Accelerometer-Based Dynamic Health Monitoring Of The Swarnamukhi River Bridge With Seasonal Vibration Evaluation

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ABSTRACT

Ensuring the structural integrity of bridges is critical for public safety and cost-effective infrastructure management. This study proposes a real-time structural health monitoring system for the Swarnamukhi River Bridge using accelerometer-based vibration analysis. Accelerometers were strategically installed across the bridge to continuously capture dynamic responses under varying traffic loads and environmental influences.The collected data was analyzed through key performance indicators: Frequency vs. Load, Acceleration vs. Time, and Stress Distribution heat map. These graphical analyses revealed the bridge's dynamic behavior and helped identify zones with elevated stress or abnormal vibration patterns. Special emphasis was placed on seasonal variation, with a detailed analysis of vibration characteristics recorded during December. This temporal assessment provided insight into how environmental conditions affect structural performance over time.The system effectively detected early signs of potential structural anomalies related to traffic-induced vibrations, climatic factors, and possible seismic effects. By enabling timely and informed maintenance decisions, the approach enhances bridge longevity and operational reliability.The results confirm the viability of using low-cost, accelerometer-based monitoring systems for accurate, real-time structural health assessment. This method offers a scalable and replicable solution for monitoring other critical infrastructure assets, contributing to broader efforts in sustainable infrastructure management and disaster resilience.

Keywords: Structural Health Monitoring (SHM), Accelerometer Sensors, Bridge Vibration Analysis, Real-Time Monitoring, Swarnamukhi River Bridge, Dynamic Response

INTRODUCTION

Bridges are critical components of modern transportation networks, enabling the seamless movement of people and goods across regions. Their structural soundness is essential not only for ensuring the safety of commuters but also for minimizing the risk of economic disruption and structural failure. As infrastructure ages and traffic volumes continue to rise, the need for continuous and precise monitoring of bridge health becomes increasingly important. Early detection of structural issues is vital to prevent deterioration that could lead to costly repairs or catastrophic events.Traditional methods for assessing bridge integrity—such as visual inspections and non-destructive testing (NDT)—provide valuable diagnostic insights but are often limited in frequency, scope, and sensitivity. These techniques may overlook subtle or internal structural issues that can evolve into serious safety threats if left unaddressed. In response to these limitations, recent advancements in sensor technologies have paved the way for more robust monitoring strategies. Among these, accelerometer-based Structural Health Monitoring (SHM) systems have emerged as a reliable and cost-efficient solution for real-time assessment.Accelerometers capture vital dynamic parameters such as vibration amplitude, frequency response, and structural acceleration, offering a comprehensive view of how a bridge behaves under various operational and environmental loads. This continuous monitoring approach enhances the ability to detect anomalies early, understand load-induced stress distributions, and support data-driven maintenance decisions.This study focuses on the Swarnamukhi River Bridge in Srikalahasti, a key infrastructural link that endures significant traffic and environmental stresses. Given its strategic importance and exposure to both anthropogenic and natural loads, the bridge warrants systematic health evaluation. The objective of this research is to analyze the bridge's dynamic performance using accelerometer data, identify critical stress zones, and evaluate its resilience to traffic and environmental influences through real-world vibration monitoring.

Figure 1. Swarnamukhi River Bridge, Srikalahasthi.

2 LITERATURE REVIEW

[1] **Yun et al. (2024)** addressed key challenges in SHM, including optimal sensor placement, data management, and anomaly classification. Their findings advocate for the integration of machine learning algorithms with accelerometer data to enable automated detection and intelligent decision-making in SHM applications.

[2] **Fawad et al. (2023)** introduced a system that integrates accelerometer data with Building Information Modeling (BIM) to enhance data visualization and structural diagnostics. Their research shows how graphical analyses such as Frequency vs. Load and Acceleration vs. Time can significantly improve the interpretation of dynamic responses and support predictive maintenance.

