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Damage Detection in Gusset Plates of Steel Truss Bridges using Modal Parameters: Experimental and Numerical Study

Kristijanto, H.[1]*, Fitriyah, D.K.[2], and Habieb, A.B.[1]
[1] Department of Civil Engineering, Sepuluh Nopember Institute of Technology, Surabaya, INDONESIA
[2] Department of Civil Engineering, Adhi Tama Surabaya Institute of Technology, Surabaya, INDONESIA

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Corresponding Author:
Kristijanto, H.
Department of Civil Engineering,
Sepuluh Nopember Institute of Technology,
Surabaya, INDONESIA
Email: heppy.k@its.ac.id

Abstract

Corrosion in gusset plate elements has become a critical factor in bridge structural failures, emphasizing the need for more accurate and reliable damage detection methods. Conventional visual inspections are limited in precision and cannot provide real-time monitoring, underscoring the importance of advanced techniques. This study proposes a vibration-based Structural Health Monitoring (SHM) approach employing modal parameter indices, namely Mode Shape (MS), Mode Shape Curvature (MSC), Mode Shape Slope (MSS), and Mode Shape Curvature Square (MSCS), to detect damage in bridge components. Damage scenarios were simulated by introducing gusset plate cuts of 5%, 10%, and 20% to represent different levels of corrosion. The results indicate that MSC and MSCS are the most reliable methods for identifying damage locations in complex structural systems, as they capture mode shape alterations with high sensitivity. Furthermore, the accuracy of modal parameter analysis improves with increasing damage severity. These findings confirm MSC and MSCS as robust tools for early-stage corrosion detection in SHM applications.

INTRODUCTION

Structural failure detection in bridges has become a key research focus, especially after the 2007 collapse of the I-35W Bridge in Minneapolis. Studies identified gusset plate failure as a major contributing factor. Even minor, undetected damage (Figure 1) can shorten a bridge's service life and lead to serious structural failure as key components degrade.

The gusset plate, which connects the main truss to the deck, is crucial to structural integrity. Corrosion in this area can cause cracks that spread under load [1], potentially leading to progressive collapse (Figure 2) [2].

The bridge was about 40 years old [2], nearing the end of its service life. Bridges with a service life of 30 to 40 years should be prioritized for evaluation [3]. Poor maintenance likely accelerated damage to critical components such as the gusset plate. This incident emphasizes the need for regular monitoring and timely repairs. However, conventional inspections, mainly visual checks using simple tools [4], often miss early or hidden damage, especially in complex structures like steel truss bridges.

Visual inspections also depend heavily on the inspector's skill and experience [5], making them less reliable for detecting subtle damage in real time. To overcome these limitations, researchers have developed vibration-based damage detection (VBDD) methods as a more objective and accurate alternative [6], [7].

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(a) Corrosion at Roller Bearing (b) Corrosion at Gusset Plate

Figure 1. Corrosion Observed on the I-35W Bridge at (a) the Roller Bearing and (b) the Gusset Plate [2]

Figure 2. Photograph of the I-35W Bridge Collapse [2]

Vibration-Based Damage Detection (VBDD) identifies structural damage by analyzing changes in physical properties (mass, damping, and stiffness) that influence a structure's vibration behavior. Damage typically alters modal properties like natural frequency and mode shape [8], [9]. VBDD methods are generally divided into traditional and modern approaches. Traditional methods focus on parameters such as modal strain energy, frequency, and damping, and are commonly applied through techniques like acoustic emission, ultrasonic testing, thermal imaging, and vibration analysis [10], [11]. Several studies have explored VBDD for identifying damage location [12]. However, accurately locating damage remains a key challenge in Structural Health Monitoring (SHM), especially for complex structures like steel truss bridges [13].

Several recent studies have evaluated VBDD algorithms in both experimental and numerical settings. Moradipour et al. [10] evaluated the Modal Strain Energy (MSE) method experimentally and numerically on a steel truss bridge model with simulated damage up to 5%. The first five vertical vibration modes were used as analysis parameters. The results showed that the MSE method is effective in monitoring structural conditions and accurately identifying damage locations. Manoach et al [14] examined several modal parameter methods including Modal Displacement, MSS, Modal Curvature, MSCS, and MSE, for damage detection in a beam specimen. Using both finite element analysis and experimental testing under intact and damaged conditions, all methods effectively identified the induced damage.

Zhou et al. [15] applied five VBDD algorithms (CMS, MSC, CF, DI, and CUFC) on a dismantled bridge girder. Despite using only six sensors and the fundamental vibration mode, all methods localized low-level damage effectively. Frans et al. [16] compared MSC and DLV methods on various truss damage types and found both algorithms sensitive and reliable, with DLV pinpointing damaged members well.

Further, Janeliukstis et al. [17] introduced Dynamic MSCS to detect cracks in concrete railway sleepers using modal deflection data, while Rucevskis and Wesolowski [18] used MSCS to locate damage in aluminum beams without full modal data.

Building on this foundation, the present study compares four VBDD algorithms to detect gusset plate damage in steel truss bridges. Using both experimental and numerical methods, artificial damage levels of 5%, 10%, and 20% are introduced at different gusset locations. Analysis focuses on changes in mode shapes and algorithm sensitivity, tested on a 1:12 scale steel truss bridge model.

DAMAGE DETECTION BASED ON PARAMETER MODAL

The four Vibration-Based Damage Detection (VBDD) algorithms employed in this study include the Mode Shape Index (MSi) [18], Mode Shape Slope Index (MSSi) [18], Mode Shape Curvature Index (MSCi) [15], and Mode Shape Curvature Square Index (MSCSi). These methods are commonly used for identifying damage locations in structures by calculating mode shape curvature [19]. In this study, the methods will be tested for their sensitivity to artificial damage. A detailed summary of the VBDD formulation techniques is presented through the referenced literature.

Mode Shape (MS) Damage Index

This method is relatively simple and utilizes the mode shape damage index to represent the changes in mode shapes between the undamaged structure and the damaged structure [18].

$$\Delta \upsilon_i = \left|\upsilon_i^d - \upsilon_i\right| \tag{1}$$

Where υ_i^d is the mode shape of the damaged structure, υ_i is the mode shape of the intact structure, and i represents the measurement point [18].

