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Sustainable Bridge Management Strategy through Modern Smart Phones

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Abstract: Bridge infrastructure is aging rapidly across the globe, faces increasing challenges due to fatigue, dynamic loads, and environmental deterioration, which pose risks to the structural safety and long-term sustainability. While traditional Structural Health Monitoring (SHM) systems are more reliable, they often require expensive equipment, skilled technicians, and can cause traffic disruptions during installation. This paper presents an alternative approach to bridge management that is sustainable, non- destructive, and cost-effective which uses modern smartphones as SHM tools. Modern smartphones are now equipped with highly sensitive accelerometers and gyroscopes and can collect vibration and movement data from bridges with surprising accuracy during normal train operations. In this study, commercially available smartphones were directly mounted on bridge elements and data was collected using the "Phyphox" mobile application during live train passages. The acceleration data along three orthogonal directions was processed to extract key dynamic characteristics such as natural frequencies, velocity and mode shapes, which are critical indicators of structural integrity. The findings indicate that smartphone sensors are capable of capturing meaningful structural vibrations suitable for condition assessment, especially for preliminary diagnostics and routine inspections. The methodology was tested on a case study steel railway bridge in the Sri Lanka Railways network. Results confirm the adaptability, practicality, and accuracy of smartphone-based monitoring in real-world conditions. This approach allows for more frequent, scalable, and inclusive monitoring, especially in remote or resource-constrained environments, promoting sustainability through reduced costs, minimized carbon footprint, and enhanced community involvement. By enabling proactive maintenance, this strategy contributes to safer, more resilient infrastructure in line with sustainable development goals.

Keywords: smartphone sensor; steel railway bridge; structural health monitoring; sustainability in infrastructure; vibration analysis

Introduction

The monitoring and maintenance of civil infrastructure have become a global priority, as many structures face the combined challenges of aging, rising traffic demands, and exposure to harsh weather conditions and pose significant risks to safety and serviceability. Structural health monitoring (SHM) has become increasingly important for guaranteeing the safety, resilience, and longevity of critical infrastructures, particularly bridges, by enabling continuous or periodic assessment of structural performance through measurements of vibrations, deformations, and other response characteristics [1], [2]. Traditionally, SHM has depended on high-precision and costly devices like piezoelectric accelerometers, laser Doppler vibrometers, and fiber optic sensors. These conventional devices offer very accurate measurements, but their high cost and logistical needs make them unsuitable for widespread implementation [1]. To address these limitations, recent years have witnessed a growing move toward affordable, scalable, and easy-to-deploy sensing technologies that can generate sufficiently reliable data, offering a practical alternative to conventional systems in many scenarios.

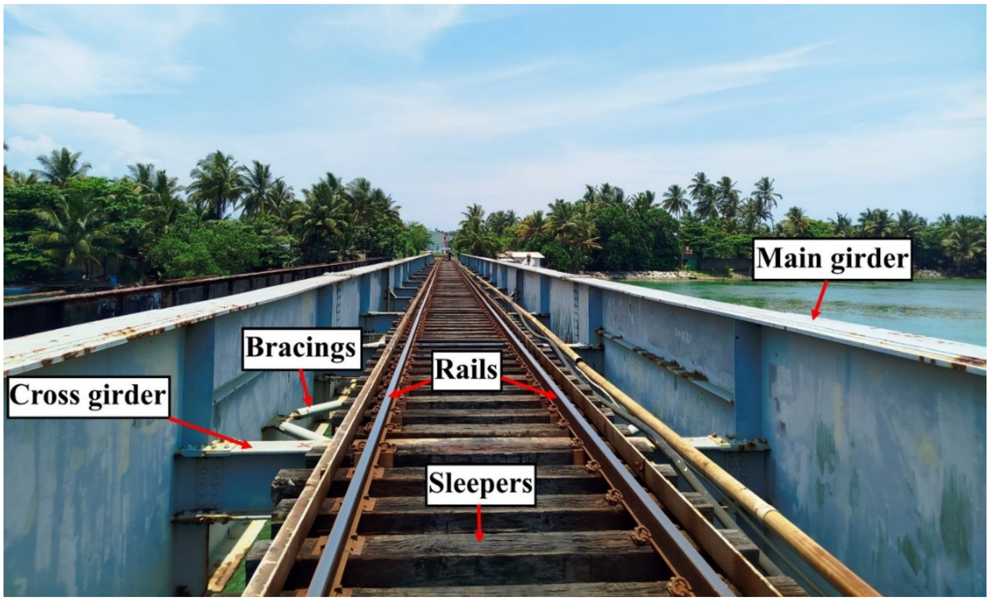
Among these alternatives, Micro-Electro-Mechanical Systems (MEMS) accelerometers have proven to be one of the most promising technologies, offering affordable, and adequate sensitivity for vibration-based monitoring [2]. Modern smartphones, which embed MEMS accelerometers and gyroscopes as standard components, have become an important point of this development. Their portability, and ability to record vibration data with growing levels of precision have created new opportunities for SHM [2], [3]. Studies have shown that smartphones can be utilized not only in controlled laboratory settings but also in real-world conditions to extract modal properties such as natural frequencies, damping ratios, and mode shapes of bridges and buildings [4], [5].

The integration of smartphone technology into SHM is not limited to hardware capabilities. Recent developments in software applications and machine learning have demonstrated that data collected by smartphone sensors (Commercial sensors) can be processed in near real time to detect structural anomalies. For instance, the App4SHM platform developed by [5] leverages the onboard accelerometer of smartphones and combines it with machine learning algorithms to compare vibration signatures with baseline datasets, thereby enabling fast and user-friendly damage detection. Such approaches highlight the dual role of smartphones as both data acquisition devices and data processing platforms. At the same time, smartphone-based SHM studies emphasize the role of mobile sensing in advancing low-cost monitoring solutions [6] and, vibration-based modal identification, vision-based deformation monitoring, and mobile drive-by surveys, demonstrating the breadth of possibilities enabled by consumer devices [7].

