

Vibration and Modal Analysis for Damage Detection in Cantilever Beams: Assessing Presence, Location, and Severity Through Numerical and Experimental Approaches

RAKESH KATAM, GOVARDHAN POLEPALLY,
VENKATA DILIP KUMAR PASUPULETI
and PRAFULLA KALAPATAPU

ABSTRACT

Ensuring the reliability and safety of engineering structures requires an accurate assessment of structural damage. This study employs analytical, computational, and experimental techniques to detect and evaluate the presence, location, and severity of damage in a cantilever beam. A vibration-based approach is utilized, focusing on key modal parameters such as natural frequencies and mode shapes to assess structural integrity. And to simulate the beam's dynamic behaviour under various damage conditions, a finite element model (FEM) is developed. Experimental validation is carried out through vibration testing, where frequency shifts and mode shape variations are recorded for different damage locations and depths. The results indicate a strong correlation between damage severity and changes in modal properties, with a noticeable decrease in natural frequencies and alterations in mode shape curvature as damage intensity increases.

A total of 19 numerical and experimental case studies are conducted, achieving approximately 90% accuracy in identifying the presence, location, and severity of damage. This study also presents a comparative analysis of numerical predictions and experimental findings, demonstrating the effectiveness of frequency-based damage assessment. The proposed approach offers a reliable and scalable method for structural health monitoring, making it suitable for real-world engineering applications. These findings contribute to the advancement of damage detection techniques, enabling early intervention and enhancing overall structural safety.

Keywords: Damage Assessment, Vibration Analysis, Modal Analysis, Natural frequencies, experimental studies.

Rakesh Katam, PhD Student, Mahindra University, Hyderabad, India

Email: rakesh20pcie002@mahindrauniversity.edu.in

Govardhan Polepally PhD Student, Mahindra University, Hyderabad, India

Email: govardhan20pcie009@mahindrauniversity.edu.in

Venkata Dilip Kumar Pasupuleti, Associate Professor, Mahindra University, Hyderabad, India

Email: venkata.pasupuleti@mahindrauniversity.edu.in

Prafulla Kalapatapu, Assistant Professor, Mahindra University, Hyderabad, India

Email: prafulla.kalapatapu@mahindrauniversity.edu.in

INTRODUCTION

Structural Health Monitoring (SHM) has emerged as a critical discipline for ensuring the long-term safety and reliability of civil, mechanical, and aerospace structures. It involves the continuous or periodic assessment of structural conditions using integrated sensor networks and diagnostic algorithms that interpret dynamic responses. This monitoring aims not only to detect failure when it occurs but to identify its location at its earliest stages, thereby enabling proactive maintenance and reducing the likelihood of catastrophic failure. The basic foundation of SHM is to compute the data obtained from instrumentation for finding dynamic characteristics of the system, which helps in deriving the damping as well as the existence of the damage [1,2]. These approaches often have a lower cost than alternatives since they are robust and conceptually straightforward. When employing data-driven methodologies, Vibration-based SHM (VBSHM) for damage detection may be evaluated using both parametric and non-parametric methods [3]. Parametric assumes the structure responds in some predetermined manner that can be simulated by an analytical or numerical model, such as the usually used finite element model (FEM). Non-parametric methods do not assume a predefined model structure. They rely on data-driven techniques to extract features or detect changes directly from measurements.

Research utilising parametric approaches, such as those by Shadan et al. [4] and Kindova-Petrova [5], highlights the critical role of integrating parameter-based models with Finite Element Method (FEM) simulations for validating empirical observations. The creation of sophisticated parametric models that can replicate intricate damage mechanisms is essential for enhancing the accuracy of crack detection strategies. These models support both Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA) by providing a structured framework for interpreting dynamic responses and evaluating detection performance. While EMA depends on predefined excitation conditions, which may not always be feasible in practical settings, OMA, benefiting from natural operational data, presents a more adaptable option for field-based SHM [6].

Recent studies in SHM have increasingly relied on non-parametric, data-driven approaches for detecting and localising damage. Techniques developed by researchers such as Das et al. [7] and Yan et al. [8] utilise vibration-based features and ambient response data to infer the presence of structural anomalies without requiring predefined physical models. These methods often focus on extracting modal characteristics such as frequencies, mode shapes, and their derivatives to highlight deviations caused by damage. For example, Roy et al. [9] demonstrated that changes in mode shape curvature can effectively pinpoint damage locations, while Wang et al.'s [10] MSERV method introduced a way to isolate damage effects using mathematical decoupling. Likewise, Chinka et al. [11] and Ooijsaar et al. [12] advanced non-parametric detection by combining higher-order modal parameters and curvature-based indices to assess the presence, location, and severity of cracks. Additionally, sensor placement strategies, like the Effective Independence (EI) technique by Hung et al. [13], further enhance the reliability of these vibration-based systems by optimising data collection points. Altogether, these studies underscore the value of non-parametric approaches in SHM, especially where physical modelling is complex or infeasible.