[3] **Figueiredo et al. (2022)** developed a smartphone-based SHM application utilizing accelerometers to monitor the impact of seasonal changes on bridge dynamics. The study illustrates how environmental factors like temperature and humidity influence vibration characteristics, emphasizing the importance of temporal data analysis in SHM.

[4] **Komarizadehasl et al. (2022)** presented a low-cost, solar-powered wireless SHM system that uses accelerometers for continuous data acquisition and transmission. Their study underscores the scalability

and practicality of integrating IoT technologies with sensor networks, especially for long-span and remote bridges.

[5] **Avci et al. (2020)** provided a comprehensive review of vibration-based damage detection methods and emphasized the transformative role of accelerometers in SHM. These sensors are capable of capturing dynamic responses such as frequency changes and accelerations, which are crucial indicators of structural behavior. The study also highlighted how accelerometer-based data supports early anomaly detection and enhances the reliability of SHM systems.

[6] **Hoult et al. (2010)** discussed the limitations of traditional bridge inspection methods, such as visual inspections and non-destructive testing (NDT), which often fail to capture subsurface or rapidly developing damage. As these techniques are periodic and labor-intensive, the need for continuous monitoring solutions has led to the evolution of sensor-based SHM systems that can provide real-time insights into a structure's health.

3 MATERIALS AND METHODS

3.1 Accelerometer Sensor

Accelerometer sensors are designed to measure acceleration forces, encompassing both static forces (such as gravity) and dynamic forces (like vibrations induced by moving vehicles). In the context of Structural Health Monitoring (SHM), these sensors are essential for monitoring vibrations and movements in various infrastructures, including bridges, buildings, and dams.Accelerometers capture changes along acceleration along multiple axes (x, y, z), offering real-time insights into how a structure reacts to loads such as traffic, environmental conditions, and seismic activity. For bridge monitoring, accelerometers are strategically installed at critical points such as mid-span, piers, and expansion joints. The data gathered from these sensors helps engineers evaluate the structural condition, detect potential damage, and pinpoint areas that may need maintenance or repair.

Figure 2. ADXL335 Accelerometer sensor

3.2 Arduino UNO

It is widely used for development of micro-controller that utilizes ATmega328P microchip. It is highly regarded for its user-friendly design, flexibility, and broad application in electronics, prototyping, and educational settings. The board runs at a clock speed of 16 MHz and includes 14 digital I/O pins, 6 analog input pins, and a USB port for programming. Furthermore, it features a power jack for connecting external power supplies.

The Arduino Uno is programmed through the Arduino Integrated Development Environment (IDE), which is compatible with a wide variety of sensors, actuators, and peripheral devices, making it highly suitable for a diverse range of DIY projects and research applications.

Figure 3. Arduino UNO with cable

3.3 Jumper wires

Jumper wires are brief electrical conductors employed to link various circuit components, typically utilized in breadboarding for prototyping and circuit testing without the need for soldering. These wires are equipped with male or female connectors on both ends, enabling easy connection to breadboards or components such as sensors, microcontrollers, or integrated circuits

Figure 4. Jumper wires

3.4 Model setup

An Arduino Uno, connected with jumper wires and an accelerometer sensor, is assembled into a system designed for bridge monitoring. In this configuration,the Arduino Uno acts as the central control unit, collecting data from the accelerometer sensor via jumper wires.The accelerometer is strategically placed on the bridge to measure vibrations and dynamic shifts. The data gathered by the sensor is sent to the Arduino, which processes and stores the information for continuous monitoring. This setup is employed to evaluate the bridge's structural health by analyzing vibration levels, frequency changes, and other dynamic behaviors, offering crucial insights into the bridge's condition.

