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# AI-IoT Enabled Structural Health Monitoring of an Old Reinforced Concrete Bridge Using SAP2000 Digital Twin and FFT-Based Vibration Response

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***Abstract*—Ageing reinforced concrete bridges require continuous and intelligent monitoring because periodic inspection alone cannot reliably capture progressive deterioration, abnormal vibration or serviceability-related deflection. This paper develops a Scopus-style original research manuscript on structural health monitoring of old bridges using an integrated Internet of Things sensor network, artificial-intelligence-based anomaly interpretation and SAP2000 digital twin modelling. The framework combines accelerometers, displacement sensors, strain-oriented measurements and low-cost ESP32-based data acquisition. The Ozar Bridge in Pune is used as a case-study structure, with a 107 m length, four piers and 21.4 m short span. Field vibration responses were interpreted through Fast Fourier Transform (FFT) indicators at left, middle and right bridge locations under higher-load and light-load conditions. The middle zone produced the dominant amplitude response, reaching 4159.7 at 14.80 Hz under higher load and 1377.5 at 14.47 Hz under light load. These results show that the mid-span/central region requires higher attention during condition assessment. The proposed SHM framework offers a practical route for continuous bridge maintenance by integrating low-cost sensing, numerical validation and data-driven interpretation.**

***Index Terms*—Structural health monitoring; Old bridges; IoT sensors; SAP2000; Digital twin; FFT; Vibration response; Predictive maintenance**

## I. INTRODUCTION

Bridges are critical transport assets whose failure can lead to loss of life, economic disruption and network-level mobility impacts. Many existing bridges operate beyond their originally intended design life and are exposed to increased traffic loads, corrosion, fatigue, scouring, temperature variations and maintenance limitations. Conventional inspection methods depend on visual observation and periodic field visits; consequently, early-stage deterioration may remain undetected until repair becomes expensive or safety is compromised.

Structural Health Monitoring (SHM) addresses this limitation by continuously measuring the physical response of a structure and converting the measurements into actionable maintenance information. For bridges, vibration-based monitoring is particularly important because traffic loading excites modal characteristics such as frequency, amplitude and damping. A change in these characteristics can indicate stiffness loss, cracking, settlement, bearing deterioration or abnormal load transfer. The integration of IoT devices and artificial intelligence increases the value of SHM because sensors can transmit data continuously and learning algorithms can detect patterns that are difficult to identify manually.

This paper presents a concise research article based on an SHM framework for old bridges. It combines IoT data acquisition, FFT-based response interpretation and SAP2000 digital twin modelling. The case-study data from Ozar Bridge are used to demonstrate how vibration amplitude and frequency patterns can identify critical zones for further inspection.

## II. LITERATURE REVIEW

Recent SHM literature has moved from isolated sensor installation toward integrated cyber-physical monitoring systems. Wireless smart sensor networks reduce wiring constraints and allow deployment on existing bridges with limited disruption. Accelerometers and strain sensors are widely used for vibration and load-path identification, while displacement sensors support serviceability monitoring. Researchers have also emphasised computer vision, unmanned aerial vehicle inspection, GNSS displacement monitoring and remote sensing for large bridges.

Artificial intelligence has become central to modern SHM because the large volume of monitoring data requires automated interpretation. Machine learning methods have been applied to damage classification, anomaly detection, missing data imputation, traffic-load separation and deterioration prediction. Digital twins provide a complementary physics-based layer. A calibrated SAP2000 or finite element model can reproduce expected structural response, while deviations between measured and predicted values can indicate damage. However, a major research gap remains in low-cost implementation for old local bridges where resources for expensive monitoring systems are limited.

The current study responds to this gap by proposing an ESP32-based sensing architecture and combining it with FFT interpretation and SAP2000 model validation. The case-study orientation makes the work useful for bridge authorities and researchers interested in scalable monitoring of ageing regional infrastructure.

## III. RESEARCH GAP, NOVELTY AND OBJECTIVES

The gap addressed in this study is the lack of an integrated but low-cost SHM workflow that combines IoT field sensing, digital twin modelling and interpretable vibration indicators for old reinforced concrete bridges. The novelty lies in presenting a unified monitoring framework in which sensor data are not treated as isolated measurements but are compared with structural modelling and converted into maintenance-oriented indicators.

The objectives are: (i) to define an IoT sensor architecture suitable for old bridges; (ii) to develop a SAP2000 digital twin for response validation; (iii) to evaluate FFT amplitude and frequency response at different bridge locations; (iv) to identify critical zones in the case-study bridge; and (v) to propose a predictive maintenance route based on continuous monitoring.

## IV. MATERIALS AND METHODS

Figure 1. Field view of the Ozar Bridge selected for the SHM case study.

