Dynamic Assessment of a Railway Bridge using Operational Modal Analysis and Fast Fourier Transform: A Comparative Study with Finite Element Analysis

Riza Suwondo
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
riza.suwondo@binus.ac.id (corresponding author)

Irpan Hidayat
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
irpan@binus.ac.id

Made Suangga
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
suangga@binus.ac.id

Militia Keintjem
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia
militia.marchella@binus.ac.id

Justitia Walewangko
Struktur Pintar Indonesia, Jakarta, Indonesia
justitia@strukturpintar.com

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ABSTRACT

This research investigates the dynamic behavior of a railway bridge using both experimental and numerical methods. Field tests were conducted to capture the bridge response to live loading conditions with acceleration data collected via uniaxial accelerometers placed at critical locations along the structure. The dynamic characteristics, including the natural frequencies and mode shapes, were determined using two analytical techniques: Fast Fourier Transform (FFT) and Operational Modal Analysis (OMA). While FFT provides a frequency domain analysis, OMA enables the estimation of modal parameters, such as natural frequencies, mode shapes, and damping ratios, using the bridge's response to operational forces. The results revealed that the fundamental frequency obtained from the OMA (2.163 Hz) was higher than that obtained from the FFT (1.95 Hz) and the Finite Element Analysis (FEA) model (1.65 Hz). Additionally, the OMA produced mode shapes that were closely aligned with those predicted by the FEA, validating the accuracy of the numerical model. This study highlights the advantages of OMA over FFT, particularly the ability to capture mode shapes, and underscores the importance of integrating OMA with FEA for a comprehensive dynamic assessment of bridge structures. These findings contribute to the growing body of knowledge on structural monitoring and provide practical insights into improving bridge safety and performance.

Keywords-Dynamic Behavior; Railway Bridge; Operational Modal Analysis (OMA); Fast Fourier Transform (FFT); Finite Element Analysis (FEA)

I. INTRODUCTION

Monitoring the condition of infrastructure is imperative for ensuring safety and enabling informed decision-making by owners [1-4]. In an ideal scenario, critical infrastructure, particularly expansive bridges, should undergo frequent, objective, predictable, and reproducible monitoring [5, 6]. Resource constraints present a primary obstacle in obtaining comprehensive information [7], and until the early 2010s, the absence of computer-based methods posed a limitation to data processing. With the increasing acceptance of vibration-based structural monitoring by infrastructure owners [8], bridges are now equipped with these monitoring systems. To handle the amount of information collected effectively, the adoption of automatic methods has become necessary, replacing traditional manual tasks, such as feature extraction from a stabilization diagram. Time saving and cost efficiency have driven the development of numerous modal operational analysis algorithms since the early 2010s [9-11], particularly in the realm of bridge monitoring.

OMA serves as a valuable tool for the estimation of modal parameters [12-15]. Unlike Experimental Modal Analysis (EMA), OMA eliminates the need for prior knowledge or measurement of input forces, making it particularly applicable to structures subjected to operational or environmental forces. This method offers distinct advantages, allowing for the testing of intricate and expansive structures that may be unsuitable for EMA. Moreover, the OMA enables assessments under realistic operating conditions, encompassing considerations, such as boundary constraints and applied forcing, thereby yielding results that accurately represent the structural response. The rotating elements within the operational structures exhibit distinct excitations attributable to unbalanced and periodic disturbances. The fundamental frequency is represented by the instantaneous rotation rate, which is typically accompanied by high harmonic frequencies. These periodic input forces commonly referred to as orders, deviate from the typical assumptions made in OMA. OMA traditionally assumes uncorrelated input forces with zero mean and a flat spectrum, similar to the characteristics of white noise. Departures from this assumption may introduce inaccuracies or biases in modal estimations, thereby complicating the interpretation of OMA results.

This study aims to explore the dynamic behavior of a railway bridge through the innovative application of OMA, providing a novel approach by utilizing real-time vibration data captured by strategically placed accelerometers. Unlike conventional methods, which often rely on predefined input forces, OMA allows for the assessment of modal parameters, such as natural frequencies and mode shapes, under actual operational conditions, offering a more accurate reflection of the bridge's dynamic characteristics.

