# Vibration-Based Structural Health Monitoring A Case Study of RCC T-beam Bridge at Nakhu Khola

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## Abstract

This paper explores vibration-based structural health monitoring (SHM) for the reinforced concrete (RCC) T-beam bridge over Nakhu Khola in Kathmandu Valley, Lalitpur, Nepal, using smartphone accelerometers for data collection. Short-term ambient vibration data is analyzed using Operational Modal Analysis (OMA) methods including Peak Picking (PP), Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD), and Stochastic Subspace Identification (SSI) in MATLAB. A Finite Element Modal (FEM) is developed in CSI Bridge for validation through modal frequency and Mode shape comparison. Results indicate that smartphone sensors effectively capture first three vertical bending frequency with discrepancies from FEM 15% and modal assurance criteria for first three vertical bending mode greater than 0.95. Damage is simulated by reducing stiffness 30% at selected mid longitudinal girder elements that represent structural deterioration. The results showed that stiffness reduction caused a decrease in natural frequencies. The first vertical bending mode was found to be the most sensitive to damage. This low-cost approach is suitable for short-term SHM in seismically active regions like Nepal, facilitating rapid assessments post-events such as floods or earthquakes.

*Keywords: Finite Element Modeling, Operational Modal Analysis, RCC T-Beam Bridge, Smartphone Accelerometer, Structural Health Monitoring, System Identification.*

## 1. Introduction

Bridges are essential components of transportation infrastructure because they provide public safety, economic expansion and connectivity. Even though bridges are made to last for a long time, traffic loads, exposure to the environment and material aging can cause them to gradually deteriorate. If this degradation is not adequately monitored and maintained, it can negatively impact the structural performance of bridges(Samadi et al., 2021). There are 1719 bridges in the national highways of Nepal, as per DOR statistics of the national highway SNH 2022/23. Among them 814 bridges are RCC T-beam bridges; hence, RCC T-beam bridges are the most used bridge in national highways (STATISTICS OF NATIONAL HIGHWAY Department of Roads Government of Nepal Ministry of Physical Infrastructure and Transport, 2023).

An RCC T-beam bridge consists of a longitudinal girder, a cross girder, an intermediate slab, a cantilever slab, a footpath, and railings. In Nepal, T-beam bridges, particularly reinforced concrete (RCC) T-beam bridges, are one of the most common types due to their cost-effectiveness, structural efficiency, and suitability for mid-span lengths (10-30 m), representing a significant portion of the country's approximately 10,000 bridges (Bhandari et al., 2024).

In recent years, structural health monitoring (SHM) has developed into a powerful tool for the impartial assessment of bridge performance. SHM techniques, particularly vibration-based methods, enable the continuous or periodic assessment of structural state through measurable dynamic responses (Saidin et al., 2022). Structural health monitoring (SHM) is the process of observing and analyzing a structure over time using periodically sampled response measurements to detect changes in material or geometric properties, ensuring early warnings for defects and preventing failures (Mohamed Abdel-Basset Abdo Sc & Sc, 2014).

Structural health monitoring (SHM) is essential for bridges because many existing structures particularly in regions like Nepal are exceeding their design lives and are increasingly subjected to seismic hazards, flooding, and heavy traffic loads that accelerate deterioration processes such as cracking and corrosion. SHM systems provide continuous, real-time monitoring of structural behavior, enabling early detection of damage and facilitating condition-based maintenance that can significantly reduce lifecycle costs compared to traditional periodic inspections (Saidin et al., 2022), (Mohamed Abdel-Basset Abdo Sc & Sc, 2014). Traditional visual inspection methods may fail to identify early signs of degradation between inspection intervals, whereas vibration-based SHM offers more timely and cost-effective condition assessment and early warnings (Malinowska et al., 2025).

Equipment and tools for structural health monitoring of bridges include smartphone-based app sensors and software for analysis field vibration data is MATLAB and for FEM Modeling in CSI Bridge are used (Muhammad et al., 2024). The Phyphox mobile app was used as the primary tool, leveraging built-in smartphone accelerometers for ambient vibration measurements (100-200 Hz sampling), chosen for its low cost, ease of use in resource-limited region, and proven accuracy (<5% error for bridge frequencies), and the analysis software is MATLAB for better graph representation and FEM modeling is CSI Bridge for better software for analysis (Komarizadehasl et al., 2024).

A state-of-the-art review on smartphone sensing technology for structural health monitoring (SHM) of civil structures, leveraging built-in sensors such as accelerometers, gyroscopes, GPS, and high-resolution cameras alongside IoT and crowdsourcing paradigms. It surveys vibration-based methods for response measurement, modal identification, damage assessment, seismic monitoring, and comfort evaluation, as well as vision-based approaches for displacement tracking and surface damage detection, including third-party apps in Android and iOS like MyShake, Phyphox, and App4SHM developed for SHM purposes. The study highlights the affordability, effectiveness, and potential of smartphone-based SHM for citizen-engaged data collection, long-term infrastructure assessment, and enhanced predictive maintenance and safety strategies (Sarmadi et al., 2023). Operational Modal Analysis (OMA), which relies on environmental vibrations like traffic and wind, is especially suitable for in-service bridges where controlled stimulation is not practical. Natural frequencies, mode shapes, and damping ratios are examples of modal metrics that can indicate deterioration or damage to bridge structures' stiffness (Hamed Hasani and Francesco Fredd, 2023).

Despite growing SHM importance, The Nakhu Khola bridge, a 37 m single-span RCC T-beam structure in Lalitpur, Nepal, was taken for this thesis as it represents typical urban mid-span bridges in flood-prone areas (affected by 2024 AD floods), allowing focus on superstructure vulnerabilities like cracking under traffic loads, and its accessibility facilitated field measurements. The objectives are to measure ambient vibration characteristics using Phyphox and OMA, develop a CSI Bridge superstructure model, validate OMA results against numerical predictions, and detect potential damages (stiffness loss) for affordable SHM in Nepal.