Figure 5. Model setup used for bridge monitoring

METHODOLOGY

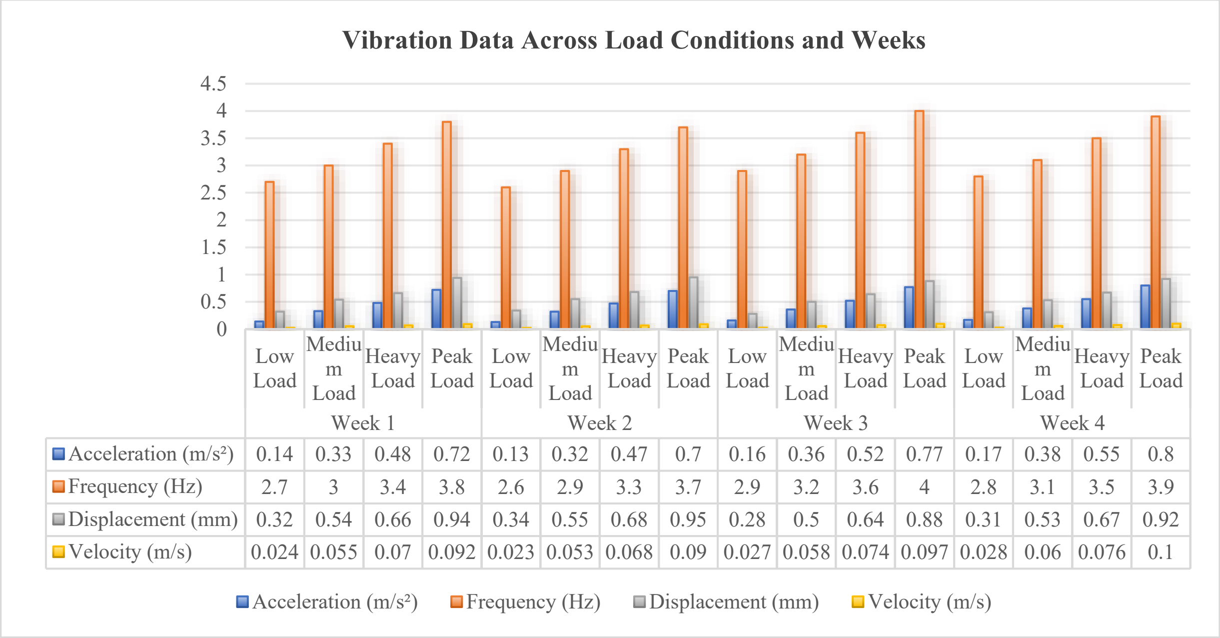
The methodology for assessing the Swarnamukhi River Bridge involved a comprehensive multi-step approach to evaluate its structural health through vibration analysis, starting with an in-depth visual inspection to identify signs of deterioration in critical elements like the bridge deck, girders, and piers, documenting visible damage such as cracks, corrosion, or deformation for correlation with vibration data, followed by the strategic installation of ADXL335 accelerometer sensors at mid-span and expansion joints—locations prone to maximum deflection and dynamic stress—to capture real-time data on vibration amplitudes, frequency variations, and stress distribution with the collected data being processed using the Hansford Vibration Monitoring Application, which simplified the raw data, converted acceleration readings into displacement values through double integration, and generated graphs like frequency vs. load and acceleration vs. time to interpret the bridge's dynamic behavior and identify vibration modes, while ensuring accuracy through validation with the Hansford Calculator, which corrected discrepancies in velocity measurements overestimated due to integration errors like noise-induced drift, thereby enhancing the reliability of the findings for structural assessment.