This method is based on the idea that the mode shape curvature of a healthy structure is smooth and can be modeled using a polynomial function. By applying polynomial regression to curvature data from a damaged structure, the curvature of the undamaged state can be estimated. Laboratory tests may show false peaks due to local disturbances, which can be mistaken for damage. To minimize such errors, averaging the damage index across all analyzed modes is recommended [18].

$$MS_i = \frac{1}{N}\sum_{n=1}^{N}(\Delta \upsilon_i)_n \tag{2}$$

Where *N* is the total number of mode shape measurements.

Mode Shape Slope (MSS) Damage Index

This algorithm uses changes in the slope of the mode shape [18].

$$\Delta \upsilon'_i = \left|\upsilon'^d_i - \upsilon'_i\right| \tag{3}$$

Where,

$$\upsilon'_i = \frac{(\upsilon_{i+1} - \upsilon_{i-1})}{2h} \tag{4}$$

$$MSS_i = \frac{1}{N}\sum_{n=1}^{N}(\Delta \upsilon'_i)_n \tag{5}$$

Where *h* is the distance between two consecutive measurement points. If there are multiple mode measurements, the index is used.

Mode Shape Curvature (MSC) Damage Index

In this algorithm, the difference in mode shape curvature between the intact and damaged structures serves as an indication of where the damage occurs [15].

$$\Delta \upsilon''_i = \left|\upsilon''^d_i - \upsilon''_i\right| \tag{6}$$

Where,

$$\upsilon"_i = \frac{(\upsilon_{i+1} - 2\upsilon_i + \upsilon_{i-1})}{h^2} \quad (7)$$

Mode Shape Curvature Square (MSCS) Damage Index

The damage index is defined as follows,

$$\Delta\upsilon''^2_i = \left|\upsilon''^{d2}_i - \upsilon''^2_i\right| \quad (8)$$

METHODS

Figure 3 outlines the research workflow, which combines numerical and experimental approaches to assess the effectiveness of four VBDD methods in locating damage in deteriorated bridge elements.

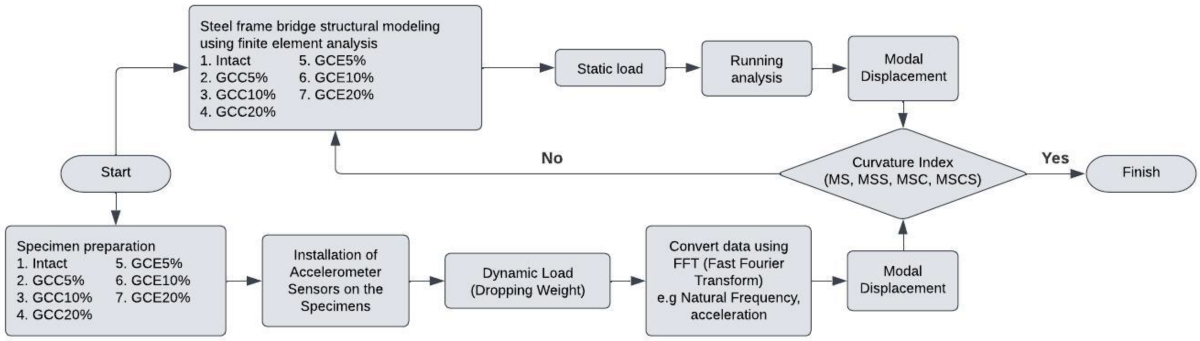


Figure 3. Research Flow Chart

The process begins with dynamic testing of a scaled steel truss bridge model. Accelerometers were used to record time-domain vibration data. This data was then converted into frequency-domain information using the Fast Fourier Transform (FFT), enabling analysis of natural frequencies and mode shape changes due to damage. Displacement values, derived from acceleration data, were key to identifying potential damage locations. Next, numerical analysis was performed using mode shape-based algorithms with ABAQUS software to identify and localize damage.

In this study, only the first mode shape (Mode 1) was used due to its stability and reliability in both simulation and experiment. As a low-order mode, it captures the overall structural behavior, is easier to measure accurately, and is more sensitive to damage, especially in gusset plates. Prior research confirms that lower modes are more effective for damage detection, while higher modes are often affected by noise and harder to interpret [8], [20], [21].

Section properties of the Truss Bridge Model

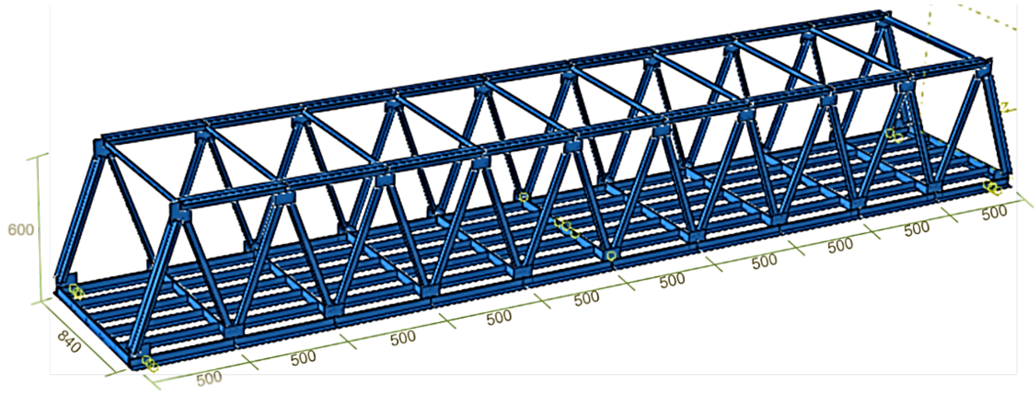
This section describes the 1:12 scale steel truss bridge model, including accelerometer placement and data acquisition method. The model, constructed from steel angle profiles, is a scaled-down version of a full-scale prototype for testing purposes.

The original bridge is 60 meters long (center to center), 10 meters wide including pedestrian paths, and 7.2 meters tall. It consists of ten equal spans, each 6 meters long. Due to laboratory space limits, the model was scaled down to 1:12, resulting in a bridge that is 500 cm long, 84 cm wide, and 60 cm tall (Table 1).

