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INTEGRATING NUMERICAL SIMULATION AND EXPERIMENTAL DATA FOR ENHANCED STRUCTURAL HEALTH MONITORING OF BRIDGES

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Abstract. *The research described in this paper aims to enhance the structural health monitoring (SHM) of highway bridges by integrating numerical simulations with experimental data. A simply supported highway bridge is studied under traffic loads, and both numerical and experimental approaches were employed. The numerical model of the bridge was developed using ANSYS, while high-resolution experimental data were collected from velocity transducers placed at key points on the bridge. The experimental data were compared with the results from the numerical model for validation. The results showed that the natural frequencies obtained from both the experimental and numerical analyses were closely aligned, demonstrating the reliability of the model. The validated model was further used to predict long-term structural behaviours under different operational conditions, contributing to better maintenance planning and the sustainability of infrastructure. The study concludes that combining numerical simulations with experimental data improves the accuracy of SHM, enabling early detection of potential structural issues and extending the lifespan of bridges. Key findings emphasize the significant role of vehicle speed in influencing the dynamic response of the bridge, as well as the importance of considering material properties and vehicle loads in predicting structural health.*

Keywords: structural health monitoring, natural frequency, mode shape, Finite Element Modeling, ANSYS, highway bridges

INTEGRACJA SYMULACJI NUMERYCZNEJ I DANYCH EKSPERYMENTALNYCH DLA ULEPSZONEGO MONITOROWANIA STANU KONSTRUKCJI MOSTÓW

Streszczenie. *Badania opisane w niniejszym artykule mają na celu poprawę monitorowania stanu konstrukcji (structural health monitoring – SHM) mostów na autostradach poprzez integrację symulacji numerycznych z danymi eksperymentalnymi. Prosto podparty most na autostradzie jest badany pod obciążeniem ruchem drogowym i zastosowano zarówno podejście numeryczne, jak i eksperymentalne. Model numeryczny mostu został opracowany przy użyciu programu ANSYS, podczas gdy dane eksperymentalne o wysokiej rozdzielczości zostały zebrane z przetworników prędkości umieszczonych w kluczowych punktach mostu. Dane eksperymentalne zostały porównane z wynikami modelu numerycznego w celu walidacji. Wyniki pokazały, że częstotliwości drgań własnych uzyskane zarówno z analiz eksperymentalnych, jak i numerycznych były ściśle dopasowane, co świadczy o niezawodności modelu. Zweryfikowany model został następnie wykorzystany do przewidywania długoterminowych zachowań strukturalnych w różnych warunkach operacyjnych, przyczyniając się do lepszego planowania konserwacji i zrównoważonego rozwoju infrastruktury. W badaniu stwierdzono, że połączenie symulacji numerycznych z danymi eksperymentalnymi poprawia dokładność SHM, umożliwiając wczesne wykrywanie potencjalnych problemów strukturalnych i wydłużając żywotność mostów. Kluczowe wyniki badań podkreślają istotną rolę prędkości pojazdu we wpływie na dynamiczną reakcję mostu, a także znaczenie uwzględnienia właściwości materiału i obciążeń pojazdu w przewidywaniu stanu konstrukcji.*

Słowa kluczowe: monitorowania stanu konstrukcji, częstotliwość drgań własnych, mode shape, modelowanie metodą elementów skończonych, ANSYS, mosty na autostradach

Introduction

Bridges are essential to modern infrastructure networks, providing vital economic and societal connections. Their structural integrity is of utmost importance, as they are subjected to various operational and environmental stresses that can contribute to their deterioration over time. The preservation and safety of these structures represent a significant challenge for civil engineers. In the past, evaluating the safety and efficiency of bridges mainly involved physical inspections and basic non-destructive testing methods. However, these methods have drawbacks, including high expenses, potential invasiveness, and limitations in detecting subsurface defects. Therefore, a growing demand for more advanced and less intrusive monitoring techniques is growing. Thanks to the development of computational tools and sensor technologies, structural health monitoring (SHM) is rapidly evolving [3, 6]. These advancements present exciting opportunities to address the limitations of traditional methods by enabling more precise and immediate tracking of bridge conditions.

Over the past few decades, numerical simulation has become an invaluable asset in SHM, empowering engineers to model complex behaviours accurately under diverse load scenarios. Finite Element Modeling (FEM) has proven especially valuable in this regard, enabling detailed simulations of structural responses to various conditions, predicting potential points of failure, and aiding in the optimisation of maintenance schedules. Simulating long-term deterioration under environmental factors is a remarkable advantage, granting engineers insight into the effects of variables such as load, wind, and temperature fluctuations over extended periods.