SHM has evolved significantly with the integration of non-parametric, vibration-based techniques that detect and localise damage using measured dynamic responses

rather than predefined structural models [14]. These methods leverage changes in modal parameters such as natural frequencies, mode shapes, and their derivatives to identify anomalies, offering flexibility and efficiency in real-time monitoring. Advancements in sensor placement and data interpretation have further improved detection accuracy, making non-parametric approaches increasingly vital in complex or operationally constrained environments.

METHODOLOGY

The novel methodological framework is designed to detect, locate, and quantify cracks in steel cantilever beam structure through vibration-based analysis, as is illustrated in Figure 1. Recognising the shortcomings of traditional methods that rely solely on frequency shifts, particularly their reduced sensitivity to small-scale damage and limited spatial resolution, a new hybrid approach is proposed: Frequency-Derived Mode Shape Curvature (FDMC).

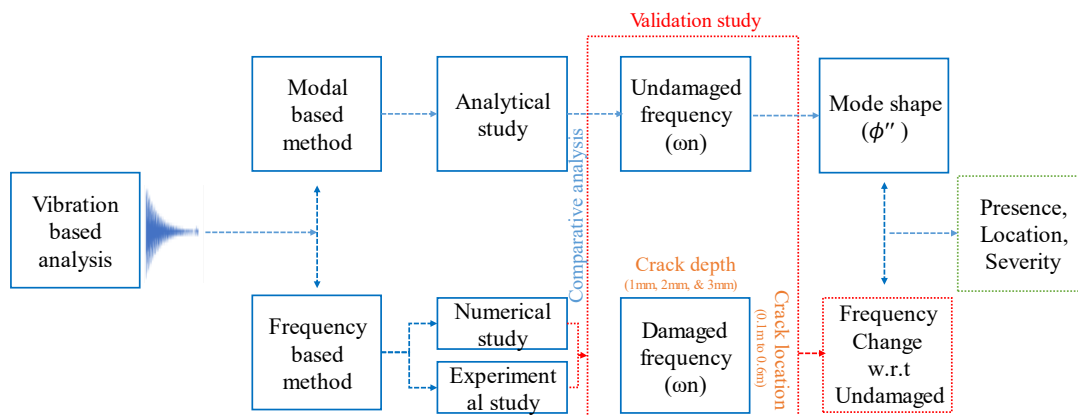


Figure 1. The methodological workflow is considered for the study.

The methodology progresses through several structured phases. Initially, modal frequencies are extracted from vibration response data using both time-domain and frequency-domain tools. However, earlier studies have shown that frequency changes alone can be inconclusive due to modal insensitivity and the influence of environmental variability. To overcome this, FDMC integrates frequency and mode shape information by analysing how specific frequency components interact across spatial vibration patterns.

The second phase introduces a coupling mechanism that links changes in frequency with variations in mode shape curvature. Instead of treating these parameters independently, FDMC quantifies their co-evolution, offering a more robust signal for damage detection, localisation, and severity. This is achieved through spectral decomposition techniques, including the Fast Fourier Transform (FFT), and enhanced by curvature-based mode shape derivatives. By correlating frequency shifts with geometric distortions in mode shapes, FDMC identifies damage with greater localisation precision.

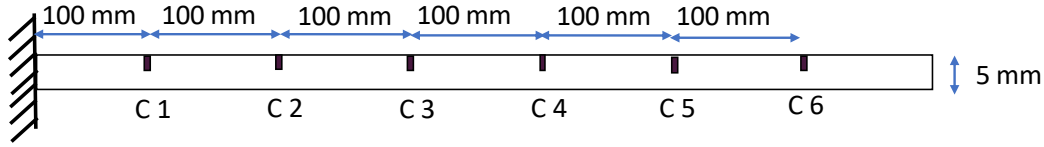


Figure 2. Locations of the cracks for both numerical and experimental studies.

To test the method's scalability and performance under different operational conditions, a numerical study and experimental study using sensor data are conducted at multiple crack locations as shown in Figure 2. The method does not rely on prior structural models, making it applicable to a wide range of beam-like systems.

TABLE I. MATERIAL PROPERTIES

Material	Density (ρ)	Young's modulus (E)	Moment of inertia (I)
Steel	7850 kg/m ³	2.1 X 10 ¹¹ N/m ²	260.41X 10 ⁻¹¹ m ⁴

To simulate the structural behavior of the cantilever beam and validate the proposed methodology, a comprehensive finite element model (FEM) was developed using ANSYS software with the mesh size of 2mm. The model was constructed to closely replicate the geometry and boundary conditions of the experimental specimen. The modelled beam consisted of mild steel with dimensions of 0.7 m in length, 0.025 m in breadth, and 0.005 m in depth. The material properties were considered from Table I.