Overall, smartphones and low-cost MEMS sensors are changing the field of SHM, providing an affordable and practical way to make structural monitoring accessible to everyone. With their wide availability, portability, and processing capability, smartphones can substantially reduce both the cost and complexity of SHM, while also enabling broader monitoring coverage and faster evaluations.

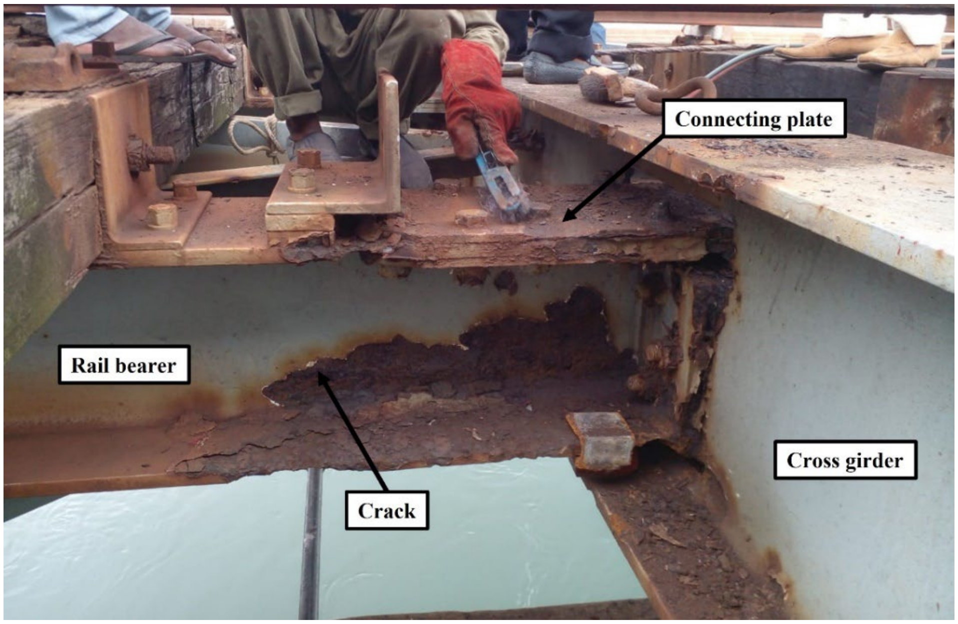
In this study, the longest and one of the busiest plate girder bridges on the coastal railway line in Sri Lanka was visually inspected, and several structural defects were identified. As shown in **Figure 1**, the bridge consists of main girders, cross girders, rail bearers, sway bracings, and wind bracings, which together ensure load transfer and overall stability [8].

Figure 1: Typical Components of a plate girder railway bridge (With the permission of Sri Lankan Railways*)*



However, the cross girder–rail bearer connection (**Figure 2**) exhibited severe corrosion and material loss, which is a deterioration typical in coastal environments and requires frequent replacement during maintenance. In response, this study aims to investigate the feasibility and introduce a methodology for employing smartphones as a Structural Health Monitoring (SHM) tool to support effective bridge management [8].

Figure 2: Deteriorated area of the cross girder -rail bearer section (With the permission of Sri Lankan Railways)



Literature Review

Recent years have witnessed a surge in the use of smartphones and low-cost sensors as alternatives to traditional SHM systems. Several studies have established that modern smartphones, when deployed in static or mobile configurations, can effectively capture modal parameters of bridges and buildings. Smartphones mounted in vehicles could extract natural frequencies of a bridge with strong agreement to operational modal analysis, thus validating the concept of drive-by monitoring [4]. Complementing this, 'App4SHM', a dedicated smartphone application was developed which employs onboard accelerometers and machine learning to perform near real-time damage detection [5]. Together, these contributions highlight the potential of smartphones for capturing essential structural response data, while also showing how software integration can transform raw vibration signals into actionable information.

The use of smartphones in SHM is further reinforced through comprehensive reviews that contextualize these technological advancements. An overview of smartphone-enabled sensing technologies has highlighted their advantages in accessibility and scalability [6], while studies focusing specifically on bridge monitoring have detailed their application in vibration-based and mobile SHM approaches [7]. Their review identified three principal domains of smartphone application: vibration-based identification, vision-driven deformation measurements, and drive-by or pedestrian survey methods. These reviews collectively underline the breadth of applications possible through smartphone technology and underscore its potential to complement, rather than replace, traditional sensor deployments. In addition, distributed low-cost sensor networks, as demonstrated in [3] on the Golden Gate Bridge, show how arrays of smartphones and consumer-grade sensors can be synchronized to provide multi-output modal identification of large structures. This approach extends the monitoring capacity of smartphones beyond single-point measurements, offering a framework for dense sensor coverage at minimal cost.