Table 1. Case-study bridge details

| Parameter | Description |
| --- | --- |
| Name of bridge | Ozar Bridge |
| Location | Pune, Maharashtra |
| Length | 107 m |
| Bridge type | Reinforced concrete bridge |
| Study components | Beam and pier |
| Short span | 21.4 m |
| Number of piers | 4 |
| Construction period | 09/02/1977 to 09/02/1979 |

The proposed SHM workflow includes four interconnected layers. The sensing layer records structural response using accelerometers, displacement-related sensors and other field instruments at critical bridge locations. The communication layer transfers readings through a wireless IoT network. The processing layer filters noise, extracts FFT frequency-domain features and organises the response into interpretable indicators. The analytical layer uses SAP2000 modelling to compare measured behaviour with expected structural response. Together, these layers provide a data-to-decision framework for maintenance planning.

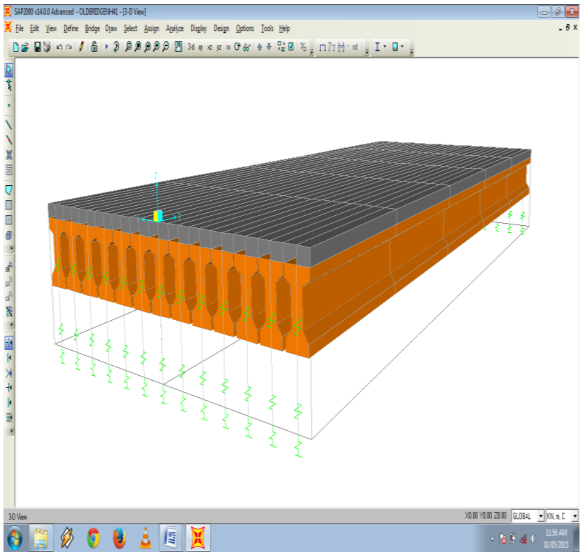

Figure 2. SAP2000 model view used for bridge response simulation and digital twin development.

Table 2. ESP32-based monitoring system connectivity

| Component/Terminal | ESP32 Pin | Connection Type | Purpose |
|---|---|---|---|
| ADXL345 SDA | GPIO 21 | I²C | Acceleration response acquisition |
| ADXL345 SCL | GPIO 22 | I²C | Clock signal for the sensor bus |
| LCD SDA | GPIO 21 | I²C | Shared display data bus |
| LCD SCL | GPIO 22 | I²C | Display clock signal |
| Ultrasonic Trigger | GPIO 5 | Digital Output | Deflection or load-proxy monitoring |
| Ultrasonic Echo | GPIO 18 | Digital Input | Distance-response acquisition |
| Power | 3.3 V/GND | Power | Low-voltage sensor network |

## V. SAP2000 DIGITAL TWIN AND IOT-BASED MONITORING PROCEDURE

The digital twin model was developed in SAP2000 using geometric, material and boundary condition information from the bridge. The model provides a baseline response under expected support and loading conditions. Sensor-based observations can then be compared with the model to identify abnormal deformation or vibration. The IoT arrangement enables continuous measurement without requiring constant manual inspection. FFT is used because it converts time-domain vibration signals into frequency-domain indicators, making it possible to identify dominant response frequencies and localised amplitude increases.

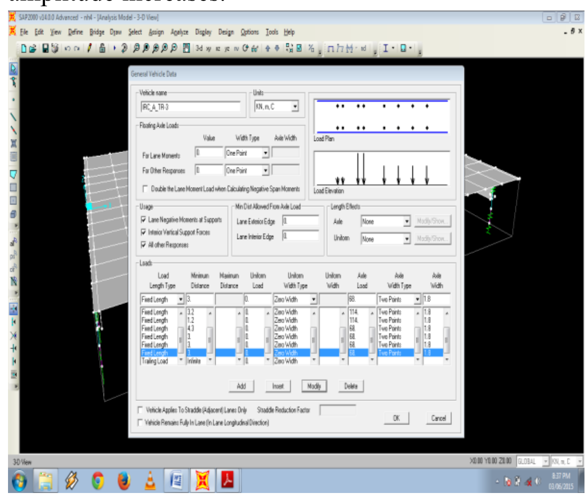

Figure 3. SAP2000 analysis interface and bridge modelling workflow adopted for response extraction.