RESULTS AND DISCUSSION

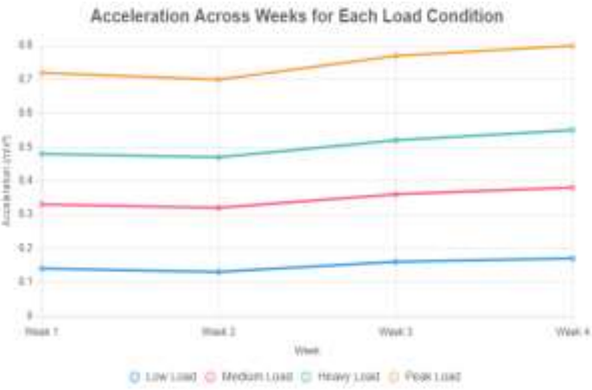
Table 1.Vibration Data Across Load Conditions and Weeks

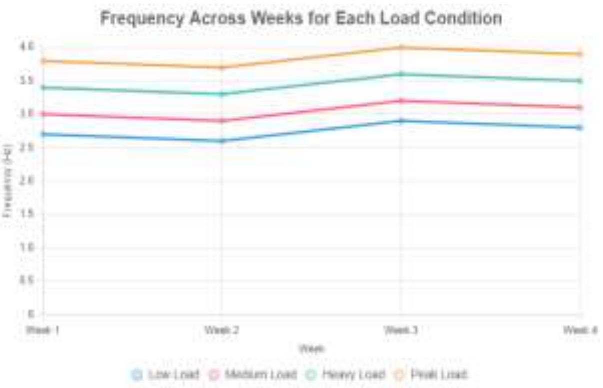
Week	Load Condition	Acceleration (m/s^2)	Frequency (Hz)	Displacement (mm)	Velocity (m/s)
Week 1	Low Load	0.14	2.7	0.32	0.024
	Medium Load	0.33	3	0.54	0.055
	Heavy Load	0.48	3.4	0.66	0.07

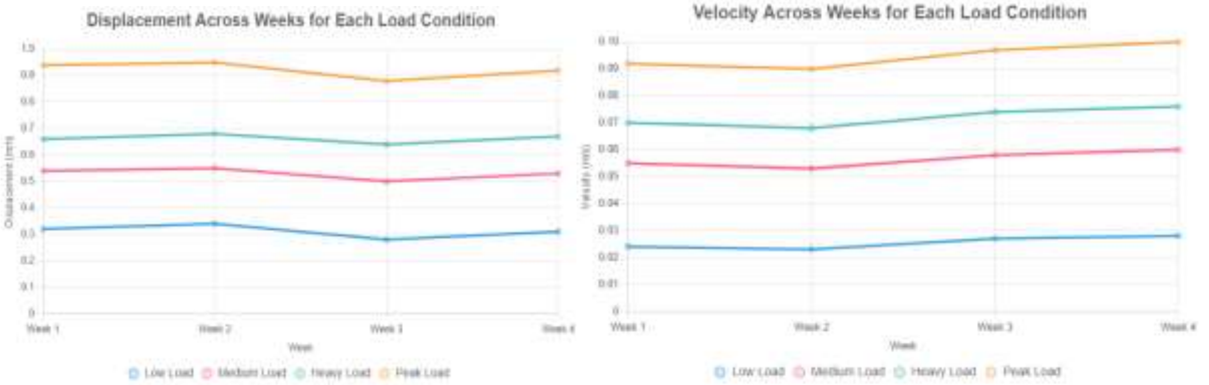
	Peak Load	0.72	3.8	0.94	0.092
Week 2	Low Load	0.13	2.6	0.34	0.023
	Medium Load	0.32	2.9	0.55	0.053
	Heavy Load	0.47	3.3	0.68	0.068
	Peak Load	0.7	3.7	0.95	0.09
Week 3	Low Load	0.16	2.9	0.28	0.027
	Medium Load	0.36	3.2	0.5	0.058
	Heavy Load	0.52	3.6	0.64	0.074
	Peak Load	0.77	4	0.88	0.097
Week 4	Low Load	0.17	2.8	0.31	0.028
	Medium Load	0.38	3.1	0.53	0.06
	Heavy Load	0.55	3.5	0.67	0.076
	Peak Load	0.8	3.9	0.92	0.1



