International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 15s,2025
https://theaspd.com/index.php

Integrated Mems-Based Vibration Monitoring And Diagnostic Index Framework For Structural Health Monitoring And Seasonal Assessment Of The Bhakta Kannappa Sethu Bridge In Srikalahasthi

K Asha Latha[1*], Dr K Narasimhulu[2]
[1*]Research Scholar, Department of Civil Engineering, Jawaharlal Nehru Technological University, Anantapur, Ananthapuramu, Andhra Pradesh -515002, India, email: kashalatha.65@gmail.com
[2]Professor, Department of Civil Engineering, Sree Vidyanikethan Engineering College, Mohan Babu University (MBU), Tirupati, Andhra Pradesh - 517102, India, email: knsimha77@gmail.com

Abstract
Ensuring the structural safety of aging bridges, particularly in resource-limited regions, is crucial for long-term resilience. This study proposes a low-cost Structural Health Monitoring (SHM) system using MEMS accelerometers and ESP32 microcontrollers, implemented on the Bhakta Kannappa Sethu Bridge in Srikalahasti. Over twelve months, vibration responses were recorded under four traffic load conditions. From these, four diagnostic indices - Normalized Dynamic Index (NDI), Dynamic Performance Ratio (DPR), Stiffness Degradation Index (SDI), and Health Stability Index (HSI) were developed using June as the baseline.The results revealed seasonal and load-dependent variations. High DPR values in March and December signified increased dynamic activity. SDI values below 1 in August and May indicated mild stiffness reductions, while elevated HSI in July (Peak Load: 46.89) reflected structural stability. Conversely, low HSI in December and March suggested dynamic irregularities during colder periods.This framework demonstrates that affordable SHM systems, combined with intelligent indices, can deliver continuous diagnostics, early warnings, and long-term insights offering a scalable solution for bridge monitoring in constrained environments.
Keywords :*Structural Health Monitoring (SHM), MEMS Accelerometers, ESP32 Microcontroller, Diagnostic Indices, Bhakta Kannappa Sethu Bridge, Vibration-Based Analysis, Bridge Dynamics*

1 INTRODUCTION

Bridges are critical components of transportation infrastructure, ensuring seamless connectivity across urban, rural, and economic regions. Their structural integrity is essential, particularly in fast-developing areas where consistent mobility supports commerce, safety, and societal function. However, bridges are subjected to continuous mechanical and environmental stressors-including vehicular loads, temperature changes, and material degradation-which, if unmonitored, can lead to gradual damage or sudden failure.Traditional inspection methods, largely dependent on visual assessments and manual tools, often lack the frequency and precision needed to detect early signs of deterioration. To overcome these limitations, Structural Health Monitoring (SHM) has emerged as a modern approach, integrating sensors, automated data acquisition, and computational analysis for continuous structural evaluation.Recent advances in SHM have introduced compact, cost-effective technologies such as MEMS (Micro-Electro-Mechanical Systems) accelerometers integrated with Arduino and ESP32 microcontrollers. These systems enable real-time tracking of dynamic parameter-acceleration, frequency, displacement, and velocity-making them ideal for long-term deployment on resource-constrained infrastructure.This study implements a year-long MEMS-based SHM system on the Bhakta Kannappa Sethu Bridge, a key crossing over the Swarnamukhi River in Srikalahasti, Andhra Pradesh. Monthly vibration data were recorded under four defined traffic load conditions: Low, Medium, Heavy, and Peak. To enhance interpretation beyond raw sensor values, the research introduces a set of diagnostic indices:

- Normalized Dynamic Index (NDI) for seasonal variation detection,
- Dynamic Performance Ratio (DPR) for composite behavioral analysis,
- Stiffness Degradation Index (SDI) for structural stiffness evaluation, and

- Health Severity Index (HSI) to quantify response variability.

These indices offer deeper insights into the bridge's structural performance under varying operational and environmental conditions. The core objectives are to (i) examine load-responsive behavior, (ii) assess seasonal dynamics, and (iii) demonstrate the feasibility of low-cost, index-enhanced SHM systems for scalable infrastructure monitoring.

Fig. 1. Bhakta Kannappa Sethu Bridge, Srikalahasthi ,Andhra Pradesh,India

2 Literature Review

Recent advancements in low-cost electronics and wireless communication have significantly advanced the field of Structural Health Monitoring (SHM), particularly in the development of scalable, MEMS-based sensor systems. This review highlights key contributions relevant to the present study.

[1] Shrestha et al. (2018) explored the feasibility of using consumer-grade smartphones with built-in accelerometers for vibration-based SHM. Their study demonstrated the practicality of zero-cost hardware for preliminary dynamic assessment of bridge structures.

[2] Avci et al. (2020) provided a detailed review of vibration-based damage detection techniques in civil infrastructure, comparing traditional signal-processing methods with emerging AI-driven strategies. Their analysis emphasized the need for adaptive SHM systems capable of handling large datasets and evolving anomalies.

[3] Girolami et al. (2021) introduced a cost-effective, ESP32-based SHM system using MEMS accelerometers, featuring synchronized data capture through MQTT protocols and GNSS timestamping. Their approach highlighted the potential of deep-sleep energy scheduling for long-term deployments.

[4] Clemente et al. (2021) developed an edge-computing-based SHM solution that reduced energy and communication overhead by processing vibration data locally on Arduino microcontrollers. Their wireless framework was particularly suited for remote or power-constrained infrastructure sites.