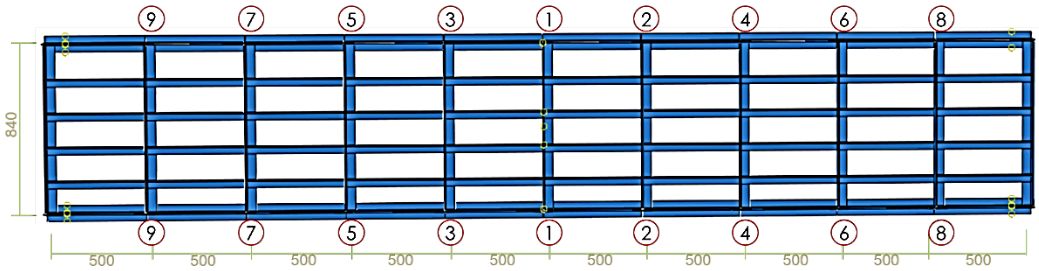
Table 1. Dimensions of the Truss Bridge Model

Superstructure	Original Model Dimensions (mm)	Scaled Model Dimensions (mm)
Bridge length	60000	5000
Bridge width	10000	840
Bridge height	72000	600
Transverse girder spacing	6000	50
Longitudinal girder spacing	1920	160

In the finite element model, the bridge ends are supported by pinned and roller supports that only allow translational forces. The entire structure uses structural steel with a Young's modulus of 200,000 MPa and a Poisson's ratio of 0.3. Each truss element is built from angle steel profiles (Table 2), connected using 4 mm thick gusset plates (Figure 4). All modeling and analysis were done using ABAQUS software.



(a) Dimensions of the 1:12 Scale Laboratory Bridge Model



(b) Accelerometer Sensor Layout

Figure 4. (a) 1:12 Scale Laboratory Bridge Model and (b) Accelerometer Sensor Layout

Table 2. Section Properties of the Laboratory-Scale Bridge Model

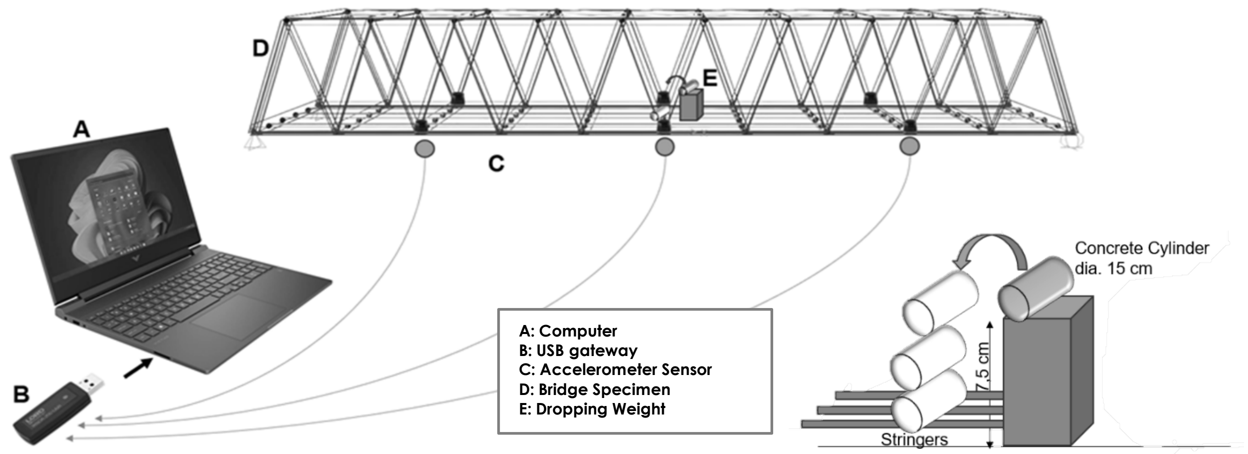
Bridge Member	Steel Profile
Main truss frame	2L 40x40x4
Diagonal truss member	L 30x30x3
Cross girder	L 50x50x5
Longitudinal girder	Lx40x40x4
Top chord	L 30x30x3
End portal	L 30x30x3
Gusset plate	4mm steel plate

Experimental Set-Up

The specifications and cross-sections of the scaled bridge model are listed in Tables 1 and 2. The model was supported by pinned and roller bearings to simulate real boundary conditions. Accelerometers were installed (Figure 4) to capture the structure's dynamic response. Ideally, 18 accelerometers were needed to monitor all gusset plate points. However, due to equipment limits, only 6 were used. To address this, a relocation method was applied: two accelerometers stayed fixed at mid-span, while the other four were moved sequentially to cover all points.

This relocation approach was justified based on a comparative analysis, which showed that the experimental results using six accelerometers yielded mode shape patterns comparable to those from the FEM simulation where all nine points were monitored at once. These findings confirm that the relocation method, despite the restricted number of sensors, is capable of providing accurate and representative dynamic data of the structure.

The experimental test used a dropping weight impact method [22], as shown in Figure 5(b). A 12 kg concrete cylinder (15 cm diameter) was dropped from a height of 17.5 cm onto the mid-span cross beam of the scaled bridge model equipped with accelerometers. This impact generated vibrations, and the accelerometers recorded the structure's dynamic response. The data were then processed into displacement values at each point, with maximum displacements used for modal analysis. Each test was repeated three times for accuracy.



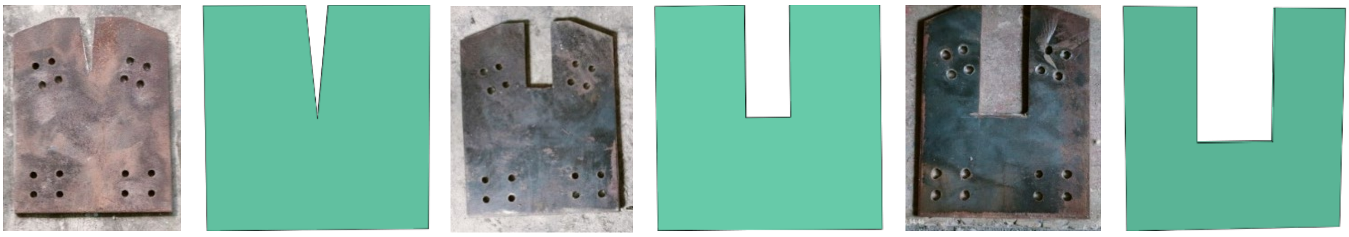
(a) Experimental Set-up (b) Dropping Weight

(b) Figure 5. (a) Experimental Set-Up dan (b) Dynamic Load in the Experimental Test

Six artificial damage scenarios on the gusset plates were tested, as shown in Table 3 and Figure 6. These scenarios represent common real-world damage such as corrosion and tearing [23], [24]. If undetected, such damage can worsen over time and lead to structural failure [1], [25]. The scenarios were created to assess how effectively the Vibration-Based Damage Detection (VBDD) methods can identify damage in gusset plates.