# 2. Methodology

## 2.1 Research Framework

A conceptual frame work for the detailed analysis of this study is shown in flowchart as below:

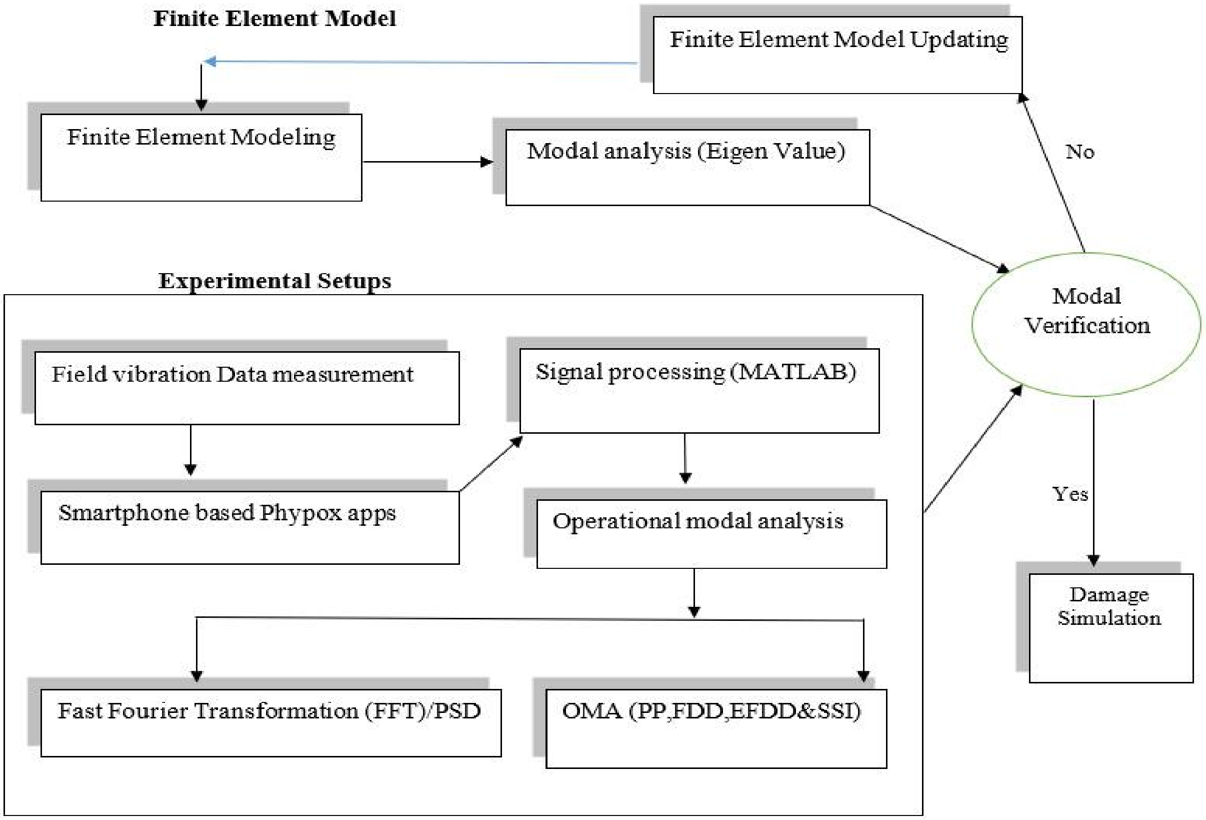


Fig. 1: Flowchart for Research Methodology

## 2.2 Material Properties and Specification

The material properties used in the numerical model is defined as follows, given in Table 1:

Table 1: Material definitions for Concrete and Rebar used in the numerical model

| For Concrete | |
|---|---|
| Region | India |
| Material Type | Concrete |
| Standard | India |
| Grade | M30 |
| **For Rebar** | |
| Region | India |
| Material Type | Rebar |
| Standard | India |
| Grade | HYSD415 |

The material properties were taken from Design report and IS Code, utilized in the numerical model correspond to concrete, characterized by a specific weight, strength, Poisson's ratio, and modulus of elasticity of 30 MPa, 30 MPa, 0.2, and 30 MPa, respectively. And the rebar used is HYSD415

$$E=5000\sqrt{fc}$$

Table 2: Material properties for Concrete and Rebar used in the numerical model

| **Material properties for concrete** | | |
|---|---|---|
| Concrete | Material name | M30 |
| | Weight per unit volume | 24.9926 KN |
| | Modulus of elasticity | 2.79 E+07 KN/m² |
| | Poisson ratio | 0.2 |
| | Coefficient of thermal expansion, A | 1.300E-05 per degree C |
| | Standard | IS |
| **Material properties for Rebar** | | |
| Rebar | Material name | HYSD Grade415 |
| | Weight per unit volume | 76.9729 KN |
| | Modulus of elasticity | 2.000E+11 KN/m² |
| | Poisson ratio | 0.3 |
| | Coefficient of thermal expansion, A | 1.170E-05 per degree C |
| | Standard | IS |

Table 3: Section Properties

| **Frame Section** | | |
|---|---|---|
| Longitudinal Girder | Section Name | LG |
| | Material | M30 |
| | Concrete reinforcement bar | HYSD415 |
| | Design Type | Beam (M3 design only) |
| Cross Girder | Section Name | CG |
| | Material | M30 |
| | Concrete reinforcement bar | HYSD415 |
| | Design Type | Beam (M3 design only) |
| **Area Section** | | |
| Deck | Section | Deck |
| | Design Type | Shell-thin |
| | Material | M30 |

## 2.3 Bridge and their Description

The bridge considered in this thesis is an RCC T-beam bridge constructed over Nakhu Khola in Lalitpur, Nepal. The bridge is a single-span structure with a total span length of 37 m and an overall deck width of 10.9 m, comprising a 6.5 m wide carriageway and 2.0 m wide footpaths on both sides. The superstructure consists of 3 longitudinal reinforced concrete T-girders having a depth of 2.5 m and a web width of 0.5 m, spaced at 3.0 m center-to-center. The longitudinal girders are interconnected by 5 Reinforced concrete cross girders of 2.0 m depth and 0.3 m width, spaced at 7.35 m center-to-center. The deck slab is 0.20 m thick and cast monolithically with the girders. The bridge is constructed using M30 grade concrete and Fe415 grade reinforcement taken from as build drawing. Built in the year 2016 AD, the bridge carries urban traffic and is located in a flood-prone area, making it a representative case for vibration-based structural health monitoring of RCC T-beam bridges in Nepal. This bridge was selected as the case study to evaluate its dynamic characteristics, assess its current structural condition, and demonstrate the applicability of operational modal analysis techniques for urban bridges.