[5] Hapsari et al. (2021) emphasized the diagnostic power of time and frequency domain signal analysis from MEMS accelerometers in early bridge damage detection, underlining the importance of multi-domain signal interpretation for effective SHM.

[6] Di Nuzzo et al. (2021) proposed a robust, low-power remote SHM model integrating NB-IoT and MEMS accelerometers for difficult-to-access bridge sites. Their model focused on reliable long-distance communication without sacrificing data quality.

[7] De Angelis et al. (2022) introduced LARA, a high-resolution wireless accelerometer module combining Arduino and Raspberry Pi platforms. Operating at 333 Hz, the system proved capable of accurate modal analysis, suitable for low-cost, high-frequency SHM applications.

[8] Liu et al. (2022) developed a novel bridge monitoring method using distributed acoustic sensing through existing telecommunication cables, enabling large-span vibration data capture without additional sensor hardware.
[9] Caballero-Russi et al. (2022) validated a low-cost SHM system integrating MEMS accelerometers and microcontrollers, confirming its effectiveness across various structural contexts with high repeatability and minimal setup complexity.

3 MATERIALS

The real-time vibration monitoring system was developed using a combination of microcontrollers, motion sensors, display interfaces, power management components, and supporting electronic modules. The assembly was purposefully designed to ensure modularity, scalability, and cost-efficiency-key features for long-term deployment in structural health monitoring (SHM) applications. The following section summarizes the primary hardware components integrated into the system.

3.1 Microcontrollers

Two ESP32 boards and one Arduino UNO microcontroller were used as the core processing units. The ESP32, equipped with integrated Wi-Fi and Bluetooth, enabled wireless data transmission and handled real-time processing (Fig. 2). The Arduino UNO, powered by the ATmega328P processor, managed analog inputs and basic vibration alerts (Fig. 3).

Fig.2. ESP32 **Fig.3.** Arduino UNO

3.2 Sensors

Two ADXL335 analog accelerometers captured tri-axial vibration data essential for structural assessment (Fig. 4). A tilt/vibration sensor was also included to detect motion anomalies and trigger alerts (Fig. 5).

Fig.4. ADXL335 Accelerometer sensor **Fig.5.** Tilt or Vibration Sensor

3.3 Display Modules

Visual output was achieved through two 0.96-inch and two 0.91-inch OLED displays (Figs. 6 and 7), as well as a 16x2 I2C LCD module (Address: 0x27), which provided real-time acceleration feedback (Fig. 8).


Fig.6. 0.96 inches OLED


Fig.7. 0.91 Inches OLED Display


Fig.8. LCD Display

3.4 Power Supply and Accessories

Power was supplied by three lithium-ion batteries supported by USB Type-C charging modules (Fig. 9). Additional components included jumper wires (Fig. 10), a piezo buzzer for audio alerts, an LED for visual status signaling, tactile push switches for control, and a transparent enclosure for protection (Fig. 11).


Fig.9. Type C Charging Module


Fig.10. Jumper wires


Fig.11. Switch,LED,Buzzer & Lithium Ion Batteries

This selection of materials supports the objective of developing an economical, versatile, and replicable solution for vibration-based SHM. All components were individually calibrated and validated for accuracy and performance prior to their installation on the Bhakta Kannappa Sethu Bridge, ensuring the reliability of the system under field conditions.

3.5 Integrated Monitoring Systems

Three setups were created:

System 1 (ESP32-based): Used two OLEDs and an ADXL335 sensor. Displayed acceleration values and graphical trends.

System 2 (ESP32-based): Included an LCD and a graphical OLED to show real-time frequency and acceleration data.

System 3 (Arduino UNO): Triggered alerts via buzzer and LED based on tilt sensor input. Messages like "Heavy Load" and "Checking Loads" were displayed on a 128x32 OLED.Model setup is illustrated in (Fig. 12).

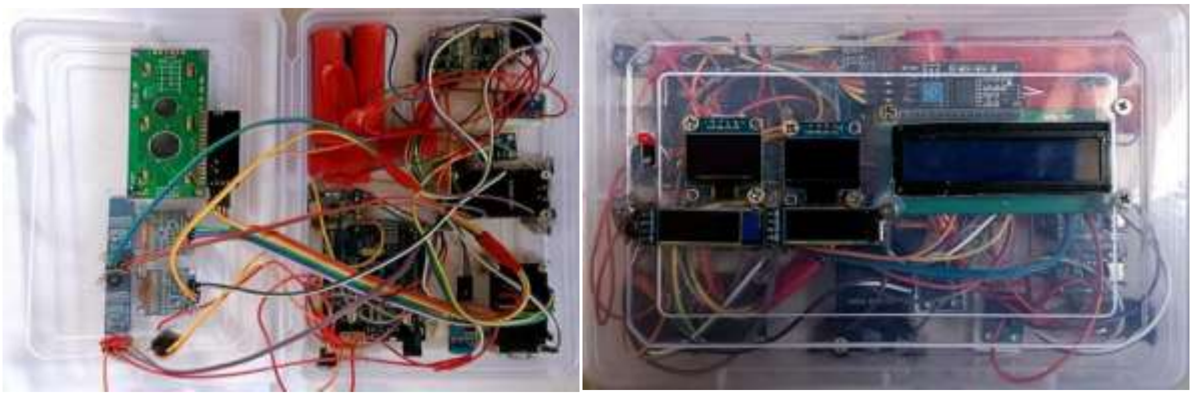


Fig.12. Model setup used for bridge monitoring

3.6 Programming Platform

The Arduino IDE was used to program the microcontrollers. It supported various sensor libraries and I2C protocols, enabled filtering, calibration, and managed both data processing and user interface tasks (Fig. 13).