By employing a validated numerical model developed in ANSYS and integrating it with high-frequency data from strategically placed velocity transducers on a simply supported highway bridge, this study aims to bridge the gap between numerical simulations and experimental methodologies in bridge monitoring. This research seeks to determine the vibration response of the bridge through field data, which most researchers use for SHM [2, 9], and develop a numeral model. Validate this numerical model against experimental observations [11]. Then, the validated model will be utilised to simulate long-term structural behaviours and predict potential deterioration by parametric study [4]. Finally, applying these methodologies will be demonstrated to enhance the sustainability and safety of bridge infrastructures. This paper presents an innovative approach that integrates numerical simulation with experimental data to improve the SHM of bridges.

1. Material and methods

1.1. Description of test bridge

The bridge under study is located in India, as shown in Fig. 1, with coordinates of Latitude 22°12’11.81" and Longitude 87°33’25.97". The grade of concrete used in the bridge is M30. This new bridge, called Badalpur Bridge, replaces existing narrow bridges over canal Badalpur under the Midnapore Highway Division in Purba Paschim Medinipur. The details of the bridge are presented in Table 1.

Table 1. Dimension details of bridge

Description of bridge	Badalpur bridge
Length (m)	58.12
Span scheme	3 no’s SS span @ 18.75 m c/c of bearing
Decking type	Five no’s of RCC girder with deck slab superstructure
Depth of deck (m)	2.050
Total width of bridge (m)	15.55
Bearing type	Elastomeric

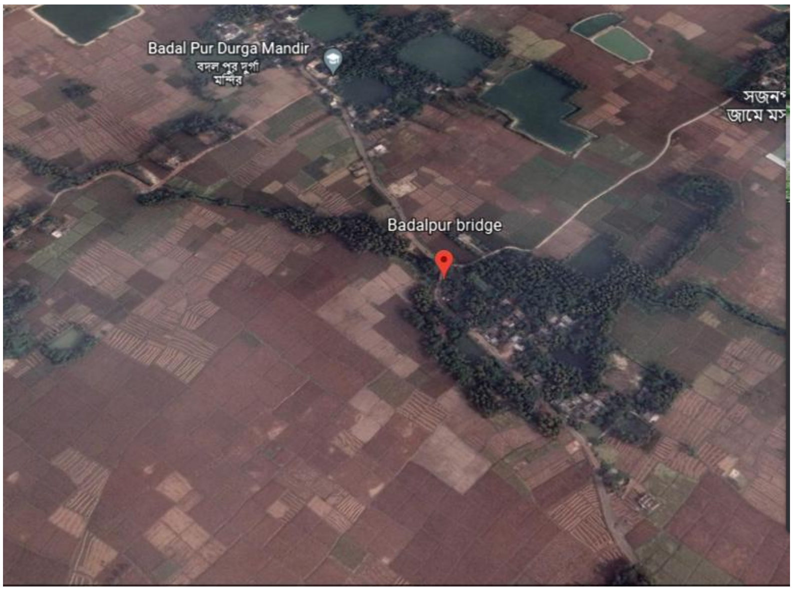

Fig. 1. Location of bridge (Source-Google)

1.2. Instrument details

Minimate Blaster is selected for the data collection shown in Figure 2. This is because accelerometers are relatively expensive, have lower sensitivity and require additional electronics for signal conditioning [10]. Charge amplification electronics are needed to produce a signal suitable for recording by the accelerometer, for which power sources are required. On the other hand, geophones are passive devices that create a voltage that can be recorded without additional amplification or conditioning.

The sensor measures transverse, vertical and longitudinal ground vibration regarding particle velocity. Transverse ground vibration agitates particles in a side-to-side motion. Vertical ground vibration agitates particles in an up-and-down motion. Longitudinal ground vibration agitates particles in a back-and-forth motion progressing outward from the event site.