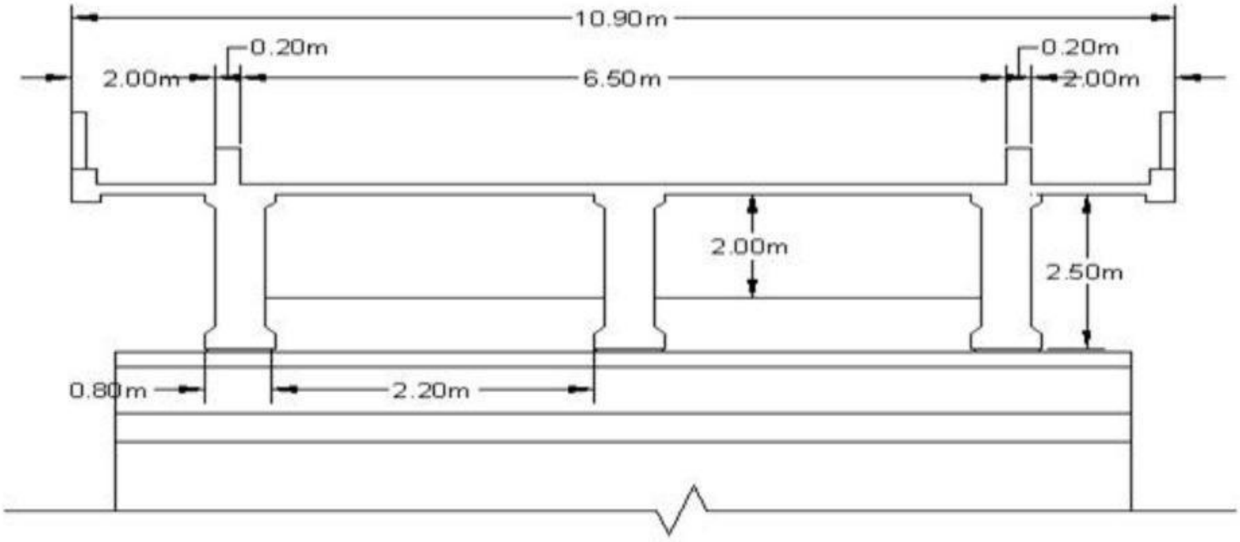


Fig. 2: Cross-section of RCC T-Beam bridge

## 2.4 Placement of smartphone sensor on Bridge

To record the first several vertical bending modes, sensors were positioned at key points on the bridge, such as the deck's mid-span and quarter-span (Chopra, n.d.et.all.2017). For this study, Z-axis of the accelerometers was oriented perpendicular to the deck surface so, Smartphone was placed on deck. The sensors were mounted directly on flat concrete surfaces using a combination of strong adhesive and securing tape to ensure firm contact and minimize relative motion or measurements noise. All the measurements were conducted under normal traffic conditions, with the bridge carrying typical vehicular loads, to capture realistic ambient vibration responses without including any additional dynamic excitation. Excitation sources included ambient vibrations from wind, traffic, and micro-tremors.

## 2.5 Data Processing

Before modal analysis, the raw acceleration data from the bridge's ambient vibration measurements were pre-processed in MATLAB to ensure accuracy and reliability. In order to remove mean offsets and low-frequency drifts, the signals were first detrended. To eliminate noise outside of the usual bridge vibration frequency range while maintaining the structural response, a 0.5–20 Hz Butterworth band-pass filter was used. To enhance the statistical stability of spectral estimations, the filtered signals were divided into segments with 50% overlap. After that, Welch's approach with a Hamming window was used to calculate the Power Spectral Density (PSD), which produced a smooth frequency spectrum for identifying dominant vibration modes. Using the Peak Picking (PP) approach, natural frequencies were extracted from the PSD's dominant peaks. Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD) techniques were used to extract additional modal parameters, such as mode shapes and damping ratios, while Stochastic Subspace Identification (SSI-COV) was used in the time domain to validate the identified modes using stabilization diagrams. Lastly, the Modal Assurance Criterion (MAC) was used to compare the findings of the finite element model with the experimentally obtained mode shapes. High MAC values demonstrated a strong correlation and confirmed the validity of the identified modal parameters.

## 2.6 Finite Element Model (FEM) of Bridge

Finite Element Analysis was conducted to determine the modal frequencies and their corresponding mode shapes using the CSI Bridge2016v23 software on the bridge model. In this model, the girders were depicted using line elements, while the concrete deck was represented by shell elements. To ensure consistency, the boundary conditions for this bridge model were set to match those of the respective bridges.