A distinctive contribution of the current study is the comparative analysis between OMA and the widely practiced FFT, with the latter serving as a benchmark. While FFT is a familiar and established technique in structural dynamics [16-18], it is demonstrated how OMA can reveal additional dynamic properties, such as mode shapes, without requiring controlled input forces, thus offering potential advantages in complex in situ scenarios. By highlighting the effectiveness and precision of the OMA, this research expands the applicability of modern modal analysis techniques to railway bridge structures, ultimately contributing to more reliable and efficient infrastructure monitoring and management practices.

II. OMA VERSUS FFT

In structural dynamics, both OMA and FFT are widely used methods for identifying and analyzing the vibrational characteristics of structures. However, despite their common goal of determining modal parameters, such as natural frequencies, mode shapes, and damping ratios, these techniques differ significantly in their approach, application, and underlying assumptions.

OMA determines the dynamic characteristics of structures by analyzing their response to operational or ambient excitations. Unlike EMA, which requires controlled excitation forces, such as impact hammers or shakers, OMA relies on the natural forces acting on the structure, including wind, traffic, and environmental loads. This makes OMA a non-intrusive and practical approach, particularly suitable for large or complex structures, such as bridges, high-rise buildings, and offshore platforms [19-22].

The primary objective of OMA is to extract modal parameters, including natural frequencies (fn), damping ratios (ζ), and mode shapes (ϕn). These parameters are crucial for understanding the response of structures to dynamic loading. Vibration data are collected using sensors, such as accelerometers, which measure the structural response in terms of acceleration. Because the excitation forces are unknown in the OMA, the method assumes that the input forces are random, uncorrelated, and have a flat power spectral density akin to white noise. This assumption simplifies the identification of modal parameters and allows OMA to treat the input forces as broadband noise.

The mathematical foundation of the OMA can be expressed using the equation of motion (1) for a Multi-Degree-Of-Freedom (MDOF) system under ambient excitation:

$$M\ddot{u}(t)+C\dot{u}(t)+Ku(t)=f(t) \quad (1)$$

where M, C, and K represent the mass, damping, and stiffness matrices, respectively, $u(t)$ is the displacement vector, and $f(t)$ is the external force vector, which is treated as a stochastic process (white noise) in the OMA.

By analyzing the response $u(t)$, OMA seeks to estimate the modal parameters of the system. It employs various methods to achieve that, with one of the most commonly used techniques being Stochastic Subspace Identification (SSI). SSI constructs a state-space model from the measured data and decomposes the state matrix to extract the modal properties. The state-space model is given by:

$$\left.\begin{aligned} x_{k+1} &= Ax_k + w_k \\ y_k &= Cx_k + v_k \end{aligned}\right\} \quad (2)$$

where x_{k+1} is the state vector, A is the state matrix containing information on the natural frequencies and damping, y_k

represents the measured output (acceleration data), and w_k and v_k are the white noise sequences.

Another method frequently used in OMA is Frequency-Domain Decomposition (FDD), which decomposes the response Power Spectral Density (PSD) matrix into singular values, with the peaks in the singular values corresponding to the natural frequencies of the structure.

Once the natural frequencies are identified, the corresponding mode shapes and damping ratios are extracted. Mode shapes provide insights into the deformation pattern of a structure at each natural frequency, whereas damping ratios reflect the rate at which vibrations decay. These modal parameters are critical for evaluating the structural health and performance under dynamic loading conditions. The OMA follows a systematic workflow starting with the installation of accelerometers at key locations on the structure. Then data are collected under ambient conditions, and preprocessing steps, such as filtering, detrending, and normalization, are applied to improve data quality. Statistical or frequency-domain methods, such as SSI or FDD, are used to estimate modal parameters, which are validated against known values or analytical models.

Overall, OMA is an efficient and non-intrusive method for assessing the dynamic behavior of large and complex structures in real-world conditions. This eliminates the need for artificial excitation forces, making it highly applicable to operational settings. The flexibility and accuracy of OMA in identifying modal parameters without the need for input force measurements make it a powerful tool in structural dynamics analysis. FFT is a powerful mathematical tool used to analyze signals in the frequency domain, which renders it an essential technique in structural dynamics and vibration analysis [23]. This algorithm efficiently computes the Discrete Fourier Transform (DFT) of a sequence, enabling the conversion of time-domain signals into their frequency components. By transforming a signal into the frequency domain, FFT provides insights into the dominant frequencies, amplitudes, and phases of vibrations in a structure, allowing engineers to understand how different modes of vibration contribute to the overall response.

