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* **Corresponding authors**.
abdulwahidwahidi871@gmail.com
Abdulrahman_sorgul@yahoo.com
bashir.aasim83@gmail.com

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Structural Health Assessment of Composite Steel Beams: Evaluating Pre-Damage and Post-Damage States using Modal Analysis

Abdul Wahid Wahidi[1]*, Mohammad Sorgul Abdul Rahman[1]*, Bashir Ahmad Aasim[2]*, Abdul Khaliq Karimi[3]

1 Department of Civil Engineering, Engineering Faculty, Kandahar University, Kandahar 8301, Afghanistan
2 Design Engineer, Hope Design Co., Ltd, Okinawa, Japan
3 Finite Element Analyst, Chuo Construction Consultant Co., Ltd, Okinawa, Japan

Abstract

Background/Objectives: Composite materials, formed by combining two or more distinct substances at the macroscopic level, exhibit enhanced mechanical properties not attainable by individual constituents. In structural engineering, steel composite beams—comprising a steel girder and a reinforced concrete slab connected via shear connectors—serve as a fundamental element in bridge and building construction. This study aims to evaluate the structural health of such composite beams, focusing on their vibrational response before and after sustaining damage under loading conditions. **Methods:** A composite preflex girder was subjected to a four-point bending test to simulate realistic structural loading. The Vibration-Based Damage Detection Method (VDDM) was applied to capture dynamic changes using accelerometer-based measurements. Modal parameters, especially the natural frequencies, were recorded and analyzed for both undamaged and damaged states to assess the impact of structural degradation. **Findings:** The results revealed a consistent and measurable decrease in natural frequencies following the induced damage, indicating a significant reduction in structural stiffness. This frequency drop validates the sensitivity of vibrational parameters to internal damage and confirms their suitability for detecting and quantifying deterioration in composite beams. **Novelty:** This study demonstrates the applicability of the VDDM as a practical, non-destructive tool for real-time structural health monitoring. By applying this method to a full-scale preflex composite beam, the research offers a simplified, cost-effective approach for early damage detection in steel-concrete structures, which is essential for ensuring structural safety and prolonging service life.

Keywords: Structural health monitoring; Preflex beam; Natural frequency; Non-destructive testing; Damage detection

1 Introduction

Composite steel-concrete beams, due to their ability to combine the compressive strength of concrete with the tensile resilience of steel, have become an integral component in modern infrastructure. Their growing application in bridges and buildings calls for reliable and efficient structural health monitoring (SHM) techniques to ensure long-term performance and safety. Damage in such systems, including cracking and material fatigue, can critically affect serviceability and lead to catastrophic failure if left undetected.

Over the past decade, numerous researchers have explored non-destructive evaluation (NDE) methods to detect damage in structural systems. Among these, vibration-based methods have gained prominence due to their sensitivity to changes in dynamic properties such as natural frequency, damping, and mode shapes. Studies such as those by Sridhar and Prasad[1], Aasim et al.[2–5], and Romer et al.[6] confirm the effectiveness of frequency-based metrics in identifying stiffness degradation.

However, a critical gap remains in the application of these techniques under field conditions. Traditional laboratory setups often require fixed equipment, sophisticated computational resources, and post-processing steps that limit real-time applicability. Recent innovations have attempted to address these constraints [7-10,15,16]. For instance, Sharma et al.[7] implemented machine learning to enhance the interpretability of vibrational data, while Wang and Zhou[8] proposed hybrid sensor networks for multimodal data acquisition. Despite these efforts, challenges related to cost, computational load, and deployment complexity persist.

Our study builds on these advancements by proposing a simplified, portable system that employs VDDM using accelerometers. The system is designed to detect reductions in natural frequency due to structural damage and has been tested on a full-scale preflex beam—a critical component in bridge design that combines prestressed concrete with steel framing for enhanced load resistance of the specimen as shown in figure 1. The goal is to deliver an efficient, low-cost SHM tool that is deployable in real-time and suitable for in-situ monitoring.