### 2.6.1 3D Model (FEM) of Bridge

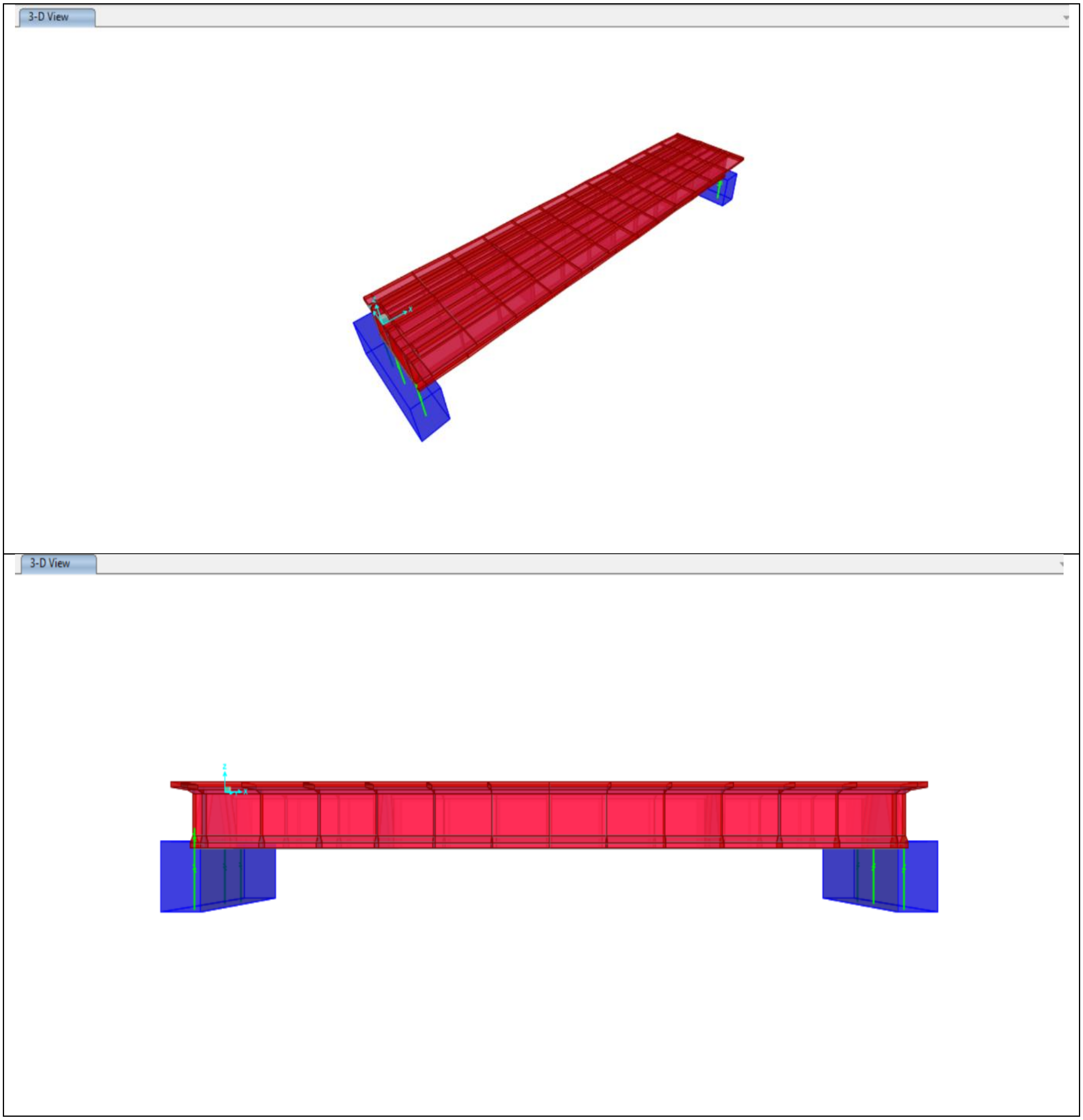
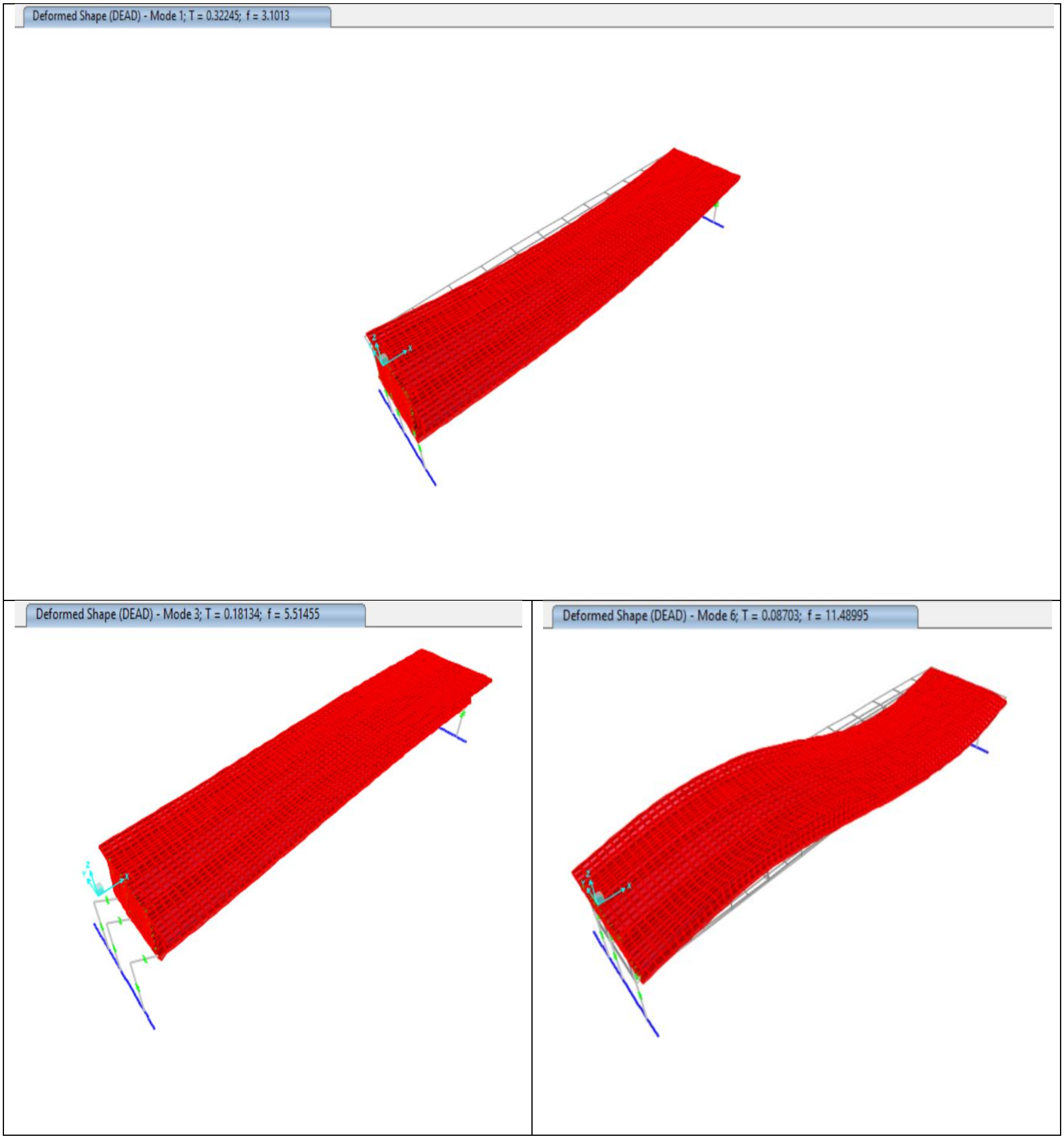


Fig. 3: 3D Modeling of RCC T-Beam bridge

### 2.6.2 Finite Element Model Deformed Shapes


Deformed Shape (DEAD) - Mode 1; T = 0.32245; f = 3.1013

Deformed Shape (DEAD) - Mode 3; T = 0.18134; f = 5.51455

Deformed Shape (DEAD) - Mode 6; T = 0.08703; f = 11.48995

Fig. 4: Deformed Shape of Bridge

## 3. Results and Discussion

### 3.1 Raw Acceleration Data

Vibration data was collected using the phyphox smartphone application, which provides high-precision accelerometer access suitable for structural vibration measurements. Recordings lasted approximately 10 minutes per setup at a sampling rate of 100 Hz. The smartphone was securely placed on the bridge deck at mid-span and quarter-span points to capture vertical accelerations under ambient excitation from passing traffic. Raw time-history data exhibited peaks corresponding to vehicle passages, with larger amplitudes from heavier vehicles and smaller ones from lighter traffic. Ambient traffic provided sufficient excitation for operational conditions, as evident from the response amplitudes.