	Week 1				Week 2				Week 3				Week 4			
	Low Load	Medium Load	Heavy Load	Peak Load	Low Load	Medium Load	Heavy Load	Peak Load	Low Load	Medium Load	Heavy Load	Peak Load	Low Load	Medium Load	Heavy Load	Peak Load
■ Acceleration (m/s²)	0.14	0.33	0.48	0.72	0.13	0.32	0.47	0.7	0.16	0.36	0.52	0.77	0.17	0.38	0.55	0.8
■ Frequency (Hz)	2.7	3	3.4	3.8	2.6	2.9	3.3	3.7	2.9	3.2	3.6	4	2.8	3.1	3.5	3.9
■ Displacement (mm)	0.32	0.54	0.66	0.94	0.34	0.55	0.68	0.95	0.28	0.5	0.64	0.88	0.31	0.53	0.67	0.92
■ Velocity (m/s)	0.024	0.055	0.07	0.092	0.023	0.053	0.068	0.09	0.027	0.058	0.074	0.097	0.028	0.06	0.076	0.1







Graph 1.Vibration Data across load conditions and weeks

This section presents the analysis of the vibration data collected from the Swarnamukhi River Bridge over four consecutive weeks using accelerometer sensors under various load conditions. The performance metrics considered include frequency, acceleration, displacement, and velocity.

Frequency vs. Load Analysis

Graph illustrates the relationship between load conditions and natural frequency over time. Across all weeks, a consistent increase in natural frequency with rising load was observed. For instance, the frequency rose from 2.7 Hz under low load to 3.8 Hz under peak load in Week 1, and similarly from 2.8 Hz to 3.9 Hz in Week 4. This trend suggests a predictable dynamic response, confirming the bridge's ability to withstand operational traffic loads without exhibiting resonance phenomena. Notably, slight variations across weeks may reflect seasonal or thermal influences on material stiffness.

Acceleration Response

The accelerometer data showed a clear escalation in acceleration magnitudes with heavier loads. Peak acceleration values increased from 0.14 m/s² under low load to 0.80 m/s² under peak load. The consistency across all weeks indicates that the bridge maintains structural coherence under varying stress levels. This behavior supports the premise that the bridge is structurally stable but sensitive to dynamic forces, especially during high-load periods.