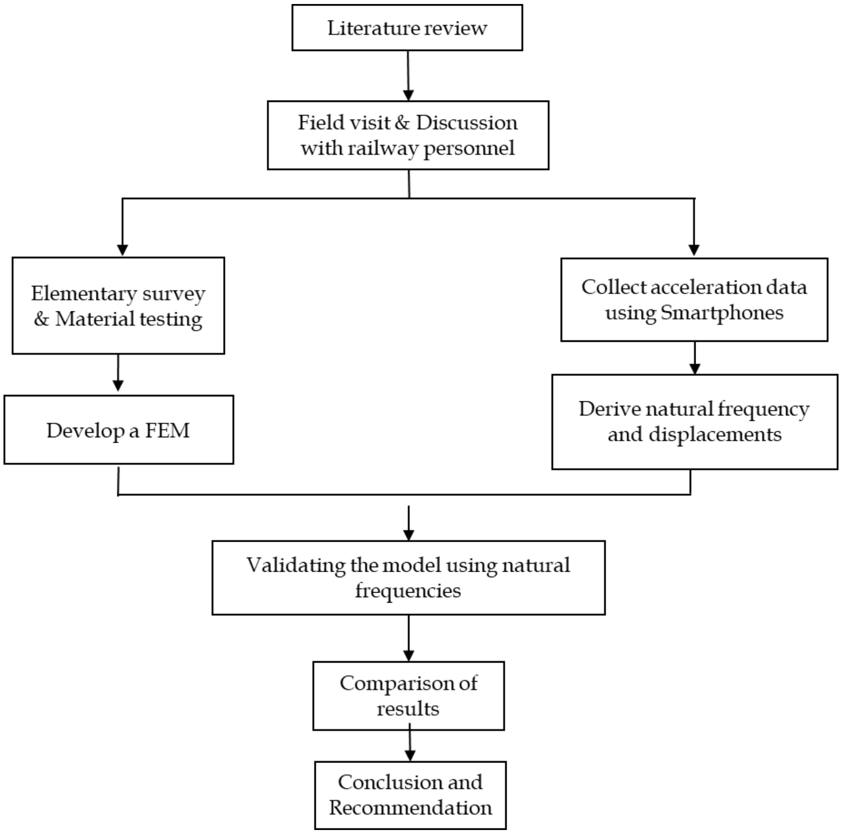
The promise of these novel sensing approaches gains further credibility when viewed against the backdrop of traditional full-scale damage identification studies. One of the earliest large-scale validations was conducted, using modal parameter changes to detect damage in a seven-story building slice subjected to ambient and low-amplitude excitations [1]. Their results, validated through finite element updating, set a benchmark for subsequent smartphone-based studies that seek to replicate such precision using more accessible technologies. Similarly, [2] showed how citizen science networks using low-cost MEMS sensors could successfully record earthquake ground motions, illustrating how mass participation and distributed deployments can overcome the limitations of localized, high-cost monitoring stations. These insights have strong parallels with smartphone-based SHM, where the ubiquity of devices offers unprecedented opportunities for crowd-sourced structural monitoring across diverse geographical regions.

Taken together, the reviewed literature converges on a central theme: smartphones and low-cost MEMS sensors are transforming SHM by making it more accessible, scalable, and versatile. Whether embedded in vehicles for drive-by monitoring, packaged as applications for real-time damage detection, deployed in dense arrays for modal analysis, or used in citizen science networks for seismic response, these technologies collectively demonstrate that reliable structural monitoring no longer needs to be constrained by high costs or limited coverage. At the same time, challenges remain in terms of data quality, environmental noise, standardization of measurement protocols, and validation against traditional high-precision sensors. The literature suggests that hybrid approaches, integrating smartphones with conventional monitoring systems and advanced data analytics, offer the most promising pathway for overcoming these limitations while leveraging the unique strengths of smartphone sensing.

Methodology

The research methodology adopted in this study followed a systematic framework to ensure a comprehensive understanding and reliable analysis of the structural behavior of the selected railway bridge.

Figure 3: Systematic framework adopted for the research methodology



The systematic framework is illustrated in Figure 3. It began with a literature review, followed by field visits and discussions with railway personnel to understand bridge conditions. An elementary survey and material testing were conducted to obtain essential data for modelling. A Finite Element Model (FEM) was then developed in SAP2000, while smartphone-based vibration data were collected to derive natural frequencies and displacements. The numerical model was validated using these experimental results, followed by a comparison of outcomes and the formulation of conclusions and recommendations for sustainable bridge monitoring.

Determination of material properties and structural section characteristics

The mechanical properties of the steel used in the bridge were obtained from laboratory testing reported in [1], and the values are presented in **Table 1**. These properties provided essential input parameters for the numerical modelling.

Table 1: Mechanical properties of S355 steel (Source: [1])

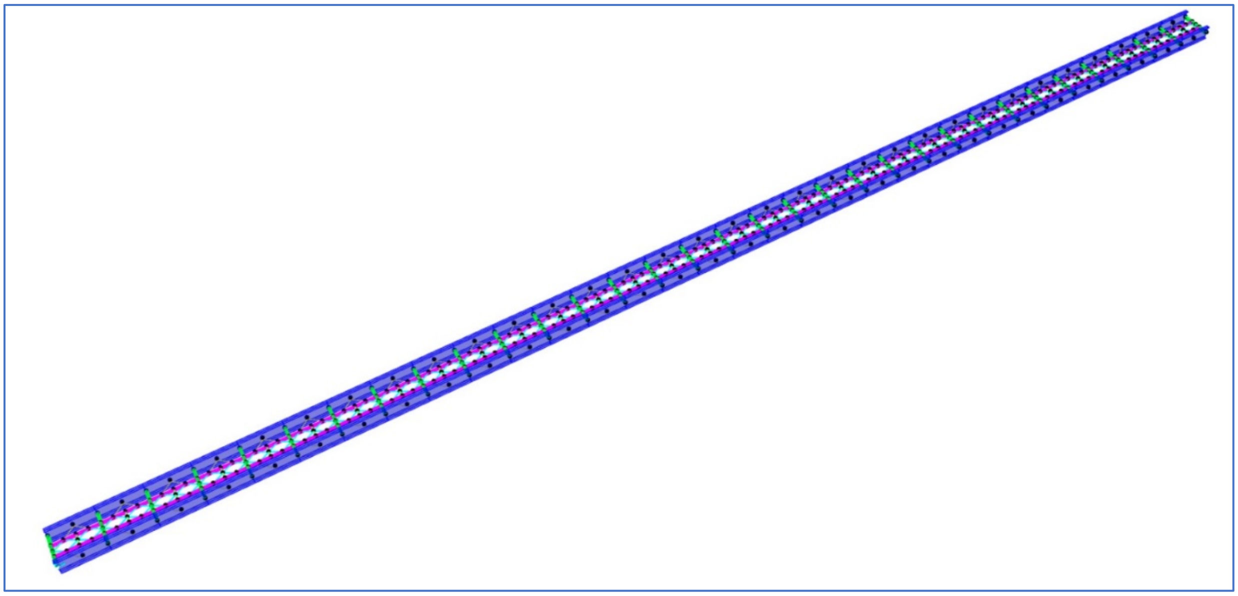
Mechanical Properties	**Value**
Yield strength (MPa)	355
Ultimate tensile strength (MPa)	433
Strain at break (mm/mm)	0.36
Tensile stress at break (MPa)	287

In addition, the steel section types and their geometric dimensions were identified in [8]. The combined information on material properties and section characteristics formed the fundamental basis for the development of the Finite Element Model (FEM).