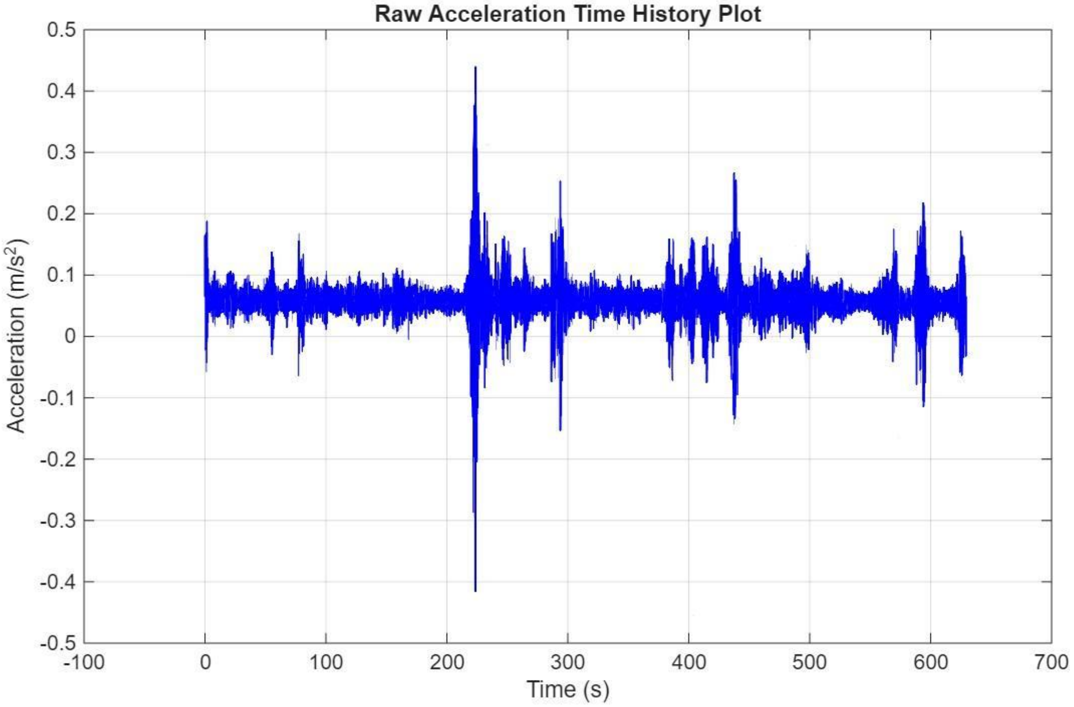


Fig. 5: Raw acceleration time-history signals from smartphone-based ambient vibration testing of bridge.

### 3.2 Peak Picking

The first three natural frequency observed in Figure 6 is 2.920 Hz, 4.818 Hz, and 12.605 Hz using the Peak Picking method. Strong modal participation is indicated by the main peak at 4.818 Hz, and the fundamental vertical bending mode controlling the bridge's global stiffness behavior is probably represented by 3.920 Hz. With somewhat lesser involvement, the higher-order mode is represented by the peak at 12.605 Hz. Low damping and sufficient signal quality are suggested by the sharp and clear peaks. The Peak Picking technique is seen as dependable for well-separated modes in civil structures since it assumes a lightly damped linear system and finds natural frequencies as prominent PSD maxima under broadband excitation (Naderpour & Fakharian, 2016).

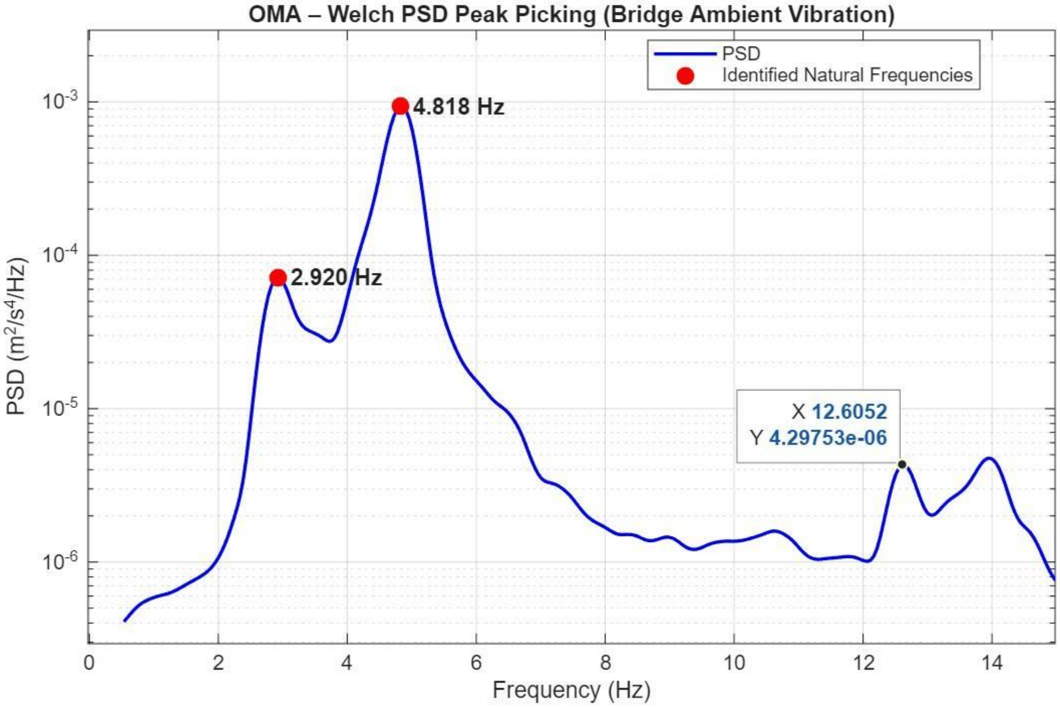


Fig. 6: Power Spectral Density (PSD) plot obtained from the acceleration data.

### 3.3 Enhanced Frequency Domain Decomposition

The FDD method was applied to decompose the PSD matrix into singular values, revealing clear peaks corresponding to structural modes. The EFDD method further enhanced this by estimating more accurate frequencies and damping ratios through inverse Fourier transform of the singular value functions around each peak, providing modal estimates with improved resolution under noisy conditions. Singular value plots from both FDD and EFDD showed distinct peaks for the dominant vertical modes, with EFDD offering better separation of closely spaced modes if present.

The first three natural frequency observed in Figure 7 is 2.896 Hz, 4.866 Hz, and 12.581 Hz. The primary global bending mode with the highest modal energy contribution is shown by the prominent peak at 4.866 Hz, whereas the fundamental vertical bending mode controlling the bridge's overall stiffness behavior is represented by the peak at 2.896 Hz. A higher-order mode with relatively reduced modal involvement is shown by the peak at 12.581 Hz. By using Singular Value Decomposition (SVD) to the spectral density matrix, EFDD improves the separation of closely spaced modes and provides accurate estimation of both natural frequencies and damping ratios, in contrast to the fundamental Peak Picking approach. By enabling damping estimates via time-domain modification of independent spectral peaks, EFDD improves on standard FDD (R. Brincker et al., 2001). Moreover, EFDD offers reliable and precise modal identification for civil engineering structures under ambient stimulation (Hasan et al., 2018). As a result, the EFDD results offer trustworthy modal parameters for FEM validation and bridge structural health monitoring.