In structural engineering, FFT is commonly applied to analyze the vibration data recorded from sensors, such as accelerometers, to identify the natural frequencies and other dynamic properties of a structure. The relationship between the time-domain signal and its frequency-domain representation is governed by Fourier Transform, which decomposes a time-varying signal into a sum of sinusoidal components, each associated with a specific frequency. For a continuous-time signal $x(t)$, the Fourier Transform is defined by:

$$X(f)=\int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \qquad (3)$$

where $X(f)$ is the frequency-domain representation of the signal, $x(t)$ is the time-domain signal, f is the frequency, and j is an imaginary unit.

However, in practical applications, such as vibration analysis, the signal is usually sampled at discrete intervals, making it necessary to use DFT [24]. The DFT for a discrete signal x[n] with N data points is expressed by:

$$X[k]=\sum_{n=0}^{N-1} x[n]e^{-j\frac{2\pi}{N}kn} \qquad (4)$$

where $X[k]$ represents the frequency component of the index k, $x[n]$ is the sampled time domain, and N is the number of samples.

FFT is an optimized version of DFT that reduces its computational complexity from O(N^2) to O(N log N), rendering it more practical for analyzing large datasets. By applying FFT to the vibration data, engineers can extract the dominant frequencies at which the structure vibrates, known as the natural frequencies, as well as the amplitude and phase of each vibration mode.

In structural health monitoring, FFT is particularly useful for identifying peaks in the frequency spectrum that correspond to the natural frequencies of the structure. These peaks provide valuable information regarding the dynamic behavior of the structure, allowing engineers to assess their condition, detect potential damage, and evaluate the effectiveness of retrofitting measures. One of the key advantages of FFT is its ability to analyze stationary signals, where the frequency content does not change significantly over time. However, this also presents a limitation, as FFT is less effective for non-stationary signals, where the frequency components may vary over time. In such cases, alternative techniques, such as wavelet transform or time-frequency analysis may be more appropriate.

III. METHODS

The current study investigates the dynamic behavior of a railway bridge under live load conditions by employing both OMA and FFT techniques. The bridge under consideration was a three-span structure with two outer spans measuring 54 m each and a central span of 90 m (Figure 1). The piers were rigidly connected to the girder to ensure a fixed connection, which significantly influenced the overall dynamic performance of the bridge.

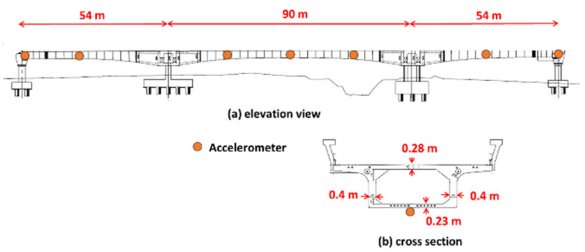


Fig. 1. Railway Bridge Layout and Sensor Placement for Dynamic Performance Testing.

Uniaxial accelerometers were strategically placed at seven critical locations along the girder to capture the bridge response to dynamic loading. These locations were selected to ensure a comprehensive coverage of the response of the structure, enabling the capture of vital data related to the vibration modes across all spans. Table I provides the accelerometer specifications.

TABLE I. ACCELEROMETER SPECIFICATIONS

Range	± 2
Frequency response [Nominal, 3 dB] (Hz)	0 – 300
Differential sensitivity (mV/g)	1000
Output noise, differential [rms, TYPICAL] (µg/√Hx)	7
Max mechanical shock [0.1 ms] (g)	2000

A performance test was conducted on the bridge by applying a live load to simulate real train loading conditions. To achieve this, a total load of 44 tons were applied, which was equivalent to 70% of the maximum allowable live load. This loading scenario was created by placing sandbags within a train to simulate a specified load distribution. The load was applied progressively to ensure that the bridge experienced conditions representative of typical operational loads. During the test, the train crossed the bridge at a maximum speed of 40 km/h, thereby creating dynamic forces on the structure. As the train traversed the bridge, accelerometers recorded the resulting acceleration at each of the seven locations. The recorded acceleration data provided a direct measure of the bridge response to the applied live load, thereby capturing the vibrations induced by the passing train.