Numerical modelling

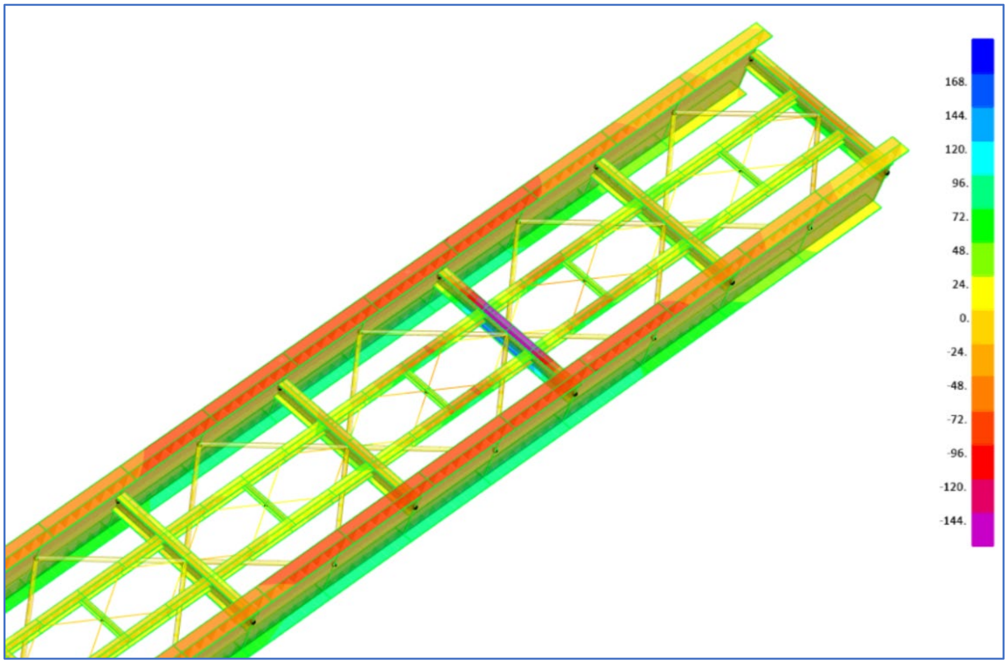
A Finite Element Model (FEM) of the bridge was developed using SAP2000 v23 software to simulate its structural behavior under train loading. The model is illustrated in **Figure 3**. The applied loading conditions included the train load, which was represented as a static load in the analysis. To account for the dynamic effects of train movement, a dynamic amplification factor of 1.5 was applied to the live load, in accordance with established practices [9].

Figure 4: 3D finite element model developed using SAP2000



The analysis was then carried out to evaluate the structural response of the bridge. The resulting stress distribution obtained from the analysis is presented in **Figure 4**, which highlights the stress patterns developed in the critical members of the bridge.

Figure 5: Finite element analysis results



Vibration analysis

For the experimental component, vibration measurements were obtained using four smartphones (iPhones), which were securely mounted at four different locations (**Figure 5**) using high-strength double-sided adhesive tape to minimize relative movement during measurements, as shown in **Figures 6 and 7**. Acceleration data in the (x), (y), and (z) directions were recorded using the "Phyphox" mobile application, which enables the extraction of raw sensor readings. The measurements were collected continuously during train crossings, generating time-history data that captured the dynamic response of the bridge.

Figure 6: Plan view of smartphone locations

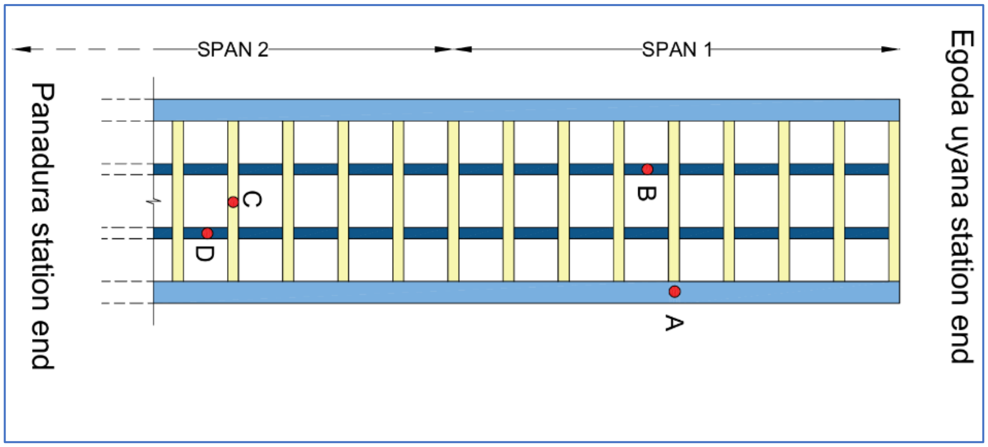
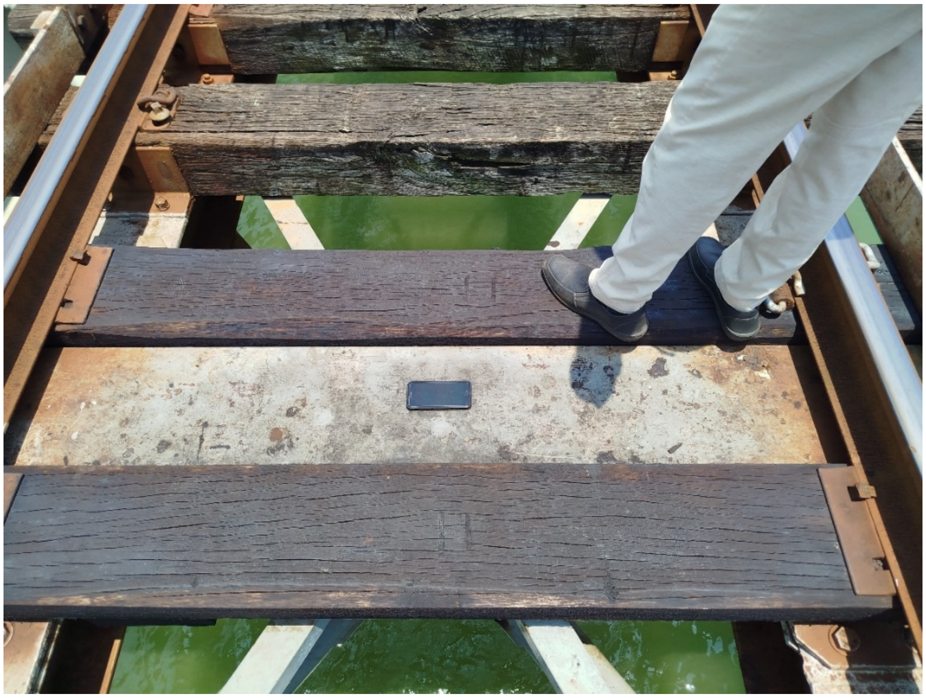


