noise, power reliability, and long-term data management are still under exploration. Despite these issues, the literature highlights a strong potential for IoT-based SHM to improve infrastructure safety and maintenance strategies when scaled to real-world applications.

Validation of Sensor by Lab Scale Model

To ensure the accuracy and reliability of sensor readings, the lab-scale model played a critical role in validating the performance of the installed sensors. The experimental setup provided a controlled environment where structural responses could be monitored under known conditions. Sensors such as strain gauges and accelerometers were integrated into the model to capture real-time data during loading and vibration tests. These sensor outputs were then cross-verified using traditional measuring instruments like dial gauges and displacement indicators. By comparing the electronic sensor data with physical measurements, the consistency and precision of the sensors were evaluated. Any observed discrepancies were analysed and addressed through calibration and adjustment. This validation process confirmed that the sensors were functioning correctly and that the collected data could be confidently used for further structural analysis. The lab-scale model thus served not only as a testing platform but also as a means to establish trust in the accuracy of the IoT-based monitoring system.

Sr No.	Material	Measure
1	Wooden Bridge	Vibration
2	Steel Scale	Deformation
3	Concrete Cube	Moisture

Experimental Setup 1) Wooden Bridge

The experimental setup for this study was carefully designed to enable accurate, real-time monitoring of structural models using IoT-enabled sensors. Test specimens included cement mortar blocks, wooden beams of both rectangular and I-shaped cross-sections, and steel beams with U-sections. Each specimen was instrumented with an array of sensors such as strain gauges and accelerometers, while environmental sensors monitored temperature and humidity to account for varying ambient conditions. Microcontroller platforms—including Arduino UNO boards and Node MCU ESP8266 modules—served as the core data acquisition units. These controllers collected sensor readings and facilitated wireless transmission to a central database or cloud-based dashboard for immediate analysis.

Mechanical tests, such as three-point bending for mortar and timber samples and vibration monitoring on a vibration table, were conducted to evaluate each structure's behaviour under controlled loading. The wireless system allowed engineers to remotely assess critical parameters like strain, displacement, and vibration responses, thus minimizing the need for direct manual involvement.

The arrangement of both wired and wireless sensors across the specimens provided comprehensive coverage that ensured integrity and reliability in the data collected. System calibration and synchronization were regularly performed to maintain measurement accuracy and prevent drift. All electrical connections and power supplies, including rechargeable lithium-polymer batteries, were selected for stability and longevity, supporting continuous monitoring during extended experiments. This setup created a robust test-bed for validating the capabilities and reliability of IoT-based structural health monitoring systems.

Figure-1 Accelerometer Sensor on Bridge

Figure-2 Bridge scaled model

2) Steel Scale

In this study, a strain gauge was mounted on a steel scale to measure surface strain resulting from applied loads. The steel scale served as a basic structural element that allowed controlled deformation, making it ideal for laboratory testing. Before applying the sensor, the surface was cleaned thoroughly to remove dust, oil, or oxidation, ensuring proper adhesion and accurate strain transfer. A suitable adhesive was used to bond the strain gauge firmly to the scale, allowing it to respond directly to any elongation or compression experienced by the metal. The electrical leads from the sensor were connected with precision and insulated to prevent noise or signal loss during data transmission. As force was applied, the strain gauge detected the subtle deformation of the scale by converting mechanical strain into changes in electrical resistance, which were then processed by a microcontroller system for real-time monitoring. To ensure the reliability of the strain measurements, a dial gauge was used in parallel for validation. The dial gauge, known for its high sensitivity in detecting small displacements, was positioned to measure the deflection at the midpoint of the scale. As the load increased, readings from both the strain gauge and the dial gauge were recorded simultaneously. This allowed for direct comparison between the electrical output of the strain sensor and the physical displacement measured mechanically. The consistency between these two data sets confirmed the accuracy of the strain gauge and validated its calibration. This dual measurement approach strengthened confidence in the experimental results and demonstrated the effectiveness of combining electronic sensing with traditional mechanical validation in structural monitoring applications.