Fig 1. Tested samples of concrete

2 Methodology

2.1 Girder Specifications

The test specimen selected for this study was a 5-meter-long preflex composite beam designed to simulate real-world bridge components. The steel girder had flange and web thicknesses of 16 mm and 9 mm, respectively, offering a balance between strength and flexibility as shown in figure 2. Reinforcement was provided using 16 mm longitudinal bars and 10 mm transverse stirrups. Shear ribs were strategically placed at varying intervals to analyze their effect on stiffness and vibration characteristics. This heterogeneous configuration allowed for a detailed assessment of how reinforcement and shear components influence modal response.

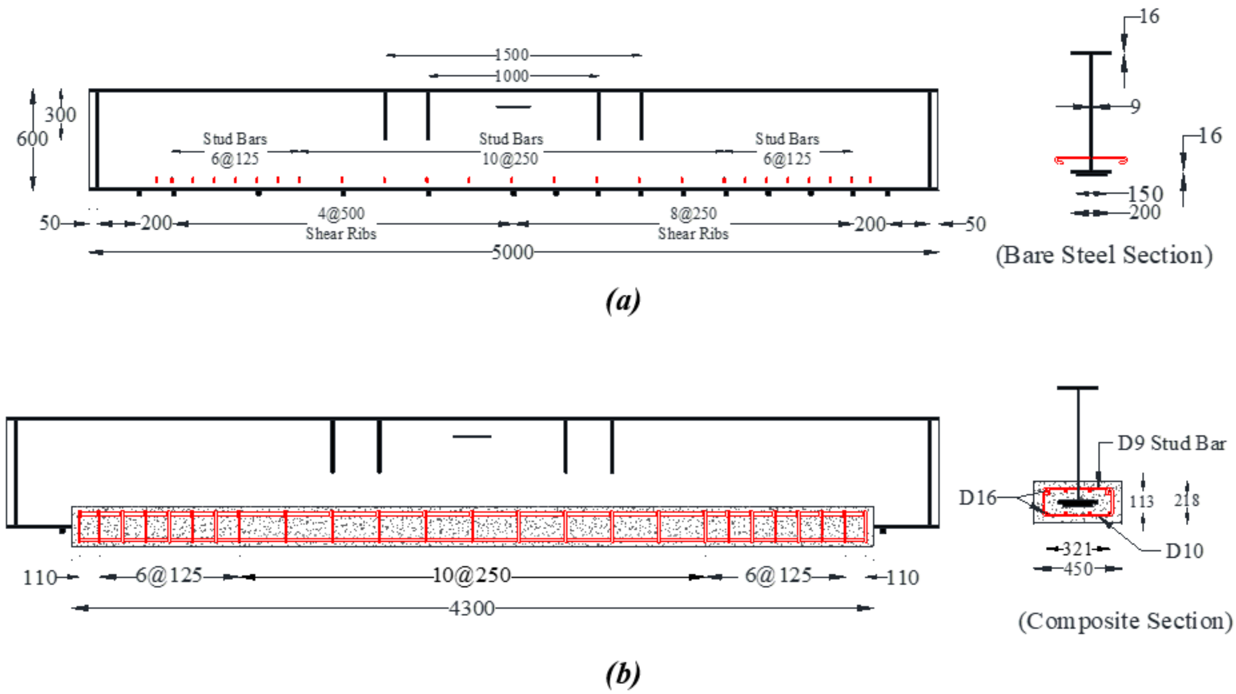

Fig 2. Geometric specifications of the beam, (a) steel frame, (b) composite section

2.2 Preflexing beam

The construction of the preflex beam adhered to standard prestressed composite girder practices. Initially, a steel I-girder was subjected to an upward camber using four-point bending. While held in this cambered position, a concrete flange was cast onto the bottom flange of the girder. After the concrete attained its target strength, the external load was removed, inducing compressive prestress into the concrete section through the elastic recovery of the steel.

Preflex technology, first introduced in Belgium and Japan during the 1950s and later adopted in Germany, the UK, and South Korea, efficiently combines steel and concrete to enhance stiffness and load-bearing capacity. The concrete flange, located in the tensile zone, contributes approximately 35–40% to the total moment of inertia of the cross-section under live loads[(6)]. This composite action improves structural efficiency and enables the design of slender members.

Prestressing is typically achieved through pre-deflection (cambering), although it can also involve prestressed tendons. In some cases, a combination of both methods is employed to optimize strength and serviceability[(9,10)]. The concrete flange must be prestressed to avoid cracking throughout its service life, especially as it lies in the tensile region.