Figure 7: Smartphone fixed on the Rail bearer (Source: [8])

Figure 8: Smartphone fixed on the Cross girder (Source: [8])



The resulting acceleration–time histories of each location are illustrated in ***Figures 8, 9, 10 and 11****, which highlight the variations in acceleration corresponding to the passage of the train over the structure* [8].

Figure 9: Acceleration vs time graph for location A

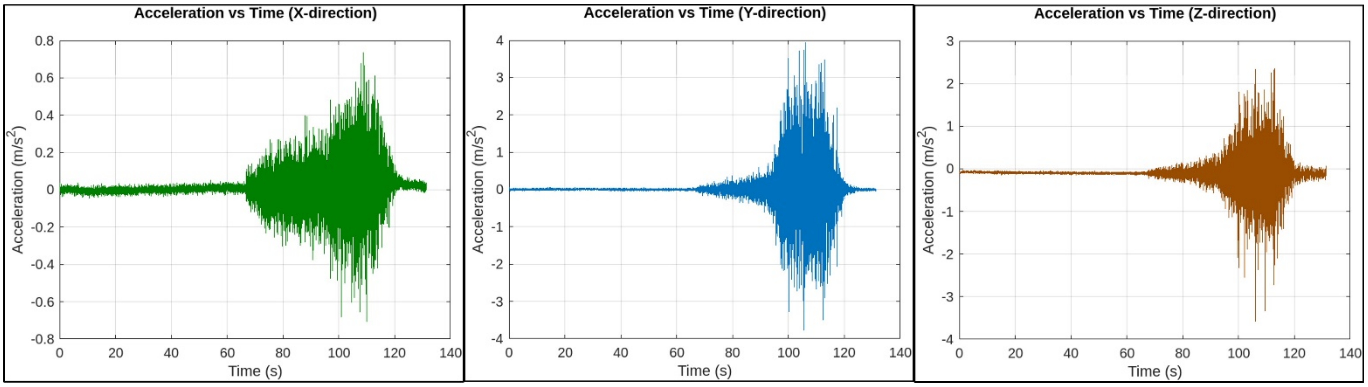


Figure 10: Acceleration vs time graph for location B

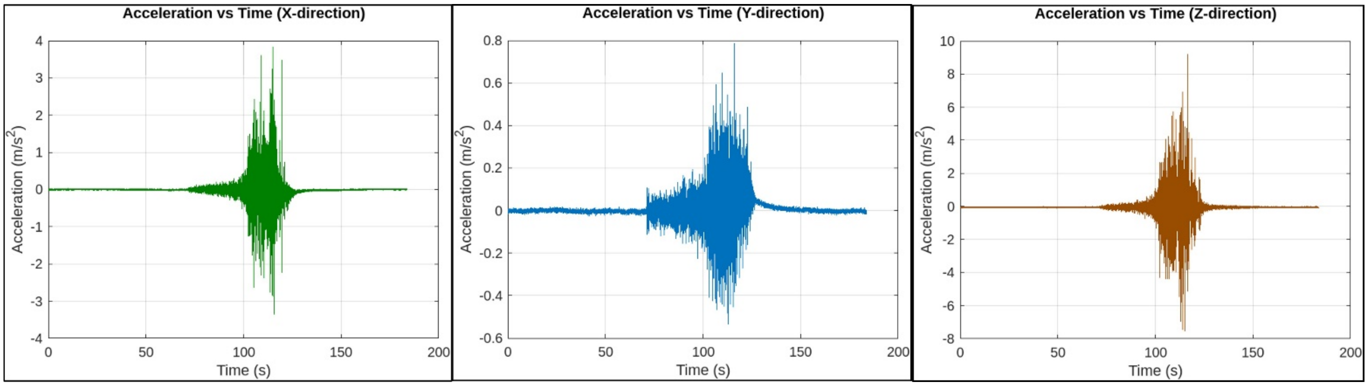


Figure 11: Acceleration vs time graph for location C

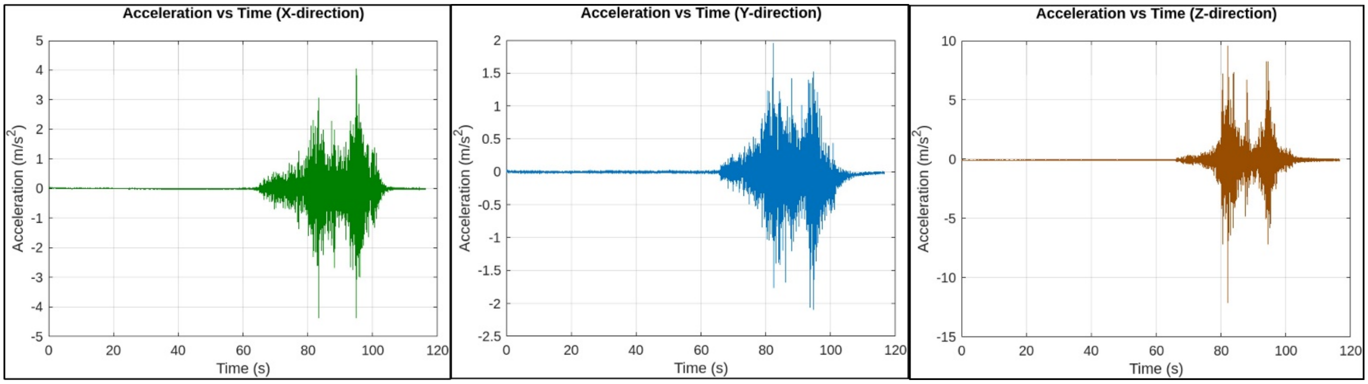