Table 3. Artificial Damage Scenarios

Damage Scenario	Code	Damage Location Variation
Gusset plate tear 5%	GCC5%	0.5 L / Mid-span
Gusset plate tear 10%	GCC10%	0.5 L / Mid-span
Gusset plate tear 20%	GCC20%	0.5 L / Mid-span
Gusset plate tear 5%	GCE5%	1/5 L / Edge of span
Gusset plate tear 10%	GCE10%	1/5 L / Edge of span
Gusset plate tear 20%	GCE20%	1/5 L / Edge of span



(a) 5% Cut of Gusset Plate (b) 10% Cut of Gusset Plate (c) 20% Cut of Gusset Plate

Figure 6. (a) 5% Cut of Gusset Plate, (b) 10% Cut of Gusset Plate, and (c) 20% Cut of Gusset Plate

RESULTS AND DISCUSSION

The numerical analysis starts with modeling the bridge (Tables 1 and 2), followed by applying a static load equal to the 12 kg dropped mass used in the experiment. This load is placed at the mid-span, matching the experimental setup. Displacement at each point is then used to validate the experimental results. Mode shapes from the finite element model are also used to compute damage indices. The displacement data are analyzed using four damage detection methods, with results detailed in Sections 4.1 to 4.6.

Damage Detection on the GCC 5% Model at Mid-Span

The first stage analyzes the 5% cut damage scenario on the gusset plate at mid-span. Displacement modes at each observation point are evaluated based on the experimental setup (Figures 7 and 8). Finite element results are visually presented in Figure 7.

Figure 9 shows the displacement mode pattern for the 5% mid-span damage scenario. All four modal parameters (MS, MSS, MSC, MSCS) successfully identified the damage in the experimental results. In the FEM analysis, MS and MSC demonstrated high accuracy, with a peak at node 0.5 confirming effective damage localization by MSS and MSC.

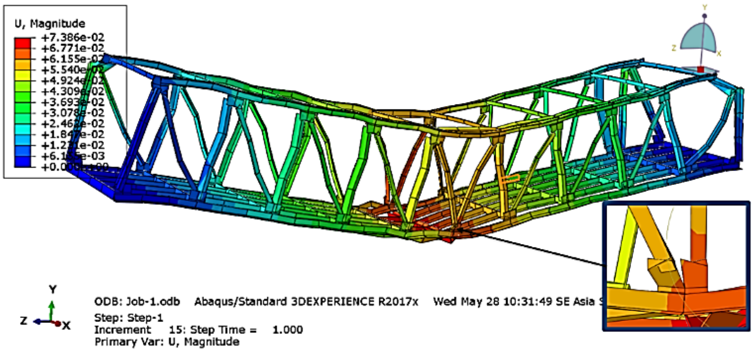


Figure 7. Bridge Modal Analysis with 5% Cutting Damage of the Gusset Plate in the Mid-Span

Figure 8. Experimental Set-up of 5% Cut Damage on Gusset Plate at Mid-span

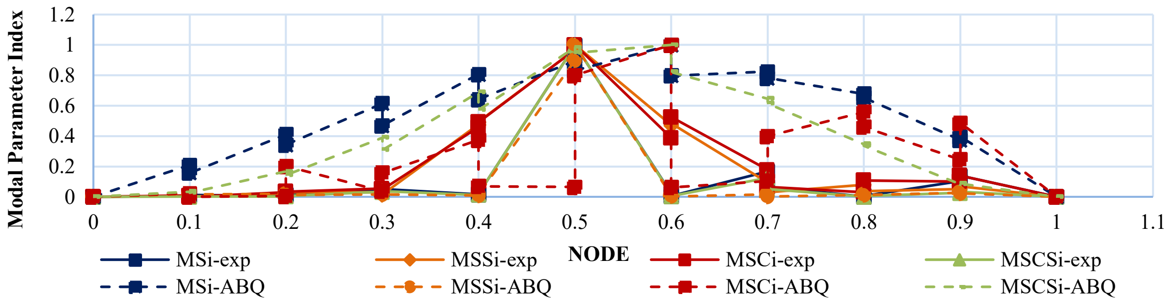


Figure 9. Curvature Patterns from Four Modal Parameter Methods Detecting 5% Gusset Plate Damage at Mid-span

Table 4. Error Metrics of Modal Methods in Identifying Mid-Span Damage (5% GCC)

Modal Parameter	Nodes											SSE
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
MSi	0.00	0.04	0.16	0.63	0.63	0.03	0.95	0.51	0.46	0.07	0.00	3.48
MSSi	0.00	0.00	0.00	0.22	0.23	0.01	0.23	0.01	0.00	0.00	0.00	0.69
MSCi	0.00	0.00	0.03	0.01	0.18	0.82	0.37	0.11	0.28	0.12	0.00	1.92
MSCSi	0.00	0.00	0.03	0.46	0.46	0.00	0.96	0.32	0.12	0.00	0.00	2.35

To evaluate the accuracy of FEM compared to the experiment, SSE values were calculated (Table 4). SSE (Sum of Squared Errors) is a statistical method used to quantify the overall deviation between the observed (actual) values and the predicted values [26]. Lower SSE values indicate better alignment with experimental results. MSSi (0.69) and MSCi (1.92) had the lowest SSE, indicating higher accuracy in detecting damage at node 0.5.