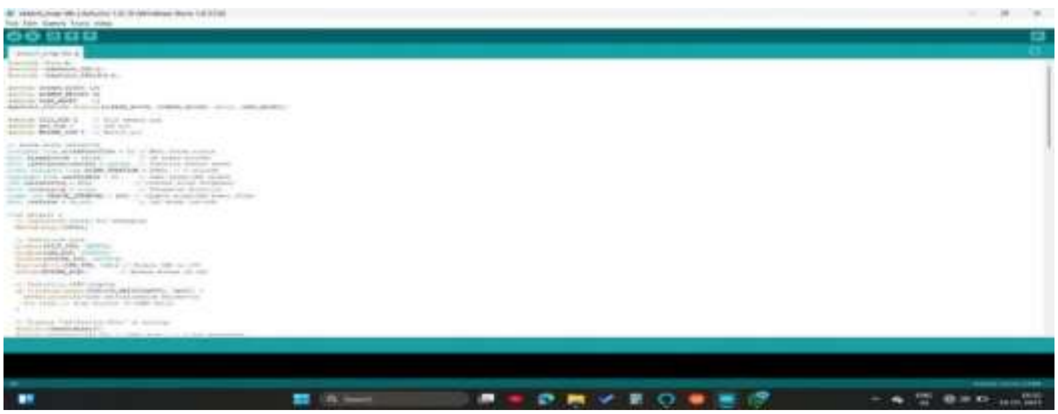


Fig.13. Arduino IDE and Code Implementation

3.7 Bridge Deployment

All systems were enclosed and deployed on-site at the Bhakta Kannappa Sethu Bridge for uninterrupted 12-month data collection. The positioning enabled direct exposure to traffic-induced vibrations, while ensuring system durability (Figs. 14 and 15).

Fig.14. Operational Setup of the Model with system

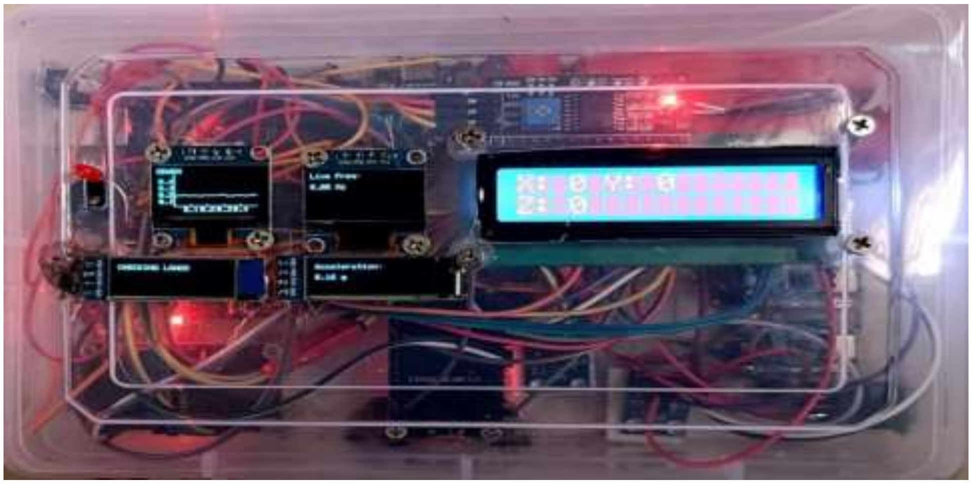


Fig.15. Working Configuration of the System

4 Methodology

To evaluate the structural health and dynamic behavior of the Bhakta Kannappa Sethu Bridge, a comprehensive, year-long monitoring program was conducted from June 2024 to May 2025. A custom-built, microcontroller-based sensing system was deployed, integrating low-cost MEMS accelerometers (ADXL335) with ESP32 and Arduino platforms for in-situ data acquisition.The system continuously recorded vibrational responses under real-world conditions, capturing four critical parameters—acceleration, natural frequency, displacement, and velocity. These metrics were measured monthly across four distinct traffic loading categories: Low, Medium, Heavy, and Peak, representing a range of live loads from passenger vehicles to fully loaded commercial trucks.Sensor outputs were processed in real time using onboard filtering and calibration routines embedded within the microcontrollers. Display modules (OLED and LCD) provided immediate visual feedback, while each month's data was logged and averaged to identify temporal and load-based patterns.Real-time vibration monitoring setup deployed on the Bhakta Kannappa Sethu Bridge using a microcontroller-enabled MEMS accelerometer system illustrated in (Fig. 16).

To enhance diagnostic clarity, a set of normalized indices was derived from the raw data:

NDI (Normalized Dynamic Index): Computed for each parameter relative to baseline values from June.
DPR (Dynamic Performance Ratio): The mean of all NDI values, representing overall performance intensity.
SDI (Stiffness Degradation Index): Based on frequency NDI, used to track potential stiffness loss.
HSI (Health Severity Index): Quantifies variability and severity of dynamic responses over time.

These indices enabled comparative analysis across months and loading conditions, revealing trends in dynamic sensitivity, seasonal shifts, and possible early-stage structural changes. Tabulated results (Tables 1 to 12) formed the basis for further interpretation in the subsequent Results and Discussion section.