RESULTS AND DISCUSSION

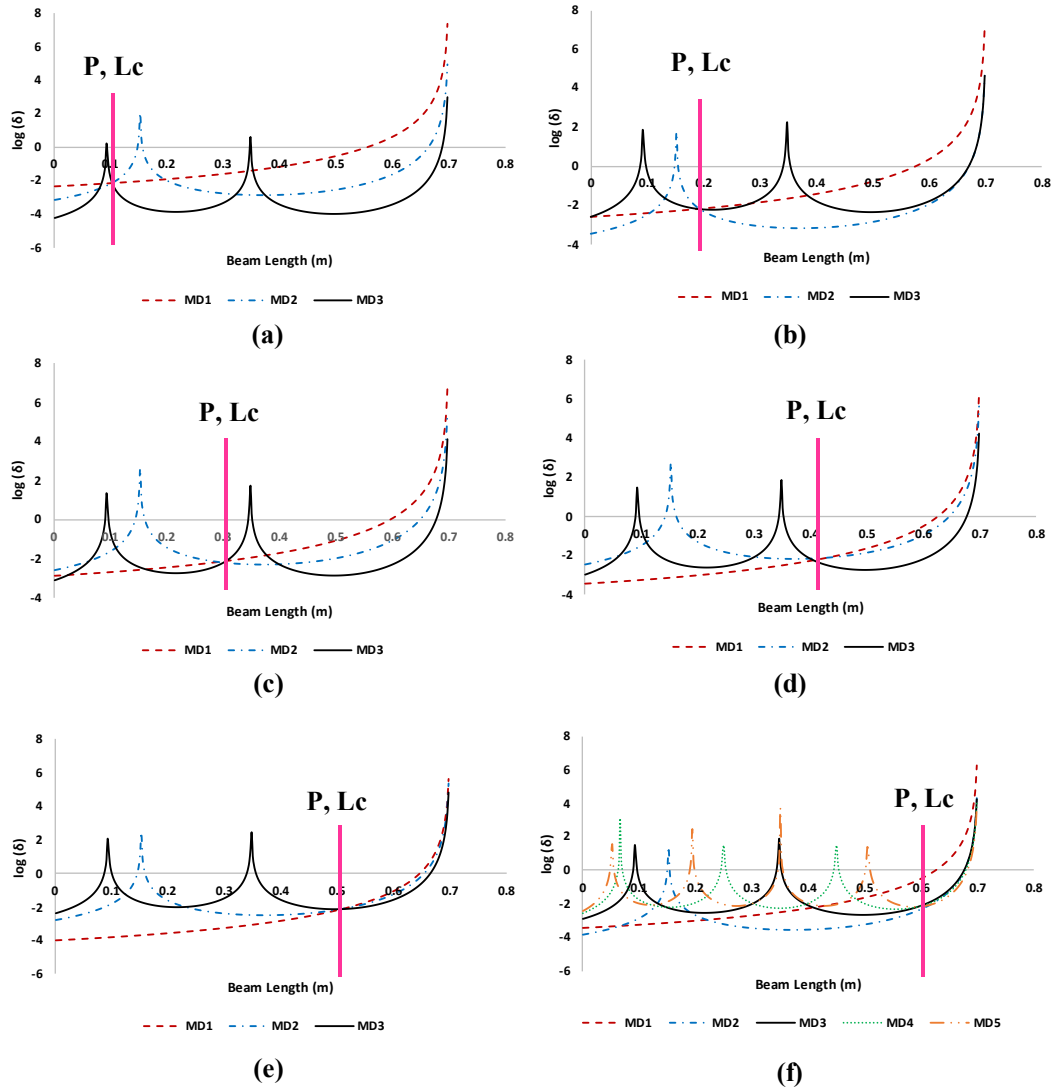
The study presents and examines the outcomes derived from the application of a newly developed technique aimed at improving the precision of identifying the damage detection, its location and severity for a steel cantilever beam. The proposed approach systematically analyses the dynamic behaviour patterns observed in both experimental measurements and numerical simulations. By comparing these patterns with analytical reference solutions, the method not only validates its effectiveness but also highlights the advantages over traditional vibration-based detection methods. Through this integrated evaluation, the strengths, limitations, and practical implications of the FDMC technique are critically assessed, providing a deeper understanding of its performance across varying crack scenarios, damage severities, and sensor configurations.

Numerical Study

As mentioned above, 18 damaged cases are used to understand the damage presence, its location, and severity from the numerical model, with the induced crack depths of 1 mm, 2 mm, and 3 mm. The locations of the cracks are considered at 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, and 0.6 m from the fixed end. Each crack depth is identified for different locations of the damage as follows, and the Undamaged specimen is provided with the first three bending frequencies (F1– 8.34 Hz; F2- 52.23 Hz; and F3- 146.61 Hz)

CASE_ 1: LOCATION IDENTIFICATION WITH CRACK DEPTH 1mm

The natural frequencies for various crack locations, each with a 1 mm depth, were analysed in this study. Due to the beam's structural characteristics and support conditions, only bending modes were selected for investigation. To assess the presence (P) and location (Lc) of cracks, the first three to five bending modes were extracted and examined, as illustrated in Figure 3.



MD1- mode difference-1; MD2- mode difference-2; MD3- mode difference-3; MD4- mode difference-4; MD5- mode difference-5

Figure 3. Crack presence and location prediction from numerical analysis for 1mm intensity (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, (d) 0.4 m, (e) 0.5 m, (f) 0.6 m.