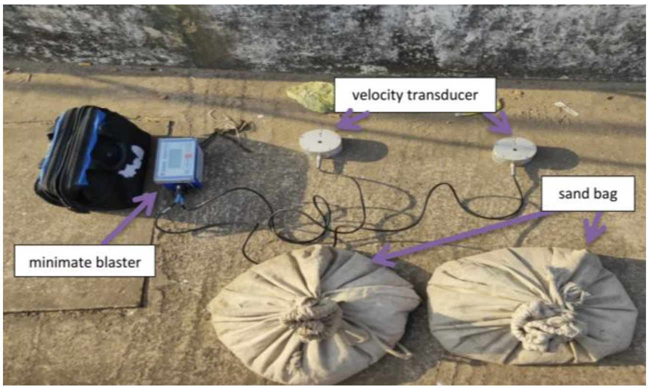

Fig. 2. Minimate blaster & transducer

1.3. Sensor placement and data collection

The sensor is placed on the superstructure [5, 7, 12] and at the bridge's mid-span, as represented in Figure 3. It is placed on both sides of the bridge. Sensor-I is placed in the direction of traffic movement, and sensor-II is placed on the opposite side of the bridge against the traffic movement. Since no significant natural frequencies are anticipated at the pillars or the beginning and end of a bridge, it is unnecessary to install sensors in these locations [8]. The data is recorded for vehicles moving with two-axle trucks at different speeds. Figure 4 shows the movement of the truck on the bridge. Table 2 shows the data recorded by the sensor.

1.4. Numerical simulation

The Finite Element Method (FEM) is a computational technique widely used in engineering and mathematical modelling to solve complex physical problems [13]. FEM allows for detailed numerical approximation of structures under various conditions.

In this study, ANSYS is used for simulation by meticulously configuring the model parameters, including detailed geometry, material properties, and boundary conditions; ANSYS enables precise simulation of structural responses.

Modal analysis is used to identify a structure's natural frequency and normal mode. Knowing the natural frequency is crucial to avoid resonance, which occurs when an object vibrates at a frequency equivalent to its natural frequency, resulting in a significant increase in vibration amplitude that can lead to irreparable damage. By identifying the natural frequency, we can take measures to control it, such as adding mass or changing material properties. Additionally, understanding the mode shapes of the object can give insights into how the design will behave and enable us to add stiffness to fortify the design for better operation. The data obtained from the modal analysis is also helpful in performing forced vibration, allowing for a complete understanding of the behaviour of the structure under different conditions.

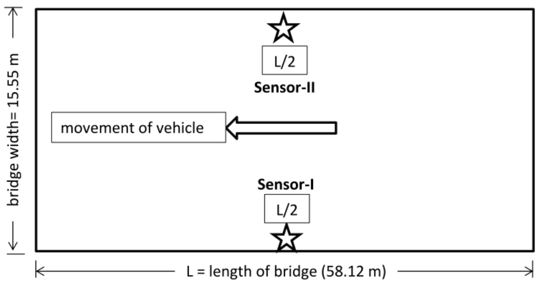

Fig. 3. Schematic representation of bridge with sensor placement and vehicle movement

Fig. 4. Movement of truck on bridge for speed 33.32 km/h

2. Results and discussion

2.1. Experimental results

The data collected for Badalpur Bridge is presented in Table 2. When the vehicle entered the bridge, the bridge responded. The response of the bridge is represented in the form of a waveform. Since two sensors were placed on both sides of the bridge, the two waveforms are shown in Figure 5 and Figure 6 for sensor-I and sensor-II, respectively, for a speed of 33.32 km/h. There are five experimental data for the truck moving at different speeds, and it isn't easy to show all the waveforms for each speed. Figure 7 and Figure 8 shows the FFT of the waveform for a speed of 33.32 km/h.

The section on ambient vibration, after excitation occurs, is essential for calculating natural frequency [8]. The structure's natural frequency is best indicated by the residual vibration, which continues after the load has left the span [1]. With this concept, the residual vibration is selected from each waveform for all the speeds mentioned in Table 1, and FFT was done to know the bridge's natural frequency. The forced frequency is calculated when the vehicle is moving on the bridge. From Table 2, it is clear that the bridge's natural frequency lies between 9 Hz to 9.5 Hz.

Table 2. Experimental test result

S.No	Position of sensor	Speed (km/hr)	PPV (mm/s)	Natural frequency (Hz)
1	I	28.6	2.159	9.25
	II	28.6	1.524	9.50
2	I	33.32	2.413	9.50
	II	33.32	2.921	9.50
3	I	41.02	2.921	9.50
	II	41.02	2.286	9.50
4	I	52.31	2.794	9.50
	II	52.31	2.54	9.50
5	I	58.93	2.921	9
	II	58.93	1.905	9