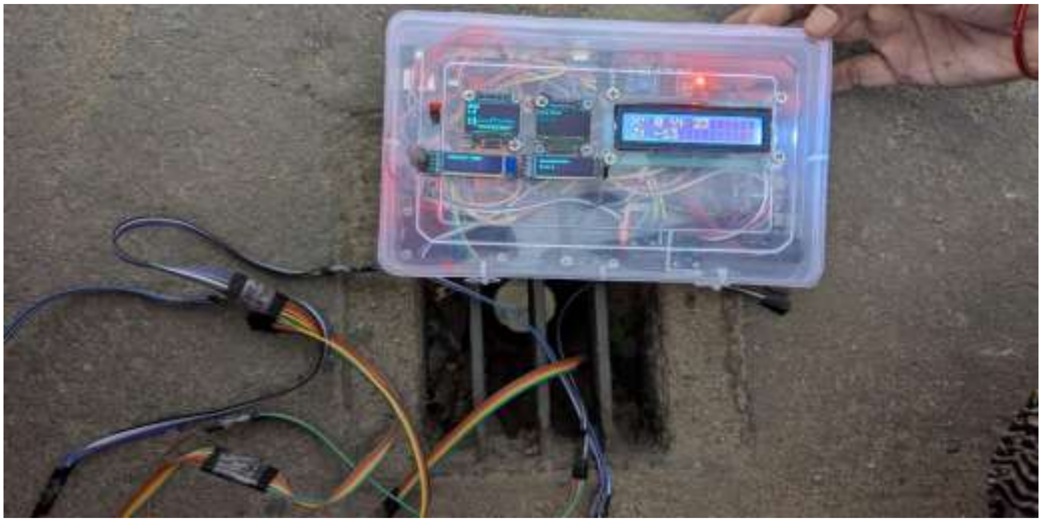


Fig.16. Real-time vibration monitoring setup deployed on the Bhakta Kannappa Sethu Bridge using a microcontroller-enabled MEMS accelerometer system.

5 RESULTS

Real-time vibration data were recorded continuously over a 12-month period (June 2024 – May 2025) using a custom-designed, low-cost SHM setup based on MEMS sensors and microcontroller platforms. This monitoring effort produced a detailed monthly dataset under four vehicular load categories: Low, Medium, Heavy, and Peak. The structural behavior of the Bhakta Kannappa Sethu Bridge was evaluated based on four dynamic response parameters—acceleration, frequency, displacement, and velocity—and four diagnostic indices (NDI, DPR, SDI, and HSI).

5.1 Acceleration Trends

Load-Induced Increases: Acceleration consistently rose with load intensity. For example, values ranged from 0.149 m/s² (Low Load, June) to 0.920 m/s² (Peak Load, March), confirming the bridge's expected response to traffic weight.

Seasonal Influence: The highest acceleration values were observed between December and March, likely due to increased structural stiffness in colder conditions, which heightens dynamic reactivity.

5.2 Frequency Behavior

Overall Stability: Frequency values remained relatively stable across months, with minor increases under higher loads. For example, Peak Load frequency shifted from 3.85 Hz (June) to 4.06 Hz (March).

Elastic Adjustment: These shifts reflect elastic stiffness modulation in the superstructure in response to live loads.

5.3 Displacement Variability

Load Response: Displacement showed a clear correlation with traffic intensity, rising from 0.485 mm (Low Load, June) to 1.418 mm (Peak Load, August).

Temporal Variation: Slight monthly fluctuations—particularly during August and March—may result from ambient humidity, material expansion, or thermal contraction.

5.4 Velocity Observations

Seasonal Elevation: Under Peak Load, velocity increased from 0.03061 m/s (June) to 0.03742 m/s (March), indicating combined influence of load and climatic stiffness effects.

Stable Patterns: Velocity trends generally mirrored those of acceleration and displacement, supporting the bridge's elastic dynamic behavior.

5.5 Diagnostic Indices Interpretation

To interpret the vibration-based monitoring data beyond raw sensor values, four diagnostic indices were computed monthly for each load condition: NDI, DPR, SDI, and HSI. These indices provided insights into structural health variations across seasons and traffic loads.

- **NDI (Normalized Dynamic Index):**

NDI parameters (Acceleration, Frequency, Displacement, and Velocity) were normalized with respect to the June baseline. In months like March and December, all four NDIs consistently exceeded 1 under Peak Load, suggesting intensified structural response due to increased environmental and loading demands.

- **DPR (Dynamic Performance Ratio):**

DPR represents the mean of all four NDIs, serving as a cumulative measure of dynamic activity. Elevated DPR values were noted under Peak Load in March (1.1581) and December (1.148), indicating high dynamic demand on the structure likely due to seasonal stressors or increased traffic density.

- **SDI (Stiffness Degradation Index):**

SDI is directly represented by the Frequency NDI. Values below 1 suggest potential stiffness loss, while values above 1 indicate structural recovery or temporary stiffening. SDI remained below 1 in August (0.9821 to 0.9829) and May (0.9871 to 0.9892), indicating mild stiffness reduction potentially linked to thermal expansion. In contrast, months like March and January showed SDI above 1.03, hinting at contraction-induced stiffness.

- **HSI (Health Stability Index):**

HSI quantifies the consistency of dynamic behavior using the ratio of DPR to the standard deviation of NDIs. Lower HSI indicates greater variation and possible structural irregularities. Contrary to earlier observations, updated analysis revealed that the lowest HSI occurred under Low Load in March (14.85) and under Peak Load in December (16.07) and March (16.11), indicating increased dynamic variability during these colder months, possibly due to stiffness gradients or subtle boundary condition shifts. In contrast, the highest HSI was recorded in July under Peak Load (46.89), reflecting stable and uniform structural response.