TABLE II. THE FIRST THREE BENDING FREQUENCIES NUMERICAL ANALYSIS (CASE 1)

Location	F1 (Hz)	$ \Delta f1 $	F2 (Hz)	$ \Delta f2 $	F3(Hz)	$ \Delta f3 $
0.1	8.30	0.0048	52.19	0.0008	146.22	0.0001
0.2	8.31	0.0028	52.21	0.0004	145.81	0.0027
0.3	8.33	0.0013	52.09	0.0028	146.09	0.0008
0.4	8.33	0.0004	52.05	0.0035	146.05	0.0011

0.5	8.34	0.0001	52.14	0.0018	145.63	0.0040
0.6	8.34	0.0004	52.23	0.0002	146.04	0.0012

For the first bending mode, the frequency values range between 8.30 Hz and 8.34 Hz. It was observed that specimens with cracks positioned further from the fixed end exhibited slightly higher frequencies, reflecting lesser stiffness loss. This outcome aligns with the fundamental principle that structural stiffness is more significantly compromised when damage occurs closer to the fixed boundary. Similarly, the second and third bending modes demonstrated frequencies between 52.05 Hz – 52.23 Hz and 145.63 Hz – 146.22 Hz, respectively, reinforcing the trend that damage near the support has a greater impact on reducing the natural frequencies, as shown in Table II. In the case of the undamaged beam (Numerical Undamaged, NUD), the first three bending frequencies were recorded at 8.34 Hz, 52.23 Hz, and 146.21 Hz, serving as baseline references for comparison against the damaged scenarios.

CASE_2: LOCATION IDENTIFICATION WITH CRACK DEPTH 2mm

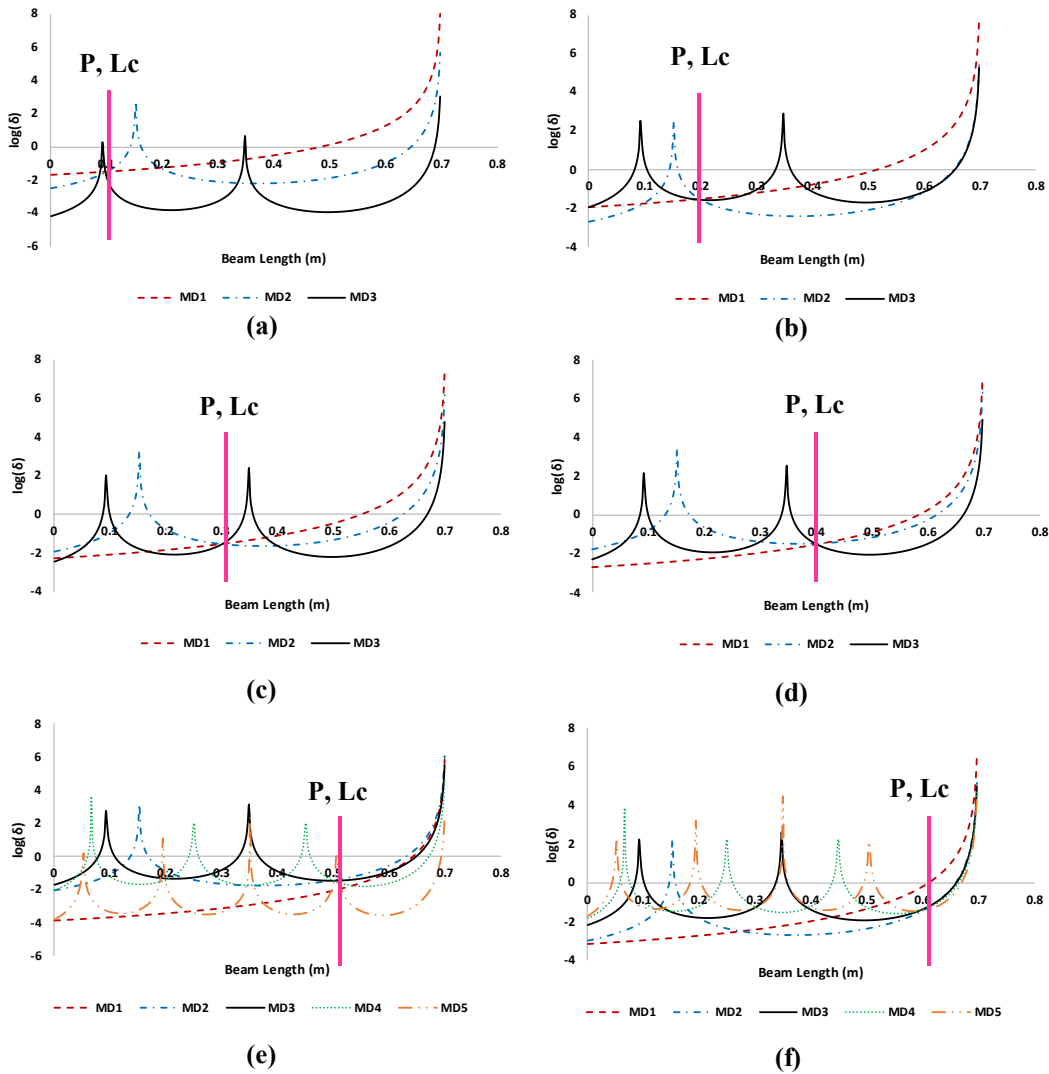


Figure 4. Crack presence and location prediction from numerical analysis for 2mm intensity (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, (d) 0.4 m, (e) 0.5 m, (f) 0.6 m

In this case, the natural frequencies associated with a 2 mm crack depth at various locations along the beam were evaluated, as presented in Table III. Similar to the previous analysis, only bending modes were considered due to the beam's uniform cross-section and boundary conditions favouring flexural behaviour. The first three to five bending modes were extracted to study the influence of crack presence (P) and its position (Lc). Figure 4 illustrates the presence and location of different crack locations for the damage intensity of 2mm.