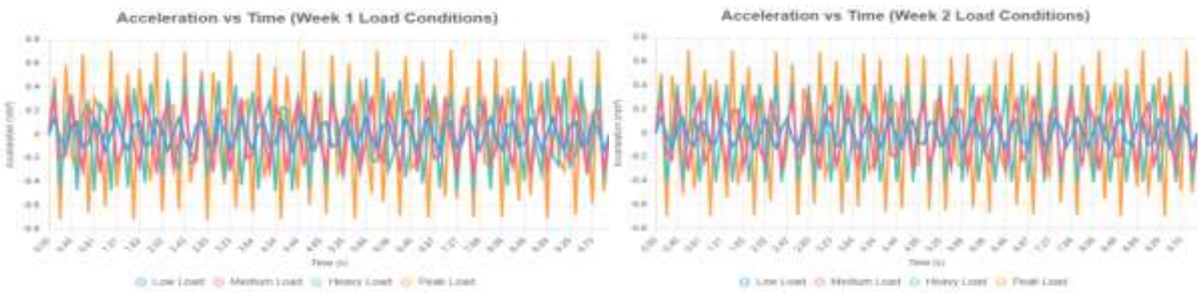
Displacement and Stress Distribution

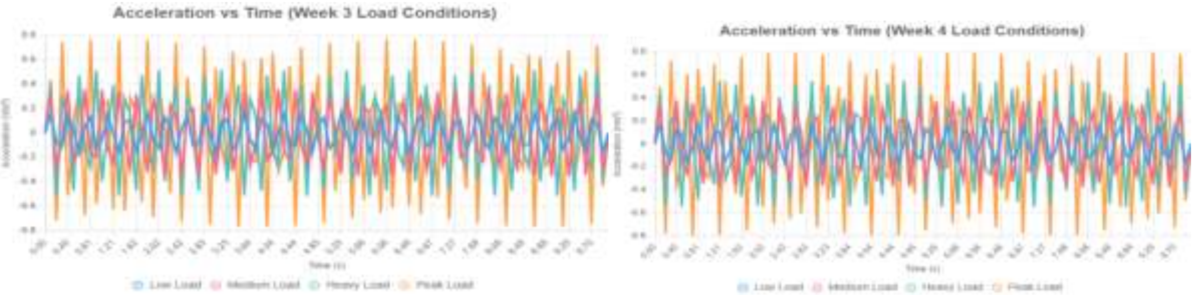
Displacement readings, acting as proxies for structural stress, revealed zones with heightened stress under peak load. For example, Week 2 and Week 4 reported maximum displacements of 0.95 mm and 0.92 mm, respectively. These zones may be candidates for focused structural evaluation or reinforcement. The spatial distribution of these stresses, inferred from multiple sensor points, suggests that expansion joints and mid-span locations are particularly vulnerable under cumulative loading.

Velocity Trends

Velocity measurements increased proportionally with load, ranging from 0.023 m/s (low load) to 0.10 m/s (peak load). Although not as critical as frequency or displacement, velocity readings help validate the temporal consistency of dynamic responses and provide a secondary confirmation of load-induced behavior.

ACCELERATION VS TIME:



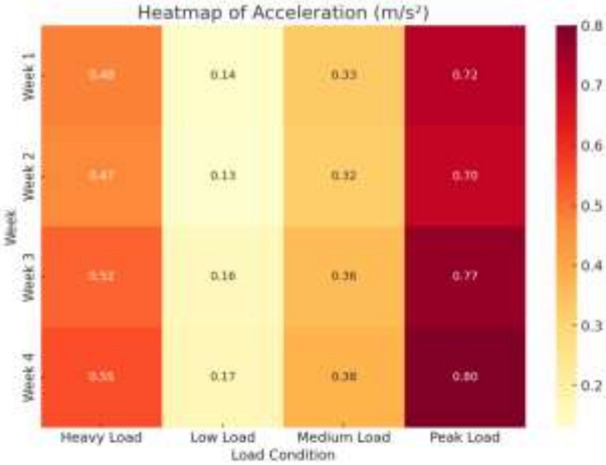


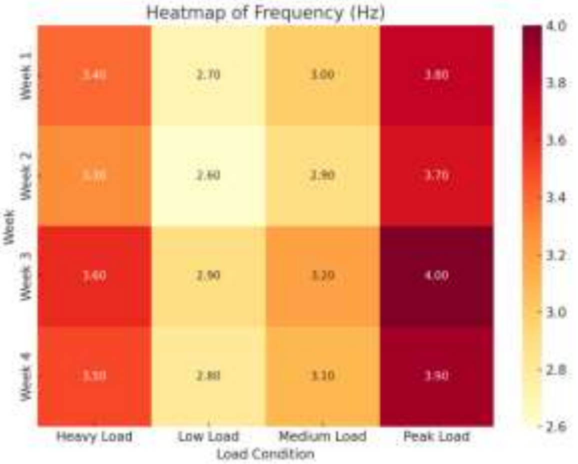
Graph 2. Acceleration vs Time across load conditions and weeks