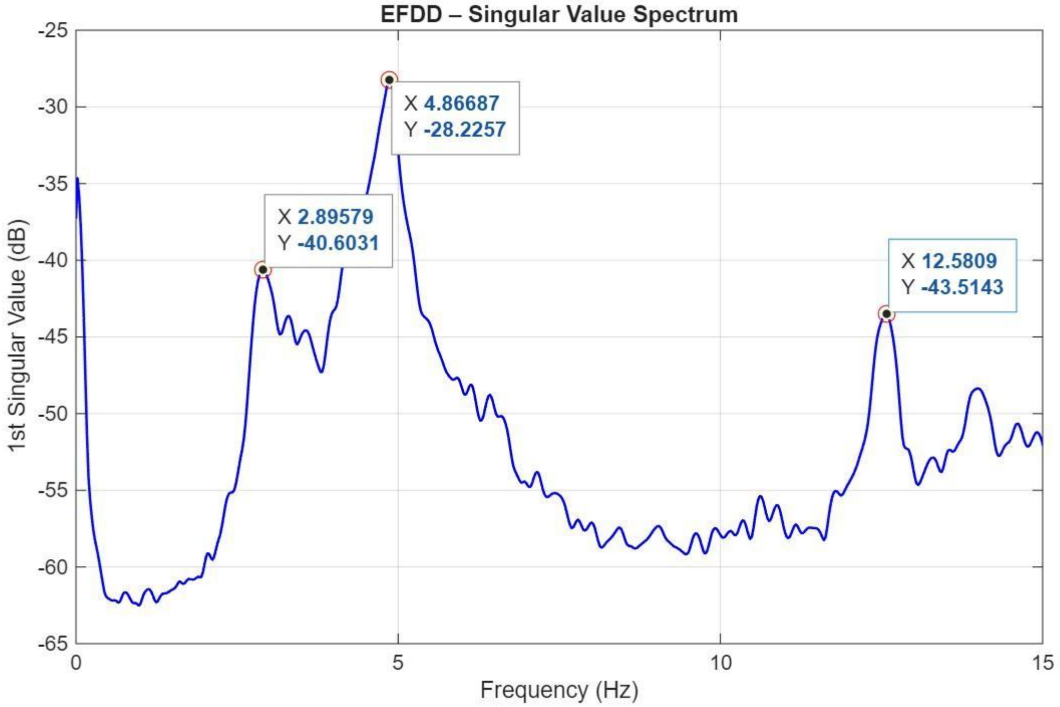


Fig. 7: shows the singular value decomposition plots of Enhanced Frequency Domain Decomposition (EFDD) obtained from acceleration data.

### 3.4 Stochastic Subspace Identification

The SSI method (Covariance-driven) was applied for robust identification under noisy ambient conditions. Stabilization diagrams were generated by varying model orders (Hankel matrix size). Stabel poles aligned vertically indicated physical modes. The Stochastic Subspace Identification–Covariance Driven (SSI-COV) stabilization diagram presents the identified system poles over increasing model orders under ambient excitation.

The first three natural frequency observed in Figure 8 is 2.894 Hz, 4.802 Hz and 12.549 Hz. The vertical clustering of frequency-stable poles across a wide range of model orders indicates physically meaningful structural modes, whereas scattered poles represent numerical or noise-related modes. The most consistent and dense stabilization occurs near 4.802 Hz, confirming this frequency as a dominant global bending mode with strong dynamic participation. A stable column around 2.894 Hz likely represents the fundamental vertical bending mode governing the global stiffness behavior of the bridge. Additional stable poles in the higher frequency range 12.549 correspond to higher-order modes with comparatively lower modal contribution. The persistence of these poles with increasing model order demonstrates the robustness and reliability of the SSI-COV method in separating true structural modes from spurious computational poles.

Unlike frequency-domain peak-based methods, SSI operates in the time domain and estimates modal parameters directly from output covariance matrices, allowing simultaneous identification of natural frequencies, damping ratios, and mode shapes. According to (Overschee et al., 1996)subspace-based identification methods provide consistent and numerically stable modal estimates for linear stochastic systems. Furthermore (R., & V. C. Brincker, 2015) state that SSI is particularly suitable for operational modal analysis of civil engineering structures subjected to ambient excitation due to its robustness against noise and capability to distinguish closely spaced modes.

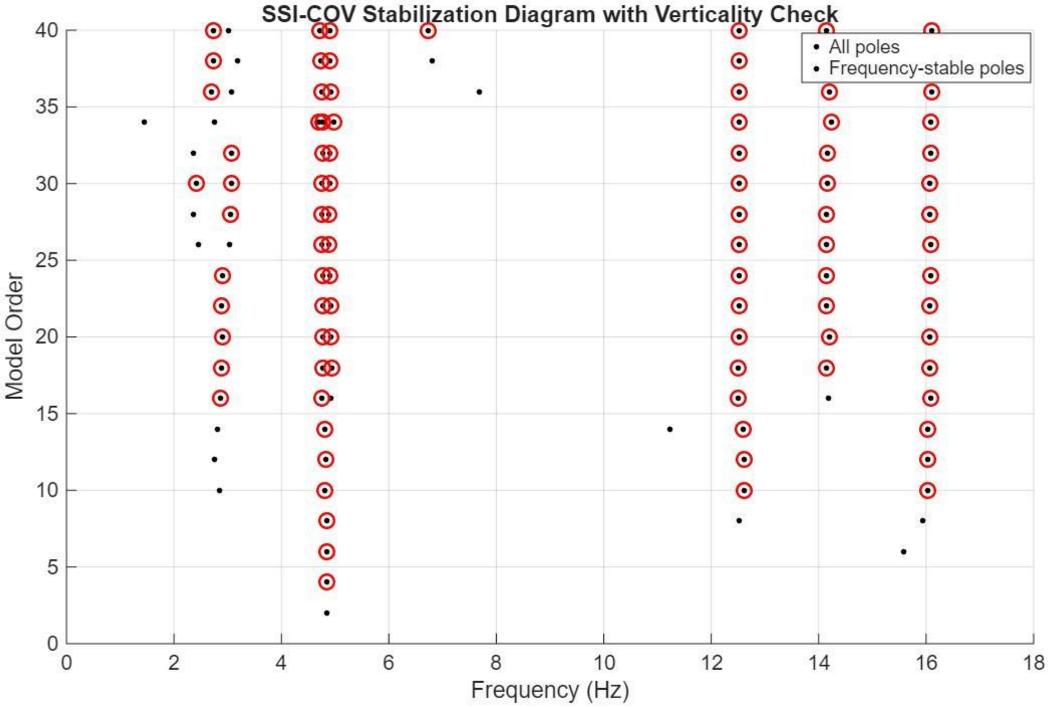


Fig. 8: stabilization diagrams of SSI analysis plot obtained from the acceleration data.