The key stages of preflex construction are summarized in Figure 3.

Stage 1: Pre-cambering of the steel girder through four-point bending.

Stage 2: Casting of the concrete flange while the steel is in tension.

Stage 3: Release of external loads to prestress the concrete.

Stage 4: Transportation and final casting of the upper deck and components on site.

Stage 5: Installation of finishing components and opening for service.

Preflex beams are widely applied in short- to medium-span railway and highway bridges due to their durability, slenderness, and resistance to deflection.

2.3 Vibration theory

The vibrational behavior of the preflex beam was analyzed using classical beam vibration theory. For a uniform, simply supported beam, the governing differential equation of motion relates the beam's transverse displacement to its material and geometric properties.

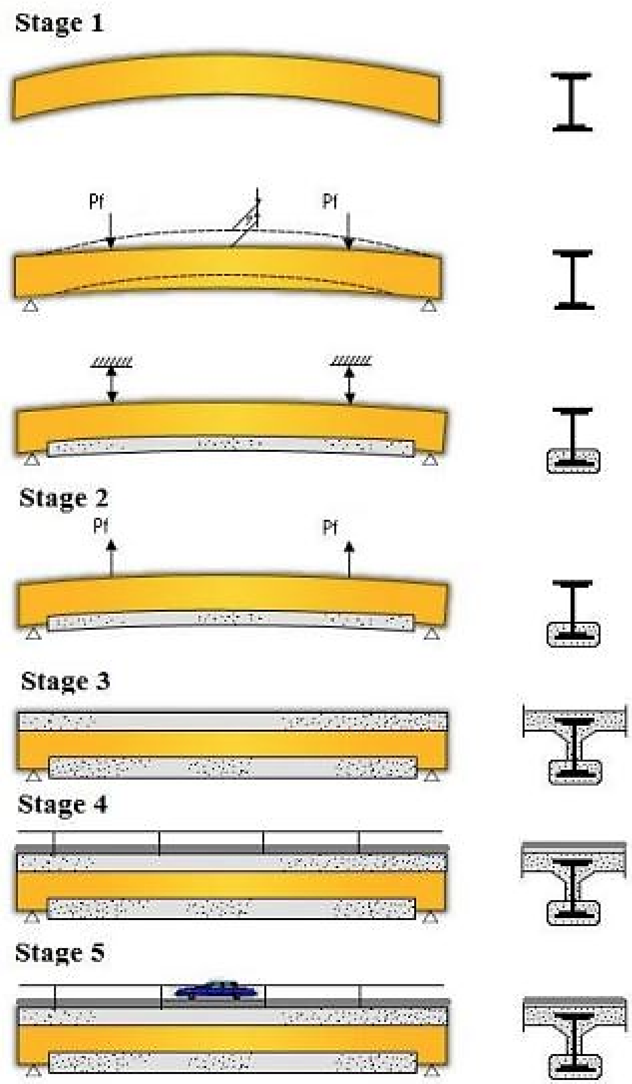

Fig 3. Construction stages of preflex beam

The analysis begins with the standard beam equation that accounts for mass density, cross-sectional area, Young's modulus, and moment of inertia. For a uniform beam, this equation simplifies considerably, allowing for a solution approach using separation of variables.

By assuming harmonic motion and applying the appropriate boundary conditions for a simply supported beam (zero displacement and bending moment at both ends), we derived the natural frequencies of vibration:

$$\omega_n = \lambda^2 \nu = \left(\frac{n\pi}{L}\right)^2 \sqrt{\frac{EI}{\rho A}} \; (n = 1, 2, \ldots) \tag{1}$$

Where L is the beam length, E is Young's modulus, I is the moment of inertia, ρ is the density, A is the cross-sectional area, and n is the mode number.