TABLE III. THE FIRST THREE BENDING FREQUENCIES NUMERICAL ANALYSIS
(CASE 2)

Location	F1 (Hz)	 \Delta f1 	F2 (Hz)	 \Delta f2 	F3(Hz)	 \Delta f3
0.1	8.16	0.0215	52.06	0.0034	146.22	0.0001
0.2	8.24	0.0119	52.13	0.0020	144.40	0.0124
0.3	8.29	0.0056	51.61	0.0119	145.69	0.0036
0.4	8.32	0.0021	51.40	0.0160	145.47	0.0051
0.5	8.34	0.0001	51.78	0.0087	143.39	0.0193
0.6	8.34	0.0007	52.18	0.0011	145.30	0.0062

CASE_3: LOCATION IDENTIFICATION WITH CRACK DEPTH 3mm

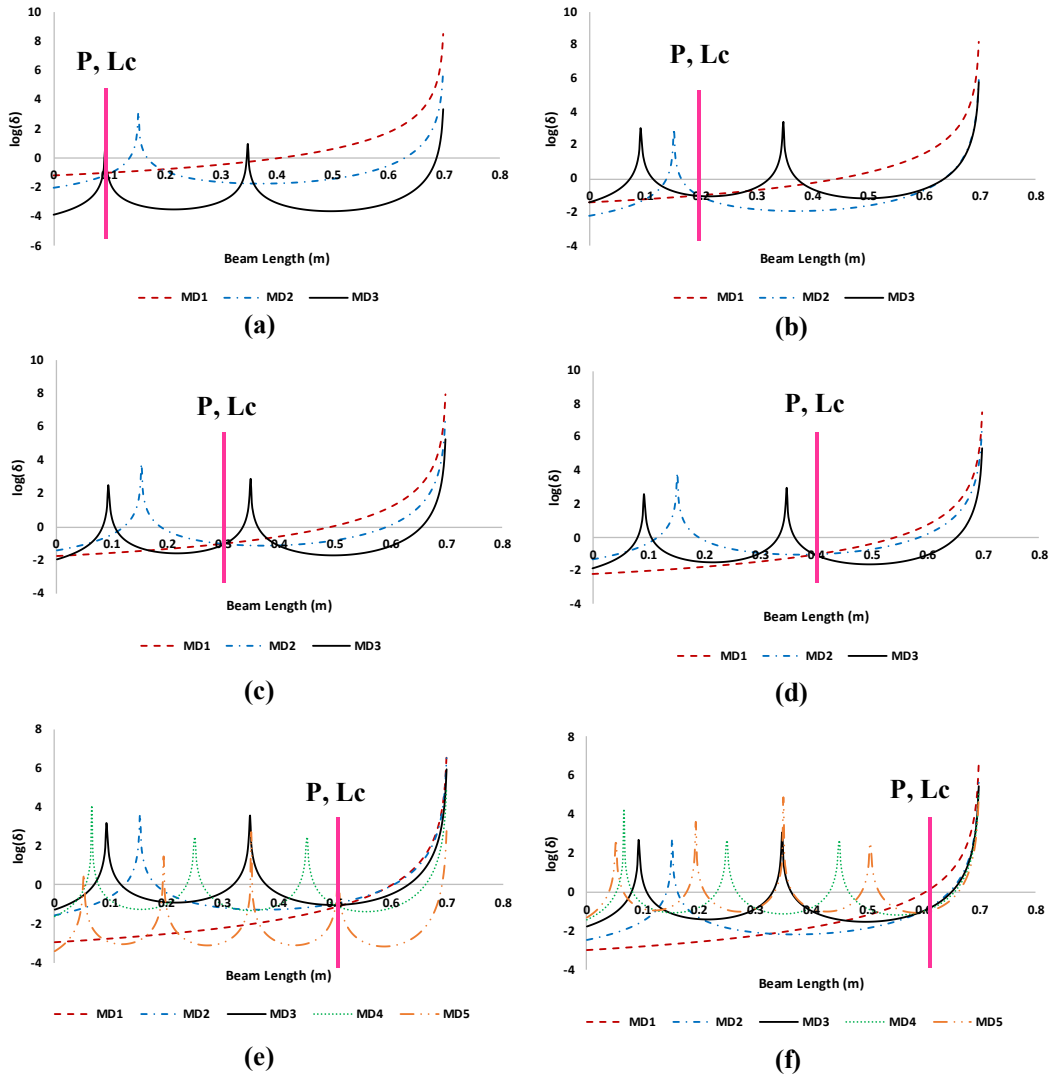


Figure 5. Crack presence and location prediction from numerical analysis for 3mm intensity (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, (d) 0.4 m, (e) 0.5 m, (f) 0.6 m

For Case 3, the study focuses on evaluating the natural frequencies corresponding to different crack locations, each with a 3 mm depth, as summarised in Table IV. Consistent with earlier cases, only bending modes were analysed, considering the beam's uniform geometry and support conditions that predominantly encourage flexural vibrations. The first three to five bending modes were extracted and assessed to investigate the effects of crack presence (P) and location (Lc). Figure 5 visually represents the crack positions and their locations in the beam.