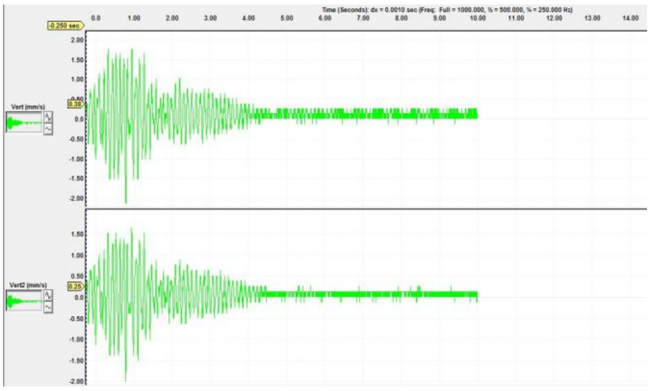

Fig. 5. Waveform at Speed 33.32 km/h – sensor I

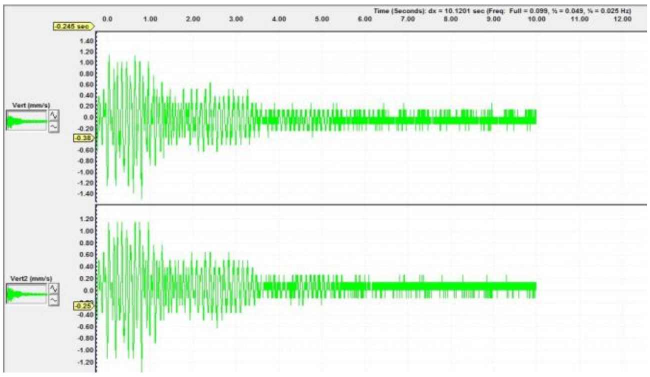

Fig. 6. Waveform at speed 33.32 km/h – sensor II

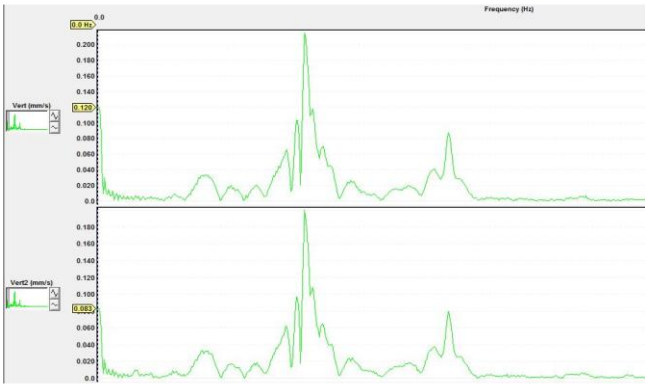

Fig. 7. Waveform FFT at speed 35.22 km/h – sensor I (forced frequency)

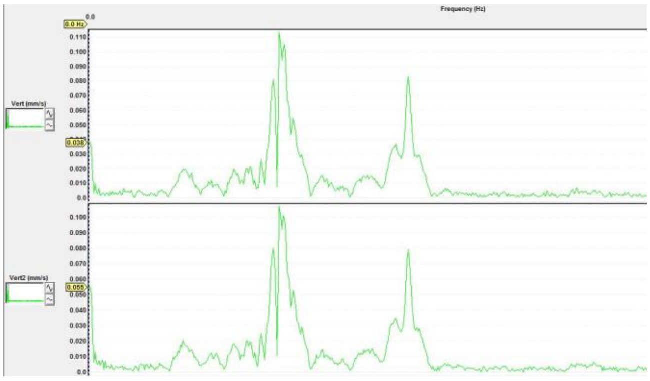

Fig. 8. Waveform at speed 35.22 km/h – sensor II (forced frequency)

2.2. Simulation outcomes

Badalpur bridge is modelled in ANSYS as per the details mentioned in Table 1. During the analysis, the stiffness behaviour of the bridge is assumed to be flexible. The material assigned to the structure is concrete of grade M30. Modal analysis is performed to determine the bridge's mode shape and natural frequency. The model has been meshed with mechanical preference, and the element order is Quadratic. The analysis result is presented in Table 3. Figure 9 shows the mode shape of the bridge.