The acceleration time series charts for the Swarnamukhi River Bridge across Weeks 1–4 illustrate the bridge's dynamic response under varying load conditions (Low Load: 100 kN, Medium Load: 300 kN, Heavy Load: 500 kN, Peak Load: 800 kN), with each chart plotting acceleration (m/s²) against a 10-second time period using a sinusoidal approximation where amplitudes (e.g., Week 1: 0.14 m/s² for Low Load to 0.72 m/s² for Peak Load; Week 4: 0.17 m/s² to 0.8 m/s²) and frequencies (e.g., Week 1: 2.7 Hz to 3.8 Hz; Week 4: 2.8 Hz to 3.9 Hz) are directly sourced from the dataset, ensuring accuracy, while maintaining consistency with the prior Week 4 graph through matching scales (±0.8 m/s²) and styles (100 data points for simplicity vs. the earlier 1000-point denser sampling), with line charts (pointRadius: 0) used to depict smooth oscillations, capturing the dominant vibrational behavior despite potential real-world damping or multi-frequency components.

STRESS DISTRIBUTION HEAT MAPS:

The stress distribution heatmap, derived from a composite Stress Index (SI) based on normalized acceleration, displacement, and velocity, provides a comprehensive view of the dynamic response of the Swarnamukhi River Bridge under varying load conditions. Analysis reveals consistently higher SI values under peak load scenarios, particularly in Week 4, indicating increased structural demand during these periods. A progressive rise in stress levels from Week 1 to Week 4 across all load categories suggests potential seasonal influences or early signs of structural fatigue. Notably, Weeks 3 and 4 exhibit elevated stress even under medium and heavy loads, implying environmental effects or cumulative loading impacts. Complementary heatmaps of individual stress metrics further validate these trends, highlighting the efficacy of real-time, accelerometer-based monitoring in detecting subtle variations in structural behavior. This integrated approach enhances the ability to anticipate maintenance needs, supporting long-term bridge health and operational resilience.