TABLE IV. THE FIRST THREE BENDING FREQUENCIES NUMERICAL ANALYSIS (CASE 3)

Location	F1 (Hz)	\Delta f1	F2 (Hz)	\Delta f2	F3(Hz)	\Delta f3
0.1	7.82	0.0622	51.73	0.0096	146.19	0.0001
0.2	8.03	0.0372	51.89	0.0066	140.68	0.0378
0.3	8.18	0.0186	50.20	0.0389	144.55	0.0114
0.4	8.28	0.0069	49.69	0.0488	144.02	0.0150
0.5	8.33	0.0011	50.86	0.0263	138.2	0.0548
0.6	8.35	0.0010	52.07	0.0032	143.6	0.0179

Experimental Study

This experimental investigation aims to validate the numerical findings related to crack detection and localisation in cantilever beam structures using vibration-based analysis. The study replicates three distinct damage scenarios, each characterised by a 1 mm crack depth positioned at various locations along the beam. Consistent with the numerical simulations, the experimental results exhibit similar trends in natural frequency variations across the different cases. However, it was observed that the actual crack locations (Figure 6) often fell between the installed sensor positions, leading to slight discrepancies in pinpointing the exact damage sites. Notably, the experimental outcomes for the third model (Model_3) closely align with the results obtained from the first two models (Model_1 and Model_2), reinforcing the reliability and consistency of the proposed detection methodology across varying damage conditions. For the scenario of undamaged, the obtained frequencies are F1- 7.69 Hz, F2- 37.79 Hz, and F3- 134.8 Hz.

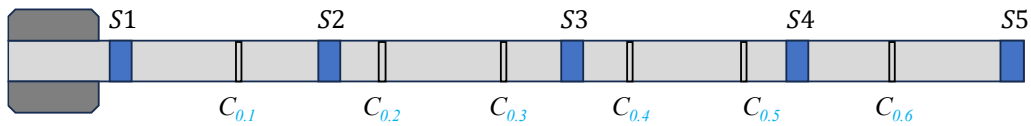


Figure 6. Different crack locations were used for the experimental study for the sensor placement.

Model_3: LOCATION IDENTIFICATION WITH CRACK DEPTH 3mm

Table V summarises the first three natural frequencies recorded for the damage scenario with a 3 mm crack depth at different locations along the beam. Measurements were taken at 0.1 m intervals, corresponding to positions 0.1 m through 0.6 m. The first bending mode frequencies were observed between 7.32 Hz and 7.62 Hz, while the second and third bending modes ranged from 38.09 Hz to 48.05 Hz and 127.7 Hz to 135.1 Hz, respectively. Relative frequency variations across these positions are also detailed within the table. Figure 7 depicts the detection of crack presence and localisation for the 3 mm damage case across all locations. It was found that the first mode was particularly effective in identifying the crack presence and location for 0.1 m, 0.2 m, 0.3 m, and 0.4 m. However, for 0.5 m and 0.6 m, the first mode showed limited contribution, and the second and third modes became more significant in pinpointing the damage. Experimental observations confirmed a consistent trend: Mode 1 showed reduced sensitivity when cracks were located at 0.5 m and 0.6 m. For all other damage cases, a combination of all three modes proved effective in accurately identifying the crack location and presence across the damaged models.