Table 3. Numerical test result

Mode shape	Natural frequency (Hz)
I	2.37
II	5.41
III	7.51
IV	9.35
V	11.98
VI	15.17

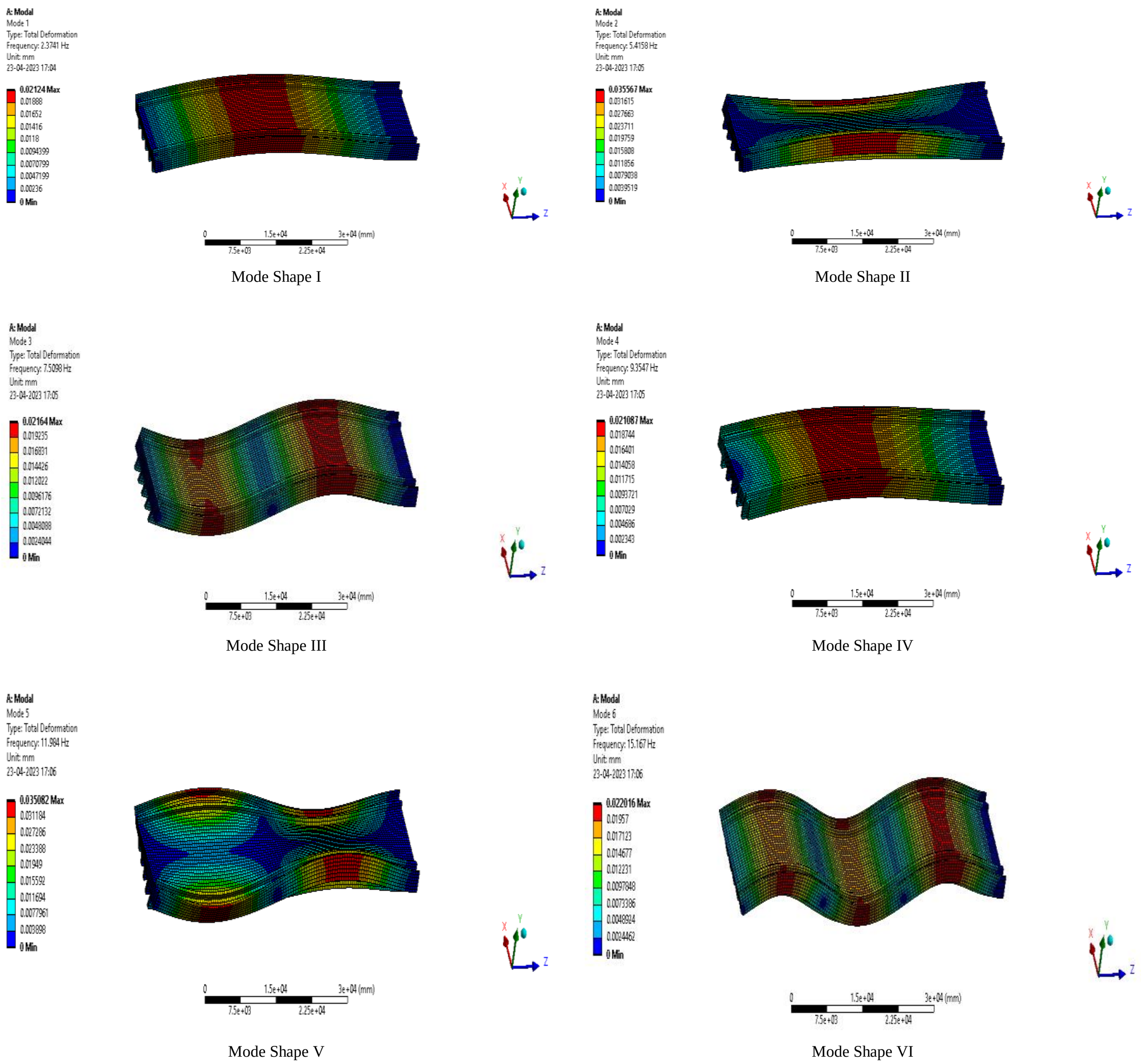

Fig. 9. Mode shape of bridge

2.3. Comparison and validation

When the vehicle leaves the bridge span, some residual vibration is present. With the help of residual vibration, the bridge's natural frequency is calculated. Based on this concept, the natural frequency of the selected bridge is calculated. For a few modes, the natural frequency obtained through residual vibration in the experimental method matches the value obtained through modal analysis.

The experimental data were collected using two minimate blasters under different speed conditions. Critical parameters such as Peak Particle Velocity (PPV), peak displacement, forced frequencies, and natural frequencies were recorded. On the numerical side, the modal analysis was conducted using ANSYS to determine natural frequencies and maximum deformations across six mode shapes.

The experimental analysis shows a range of natural frequencies, predominantly around 9.50 Hz. The numerical simulations in ANSYS yielded natural frequencies across six mode shapes, ranging from 2.37 Hz to 15.17 Hz. Mode IV produced a natural frequency of 9.35 Hz, which closely aligns with the predominant experimental natural frequency of approximately 9.50 Hz.