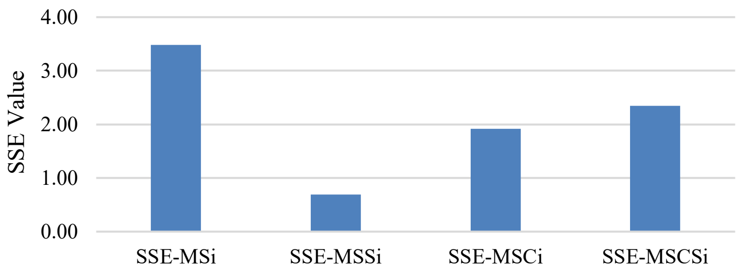


Figure 10. Sum of Squared Error Values from All Modal Parameters (5% GCC)

Figure 10 illustrates the absolute error distribution for each parameter. These results confirm that MSS and MSC are the most effective parameters for identifying mid-span gusset plate damage.

Damage Detection on the GCC 10% Model at Mid-Span

This section evaluates the 10% cut damage scenario on the gusset plate at mid-span. As shown in Figure 11, a 10% artificial cut was introduced in the structural model, with displacement modes analyzed at observation points matching the experimental setup (Figure 12). FEM results are also presented in Figure 11.

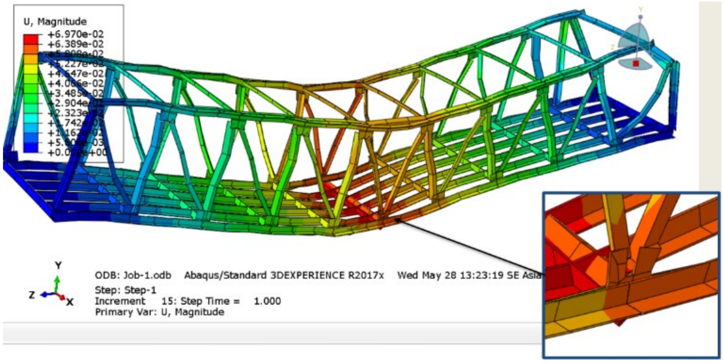


Figure 11. Bridge Modal Analysis with 10% Cutting Damage of the Gusset Plate in the Mid-span

Figure 12. Experimental 10% Tearing Damage on Gusset Plate at Mid-Span

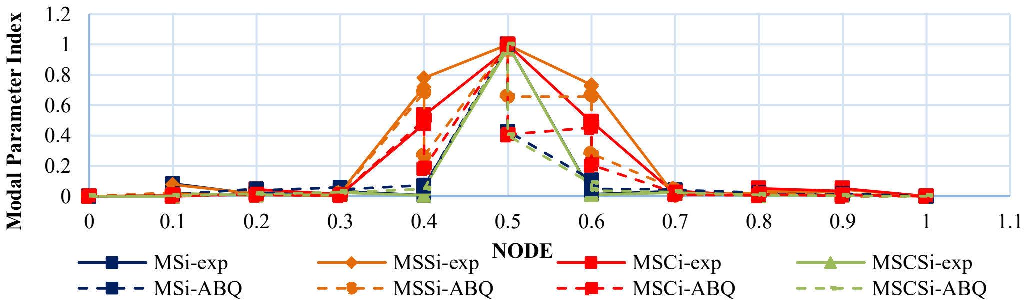


Figure 13. Curvature Patterns from Four Modal Parameter Methods in Detecting 10% Gusset Plate Damage at Mid-Span

Figure 13 illustrates the displacement mode for this damage scenario. All four modal parameters (MS, MSS, MSC, MSCS) effectively localized the damage in both experimental and FEM results, with a clear peak at the mid-span.

Table 5. Error Metrics of Modal Methods in Identifying Mid-Span Damage (10% GCC)

Modal Parameter	Nodes											SSE
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
MSi	0.00	0.00	0.00	0.00	0.00	0.33	0.01	0.00	0.00	0.00	0.00	0.35
MSSi	0.00	0.00	0.00	0.00	0.26	0.12	0.20	0.00	0.00	0.00	0.00	0.58
MSCi	0.00	0.00	0.00	0.00	0.12	0.35	0.08	0.00	0.00	0.00	0.00	0.56
MSCSi	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.36

To assess accuracy, SSE values were calculated (Table 5). All parameters showed low SSE, with MSi and MSCSi having the lowest, and MSSi and MSCi slightly higher. These values indicate all four methods reliably detect damage.

Figure 14 supports these findings, showing low absolute error values for each modal parameter method. These results confirm the effectiveness of all modal methods in identifying mid-span gusset plate damage.

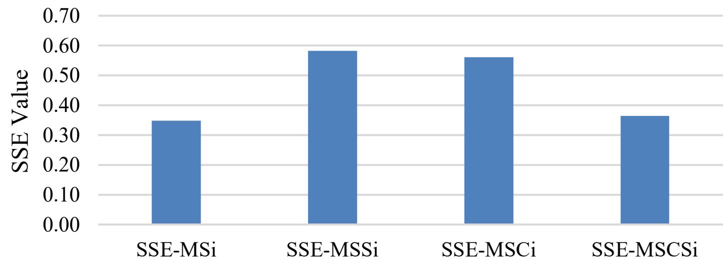


Figure 14. Sum of Squared Error Values from All Modal Parameters (10% GCC)

Mid-Span Damage Detection on the GCC 20% Model

Figure 15 shows the FEM results for the 20% gusset plate damage scenario at mid-span. Displacement modes were analyzed at each observation point, and sensor placement was adjusted to align with the experimental setup.