## VI. RESULTS AND DISCUSSION

Table 3. Maximum FFT response under higher-load and light-load conditions

| Location | Maximum Amplitude (Higher Load) | Frequency (Hz) | Maximum Amplitude (Light Load) | Frequency (Hz) |
|---|---|---|---|---|
| Left | 900.8 | 13.12 | 496.32 | 12.79 |
| Middle | 4159.7 | 14.8 | 1377.5 | 14.47 |
| Right | 1013.3 | 11.44 | 356.45 | 13.46 |

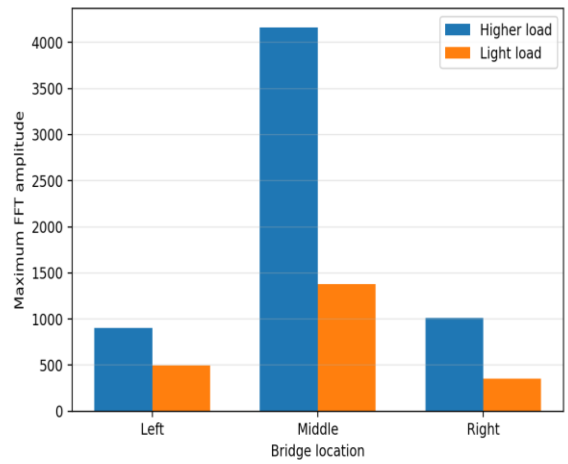


Figure 4. Comparison of maximum FFT amplitude at left, middle and right bridge locations.

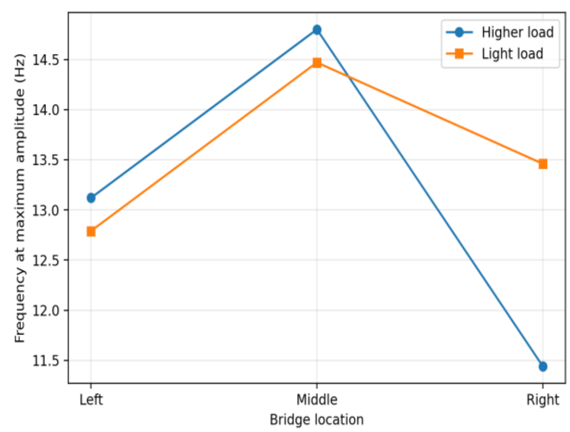


Figure 5. Frequency at maximum amplitude for higher-load and light-load bridge response.

The FFT results clearly show that the middle region of the bridge has the highest vibration amplitude under both higher-load and light-load conditions. Under higher load, the middle location reached an amplitude of 4159.7 at 14.80 Hz, which is substantially higher than the left and right responses. Under light load, the same region retained the dominant response with an amplitude of 1377.5 at 14.47 Hz. The persistence of a dominant middle-zone response under different load intensities suggests that the central portion of the bridge is the primary dynamic response zone and should be prioritised for detailed inspection, deflection monitoring and crack mapping.

The frequency values associated with maximum amplitude are clustered between approximately 11 Hz and 15 Hz. This range indicates that the monitoring system is capturing consistent vibration behaviour rather than random noise. The left and right responses are lower in magnitude, but they remain important for identifying asymmetric deterioration or bearing-related effects. The combination of amplitude and frequency interpretation provides a simple but powerful screening method: high amplitude at a consistent frequency may indicate flexibility concentration, while sudden frequency shifts over time may suggest stiffness degradation.

## VII. COMPARATIVE ANALYSIS AND PRACTICAL IMPLICATIONS

The proposed framework improves upon conventional visual inspection by providing quantitative and repeatable measurements. Compared with manual survey-based deflection monitoring, IoT sensors offer higher temporal resolution and can detect short-duration events caused by heavy vehicles. Compared with purely data-driven monitoring, the SAP2000 digital twin adds physical interpretability and helps distinguish normal operational variability from potential deterioration. For bridge authorities, this approach supports prioritised maintenance, early warning, cost reduction and improved public safety. It is especially suitable for regional bridges where a full-scale commercial monitoring system may not be economically feasible.

## VIII. LIMITATIONS

The case-study interpretation is based on selected FFT response tables and a conceptual digital twin framework. Long-term environmental effects, seasonal variation, traffic weight measurement and calibrated damage thresholds were not fully available. The present work therefore acts as a monitoring framework and preliminary response assessment rather than a complete damage diagnosis system.

## IX. CONCLUSION AND FUTURE SCOPE

This study demonstrates the feasibility of combining low-cost IoT sensing, SAP2000 digital twin modelling and FFT-based vibration interpretation for

old reinforced concrete bridge monitoring. The Ozar Bridge case study shows that the middle zone produced the dominant response under both load conditions, with maximum amplitudes of 4159.7 and 1377.5 at approximately 14.5-14.8 Hz. These findings support targeted inspection and continuous monitoring of the central span region.
Future work should include long-duration field deployment, calibration of sensor data with controlled load testing, machine learning-based anomaly classification, cloud dashboard integration and correlation of FFT features with visual damage, UPV results and finite element model updating.

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