The close alignment of Mode IV's natural frequency (9.35 Hz) from ANSYS with the experimental dominant natural frequency around 9.50 Hz validates the numerical model's ability to accurately simulate the dynamic behaviour of the bridge under realistic operational loads. This consistency supports the reliability of using such simulations for predictive diagnostics in SHM.

3. Parametric study

A parametric study is conducted to comprehensively evaluate the impact of various factors on the dynamic response of bridge structures under moving loads. This study focused on the modulus of elasticity, vehicle speed, and vehicle weight parameters influencing bridge behaviour during vehicle passage.

3.1. Variation in vehicle speed

The speed of a vehicle as it moves over a bridge significantly affects the dynamic response of the structure. Faster-moving vehicles can induce higher dynamic effects due to the rapid application and release of loads on the bridge deck. This study systematically varies the speed of vehicles across a predetermined range to observe the corresponding changes in vibration amplitudes, structural stresses, and natural frequencies of the bridge. The purpose is to identify critical speeds that may lead to resonant conditions or excessively high dynamic amplifications, which are crucial for designing speed limits and traffic management strategies on bridges. It is observed that as the speed of the vehicle increases, a significant increase in the vibration acceleration is induced, which increases vibrational responses.

3.2. Changes in modulus of elasticity

The modulus of elasticity of bridge materials, particularly in the deck, is a fundamental property that determines the stiffness and load-bearing capacity of the structure. In this study, the modulus of elasticity is varied to simulate different ageing conditions or use various construction materials. This parameter variation helps assess the sensitivity of the bridge's dynamic response to changes in material properties. Engineers can better predict potential failure modes and maintenance needs by analysing how these changes affect the bridge's ability to absorb and dissipate energy from moving loads. It is observed that changes in the modulus of elasticity do not significantly affect the strain value.

3.3. Changes in weight of vehicle moving on the bridge

The weight of vehicles travelling over the bridge directly influences the induced stresses and strains within the structural components. By adjusting the vehicle weight in the simulations, the study aims to explore how different loading conditions impact the bridge's structural responses, such as displacement, strain, and stress distribution under dynamic loading. Understanding these impacts will aid in the design of robust bridges under varying load conditions and help establish load limits to ensure long-term structural integrity. It is observed that the response of structure increases with an increase in the weight of the vehicle.

Each of these parameters, i.e. vehicle speed, modulus of elasticity, and vehicle weight, plays a significant role in the dynamic behaviour of bridges under moving loads. By systematically studying these effects, the research contributes to more accurate and effective structural health monitoring strategies and the development of safer, more durable bridge designs.

4. Conclusion

The comprehensive analysis involving experimental data and numerical simulations underscores the robust potential of integrating these approaches for bridges' structural health monitoring (SHM). The experimental results, reflecting real-world scenarios with varying vehicle speeds, provided a broad spectrum of dynamic responses. These were crucial for validating and refining the numerical models created in ANSYS. Key Findings of this study are:

Alignment of Natural Frequencies: The close alignment of natural frequencies between the experimental results and the ANSYS simulations, particularly the match around 9.50 Hz observed in most experimental cases and the 9.35 Hz from Mode IV in simulations, affirms the model's capability to accurately predict the dynamic behaviour of bridge structures under operational conditions. This alignment validates the utility of numerical simulations as a reliable predictive tool in SHM.

Range of Dynamic Responses: The experimental data revealed various dynamic responses under different vehicular loads, capturing natural frequencies as high as around 16 Hz. Although the numerical model primarily captured lower frequency ranges up to 15.17 Hz, its ability to effectively simulate the primary operational frequency range is evident. This suggests that the model can be reliably used to detect potential structural issues and plan maintenance early.

Implications for Maintenance Strategies: Integrating simulation and experimental methods facilitates a more proactive approach to maintenance. By predicting potential structural issues before they become critical, maintenance efforts can be better planned and executed, thus prolonging the lifespan of bridge structures and ensuring safety.

The study demonstrates the effectiveness of combining experimental data with numerical simulations for enhancing the structural health monitoring of bridges. This integrated approach validates simulation model reliability and enhances predictive maintenance capabilities, ensuring safer and more durable infrastructure. By continuing to refine these methods, civil engineering can better respond to the challenges of maintaining ageing infrastructure in an economically feasible and technically effective manner.

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