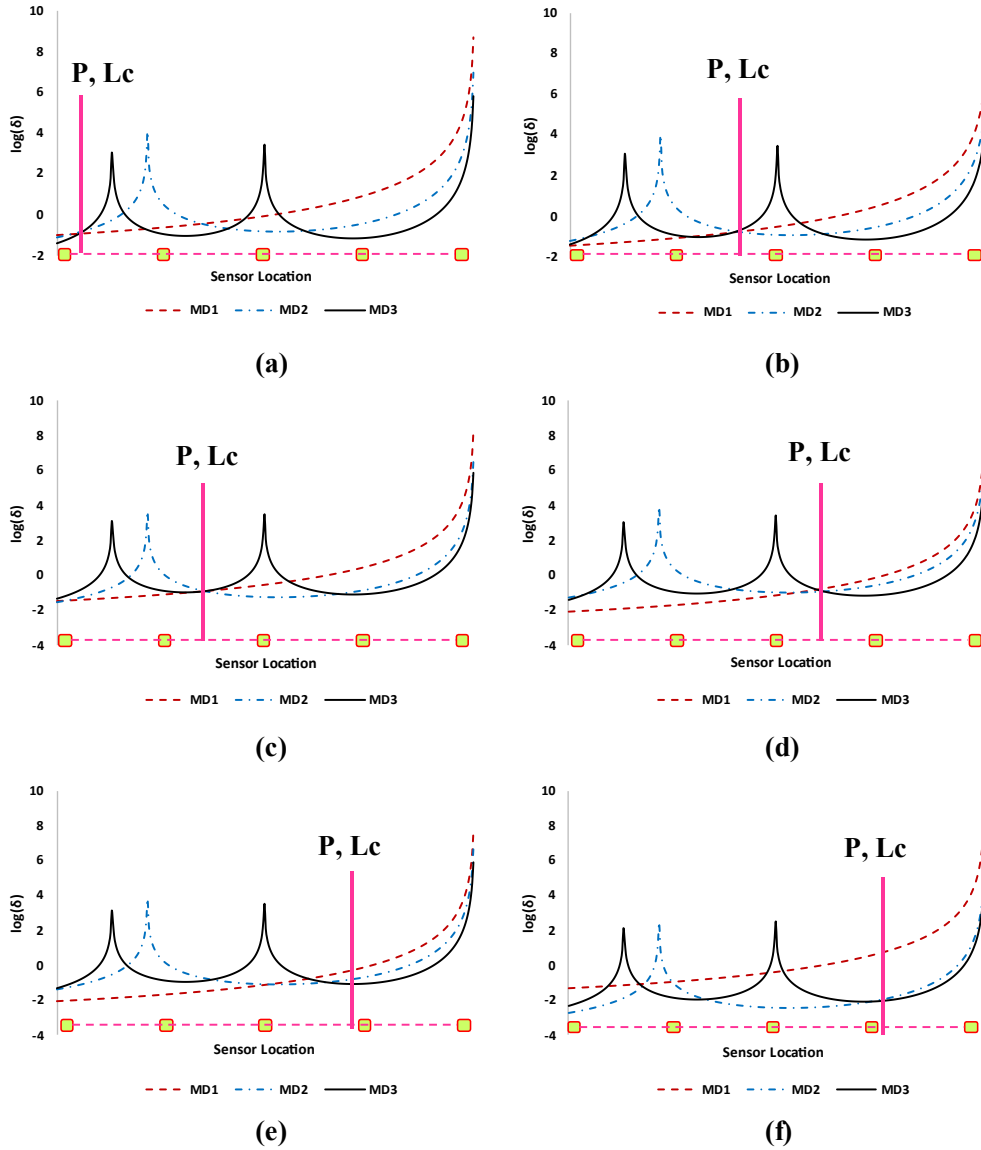


Figure 5. Crack presence and location prediction in Experimental analysis for 3mm intensity (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, (d) 0.4 m, (e) 0.5 m, (f) 0.6 m

TABLE V. THE FIRST THREE BENDING FREQUENCIES EXPERIMENTAL ANALYSIS (MODEL 3)

Location	F1 (Hz)	\Delta f1	F2 (Hz)	\Delta f2	F3(Hz)	\Delta f3
0.1	7.32	0.1072	40.87	0.0815	128.8	0.0445
0.2	7.40	0.0381	40.21	0.0640	131.2	0.0267
0.3	7.40	0.0381	38.89	0.0291	127.8	0.0519
0.4	7.32	0.0092	48.05	0.0534	129.2	0.0438
0.5	7.62	0.0095	39.26	0.0389	127.7	0.0527
0.6	7.32	0.0476	38.09	0.0079	135.1	0.0022

Overall, the experimental findings validate the numerical predictions, demonstrating that combining multiple bending modes significantly improves crack detection and localisation accuracy across all damage scenarios.

Crack Intensity

At the 0.1 m damage location, both the numerical and experimental results exhibit similar trends across the evaluated modes, reflecting a strong consistency between simulation and real-world measurements.