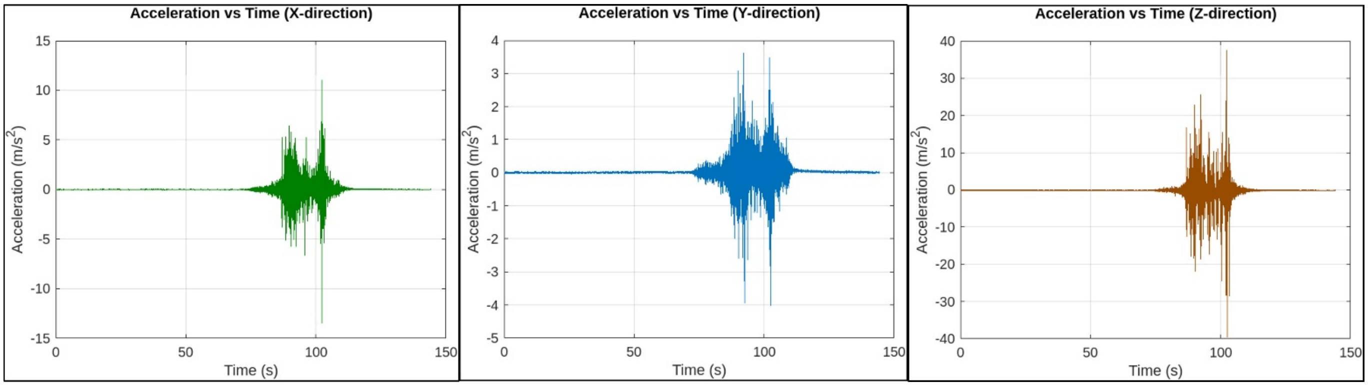


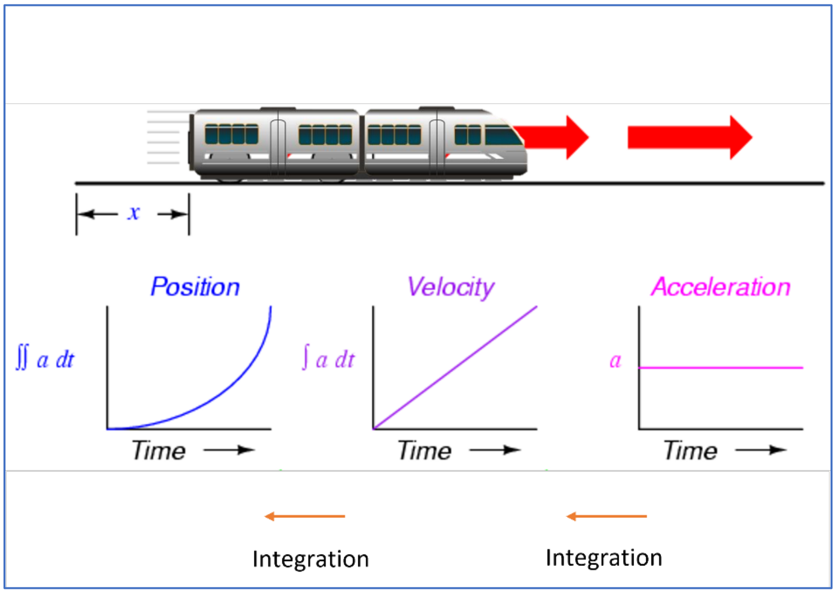
Figure 12: Acceleration vs time graph for location D



Conversion of Acceleration Data into Velocity and Displacement

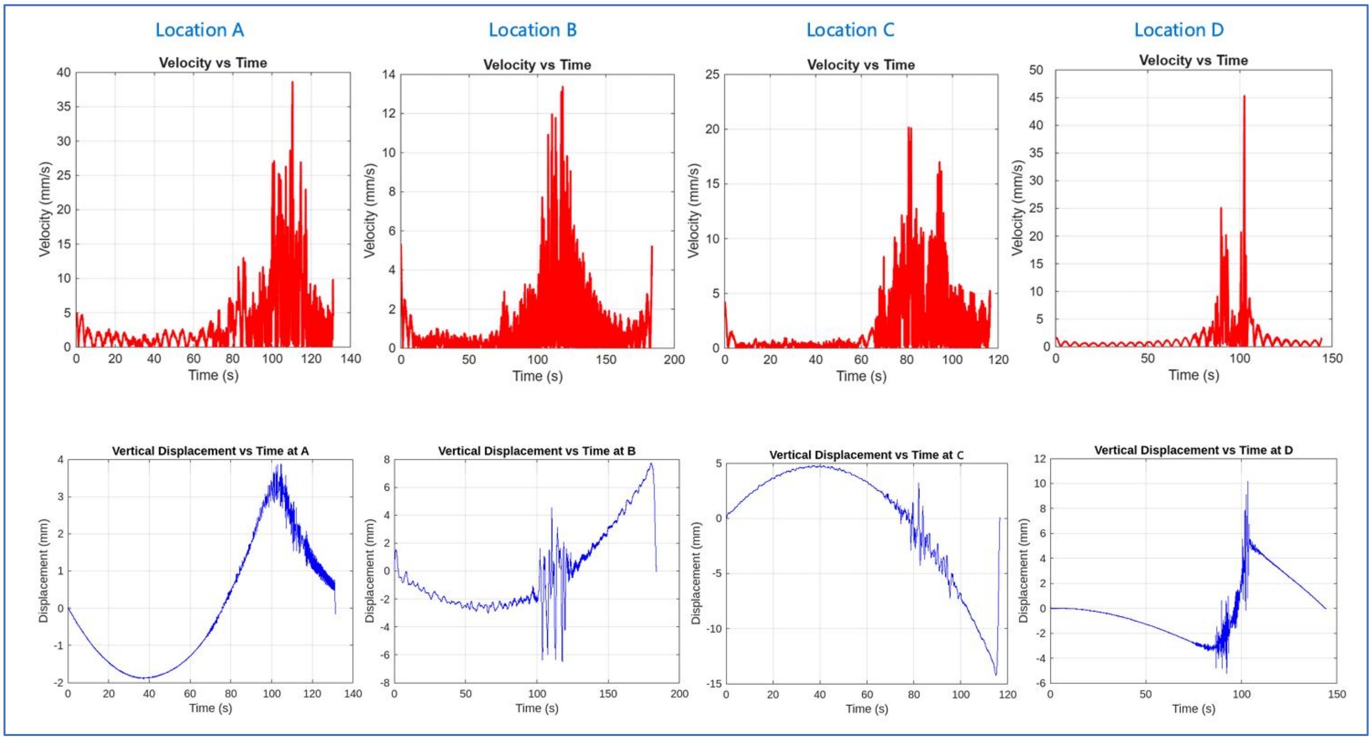
The acceleration data recorded from the smartphones were further processed in MATLAB online software to obtain velocity and displacement responses of the bridge. By performing a single numerical integration of the acceleration time histories, the velocity response was derived, and a second integration yielded the corresponding displacement response, as illustrated in **Figure 12**.