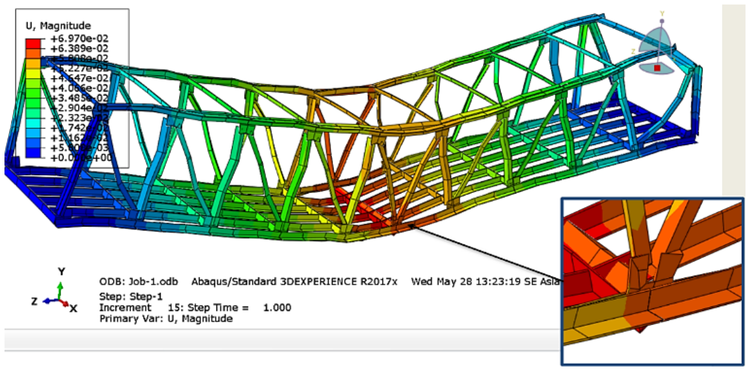


Figure 15. Bridge Modal Analysis with 20% Cutting Damage of the Gusset Plate in the Mid-Span

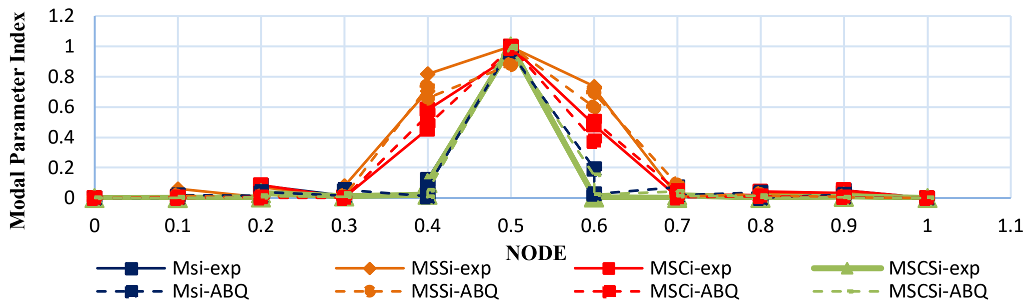


Figure 16. Curvature Patterns from Four Modal Parameter Methods in 20% Gusset Plate Damage at Mid-span

Figure 16 displays the displacement mode for this damage case. All four modal parameters (MS, MSS, MSC, and MSCS) accurately localized the artificial damage in both experimental and FEM results. Each method produced distinct curvature patterns centered at the damage point, indicating consistent detection performance.

Table 6. Error Metrics of Modal Methods in Identifying Mid-Span Damage (20% GCC)

Modal Parameter	Nodes											SSE
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
MSi	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.05
MSSi	0.00	0.00	0.00	0.00	0.03	0.01	0.02	0.01	0.00	0.00	0.00	0.08
MSCi	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.04
MSCSi	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.03

To quantify accuracy, SSE values are shown in Table 6. All methods yielded low errors, with MSCSi (0.03) and MSCi (0.04) being the most accurate, followed by MSi (0.05) and MSSi (0.08). These values confirm the strong performance of all four modal methods in identifying mid-span damage.

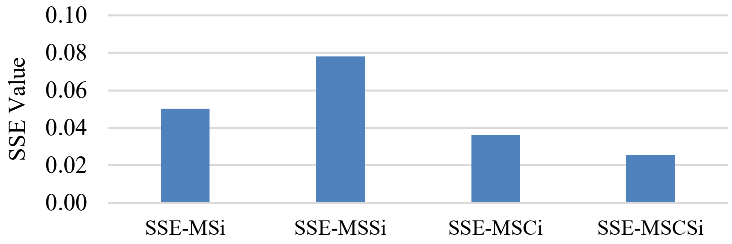


Figure 17. Sum of Squared Error Values from All Modal Parameters (20% GCC)

Figure 17 shows the total SSE for each modal parameter, confirming that MSCSi and MSCi have the highest accuracy, while MSSi shows the largest error. This supports the results in Table 6 and highlights the effectiveness of the modal parameters, especially MSCSi, in detecting gusset plate damage.

Damage Detection on the GCE 5% Model at 1/5 Span

Figure 18 shows the structural model with 5% gusset plate damage at 1/5 span. Displacement modes were analyzed at each point, with measurement positions adjusted to match the experimental setup. Finite element results are visually presented in Figure 18.

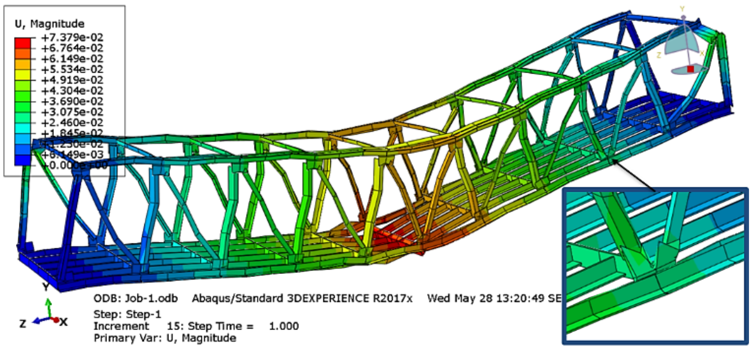


Figure 18. Bridge Modal Analysis with 5% Cutting Damage of the Gusset Plate at 1/5 of the Span

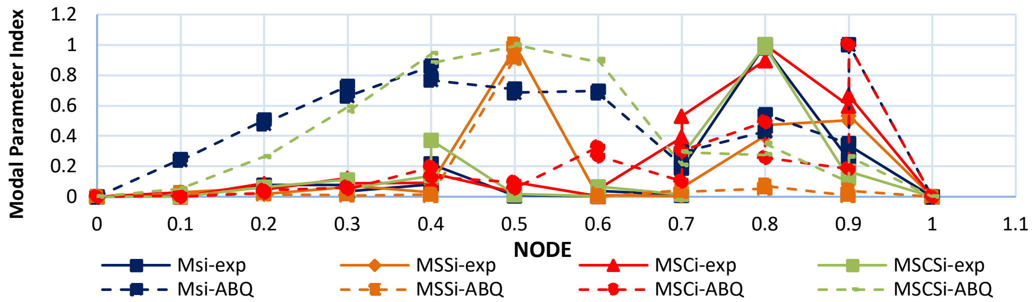


Figure 19. The Curvature Patterns of the Four Modal Parameter Methods in Detecting 5% Gusset Plate Damage at 1/5 of the Span

Figure 19 illustrates the displacement mode for the 5% GCE damage scenario. Of the four modal parameters, only MSCi consistently identified the damage location in both experimental and FEM results, as indicated by a distinct curvature peak at the 1/5 span position.