The corresponding mode shapes follow a sinusoidal pattern described by:

$$X(x) = C_2 \sin\left(\frac{n\pi x}{L}\right) \tag{2}$$

These theoretical frequencies served as a reference to compare with experimental measurements, enabling the quantification of stiffness degradation due to structural damage

3 Experimental program

3.1 Measurement under excitation

The experimental setup was designed for accuracy and repeatability in vibration measurement. A high-sensitivity AS-10TG accelerometer was mounted at the beam's mid-span to capture vertical motion. The data acquisition system (EDX-10A) recorded time-series data at a sampling frequency of 210 Hz. Dynamic excitation was induced using a calibrated 2.55 kg rubber hammer, applied consistently from a fixed height. Figure 4 and figure 5 show data acquisition system and position of the sensor.

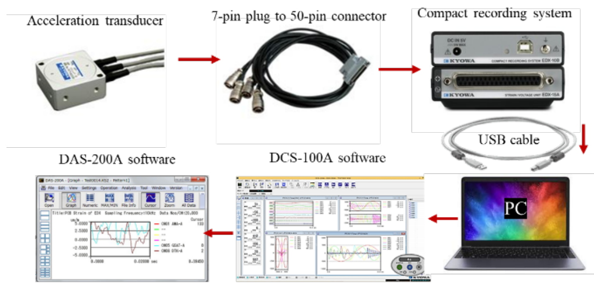

Fig 4. Vibration-based data acquisition system

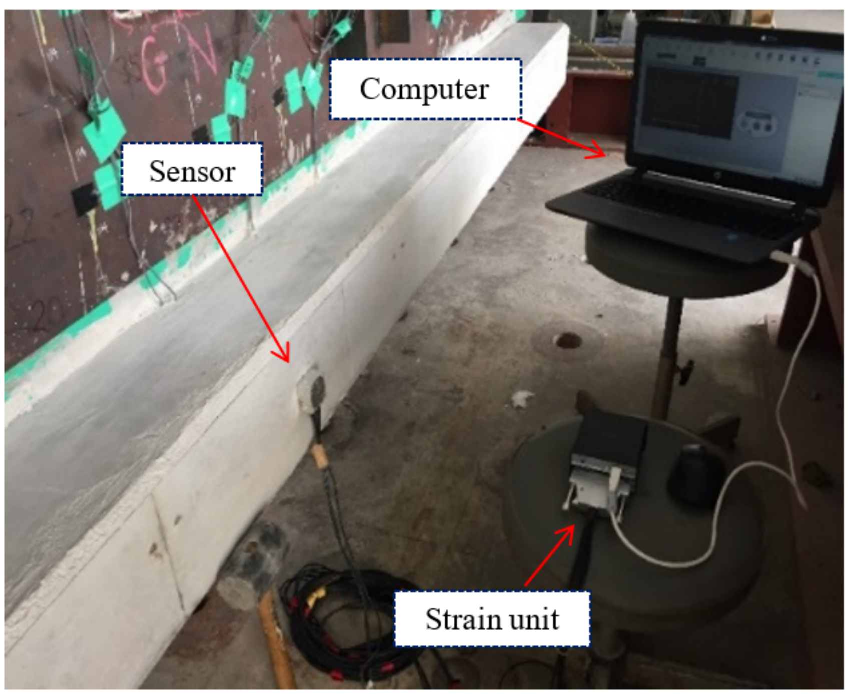

Fig 5. Sensor position and acceleration data recording from the specimen

Initial tests were conducted on the intact beam to establish a baseline for natural frequencies. The specimen was then subjected to a four-point bending test, during which cyclic loads were applied until visible cracks appeared in the lower concrete flange. Vibration data was then collected again in the damaged state. Three consecutive tests were performed for both conditions to ensure statistical consistency. The experimental program was executed under controlled laboratory conditions to minimize environmental noise and interference. Figure 6 and Figure 7. illustrate the bending load configuration and data recording of the post-damage state of the girder.