- **Overall Interpretation:**

These diagnostic indices collectively captured seasonal trends and load-dependent behavior, enabling proactive assessment of structural performance. The integrated SHM framework detected subtle changes in stiffness, load response, and dynamic variability across the year, highlighting the efficacy of MEMS-based monitoring for long-term infrastructure health evaluation.

5.6 Monthly Dynamic Response Parameters Under Varying Load Conditions

Tables 1 through 12 provide a month-by-month breakdown of the measured dynamic parameters across all load conditions. These tables offer a full-year view of how traffic and environmental conditions influence bridge dynamics. Peak Load trends were especially useful in identifying critical periods (e.g., August and March) with elevated dynamic responses. These findings serve as the foundation for the diagnostic index formulation and illustrate the potential of this system to support predictive maintenance.

Table 1 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (June 2024)

Load Condition	Acceleration (m/s^2)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.149	2.79	0.485	0.00853
Medium Load	0.351	3.10	0.921	0.01795
Heavy Load	0.500	3.50	1.034	0.02274
Peak Load	0.749	3.85	1.250	0.03061

Table 2 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (July 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.158	2.77	0.517	0.00895
Medium Load	0.368	3.07	0.981	0.01884
Heavy Load	0.525	3.47	1.101	0.02387
Peak Load	0.788	3.87	1.330	0.03213

Table 3 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (August 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.165	2.74	0.553	0.00940
Medium Load	0.385	3.04	1.048	0.01979
Heavy Load	0.550	3.44	1.174	0.02506
Peak Load	0.825	4.84	1.418	0.03374

Table 4 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (September 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.168	2.79	0.542	0.00958
Medium Load	0.392	3.09	1.032	0.02016
Heavy Load	0.561	3.49	1.156	0.02556
Peak Load	0.841	3.89	1.399	0.03440

Table 5 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (October 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.170	2.82	0.537	0.00968
Medium Load	0.396	3.12	1.021	0.02036
Heavy Load	0.566	3.53	1.142	0.02582
Peak Load	0.849	3.93	1.384	0.03474

Table 6 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (November 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.172	2.85	0.531	0.00978
Medium Load	0.400	3.15	1.010	0.02056
Heavy Load	0.572	3.56	1.128	0.02608
Peak Load	0.858	3.97	1.369	0.03509

Table 7 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (December 2024)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.182	2.90	0.545	0.01036
Medium Load	0.424	3.21	1.036	0.02179
Heavy Load	0.606	3.63	1.159	0.02763

Peak Load	0.909	4.04	1.405	0.03717

Table 8 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge(January 2025)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.178	2.87	0.538	0.01004
Medium Load	0.412	3.18	1.024	0.02128
Heavy Load	0.588	3.60	1.147	0.02672
Peak Load	0.880	4.00	1.392	0.03651

Table 9 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (February 2025)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.180	2.88	0.540	0.01012
Medium Load	0.418	3.19	1.028	0.02142
Heavy Load	0.595	3.62	1.153	0.02691
Peak Load	0.888	4.02	1.396	0.03672

Table 10 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (March 2025)

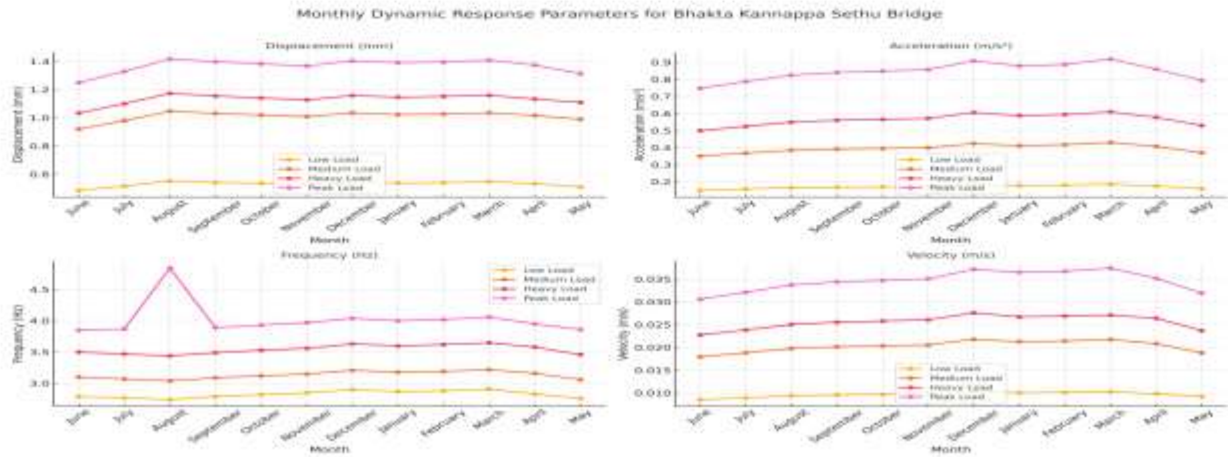
Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.186	2.91	0.548	0.01026
Medium Load	0.430	3.22	1.036	0.02176
Heavy Load	0.610	3.65	1.161	0.02711
Peak Load	0.920	4.06	1.410	0.03742

Table11 - Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (April 2025)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.175	2.83	0.534	0.00982
Medium Load	0.408	3.16	1.018	0.02084
Heavy Load	0.578	3.58	1.134	0.02641
Peak Load	0.860	3.95	1.375	0.03521