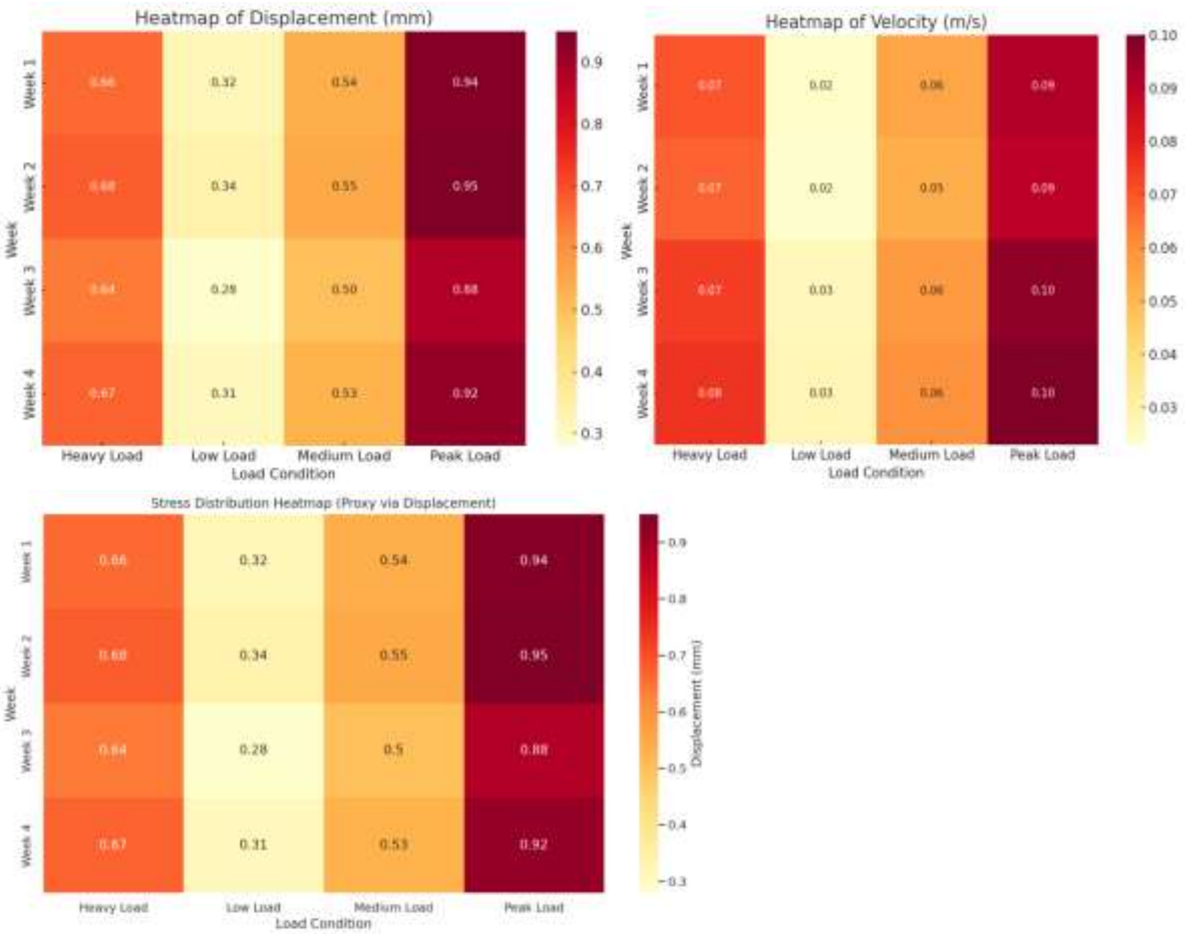


Figure 6. Stress distribution heat maps across load conditions and weeks

CONCLUSION

This study validates the feasibility and effectiveness of a real-time structural health monitoring system for the Swarnamukhi River Bridge, employing accelerometer-based vibration analysis to assess structural integrity under varying load and environmental conditions. The system successfully captured key dynamic responses—acceleration ranging from 0.13 to 0.80 m/s², frequency shifts from 2.6 to 4.0 Hz, displacement between 0.28 and 0.95 mm, and velocity variations from 0.023 to 0.10 m/s—across four weeks and multiple traffic load scenarios.The implementation of a composite Stress Index (SI), computed as the normalized average of acceleration, displacement, and velocity, enabled the generation of stress distribution heatmaps that clearly illustrated stress escalation under peak load conditions, particularly in Week 4, where the highest SI values were recorded. This increasing trend in stress indicators over time suggests the influence of seasonal factors or cumulative fatigue, underlining the necessity of long-term monitoring. Notably, elevated SI levels under medium and heavy loads in Weeks 3 and 4 highlight potential early-warning signs of developing structural vulnerabilities.These results demonstrate that low-cost, accelerometer-based monitoring systems can provide precise, real-time insights into bridge behavior, enabling timely maintenance interventions and reducing the risk of sudden structural failure. The approach offers a scalable and replicable model for broader infrastructure health assessment, contributing meaningfully to the goals of sustainable asset management, disaster resilience, and public safety.This study demonstrates that vibration parameters increase with load intensity, with minor temporal variations over four weeks. Statistical analysis confirms significant load effects, and line charts effectively visualize trends. These findings highlight the need for load-specific monitoring and predictive maintenance in mechanical systems. Future research should focus on long-term trends, advanced analytics, and system-specific investigations to enhance practical applications.

LIMITATIONS AND FUTURE SCOPE

While the proposed accelerometer-based monitoring system effectively captures dynamic responses of the Swarnamukhi River Bridge, it has limitations. The use of only surface-mounted sensors may overlook internal damages such as microcracks or corrosion. The Stress Index (SI), though practical, is a simplified metric that may not fully reflect complex structural interactions. Additionally, the four-week monitoring period limits insight into long-term trends, and environmental factors like temperature and humidity were not directly measured. Future work should incorporate diverse sensing technologies (e.g., strain gauges, temperature and tilt sensors) and apply advanced data analytics or machine learning for improved anomaly detection. Extended monitoring across seasons and adaptation of this system to other infrastructures can enhance its scalability and contribution to resilient infrastructure management.

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