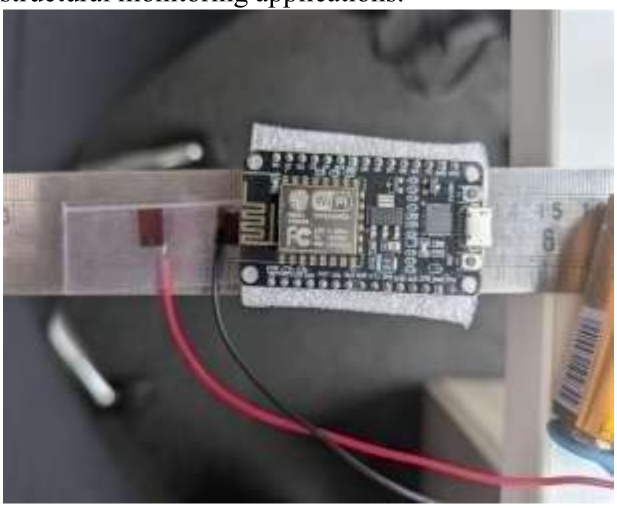

Figure-3 Strain gauge on Steel Scale

3) Concrete cube

The primary objective of this experimental investigation is to monitor and analyze the moisture content and temperature behavior in concrete samples of two distinct shapes—cylindrical (round) and cubic. These measurements are critical in understanding how concrete interacts with environmental conditions, particularly in terms of water absorption and heat retention, both of which significantly influence durability and structural performance.

The experiment begins by recording the initial dry weight of the concrete specimens using a precision digital weighing machine. This step establishes a baseline for determining how much water is absorbed by the material. Once the dry weights are documented, the samples are fully submerged in water and left undisturbed for a period of 24 hours. This soaking process allows concrete to absorb moisture through its pores, simulating exposure to a humid or wet environment.

After 24 hours, the samples are removed from the water and carefully weighed again. The increase in weight represents the amount of water retained within the material. By calculating the difference between the wet and dry weights, the moisture content absorbed by each sample can be determined. This step is essential for assessing the permeability and water absorption characteristics of different concrete shapes.

Figure-4 Concrete cube

Figure-5 Oven for validation

To further understand how temperature and humidity affect the internal state of concrete, the soaked samples are then placed in a controlled-temperature oven. This stage replicates the exposure of concrete to elevated temperatures and allows observation of moisture evaporation and thermal behavior. Simultaneously, sensors capable of measuring temperature and humidity—such as DHT11 or similar digital sensors—are attached to the surface of each sample. These sensors collect real-time data as the internal conditions of the concrete change due to heat exposure.

The final step involves comparing the sensor data with the manually calculated moisture content values. This comparison is used to validate the accuracy and responsiveness of the sensor system in detecting environmental changes within concrete materials. The experiment not only demonstrates the effectiveness of embedded sensing technologies but also provides insights into how shape and geometry may influence moisture retention and temperature response in concrete structures.

Application Used Arduino 1.8.19

The Arduino Integrated Development Environment (IDE) version 1.8.19 is a widely used open-source software platform designed to program and upload code to Arduino-compatible microcontroller boards. It provides a user-friendly interface that supports writing, editing, compiling, and uploading sketches (Arduino programs) with ease, making it ideal for beginners and experienced developers alike. Version 1.8.19 continues the legacy of the classic Arduino IDE, maintaining compatibility with a wide range of official and third-party Arduino boards. It features a simple code editor with syntax highlighting, automatic formatting, and error messages that help users debug their code efficiently. One of its key strengths is its ease of setup—users can select the board type and port from the menu and begin programming without requiring deep technical knowledge. The IDE also includes a built-in library manager, which allows users to quickly install and manage external libraries, expanding the functionality of Arduino boards with sensors, actuators, communication modules, and more. This version supports uploading code via USB to boards like the Arduino Uno, Nano, Mega, and even Wi-Fi-enabled boards like the Node MCU ESP8266, making it versatile for a range of IoT and embedded systems projects. Although newer versions of the IDE (such as Arduino 2.x) have introduced advanced features like autocompletion and a modern interface, many users still prefer version 1.8.19 for its lightweight nature, stability, and familiarity. Overall, Arduino IDE 1.8.19 remains a reliable and effective tool for developing embedded applications, learning programming, and building prototypes in academic, hobbyist, and industrial environments**.**