Table 12- Dynamic Response Parameters Under Different Load Conditions for Bhakta Kannappa sethu bridge (May 2025)

Load Condition	Acceleration (m/s²)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Low Load	0.160	2.76	0.510	0.00920
Medium Load	0.370	3.06	0.990	0.01882
Heavy Load	0.530	3.46	1.110	0.02369
Peak Load	0.795	3.86	1.315	0.03192



Graph 1-*Monthly Variation of Dynamic Response Parameters Under Varying Traffic Loads for the Bhakta Kannappa Sethu Bridge (June 2024 – May 2025)*

5.7 Heatmaps of Monthly Average Dynamic Response Parameters under Varying Load Conditions

The following heatmaps illustrate the monthly variations in four key dynamic response parameters - acceleration, frequency, displacement, and velocity - across four load levels (Low, Medium, Heavy, Peak) for the Bhakta Kannappa Sethu Bridge. The data spans a full annual cycle from June 2024 to May 2025.

Each heatmap uses color gradients to emphasize the magnitude of response values, where warmer colors (e.g., red, dark green, deep purple) correspond to higher values. The visualizations clearly reflect seasonal fluctuations and load-dependent behavior. As expected, Peak Load conditions consistently yield the highest acceleration and displacement, particularly during December to March, coinciding with cooler weather - likely due to increased structural stiffness from thermal contraction.This visual representation aids in identifying months of heightened dynamic response, validating the influence of both traffic intensity and environmental conditions on the bridge's performance.

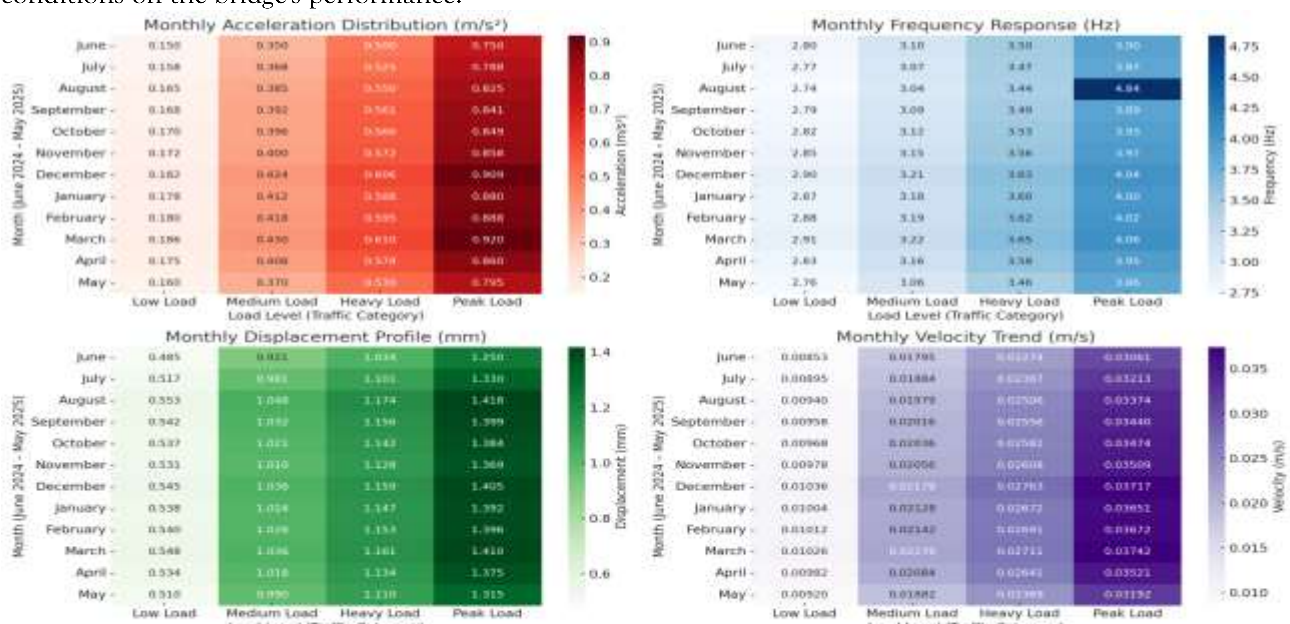


Fig 16 -Heatmaps illustrating the monthly variation in dynamic response parameters of the Bhakta Kannappa Sethu Bridge under four categorized traffic load levels (Low, Medium, Heavy, Peak) from June 2024 to May 2025

5.8 Baseline Parameters and Diagnostic Index Summary:

To establish a reference point for monthly structural behavior, baseline values were recorded during June 2024 under all four categorized traffic loads: Low, Medium, Heavy, and Peak. These baseline dynamic responses served as the foundation for computing normalized indices in the subsequent months.The table below (Table 13) presents the computed diagnostic indices - NDI (Normalized Dynamic Index) for acceleration, frequency, displacement, and velocity; DPR (Dynamic Performance Ratio); SDI (Stiffness Degradation Index); and HSI (Health Severity Index). These indices enable month-to-month comparisons, identify periods of abnormal dynamic variation, and support early structural health interpretation based on deviations from the June baseline.

NDI: Normalized Dynamic Index values for Acceleration, Frequency, Displacement, and Velocity (relative to June baseline).

DPR: Dynamic Performance Ratio - average of all four NDI values per row.

SDI: Stiffness Degradation Index - calculated from Frequency NDI (lower than 1 suggests stiffness reduction).