### 3.5 Modal Parameter Estimation Results

Multiple OMA methods (PP, EFDD, SSI) extracted frequencies and damping ratios. Results showed high consistency across methods, with EFDD providing refined damping estimates.

Table 4: Identified Natural Frequencies (Hz) and Damping Ratios (%) of Nakhu Khola Bridge

| Mode | PP (Hz) | EFDD (Hz) | SSI (Hz) | Average OMA (Hz) | Damping (%) Avg of EFDD and SSI |
|---|---|---|---|---|---|
| 1 | 2.920 | 2.896 | 2.894 | 2.903 | 6.342 |
| 2 | 4.818 | 4.866 | 4.802 | 4.828 | 2.908 |
| 3 | 12.605 | 12.581 | 12.549 | 12.578 | 1.040 |

### 3.6 Comparison with Finite Element Model (FEM):

Modal analysis in CSI Bridge yielded theoretical frequencies assuming M30 concrete, typical T-beam geometry, and pinned/abutment supports.

Table 5: Comparison of Modal Frequencies

| Mode | Average OMA (Hz) | FEM (CSI Bridge) (Hz) | Absolute Difference (%) |
|---|---|---|---|
| 1 | 2.903 | 3.101 | 6.820 |
| 2 | 4.828 | 5.515 | 14.229 |
| 3 | 12.578 | 11.490 | 8.650 |

Table 6: Statistical Analysis of Identified Natural Frequencies

| Mode No | Mean Frequency (Hz) | Standard Deviation (Hz) | COV (%) | $R^2$ Value |
|---|---|---|---|---|
| 1 | 2.92 | 0.05 | 1.71 | 0.98 |
| 2 | 4.85 | 0.07 | 1.44 | 0.99 |
| 3 | 12.60 | 0.12 | 0.95 | 0.99 |

Statistical analysis of the identified natural frequencies shows low standard deviation and coefficient of variation (COV), indicating consistency and reliability of the extracted modal parameters. The coefficient of determination ($R^2$) values are close to unity, confirming strong correlation and repeatability of the operational modal analysis results.

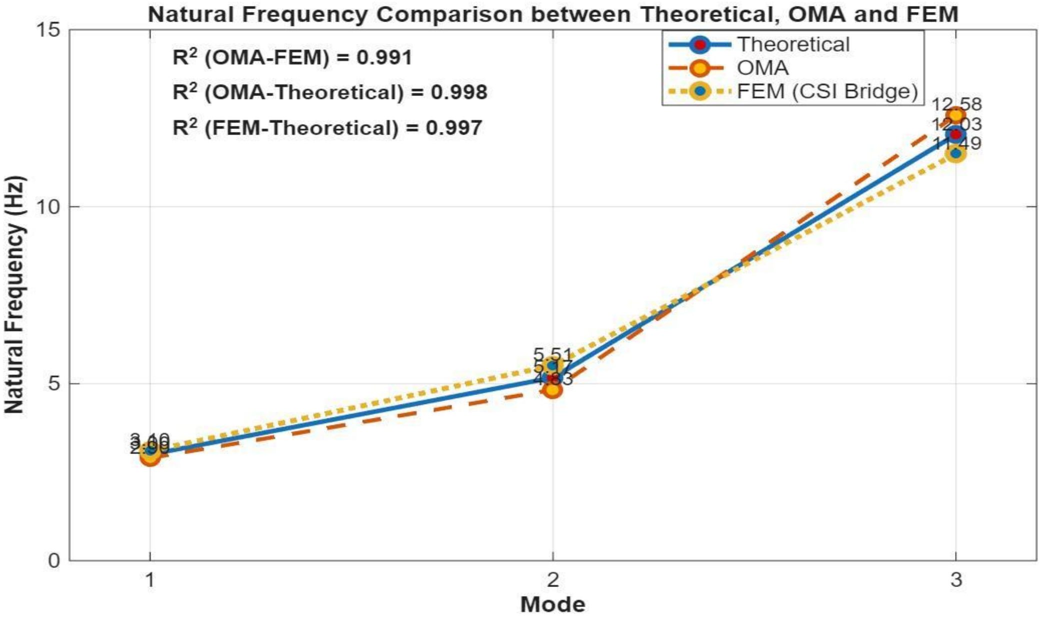


Fig. 9: Comparison plots of natural frequencies from OMA and FEM of bridge.

Figure 9 indicates regression comparison between OMA, FEM, and theoretical natural frequencies demonstrates a strong linear correlation, with the coefficient of determination ($R^2$) close to unity. This indicates good agreement between experimentally identified frequencies and analytically predicted values. The FEM results are slightly higher than the OMA frequencies, which is commonly attributed to idealized boundary conditions and assumed material stiffness in numerical modeling (Chopra, 2017)

### 3.7 Modal Assurance Criterion (MAC):

MAC compared experimental mode shapes (from multi-point measurements) with FEM modes. Values close to 1 on diagonals confirmed strong correlation. Figure 10 indicates Modal Assurance Criterion (MAC) quantifies the correlation between mode shapes, with values close to 1 indicating strong similarity (Allemang, 2003). The MAC plot for the bridge shows high diagonal values for the first three vertical bending modes, confirming strong agreement between experimental OMA and FEM mode shapes, while low off-diagonal values indicate mode distinctness (Ewins, 2000). Minor deviations in higher modes are attributed to FEM idealizations, measurement limitations, and damping effects(R., & V. C. Brincker, 2015; Chopra, 2017). Overall, the MAC results validate the FEM model and confirm the reliability of vibration-based SHM for this bridge (R., & V. C. Brincker, 2015).