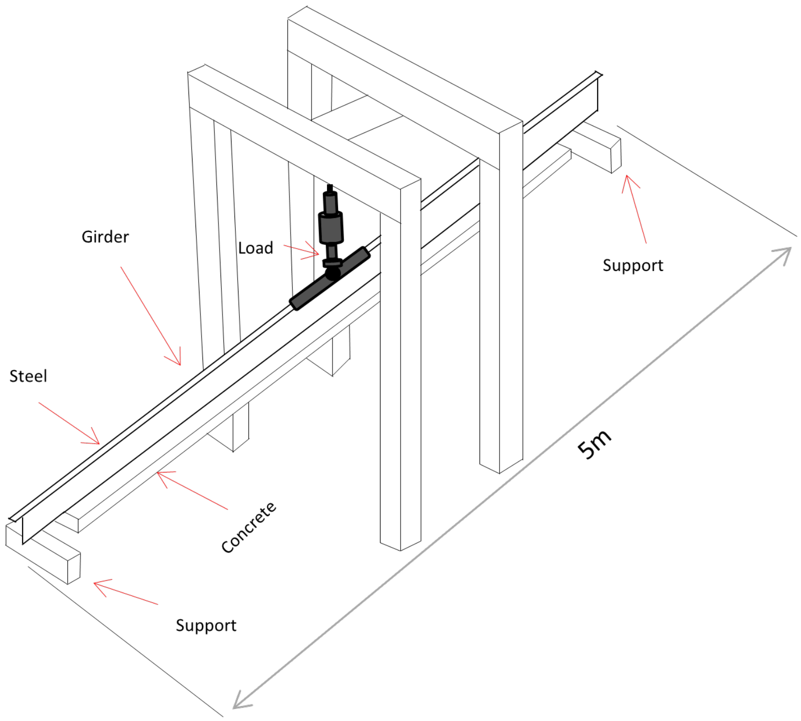

Fig 6. Four-point bending test application

Fig 7. Data acquisition of post-damage state of the girder

4 Results and Discussion

4.1 Results

The natural frequencies obtained from the three test runs for the undamaged and damaged states are shown in Table 1.

Table 1. Comparison of experimental natural frequencies

State	Test 1	Test 2	Test 3	Avg	% Drop
Undamaged	27.3 Hz	27.32 Hz	27.3 Hz	27.31	-
Damaged	25.2 Hz	25.17 Hz	25.26 Hz	25.21	7.7%

The undamaged beam exhibited a highly consistent fundamental frequency around 27.3 Hz, confirming its initial integrity. Post-damage testing revealed a consistent frequency drop of approximately 2.1 Hz, or 7.7%, across all trials. The observed reduction is attributed to the loss of stiffness due to cracking in the concrete flange. These results align with theoretical expectations and provide compelling evidence that changes in natural frequency can serve as reliable indicators of internal damage.

4.2 Discussion

This study confirms the feasibility of using natural frequency shifts for structural damage assessment in composite beams. Compared to other techniques such as frequency response function analysis or wavelet decomposition, the method demonstrated here is simpler to implement and interpret.

Our system achieved high sensitivity with a frequency shift of 7.7%, surpassing previous reports of 4–6% changes for similar damage levels[1]. The portable configuration allowed for quick deployment and minimal setup, making it suitable for on-site inspections[11]. In contrast to Aasim et al.[3,4], who required post-processing to filter and interpret data, our system enabled near real-time evaluation. Moreover, Sharma et al.[7] utilized machine learning algorithms to identify frequency anomalies but required significant computational power. Vu et al.[12] used frequency data in combination with machine learning for beam damage detection. Wang and Zhou's approach[8], while robust, involved a hybrid network of sensors and complex integration, which may not be cost-effective for small-scale monitoring.

The results obtained also highlight the repeatability and accuracy of the portable setup used. The consistent readings across all trials support the reliability of VDDM in capturing subtle structural changes. Furthermore, the test configuration, which involved realistic damage simulation using four-point bending, adds practical relevance to the study. These findings advocate for broader adoption of low-cost, high-sensitivity vibration-based SHM tools, especially in resource-constrained environments.

5 Conclusion

This study confirms that vibration-based techniques, particularly those relying on changes in natural frequency, are effective in identifying damage in composite steel-concrete beams. A 7.7% drop in the first natural frequency post-damage indicates a significant loss of stiffness, which aligns with both theoretical predictions and previous experimental findings.

The novelty of this study lies in its implementation of a portable, easy-to-use VDDM system on a full-scale preflex beam. Compared to conventional approaches, this system provides a balance of accuracy, cost-efficiency, and real-time operation. It addresses key limitations observed in earlier work, including excessive computational requirements and lack of field applicability.