Figure 13: Conversion of acceleration into velocity and displacement



However, direct integration of raw acceleration signals can introduce significant errors due to noise, drift, and local vibrations. To overcome these challenges, preprocessing techniques such as filtering, and baseline correction were applied to the acceleration data using MATLAB. These steps ensured that the integrated results were free from misleading patterns and provided accurate velocity and displacement histories. The processed results are presented in **Figure 13**, which show the velocity–time and displacement–time responses, respectively, at the four measurement locations on the bridge.

Figure 14: Velocity and Displacement vs Time at each location



Validation of Numerical model

The Finite Element Model (FEM) of the bridge was validated by comparing its natural frequency with those obtained from the experimental vibration analysis. To extract the natural frequencies from the field data, the acceleration time histories were processed in MATLAB, where the Fast Fourier Transform (FFT) was applied to compute the Power Spectral Density (PSD). The resulting PSD–frequency plots are shown in **Figures 14, 15, 16 and 17**, where the dominant peaks correspond to the natural frequencies of the bridge. From these plots, the average fundamental frequency was determined to be **0.1945 Hz**. In comparison, the first mode shape of the FEM developed in SAP2000 predicted a fundamental frequency of **0.161 Hz**. The close agreement between the experimental and numerical results indicates that the FEM accurately represents the dynamic behavior of the bridge, thereby providing sufficient confidence in considering the model as validated [8].

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Figure 16: PSD vs frequency graph for location A

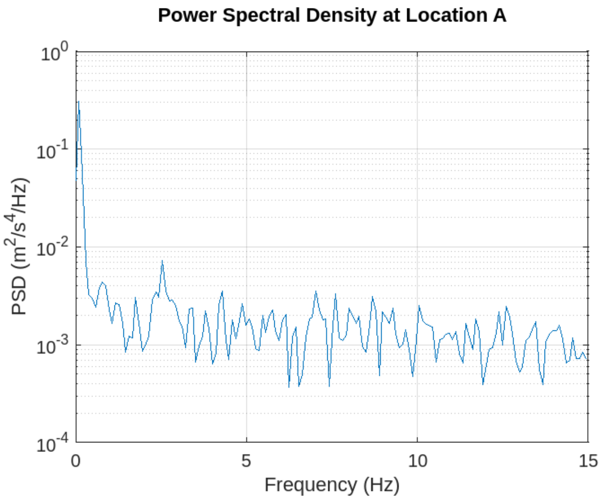


Figure 15: PSD vs frequency graph for location B

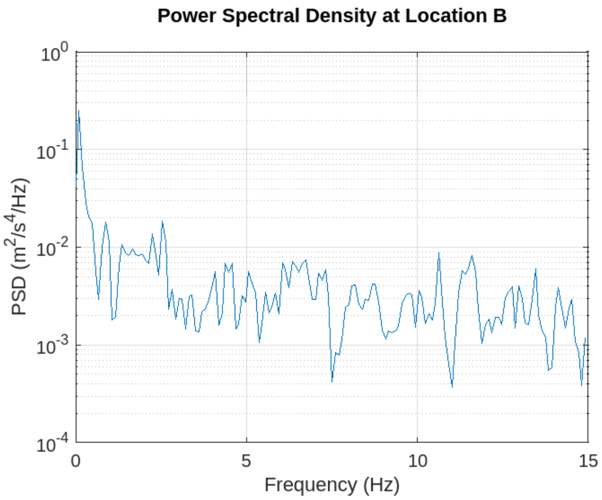


Figure 18: PSD vs frequency graph for location C

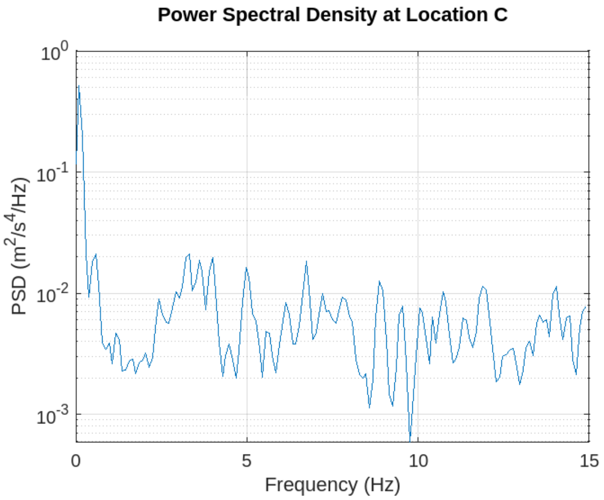
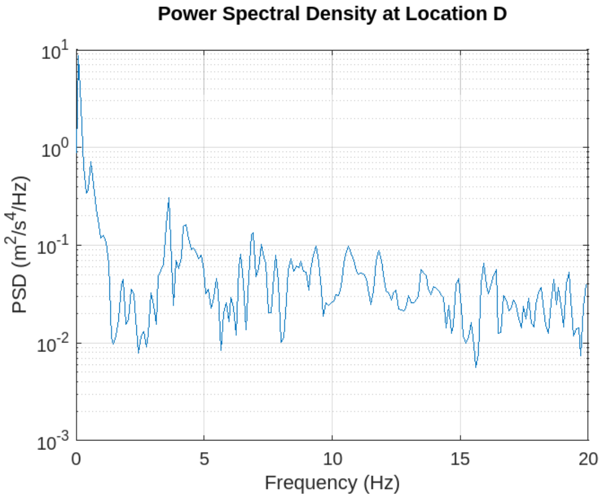