Subsequently, the captured acceleration data were analyzed to determine the dynamic behavior of the bridge. FFT was used to decompose the time-domain acceleration signals into their frequency components, allowing the identification of the dominant frequencies. OMA was implemented to estimate the modal parameters, including the natural frequencies, mode shapes, and damping ratios, by analyzing the response of the structure to ambient and operational forces. OMA was performed using the commercial software ARTeMIS Modal [25], which specializes in extracting modal parameters from measured operational responses.

Noise is an inherent challenge in field data acquisition and often results from external vibrations, electrical interference, or environmental factors. To address this issue, data were processed using filtering techniques designed to isolate the primary vibration frequencies while minimizing the background noise. For the FFT, a low-pass filter was applied to eliminate high-frequency noise components that could distort the frequency peaks. Additionally, the OMA software, specifically ARTeMIS Modal, includes automated noise reduction functions that enhance the clarity of mode shapes and modal parameters by distinguishing signal components from random noise.

By comparing the results from FFT and OMA, a comprehensive understanding of the dynamic characteristics of railway bridges was achieved. This approach enabled the identification of key vibration modes and their corresponding frequencies, offering valuable insights into the behavior of bridges under live load conditions. Additionally, the results from both FFT and OMA were compared to those obtained from FEA.

An FEA model was developed using MIDAS Civil, which is a specialized software for the structural analysis of bridges and civil infrastructure. MIDAS Civil enabled detailed modeling of the bridge's structural properties, boundary conditions, and material characteristics, providing an initial theoretical prediction of its dynamic response. This software facilitated an accurate representation of the bridge geometry and load conditions, allowing meaningful comparisons with the experimental results obtained through FFT and OMA analyses.

IV. RESULTS AND DISCUSSIONS

The dynamic response of the railway bridge is captured using accelerometers placed at seven critical locations along the bridge girder. Figure 2 illustrates the raw acceleration data obtained from the sensors during the performance test, as the train crossed the bridge. The recorded data reflect the bridge response to the live load, showing the dynamic behavior induced by the passing train.

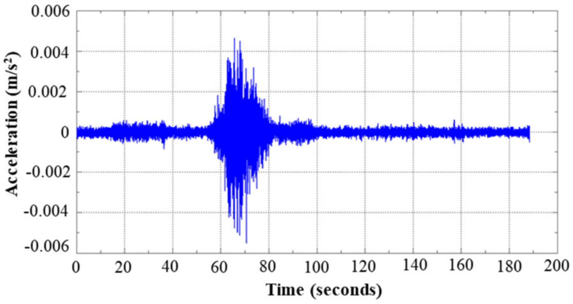


Fig. 2. Acceleration data captured by the sensors.

To extract the fundamental frequencies of the bridge, raw acceleration data were first processed employing FFT. By transforming the time-domain data into the frequency domain, FFT enabled the identification of the dominant frequencies corresponding to the natural vibration modes of the structure. The resulting frequency spectrum is displayed in Figure 3, where the prominent peaks indicate the natural frequencies of the bridge. This information is critical for understanding the dynamic characteristics of bridges and verifying their performances under operational loads.

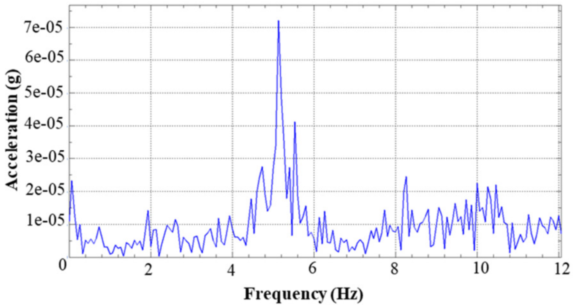


Fig. 3. FFT result.

In parallel, the same acceleration data were analyzed deploying OMA. Unlike FFT, which requires the use of predefined input forces, OMA estimates modal parameters, such as natural frequencies, mode shapes, and damping ratios, by relying solely on the operational forces acting on the structure. This method allows a more comprehensive understanding of the dynamic response of a bridge under realistic conditions. The ARTeMIS Modal for OMA effectively visualizes the bridge response and mode shapes, enabling a precise analysis of the structure's natural frequencies (Figure 4).