However, the study has certain limitations. Environmental variables such as humidity, ambient temperature, and noise were not rigorously controlled. These factors can influence sensor readings and should be accounted for in future studies. Additionally, the current approach is limited to detecting frequency shifts. More complex damage patterns may require the incorporation of mode shape and damping analyses.

Future work will focus on extending this methodology to large-scale bridge monitoring systems, incorporating wireless data transmission and machine learning for automated damage classification. Ultimately, this work contributes toward the development of scalable, non-invasive SHM solutions capable of ensuring structural safety across a range of civil engineering applications.

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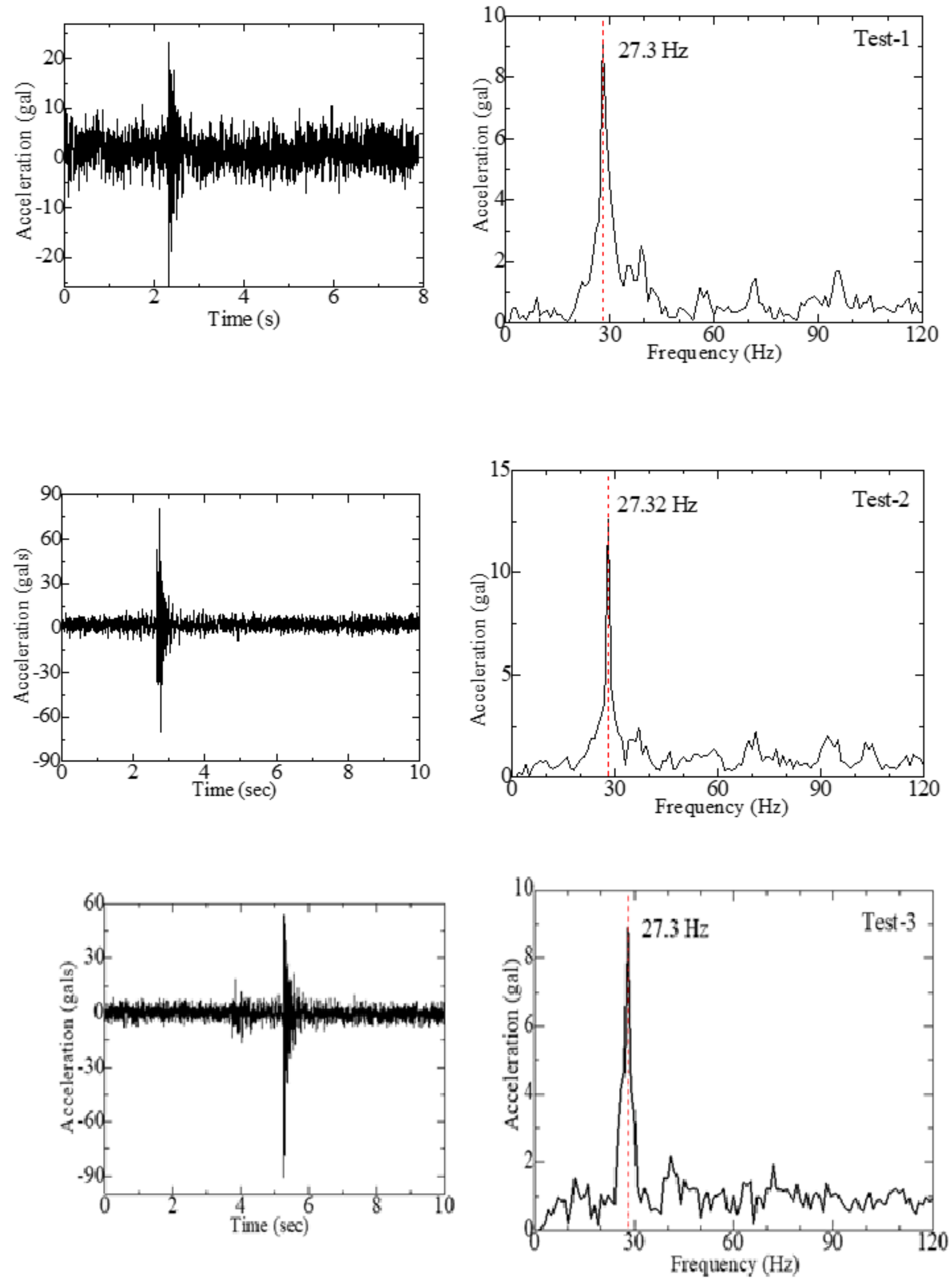