Table 7. Error Metrics of Modal Methods in Identifying 1/5 Span Damage (5% GCE)

Modal Parameter	Nodes											SSE
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
MSi	0.00	0.06	0.19	0.42	0.61	0.49	0.48	0.04	0.32	0.44	0.00	3.05
MSSi	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.16	0.25	0.00	0.43
MSCi	0.00	0.00	0.00	0.00	0.01	0.00	0.10	0.08	0.55	0.17	0.00	0.94
MSCSi	0.00	0.00	0.04	0.26	0.64	0.96	0.78	0.04	0.52	0.01	0.00	3.25

The error metrics are summarized in Table 7. While MSSi and MSCi recorded low SSE values (0.43 and 0.94, respectively), only MSCi accurately localized the damage. MSi and MSCSi produced higher SSE (3.05 and 3.25) and failed to detect the damage effectively.

Figure 20 shows the total SSE for each modal parameter, confirming that MSCSi and MSi have the highest accuracy, while MSSi shows the largest error. This supports the results in Table 7 and highlights the effectiveness of the modal parameters, especially MSCi, in detecting gusset plate damage.

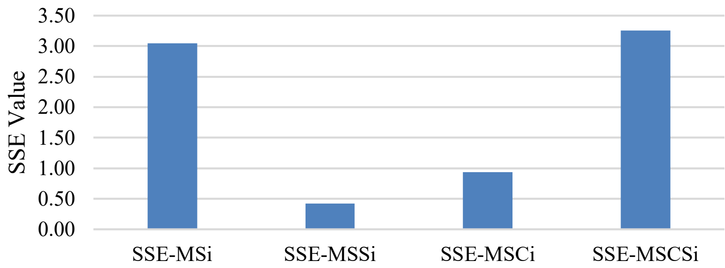


Figure 20. Sum of Squared Error Values from All Modal Parameters (5% GCE)

Damage Detection on the GCE 10% Model at 1/5 Span

Figure 21 displays the FEM model of the bridge with 10% gusset plate damage located at 1/5 of the span. Displacement modes were analyzed based on the experimental configuration, and the FEM results confirm structural deformation concentrated near the damage zone.

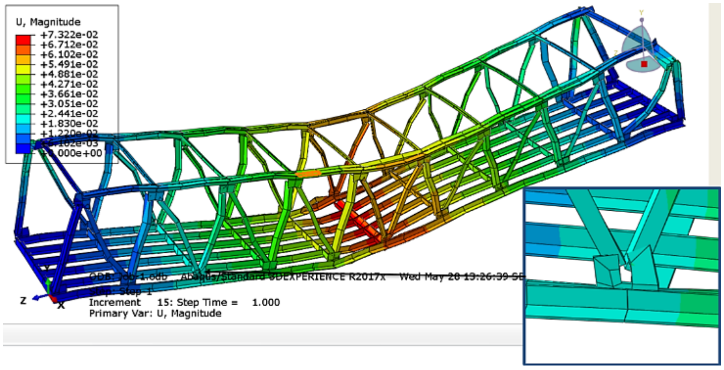


Figure 21. Bridge Modal Analysis with 10% Cutting Damage of the Gusset Plate at 1/5 of the Span

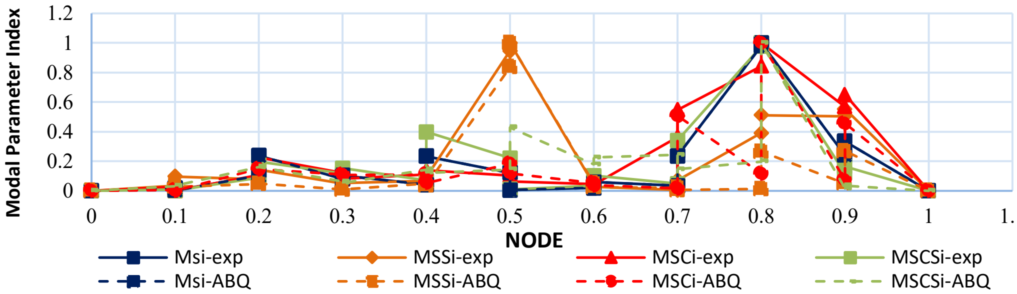


Figure 22. Curvature Patterns from Four Modal Parameter Methods Detecting 10% Gusset Plate Damage at 1/5 of the Span

Figure 22 illustrates the curvature patterns derived from the four modal parameters. The MS, MSC, and MSCS indices successfully localized the damage, as shown by clear curvature peaks at 1/5 span in both experimental and FEM data. Conversely, although MSSi shows a low RMSE, it fails to indicate the damage visually.

Table 8. Error Metrics of Modal Methods in Identifying 1/5 Span Damage (10% GCE)

Modal Parameter	**Nodes**											**SSE**
	0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	
MSi	0.00	0.01	0.01	0.00	0.03	0.04	0.01	0.02	0.59	0.06	0.00	0.77
MSSi	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.14	0.21	0.00	0.39
MSCi	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.12	0.53	0.25	0.00	0.91
MSCSi	0.00	0.00	0.01	0.01	0.08	0.17	0.02	0.04	0.61	0.02	0.00	0.95

The corresponding error metrics are presented in Table 8. MSSi and MSi record the lowest SSE values at 0.39 and 0.77, respectively. However, due to its lack of visual indication, MSSi is deemed unreliable in this damage scenario. MSCi and MSCSi both yield SSE values of 0.95 but demonstrate better consistency in detecting damage.

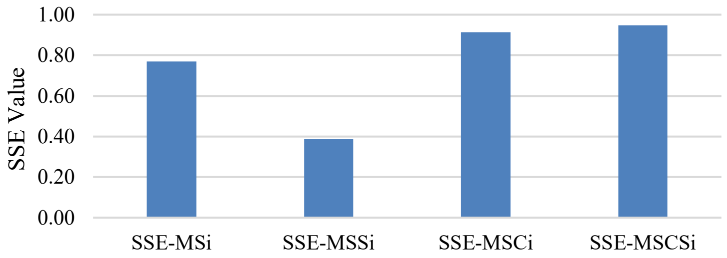


Figure 23. Sum of Squared Error Values from All Modal Parameters (10% GCE)

Figure 23 shows the total SSE for each modal parameter, confirming that MSi, MSCSi, and MSCi have higher accuracy, while MSSi records the lowest error. However, despite its low SSE, MSSi fails to visually indicate the damage location. This supports the results in Table 8 and highlights the effectiveness of the modal parameters (especially MSCi) in detecting gusset plate damage.