Table II lists the frequencies of the structures obtained using the three methodologies, FEA, FFT, and OMA. The results provide valuable insights into the dynamic behavior of railway bridges. A comparison of the fundamental frequencies derived from these methods provided a comprehensive understanding of the response of a structure under operational conditions.

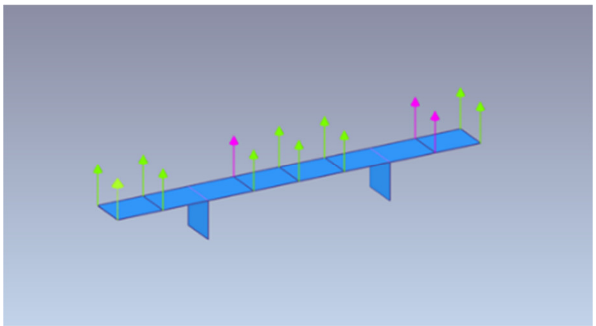


Fig. 4. ARTeMIS Modal visualization.

TABLE II. FUNDAMENTAL FREQUENCIES OBTAINED FROM EACH METHOD.

Method	Frequency (Hz)
FEA	1.65
FFT	1.95
OMA	2.163

The frequency obtained from the FEA was found to be 1.65 Hz. This result serves as the theoretical benchmark because FEA relies on idealized assumptions regarding the material properties, boundary conditions, and applied loads. Although FEA is an essential tool in the design and preliminary analysis of structures, the discrepancy between theoretical and experimental results is often attributed to the inherent simplifications and assumptions made in the modeling process. FEA does not account for real-world operational forces, environmental conditions, or structural imperfections, which may explain its slightly lower predicted frequency compared with FFT and OMA.

The FFT analysis yielded a frequency of 1.95 Hz, which was higher than that of the FEM result. The FFT decomposes the acceleration data into their frequency components by analyzing the vibration response under live loading conditions. The increased frequency compared with FEA can be attributed to the fact that FFT captures the actual behavior of the bridge under operational loads, reflecting the influence of real-world factors that are not typically incorporated into theoretical models. FFT is a reliable method for identifying dominant frequencies, but it does not provide detailed insights into mode shapes or damping ratios.

The highest frequency of 2.163 Hz was obtained through OMA, which relies solely on the ambient and operational forces acting on the structure. The OMA offers a more comprehensive view of the bridge's dynamic behavior by not only estimating the natural frequencies, but also providing information on mode shapes and damping ratios. The higher frequency of the OMA could be because of its ability to capture more realistic boundary and environmental conditions as well as its sensitivity to operational factors that are often difficult to account for in both FEA and FFT analyses. The fact that OMA yields the highest frequency among the three methods suggests that this technique effectively captures the full spectrum of dynamic influences acting on the bridge, offering a more accurate reflection of its real-world performance.

The differences in the frequencies obtained through FEA, FFT, and OMA highlight the importance of combining the theoretical, numerical, and experimental approaches for dynamic analysis. Although FEA provides a foundational understanding of the structure's behavior under idealized conditions, FFT and OMA provide additional layers of accuracy by incorporating real-world data. The higher frequencies obtained from FFT and OMA compared with FEA suggest that the theoretical model may underestimate the stiffness of the structure under actual loading conditions. The OMA, with its capacity to estimate modal parameters without requiring predefined input forces, presents the most realistic representation of a bridge's dynamic performance.

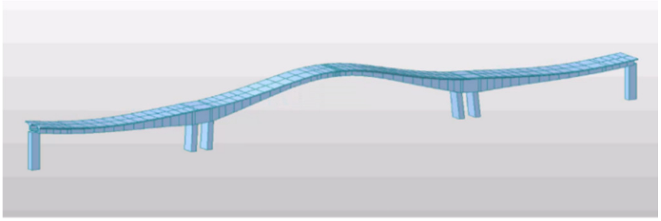
In addition to frequency analysis, a key advantage of OMA over FFT is its ability to estimate the mode shapes of the structure, which provides a more detailed understanding of the bridge's dynamic behavior. Although FFT is effective in identifying the dominant frequencies of the system, it cannot determine the corresponding mode shapes. The mode shapes are essential for visualizing how different parts of a structure deform or vibrate during excitation, and they play a crucial role in identifying the potential structural weaknesses or critical zones of stress.