Fig 8. Girder response in initial intact state

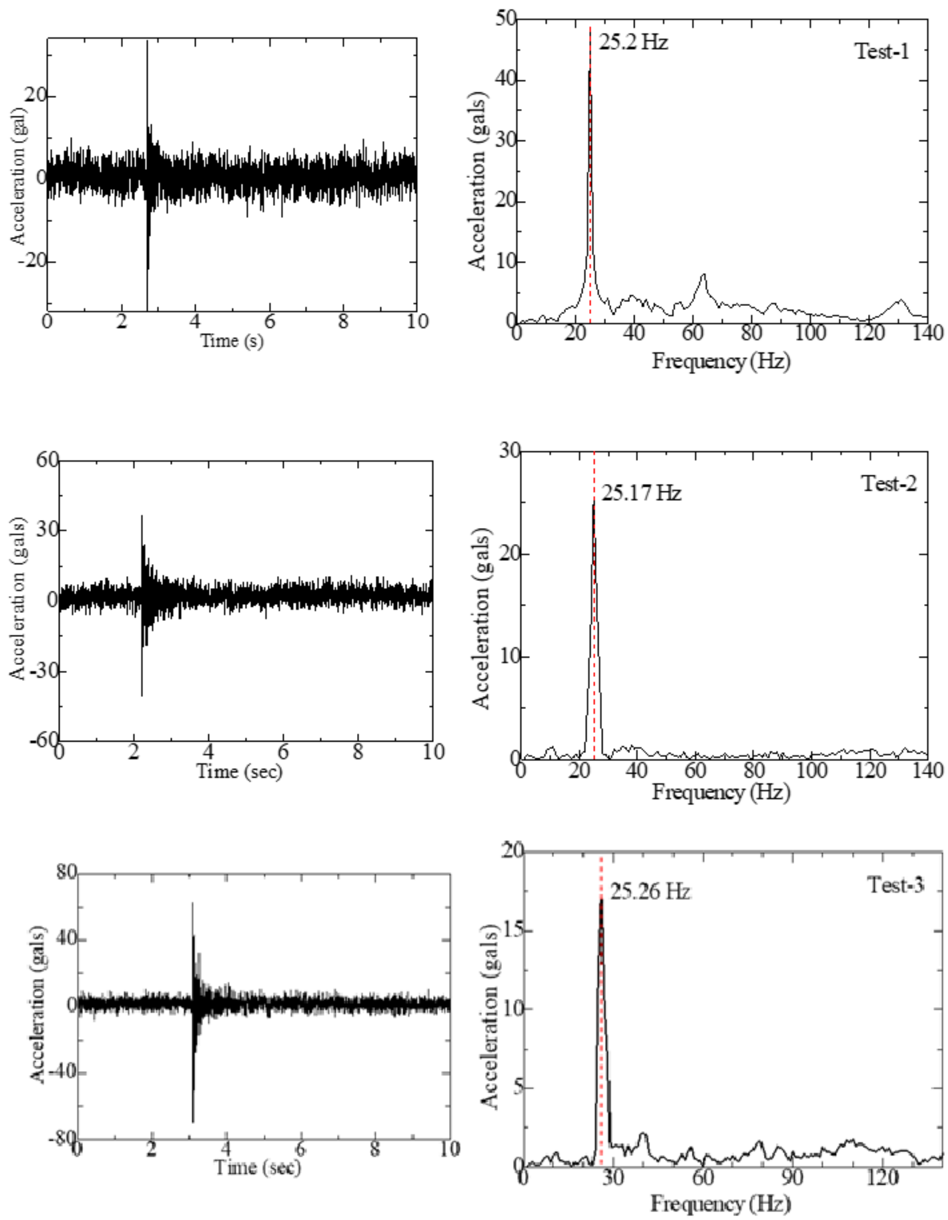

Fig 9. Girder response after the bending test (post-damage)

7 Conflict of interest

The authors confirm that there is no conflict of interest with any individual, organization or institution.

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