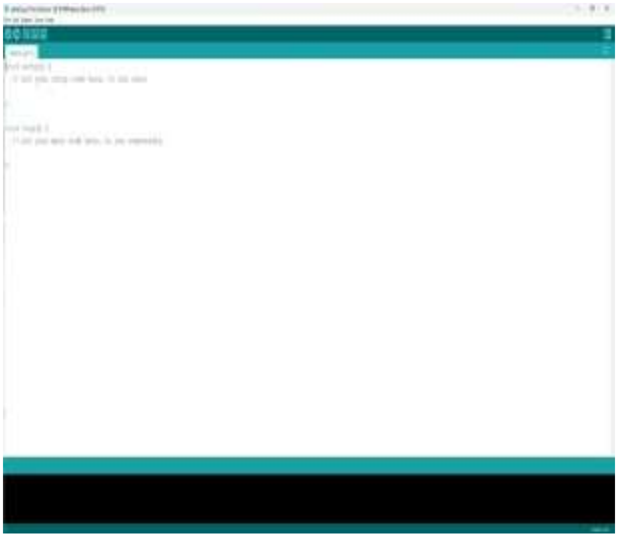

Figure-6 Arduino 1.8.19

Results of pilot experiment Wooden Bridge model

The experimental results obtained from the wooden bridge model placed on the shake table provided valuable insights into the structural behaviour under dynamic conditions. Sensors, including strain gauges and accelerometers, were mounted at critical points of the bridge to capture real-time responses during vibration testing. As the shake table operated at varying frequencies, the bridge model exhibited noticeable deflection and vibration patterns, especially at mid-span and near support regions. The strain gauge data reflected changes in surface strain corresponding to the applied motion, while the accelerometer captured the variations in acceleration with respect to time. These sensor readings were consistent and showed a logical increase in values with higher frequency inputs. Additionally, the deflection recorded by the strain gauge closely matched the readings from the displacement measuring instruments, confirming the accuracy of the sensor-based system. Overall, the experiment successfully demonstrated that the IoT-based monitoring setup is capable of capturing essential structural responses, validating its application for future real-world bridge monitoring systems.

Figure-7 Wooden Bridge on Shake table

Table-1 : Shake Table Output and Sensor Output

Sr No.	**Shake table Output X (m/s2)**	**Shake table Output Y(m/s2)**	**Shake table Output Z (m/s2)**	**Sensor output X (m/s2)**	**Sensor output Y (m/s2)**	**Sensor output Z** (m/s2)
1	0	0	9.81	0	0	9.81
2	1.48	-1.98	10.2	1.45	-1.97	10.1
3	1.52	-2.08	9.58	1.52	-2.07	9.52
4	3.21	-5.83	7.24	3.20	-5.83	7.23
5	4.26	-7.59	5.99	4.25	-7.58	5.97

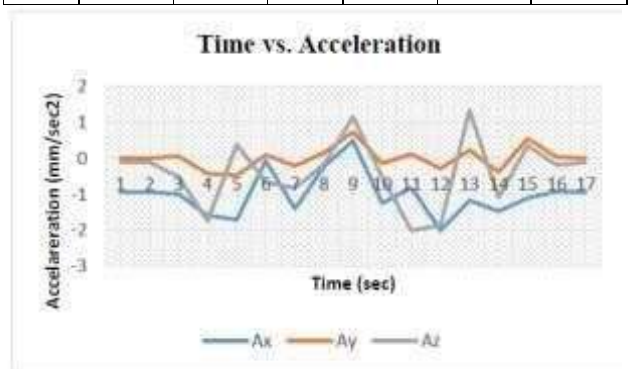

Figure-8 Results of Time vs Acceleration

Steel Scale model

The experimental analysis of the steel scale, with a strain gauge mounted on its surface and a displacement gauge positioned at the point of maximum deflection, provided detailed insights into the structural response of the element under loading. The strain gauge was installed with precision using a strong adhesive to ensure effective strain transfer from the steel surface to the sensor. Once the sensor was securely mounted, the steel scale was subjected to a gradually increasing static load applied at the center to simulate bending. As the load was applied, the strain gauge recorded variations in electrical resistance, which were then interpreted as strain using a Wheatstone bridge circuit connected to a microcontroller. Simultaneously, a mechanical displacement gauge (dial gauge) was placed directly beneath the midpoint of the scale to measure the vertical deflection resulting from the applied force. This dual-instrument approach allowed for cross-verification between the strain-induced data and the actual physical displacement.

Throughout the testing process, data collected from both instruments remained consistent and closely aligned. The strain gauge successfully captured the deformation behavior of the steel scale, while the displacement gauge provided a physical measurement of deflection that served as a reliable reference. As the load increased, both the strain and deflection values increased proportionally, confirming the linear elastic behavior of the material within the testing range. The agreement between the two measurement systems validated the calibration and accuracy of the strain gauge, demonstrating its potential for real- time structural monitoring. Moreover, the experiment reinforced the effectiveness of using a simple steel scale as a test specimen for understanding the behavior of metallic components under bending stress. These findings support the broader application of sensor-based monitoring systems in structural health evaluation, where accuracy and reliability are critical for assessing safety and performance.