Figure 17: PSD vs frequency graph for location D



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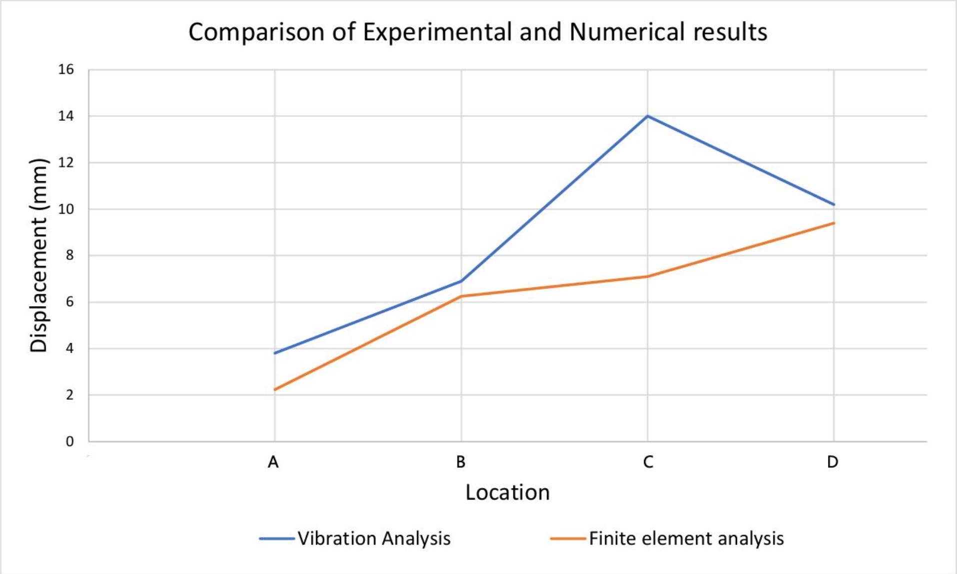
Results

The displacement results obtained from both the experimental vibration analysis and the numerical FEM were compared against the allowable serviceability limits, as presented in **Table 2** and **Figure 18.**

Table 2: Experimental, Numerical and Allowable displacement values

Location	**Experimental results (mm)**	**Numerical results (mm)**	**Allowable value (Span/600) (mm)**
A	3.8	2.23	10.12
B	6.9	6.25	10.12
C	**14**	7.1	8.37
D	10.2	9.4	10.12

Figure 19: Comparison of Experimental and Numerical displacement results



At **Locations A and B**, both experimental and numerical displacements remained well within the allowable limits (10.12 mm). This indicates that the structural performance at these points satisfies the serviceability criteria without raising concern.

At **Location D**, the experimental displacement was recorded as **10.2 mm**, which marginally exceeded the allowable limit of **10.12 mm**. However, the exceedance is minimal, suggesting the possibility of localized flexibility or minor uncertainties in measurement rather than a major structural deficiency.

At **Location C**, the experimental displacement was found to be **14 mm**, which significantly exceeded both the FEM prediction (**7.1 mm**) and the allowable serviceability limit (**8.37 mm**). This substantial deviation suggests potential localized structural issues. Notably, Locations C and D are situated near regions exhibiting severe corrosion and cracking, which may explain the higher experimental displacements recorded.

Conclusion and Discussion

The comparison of experimental displacements obtained via smartphone-based vibration analysis with numerical predictions from the finite element model (FEM) shows strong agreement at most monitoring locations. At Locations A and B, both experimental and numerical displacements remained well within allowable serviceability limits, confirming that these regions maintain sufficient stiffness under train loading. This agreement validates the FEM's ability to capture the bridge's overall dynamic behavior and demonstrates the reliability of smartphone-based measurements for assessing global structural performance.

In contrast, significant deviations were observed at Location C, where the experimental displacement (14 mm) notably exceeded both the FEM prediction (7.1 mm) and the allowable limit (8.37 mm). This suggests localized structural deficiencies, likely caused by reduced stiffness due to corrosion, cracking, or material degradation. At Location D, the experimental displacement (10.2 mm) slightly exceeded the allowable limit (10.12 mm), indicating minor local flexibility or measurement uncertainties rather than a critical structural concern. The proximity of Locations C and D to visibly deteriorated regions support the interpretation that localized defects can amplify displacements under operational loading.

Overall, these findings confirm that smartphone-based vibration monitoring can effectively capture the global dynamic behavior of bridges while also identifying localized anomalies that may require closer inspection. This approach offers a practical, non-intrusive, and cost-effective alternative to conventional structural health monitoring systems. By combining affordability, accessibility, and reasonable accuracy, smartphone-based SHM provides a sustainable solution for bridge monitoring, enabling early detection of potential structural issues and informed maintenance planning.

In summary, while FEM predictions reliably represent global behavior, smartphone-based measurements add value by revealing localized structural concerns, making this approach a promising tool for both resource-constrained and developed settings to ensure bridge safety and serviceability.

The conclusions presented in this study are directly derived from the systematic framework adopted throughout the research. The initial field investigation established the bridge's condition and informed model assumptions, while the FEM analysis quantified structural responses under operational loading. The experimental vibration measurements obtained through smartphones validated the model results and revealed localized weaknesses. Together, these stages confirmed the feasibility of smartphone-based bridge monitoring, demonstrating that the framework effectively integrates experimental and analytical methods to produce reliable, sustainable, and practical insights for bridge management.

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