Damage Detection on the GCE 20% Model at 1/5 Span

Figure 24 presents the structural model with 20% gusset plate damage at 1/5 span. Displacement modes were analyzed at each point, adjusted to match the experimental sensor positions, and visualized through FEM results.

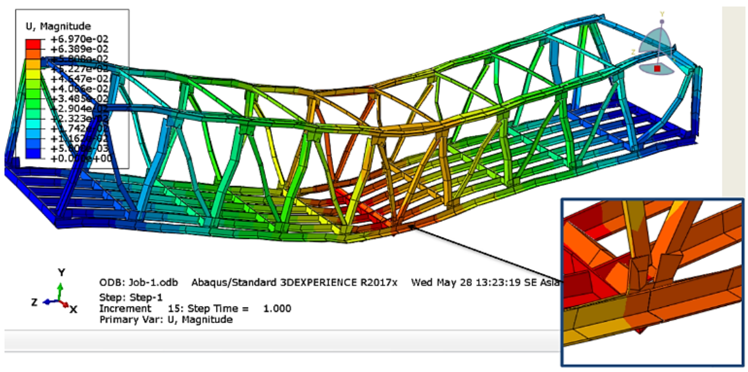


Figure 24. Bridge Modal Analysis with 20% Cutting Damage of the Gusset Plate at 1/5 of the Span

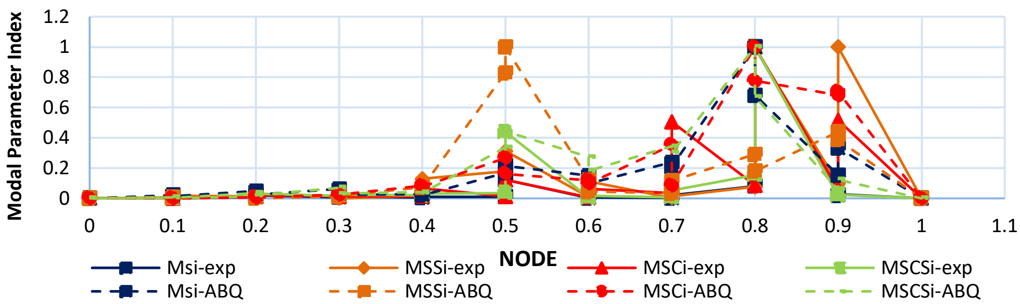


Figure 25. Curvature Patterns from Four Modal Parameter Methods Detecting 20% Gusset Plate Damage at 1/5 of the Span

Figure 25 presents the curvature pattern derived from the four modal parameters. Among these, MSCi and MSCSi exhibit pronounced peaks at the damage location in both experimental and FEM mode shapes, indicating their effectiveness in accurately detecting and localizing the 20% damage.

Table 9. Error Metrics of Modal Methods in Identifying 1/5 Span Damage (20% GCE)

Modal Parameter	Nodes											SSE
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	
MSi	0.00	0.02	0.08	0.20	0.37	0.40	0.81	0.96	0.31	0.00	0.00	3.16
MSSi	0.00	0.05	0.04	0.06	0.02	0.49	0.03	0.04	0.21	0.73	0.00	1.66
MSCi	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.30	0.28	0.74	0.00	1.33
MSCSi	0.00	0.00	0.01	0.09	0.30	0.48	0.97	0.69	0.39	0.00	0.00	2.92

Table 9 displays the associated error metrics. MSCi records the lowest SSE (1.33), followed by MSSi (1.66). Although MSCSi shows clear curvature peaks, its higher SSE (1.33) reflects reduced consistency across data points.

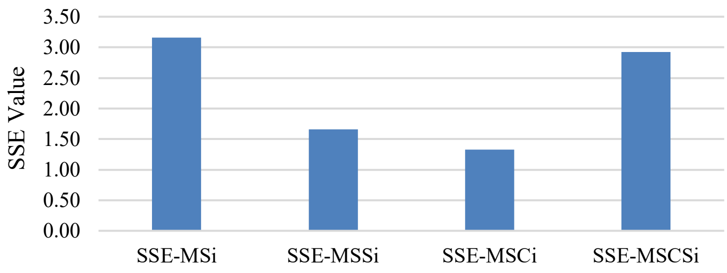


Figure 26. Sum of Squared Error Values from All Modal Parameters (20% GCE)

Figure 26 further validates these findings by demonstrating low absolute errors near the damaged zone (particularly for MSCi) thereby confirming strong correlation between experimental and numerical results. Based on these indicators, MSCi is again confirmed as the most reliable parameter for identifying 20% gusset plate damage at 1/5 span.

CONCLUSIONS

This study focuses on identifying the location of gusset plate cut damage through dynamic experimental testing on a steel truss bridge. Numerical analysis was conducted to validate the damage locations detected during the tests. The proposed damage detection approach utilizes modal parameters—vibration-based damage detection (VBDD) methods—including Mode Shape (MS), Mode Shape Slope (MSS), Mode Shape Curvature (MSC), and Mode Shape Curvature Square (MSCS). The effectiveness of MSC and MSCS was assessed through simulated gusset plate damage scenarios involving 5%, 10%, and 20% cuts at various locations.

The results indicate that among the four methods, MSC and MSCS consistently demonstrated superior performance in identifying damage locations on gusset plates. Displacement values at each measurement point—corresponding to gusset plate positions—served as reference indicators and were validated through both experimental testing and numerical simulation. Furthermore, the analysis shows that the accuracy of modal parameter methods increases with the severity of the damage, indicating that larger damage volumes lead to more reliable detection results.

From a theoretical standpoint, the dynamic response of a structure cannot, in general, be inferred solely from static analysis or modal (eigenvalue) analysis. Only in special cases where the response is strongly dominated by the fundamental (first) mode can equivalent static approximations or single-mode approaches provide reasonable predictions. Accordingly, this study is primarily applicable to systems with first-mode-dominated behavior. For more general applications, where higher modes structurally contribute to deformation and response, the proposed approach may not be directly applicable and would require further development that explicitly accounts for multi-modal effects.

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