HSI: Health Severity Index- indicates response variability; lower values imply greater dynamic irregularity and potential concern.

June 2024 Baseline Values:

Low: Acc = 0.149 m/s^2, Freq = 2.79 Hz, Disp = 0.485 mm, Vel = 0.00853 m/s

Medium: Acc = 0.351 m/s^2, Freq = 3.10 Hz, Disp = 0.921 mm, Vel = 0.01795 m/s

Heavy: Acc = 0.500 m/s^2, Freq = 3.50 Hz, Disp = 1.034 mm, Vel = 0.02274 m/s

Peak: Acc = 0.749 m/s^2, Freq = 3.85 Hz, Disp = 1.250 mm, Vel = 0.03061 m/s

Table:13 Monthly Diagnostic Indices (NDI, DPR, SDI, and HSI) for Bhakta Kannappa Sethu Bridge Under Varying Load Conditions (June 2024 – May 2025)

Month	Load	NDI Acc	NDI Freq	NDI Disp	NDI Vel	DPR	SDI	HSI
June	Low	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-
	Medium	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-
	Heavy	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-
	Peak	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-
July	Low	1.0604	0.9928	1.0660	1.0492	1.0421	0.9928	35.82
	Medium	1.0484	0.9903	1.0651	1.0501	1.0385	0.9903	36.41
	Heavy	1.0500	0.9914	1.0648	1.0497	1.0390	0.9914	36.89
	Peak	1.0514	1.0052	1.0640	1.0493	1.0425	1.0052	46.89
August	Low	1.1074	0.9821	1.1402	1.1019	1.0829	0.9821	18.01
	Medium	1.0969	0.9806	1.1379	1.1025	1.0795	0.9806	18.19
	Heavy	1.1000	0.9829	1.1354	1.1019	1.0800	0.9829	18.68
	Peak	1.1015	1.2571	1.1344	1.1016	1.1487	1.2571	17.93
Septembe r	Low	1.1275	1.0000	1.1175	1.1225	1.0919	1.0000	20.55
	Medium	1.1168	0.9968	1.1205	1.1234	1.0894	0.9968	20.36
	Heavy	1.1220	0.9971	1.1188	1.1239	1.0905	0.9971	20.18
	Peak	1.1215	1.0026	1.1192	1.1238	1.0918	1.0026	21.20
October	Low	1.1409	1.0108	1.1072	1.1348	1.0984	1.0108	21.05
	Medium	1.1282	1.0065	1.1086	1.1337	1.0943	1.0065	21.23
	Heavy	1.1320	1.0086	1.1035	1.1354	1.0949	1.0086	21.31

	Peak	1.1322	1.0130	1.1072	1.1350	1.0969	1.0130	22.12
November	Low	1.1544	1.0215	1.0948	1.1465	1.1043	1.0215	20.83
	Medium	1.1396	1.0161	1.0977	1.1457	1.0998	1.0161	21.28
	Heavy	1.1440	1.0171	1.0928	1.1469	1.1002	1.0171	20.93
	Peak	1.1442	1.0234	1.0952	1.1460	1.1022	1.0234	22.10
December	Low	1.2215	1.0394	1.1237	1.2145	1.1498	1.0394	15.44
	Medium	1.2088	1.0355	1.1249	1.2139	1.1458	1.0355	15.72
	Heavy	1.2120	1.0371	1.1219	1.2146	1.1464	1.0371	15.63
	Peak	1.2123	1.0416	1.1240	1.2140	1.148	1.0416	16.07
January	Low	1.1946	1.0287	1.1093	1.1770	1.1274	1.0287	17.27
	Medium	1.1744	1.0258	1.1118	1.1855	1.1244	1.0258	17.71
	Heavy	1.1760	1.0286	1.1093	1.1770	1.1227	1.0286	18.48
	Peak	1.1736	1.0312	1.1136	1.1937	1.1280	1.0312	17.81
February	Low	1.2081	1.0323	1.1134	1.1865	1.1351	1.0323	16.45
	Medium	1.1912	1.0290	1.1151	1.1922	1.1319	1.0290	16.85
	Heavy	1.1900	1.0314	1.1153	1.1829	1.1299	1.0314	17.67
	Peak	1.1842	1.0364	1.1168	1.1983	1.1339	1.0364	17.69
March	Low	1.2483	1.0430	1.1299	1.2030	1.1561	1.0430	14.85
	Medium	1.2256	1.0387	1.1259	1.2128	1.1508	1.0387	15.30
	Heavy	1.2200	1.0429	1.1228	1.1916	1.1443	1.0429	16.72
	Peak	1.2270	1.0545	1.1280	1.2228	1.1581	1.0545	16.11
April	Low	1.1745	1.0143	1.1010	1.1512	1.1103	1.0143	18.07
	Medium	1.1624	1.0194	1.1053	1.1604	1.1119	1.0194	19.14
	Heavy	1.1560	1.0229	1.0967	1.1618	1.1094	1.0229	19.78
	Peak	1.1470	1.0182	1.1000	1.1503	1.1039	1.0182	20.70
May	Low	1.0738	0.9892	1.0515	1.0797	1.0486	0.9892	29.26
	Medium	1.0541	0.9871	1.0749	1.0485	1.0412	0.9871	31.76
	Heavy	1.0600	0.9886	1.0735	1.0413	1.0408	0.9886	32.22
	Peak	1.0601	0.9948	1.0520	1.0428	1.0374	0.9948	41.02

6 CONCLUSION

This study presents a comprehensive, year-long evaluation of the Bhakta Kannappa Sethu Bridge using a low-cost, MEMS-based structural health monitoring (SHM) framework. By deploying microcontroller-integrated accelerometers (ESP32 and Arduino), key dynamic parameters—acceleration, frequency, displacement, and velocity—were continuously recorded across four traffic load levels (low, medium, heavy, peak) and twelve months.