Compared to similar studies, this research further highlights the efficacy of OMA in capturing operational modal frequencies and mode shapes under realistic loading conditions. Previous studies have primarily used OMA as a standalone method to assess the structural dynamics [1, 19, 26]. However, these studies often lack a comparative analysis with other experimental techniques, such FFT, which is widely applied in practice. The current study incorporates both OMA and FFT, providing a deeper understanding of the bridge's dynamic characteristics by capturing insights into mode shapes through OMA while using FFT as a conventional benchmark. This combined approach offers a more comprehensive validation framework than that of previous studies, which relied mainly on OMA and FEA comparisons.

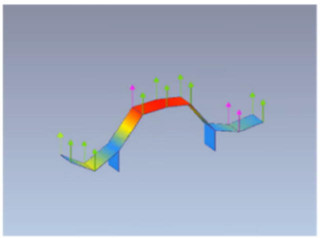
Figure 5 presents a comparison between the mode shapes obtained from OMA and those predicted by the FEA. The mode shapes generated through the OMA were derived from the actual vibration data captured during live loading conditions, offering a realistic representation of how the bridge responds under operational forces. This provides a significant advantage in understanding the behavior of bridges in real-world scenarios.

Upon comparison, the mode shapes obtained from the OMA closely resemble those predicted by the FEA model. This similarity suggests that the FEA model effectively captures the fundamental dynamic characteristics of the bridge despite the inherent assumptions and simplifications. However, the OMA results, based on actual field measurements, validate and enhance confidence in the theoretical predictions made by FEA. The alignment between the two methods confirmed the accuracy of the FEM model and demonstrated OMA’s capability to accurately capture both the natural frequencies and mode shapes of the bridge under real conditions.

The mode shapes obtained through the OMA are critical for structural assessment because they reveal local and global vibration characteristics, highlighting regions that experience higher stress and potential points of fatigue. Additionally, the practical implications of understanding mode shapes extend to bridge health monitoring because these shapes are sensitive indicators of changes in structural stiffness. A deviation in the expected mode shape could signify damage or degradation, allowing engineers to detect early stage issues before they manifest as visible structural faults. Thus, incorporating OMA into bridge health assessments not only provides a deeper understanding of dynamic behavior, but also enhances the predictive maintenance and long-term performance evaluation strategies.



(a) FEA



(b) OMA

Fig. 5. Mode shapes obtained from: (a) FEA and (b) OMA.

V. CONCLUSIONS

The current study provides a comprehensive assessment of the dynamic behavior of a railway bridge through both experimental and numerical methods, demonstrating the novel application of Operational Modal Analysis (OMA) for real-time, field-based structural assessment. By utilizing Fast Fourier Transform (FFT) and OMA to analyze the acceleration data collected from field tests, the bridge's natural frequencies and mode shapes were accurately determined. The results illustrate that OMA, unlike FFT, not only identifies natural frequencies, but also estimates mode shapes directly from operational data, offering a more in-depth and realistic understanding of the structure’s dynamic characteristics. This novel approach underscores OMA's potential to enhance in-situ structural analysis, making it a valuable tool for railway bridge monitoring and expanding the scope of dynamic assessment techniques in civil infrastructure.

The frequencies obtained from OMA (2.163 Hz) and FFT (1.95 Hz) were both higher than those predicted by the Finite Element Analysis (FEA) model (1.65 Hz), indicating some degree of deviation between the experimental results and theoretical predictions. However, the mode shapes derived from OMA are closely aligned with those from FEA, validating the accuracy of the numerical model in capturing the structural behavior.

This comparison highlights the importance of incorporating OMA into bridge monitoring practices as it provides a more realistic representation of the performance of the structure under operational conditions. This study emphasizes that combining experimental techniques, such as OMA with FEA, can enhance the reliability of structural assessments, ultimately contributing to the improved safety and long-term performance of bridges. Further research should explore the impact of different loading conditions and bridge configurations to expand the understanding of dynamic behaviors in various structural contexts.

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DATA AVAILABILITY

The data are available at https://zenodo.org/records/14213675.

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