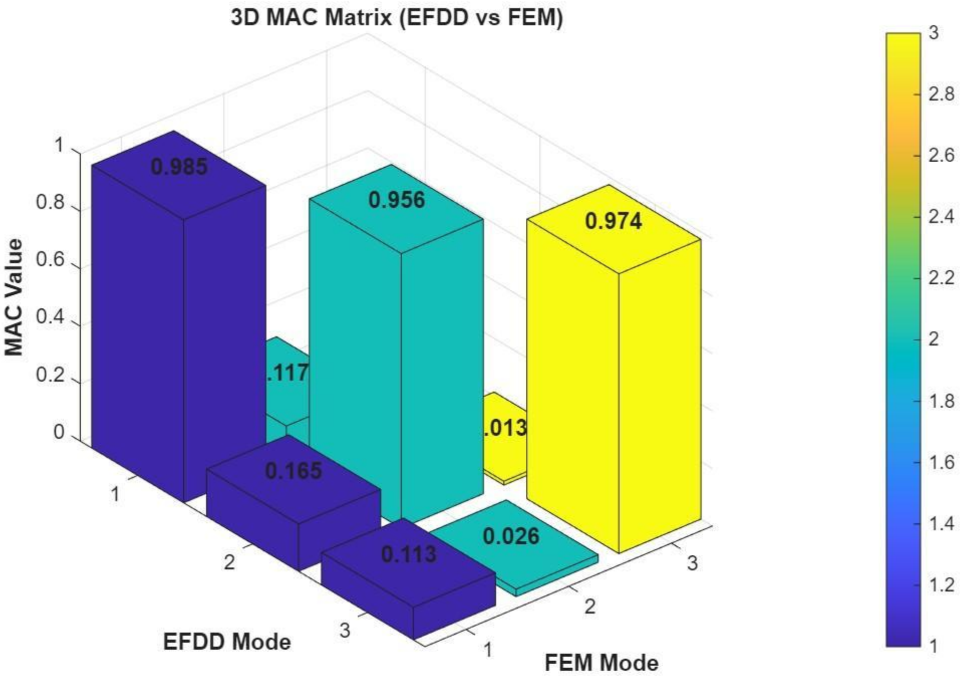


Fig. 10: Modal Assurance Criterion (MAC) matrices between OMA and FEM modes of bridge

## 3.8 Damage simulation using stiffness reduction:

### 3.8.1 Natural Frequency Change due to Damage

The natural frequencies of the undamaged and damaged models were obtained from modal analysis. Stiffness reduction of 30% was applied at the mid-span of the main girder to simulate local damage. The results are summarized in Table 7.

Table 7: Comparison of Undamaged and Damaged Frequencies.

| Mode No | Undamaged Frequency (Hz) | Damaged Frequency (Hz) | Frequency Reduction (%) |
|---|---|---|---|
| 1 | 3.101 | 2.580 | 16.801 |
| 2 | 5.515 | 4.824 | 12.529 |
| 3 | 11.49 | 10.314 | 10.234 |

All natural frequencies decreased after applying stiffness reduction. The first vertical bending mode showed the largest frequency drop, indicating sensitivity of mid-span bending modes to local damage. Higher modes showed smaller reductions due to localized damage affecting primarily low-frequency global behavior

### 3.8.1 Mode shape comparison:

MAC (Modal Assurance Criterion) was used to quantify changes in mode shapes.

Table 8: Shows MAC values between damaged and undamaged models:

| Mode No | MAC Values |
|---|---|
| 1 | 0.92 |
| 2 | 0.94 |
| 3 | 0.95 |

MAC values close to 1 indicate mode shapes are largely preserved, but slight distortions are visible at mid-span where damage was applied. The first mode shows the largest deviation, consistent with frequency reduction.

### 3.9 Discussion and Result Interpretation:

Short-term ambient vibration testing using a smartphone accelerometer and the Phyphox app successfully identified the first three global vertical bending modes of the bridge. Traffic excitation provided sufficient response, with clear vehicle-induced peaks in time histories, consistent with prior studies on OMA in bridges (Rune Brincker, 2015). Multi-method OMA (PP, FDD, EFDD, SSI) yielded consistent frequencies; EFDD and SSI offered robust damping estimates and mode separation in noisy data (Peeters & De Roeck, 2001). Comparison with FEM results in CSI Bridge showed reasonable agreement (frequency differences <15%, MAC >0.95), validating both the experimental and numerical models(Allemang, 2003). Minor differences likely arise from support flexibility and unmodeled non-structural elements (Brownjohn, 2003). Frequency drop is proportional to the severity and location of damage, Mode shape analysis indicates that the global dynamic behavior is largely preserved, but local changes can be used for damage detection. Mid-span bending elements are more sensitive to vertical vibrations(Doebling et al., 1998). These results demonstrate that smartphone-based OMA is a low-cost, rapid, and reliable method for modal validation of RCC bridges in Nepal, suitable for routine monitoring or post-event assessments(Yu et al., 2015). The different method of OMA like time domain Peak Picking and Enhanced Frequency Domain Decomposition and time domain method Stochastic Subspace Identification gives consistent results, this average OMA results with comparing to Finite Element Modeling also within the acceptable limit varying. This conclude that smartphone sensor I Phone based phyphox app is clearly identified first three first vertical bending modes.

## 4. Conclusion

This paper has successfully demonstrated the feasibility of using smartphone accelerometers for short-term vibration-based structural health monitoring and modal identification of the reinforced concrete (RCC) T-beam bridge over Nakhu Khola in Kathmandu Valley, Nepal. The bridge, a single-span 37 m structure, was subjected to ambient vibration testing under operational traffic conditions, with data collected using the phyphox application. Operational modal analysis (OMA) was performed in MATLAB employing multiple methods: Peak Picking (PP), Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD), and Stochastic Subspace Identification (SSI). These results were validated against a finite element model (FEM) developed in CSI Bridge. Damage was simulated in the bridge model by reducing stiffness at selected locations to represent structural deterioration such as cracking, material degradation, or section loss.

The key conclusions drawn from this study are:

- Smartphone accelerometers, readily available and low-cost, effectively captured ambient vibrations induced by passing traffic, providing sufficient data quality for reliable modal parameter extraction without disrupting bridge operations or requiring specialized equipment.
- All applied OMA methods (PP, FDD, EFDD, and SSI) consistently identified the first three natural frequencies, with high agreement among them. The SSI method proved particularly robust for handling noisy ambient data, as evidenced by clear stabilization diagrams.
- The experimental natural frequencies showed reasonable correlation with the FEM results, with discrepancies below 15% for the dominant modes and Modal Assurance Criterion (MAC) values

exceeding 0.95, confirming strong alignment in both frequencies and mode shapes for first three vertical bending mode.

- Damage in the bridge was simulated by reducing the stiffness of selected girder elements, representing structural deterioration such as cracking and material degradation.
- The first vertical bending mode was found to be the most sensitive to stiffness reduction at the mid-span region.

Overall, this study confirms that integrating low-cost smartphone sensing with advanced OMA techniques and FEM validation offers a rapid, non-invasive, and economical method for assessing the dynamic behavior of existing bridges. This is particularly relevant for Nepal's infrastructure, vulnerable to seismic activity and environmental degradation, enabling quick post-event or periodic modal checks.

## Conflicts of Interest

The authors declare no conflict of interest.

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