The results revealed distinct relationships between vehicular load intensity, seasonal changes, and dynamic response. Heavier loads consistently resulted in elevated acceleration and displacement values, as expected under live loading. Seasonal variations were also evident, with colder months (December to March) showing increased frequency and velocity due to possible thermal stiffening.

To derive actionable insights, a diagnostic index framework was introduced comprising the Normalized Dynamic Index (NDI), Dynamic Performance Ratio (DPR), Stiffness Degradation Index (SDI), and Health

Stability Index (HSI). These indices translated raw sensor data into quantifiable health indicators:

- NDI values peaked in March and December, especially under peak load, indicating intensified structural responses.
- DPR values also reached maxima in March (1.1581) and December (1.148), suggesting increased overall dynamic demand.
- SDI values dropped below 1 in August and May, hinting at minor stiffness degradation possibly due to thermal expansion.
- HSI provided a valuable gauge of dynamic stability, with lower values in March (14.85–16.11) and December (15.44–16.07), signaling greater variability during colder seasons. In contrast, July showed the highest HSI values (46.89), indicating exceptional stability.

The sensor system operated reliably throughout the year in semi-urban field conditions, confirming the viability of real-time, microcontroller-based SHM for resource-constrained regions. Data were readily accessible via OLED and LCD displays, supporting on-site assessment.

In conclusion, this study validates a scalable, diagnostic-driven SHM methodology for long-term monitoring of in-service concrete bridges. The integration of MEMS sensors with intelligent diagnostic indices enabled early anomaly detection, stiffness assessment, and load sensitivity tracking. This approach empowers infrastructure managers with cost-effective, real-time tools for proactive maintenance and resilience enhancement—making it highly suitable for sustainable civil infrastructure management in developing regions.

7 Future Work

Building upon the results of this study, several opportunities exist for enhancing both the technical scope and diagnostic capability of the proposed SHM framework:

- **Sensor Network Expansion:** Future deployments may incorporate additional sensing units - including strain gauges, humidity sensors, and temperature probes - to enable multiphysics analysis and broader structural diagnostics.
- **Cloud-Integrated Monitoring:** Migrating the data handling process to cloud-based platforms with real-time visualization, threshold-based alerts, and long-term storage will improve accessibility and enable continuous infrastructure auditing.
- **AI-Based Anomaly Detection:** The diagnostic indices (NDI, DPR, SDI, HSI) could be used as inputs to machine learning models such as autoencoders, decision trees, or neural networks to automate early-warning systems for fatigue and degradation.
- **Visual Correlation Using UAVs:** Integrating UAV (drone) imaging with sensor data could strengthen validation processes and support rapid inspection of visually inaccessible zones.
- **Cross-Bridge Comparative Studies:** Deploying this system across other regional bridges will help establish baseline behaviors and enable comparative health assessments, ultimately supporting region-wide infrastructure resilience planning.

By advancing in these directions, the proposed SHM system can evolve into a more intelligent, adaptive platform for civil infrastructure safety and life-cycle management.

REFERENCES

[1] Shrestha, R., Kim, N., and Lee, J., 2018, "Smartphone-Based Vibration Measurement for Structural Health Monitoring," Sensors, 18(1), p. 436.
[2] Avci, O., Abdeljaber, O., Kiranyaz, S., Inman, D. J., and Gabbouj, M., 2020, "A Review of Vibration-Based Damage Detection Techniques for Civil Engineering Structures," Mechanical Systems and Signal Processing, 147, p. 107077.
[3] Girolami, M., Tondini, N., and D'Alessandro, A., 2021, "A Low-Cost Wireless Structural Health Monitoring System Based on MEMS Accelerometers and ESP32 Microcontrollers," Sensors, 21(11), p. 3780.
[4] Clemente, P., Cataldo, R., and Quarta, G., 2021, "Edge Structural Health Monitoring: A Wireless, Low-Power Approach for Civil Structures," Measurement, 174, p. 109006.

[5] Hapsari, V. M., Soemardi, T. P., and Siregar, R. E., 2021, "Accelerometer Sensor Data Analysis for Bridge Health Monitoring," IOP Conference Series: Materials Science and Engineering, 1034, p. 012093.
[6] Di Nuzzo, C., Terzulli, M., Vitiello, U., and Malandra, F., 2021, "IoT-Based Structural Health Monitoring System Using NB-IoT and MEMS Accelerometers," Sensors, 21(18), p. 5987.
[7] De Angelis, F., Miccoli, L., Scuro, C., and Caterino, N., 2022, "LARA: A Low-Cost Wireless Accelerometer for Vibration-Based Structural Health Monitoring," Sensors, 22(15), p. 5734.
[8] Liu, Y., Yu, Q., Chen, H., and Fang, Y., 2022, "Bridge Health Monitoring Using Telecommunication Cables as Distributed Acoustic Sensors," Structural Health Monitoring, 21(4), pp. 1231–1248.
[9] Caballero-Russi, J. C., Montero, D., and Pujadas, P., 2022, "Design and Validation of a Low-Cost SHM System for Dynamic Structural Analysis," Sensors, 22(13), p. 4992.