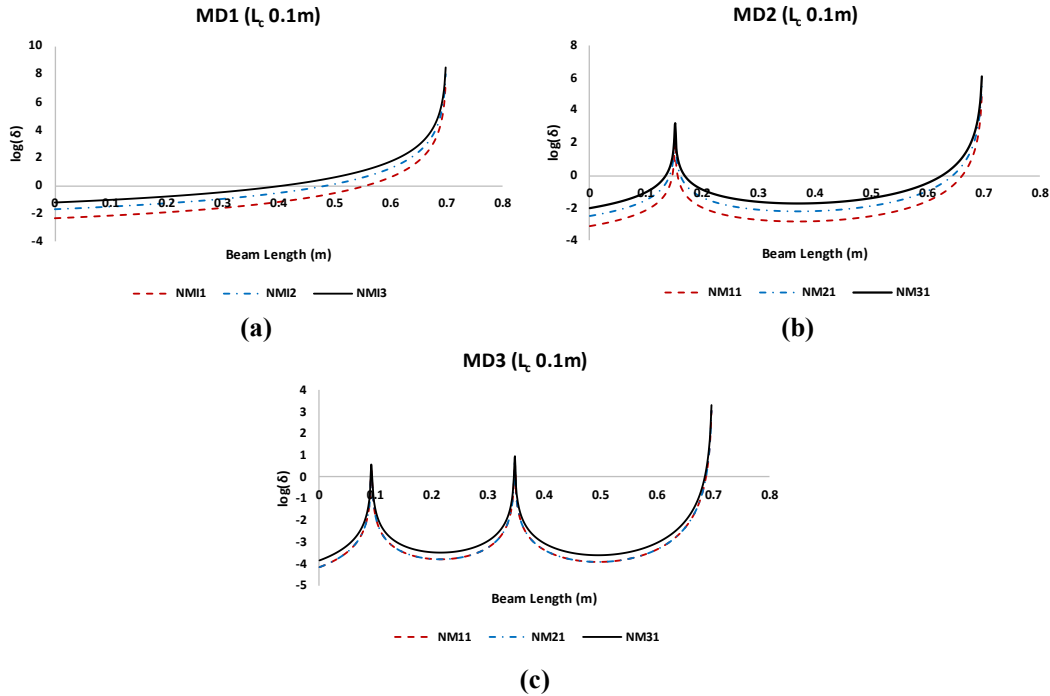


Figure 6. Damage intensity identification for the numerical study (a) 1mm, (b) 2mm, and (c) 3mm.

In the numerical results, shown in Figure 6, the crack intensity prediction gradually increases with position along the beam, particularly emphasising the stiffness loss near the damaged region. In the first mode, the intensity prediction is relatively smooth with a modest rise. In the second mode, a more pronounced peak appears around the 0.1 m mark, indicating heightened sensitivity to the presence of damage. By the third mode, the prediction becomes sharper, effectively isolating the crack location with a distinct peak.

The experimental results, presented in Figure 7, follow a very similar pattern. While minor deviations in magnitude are observed, likely due to measurement noise or slight experimental imperfections, the overall shape and peak locations remain aligned with the numerical predictions. In the first experimental mode, the crack is detected with less intensity compared to numerical values, but the general trend is preserved. In the second and third modes, the damage localisation becomes more accurate, with the third mode offering the clearest identification of the crack near 0.1 m.

Overall, both the numerical and experimental analyses demonstrate that higher bending modes provide enhanced crack detection sensitivity. The small discrepancies observed are within acceptable experimental tolerances and affirm the robustness of the proposed method in accurately predicting damage characteristics using both simulated and real-world data.

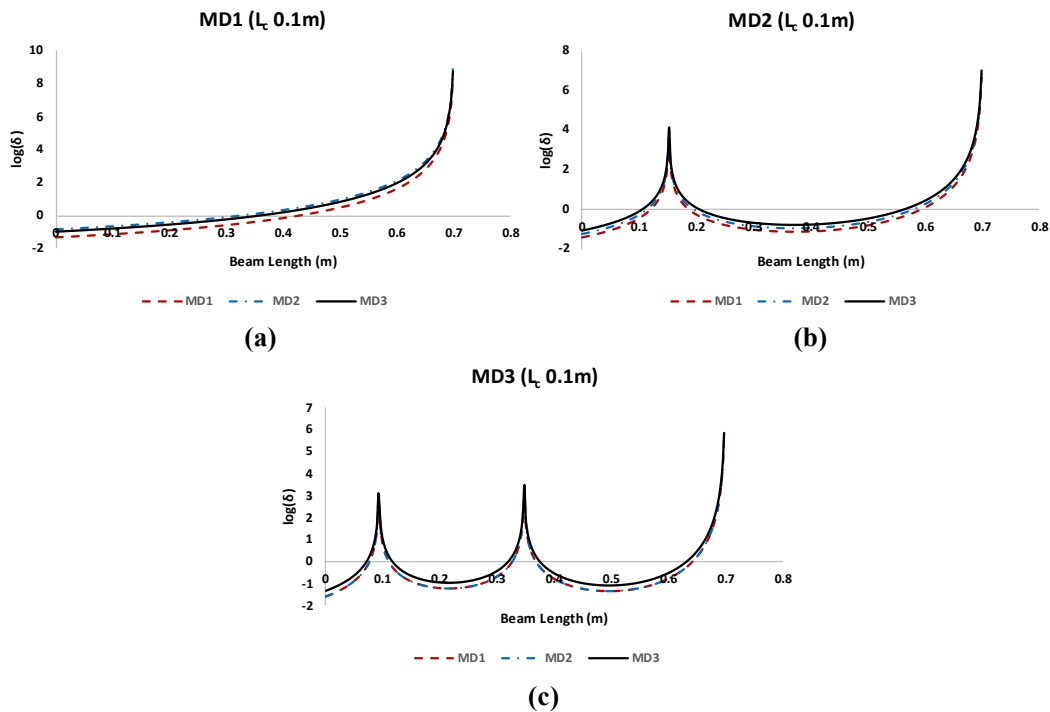


Figure 7. Damage intensity identification for the experimental study (a) 1mm, (b) 2mm, and (c) 3mm.

CONCLUSION

This study successfully developed and validated a vibration-based SHM approach for detecting, localising, and assessing cracks in cantilever beams. By integrating frequency and mode shape analysis through both numerical simulations and experimental investigations, the methodology proved to be reliable across different damage intensities and locations. A newly proposed technique, FDMC, demonstrated enhanced performance in accurately identifying crack presence and position, even when cracks were located between sensors. The results showed strong agreement between numerical and experimental findings, confirming the effectiveness of using multiple bending modes for improved crack prediction. Overall, the approach offers a practical and robust solution for early-stage damage detection in structural elements.

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