Table-2 : Dial gauge Output and Sensor Output

Sr No.	**Steel Sample No.**	**Dial gauge Displacement**	**Strain Gauge Sensor Displacement**
1	**SSG-1**	**5**	**5**
2	**SSG-2**	**6**	**6**
3	**SSG-3**	**7**	**7**
4	**SSG-4**	**5**	**5**
5	**SSG-5**	**6**	**6**

Figure-9 Results of Strain vs Time

Concrete cube

The experimental investigation using a concrete cube embedded with temperature and humidity sensors yielded important observations regarding the material's moisture behavior and thermal response. The primary goal was to monitor internal changes in humidity and temperature when the specimen was exposed to controlled heat conditions. Initially, the dry weight of the concrete cube was recorded, followed by submersion in water for 24 hours to allow moisture absorption. After soaking, the cube was reweighed to calculate the total moisture uptake. The sample was then placed inside a laboratory oven set at a consistent elevated temperature to simulate drying conditions. During the heating process, a digital sensor module—capable of measuring both temperature and relative humidity—was securely attached to the surface of the cube to monitor changes in real time. The sensor readings were transmitted to a microcontroller for continuous data logging.

As the oven temperature increased, a steady rise in the cube's surface temperature was recorded by the sensor, which closely matched the ambient oven setting. Simultaneously, a significant drop in relative humidity was observed, indicating the gradual evaporation of moisture from the concrete mass. These changes were monitored over a fixed period, allowing the analysis of moisture release patterns and thermal behavior. The real-time sensor data was then compared to calculated values derived from weight loss measurements, which were used to estimate moisture content. The comparison showed a strong correlation between the drop in weight (indicating water loss) and the decrease in humidity recorded by the sensor. This alignment confirmed the sensor's effectiveness in tracking moisture and temperature changes with accuracy. Overall, the results validated the use of embedded digital sensors for monitoring internal conditions within concrete elements and demonstrated their potential application in real-world structural health monitoring scenarios, particularly for assessing moisture ingress and thermal effects over time.

Table-3 : Experiment Output and Sensor Output

Sr No.	**Sample No.**	**Weight of Sample (gm)**	**Oven Dry Weight Sample (gm)**	**Water Content (%)**	**Results from Moisture Sensors (%)**
1	**S-1**	**951**	**947**	**0.42**	**0.45**
2	**S-2**	**944**	**941**	**0.31**	**0.34**
3	**S-3**	**941**	**938**	**0.31**	**0.35**
4	**S-4**	**940**	**935**	**0.53**	**0.60**
5	**S-5**	**960**	**956**	**0.41**	**0.48**

Figure-10 Results of Strain vs Time

RESULTS AND DISCUSSION

The experimental results from the wooden beam, steel scale, and concrete cube models demonstrated the effectiveness of IoT-based sensors in structural health monitoring. The accelerometer mounted on the wooden beam successfully captured vibration responses under varying conditions, with clear time vs. acceleration patterns reflecting typical elastic behavior. In the steel scale test, the strain gauge accurately measured surface deformation under bending, and the results closely matched the displacement readings from a dial gauge, confirming the sensor's precision. For the concrete cube, temperature and humidity sensors recorded real-time changes during oven drying, with decreasing humidity and rising temperature values aligning well with moisture loss calculated from weight differences. Together, these experiments validate the reliability of embedded sensors for monitoring structural performance across different materials and conditions.

CONCLUSION

This experimental study successfully demonstrated the integration and performance of IoT-based sensing systems for monitoring structural behavior in different lab-scale models. Through individual tests on a wooden beam, a steel scale, and a concrete cube, valuable insights were obtained regarding the capabilities of modern low-cost sensors in capturing physical changes such as vibration, strain, moisture, and temperature. In the case of the wooden beam, the accelerometer effectively recorded time versus acceleration data during vibration testing, allowing for a clear understanding of the beam's dynamic response and elastic behavior under varying excitation frequencies. The patterns observed supported the theoretical behavior expected in flexible structural elements.

The strain gauge experiment on the steel scale further validated the accuracy of sensor-based monitoring for detecting deformation under bending. The close correlation between strain readings and displacement measurements obtained from a dial gauge confirmed the precision and reliability of the sensor setup. This cross-verification process emphasized the importance of using both electronic and mechanical instruments for validating sensor performance, especially in applications where small changes in strain can significantly affect structural integrity.

For the concrete cube, the humidity and temperature sensors proved effective in tracking internal environmental changes during a drying process in an oven. The sensor data closely aligned with the calculated moisture loss based on weight differences, confirming that the system could reliably measure changes in internal conditions. This finding is particularly important for monitoring concrete structures exposed to varying environmental conditions in real applications.

Overall, the results of this study confirm that IoT-based sensors, when carefully selected and properly calibrated, can serve as powerful tools for structural health monitoring. Their ability to provide real-time data, coupled with ease of integration into various materials, makes them suitable for both laboratory research and potential field deployment. The successful use of low-cost components also suggests that such systems can be economically viable for large-scale monitoring without compromising on accuracy or performance. These experiments lay the groundwork for future developments in smart infrastructure, where continuous, automated monitoring can improve safety, maintenance, and overall structural reliability.

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