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VIBRATION-BASED DAMAGE DETECTION FOR ONE-STORY STEEL FRAME STRUCTURE USING MODE SHAPE CURVATURE

Alan Wong Zong Xiang[a], Sarehati Umar[a]*, Mohamad Shazwan Ahmad Shah[a], Seyed Jamalaldin Seyed Hakim[b]

[a]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Department of Civil Engineering, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400, Batu Pahat, Johor, Malaysia

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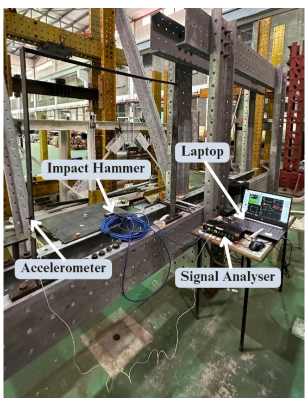
*Corresponding author
sarehati@utm.my

Graphical abstract



Abstract

Structural health monitoring techniques, particularly vibration-based damage detection, have gained significance in assessing civil structure condition. This paper focuses on utilising mode shape curvature for damage detection in a one-story steel frame structure. The study aims to overcome traditional inspection limitations by exploring vibration-based approaches. Experimental investigation is conducted to analyse intact and damaged structural modal behaviour. Modal analysis technique extracts modal frequencies and mode shapes, enabling analysis of mode shape curvature for damage detection and localisation. Preliminary findings show that damaged structures display deviations in mode shapes and reduced natural frequencies, providing evidence of structural damage. However, a significant issue arises near the support, where unexpected patterns emerge in the Total Damage Index (TDI) with increasing damage severity. This finding challenges the expected correlation between severity levels and TDI values, highlighting the need to consider factors like fixed supports. Misleading signs of damage in some segments underscore the importance of cautious result interpretation and accounting for noise. Future studies should focus on noise resistance, false indication mitigation, and understanding segments with fixed supports to enhance mode shape curvature analysis's reliability for damage detection in civil structures.

Keywords: Structural health monitoring, vibration-based damage detection, mode shape curvature, one-story steel frame structure, damage localisation

Abstrak

Teknik pengawasan kesihatan struktur, terutamanya pengesanan kerosakan berdasarkan getaran, telah mendapat perhatian dalam menilai keadaan struktur awam. Kertas ini memberi tumpuan kepada penggunaan kelengkungan bentuk ragam untuk pengesanan kerosakan dalam struktur bingkai keluli satu tingkat. Kajian ini bertujuan mengatasi kelemahan pemeriksaan tradisional dengan meneroka pendekatan berasaskan getaran. Kajian eksperimen dijalankan untuk menganalisis kelakuan ragam struktur yang tidak rosak dan yang rosak. Teknik analisis ragaman mengekstrak frekuensi modal dan bentuk ragam, membolehkan analisis kelengkungan bentuk ragam untuk pengesanan dan penentuan lokasi kerosakan. Dapatan awal menunjukkan bahawa struktur yang rosak menunjukkan perubahan dalam bentuk ragam dan nilai frekuensi tabii yang berkurang. Namun begitu, masalah timbul berhampiran sokongan, di mana corak tidak terjangka muncul dalam Indeks Kerosakan Keseluruhan (TDI) dengan peningkatan tahap kerosakan. Penemuan ini mencabar sekaitan antara tahap keparahan dan nilai TDI, menunujukkan keperluan untuk mempertimbangkan faktor seperti sokong terikat. Tanda palsu tentang kerosakan dalam segmen tertentu menekankan kepentingan tafsiran hasil dengan berhati-hati dan mempertimbangkan hingar. Kajian masa depan harus memberi tumpuan kepada rintangan hingar, pengurangan indikasi palsu, dan pemahaman segmen berdekatan sokong terikat untuk meningkatkan kebolehharapan kelengkungan bentuk ragam untuk pengesanan kerosakan dalam struktur awam.

1.0 INTRODUCTION

Rapid technological advancements in construction have emphasised the need to ensure structures' longevity and safety, including one-story steel frame structures. Despite their seemingly simple nature, these structures are susceptible to damage and deterioration over time, compromising their structural integrity. Evaluating their damage states through experimental records is necessary for detecting and localising damage, as well as developing and validating structural health monitoring techniques. This paper addresses the limitations of traditional inspections by exploring vibration-based damage detection methods, particularly mode shape curvature, which offers a reliable and accurate approach for detecting and locating damage in a structure.

1.1 Problem Statement

Identifying structural damage in the construction industry is crucial due to the potentially severe consequences it can have over time. Traditional methods like visual inspections and magnetic particle inspections have limitations in detecting damage beyond visible cracks and notches on the surface of structures (Gharehbaghi et al., 2021). These methods are subjective, relying heavily on expert judgment and often requiring challenging physical access to inspect complex or inaccessible areas (Wu et al., 2021).

In this context, vibration-based damage detection methods have emerged as a cost-effective and practical alternative. Among these methods, the utilisation of mode shape curvature shows promise in overcoming the limitations of existing techniques (Meruane et al., 2022). By focusing on the changes in the curvature of the mode shapes, this method provides a more comprehensive understanding of the structural response and is capable of identifying localised damage, even in complex structures. This approach offers an advantage over traditional methods as it goes beyond surface-level observations and provides insights into the internal condition of the structure.

However, despite its potential, there is a limited availability of experimental studies that rigorously validate the effectiveness of mode shape curvature analysis. Many existing studies are either limited in simple structures such as cantilever beam (Altunışık et al., 2019; Chinka et al., 2021; Gupta & Das, 2021; Nayyar et al., 2022; Pooya & Massumi, 2021) or based on numerical damage cases (Gomes & Giovani, 2022; Nguyen et al., 2020). This paper aims to address these challenges by conducting experimental studies on one-story steel frame structures commonly used in commercial and industrial buildings. The research will focus on evaluating the effectiveness of mode shape curvature techniques such as the the TDI method in detecting localised damage.

1.2 Objectives

The main purpose of the paper is to investigate the effectiveness of detecting structural damage through changes in vibration response. The objectives of this study are:

1. To experimentally study the behaviour of modal data in intact and damaged one-story steel frame structure.
2. To utilise mode shape curvature as a method to detect and locate damage in a one-story steel frame structure.

1.3 Scope of Study

This paper acknowledges its limitations, primarily focusing on the vibration response analysis. These limitations are:

1. The experimental verification is limited to a one-story steel frame structure.
2. The investigation examines single and multiple damage cases using the mode shape curvature (MSC) method for detecting structural damage.
3. The detection of structural damage in this study relies predominantly on analysing modal frequencies and mode shapes derived from measured frequency response function (FRF) data.

1.4 Significance of Study

The study's significance lies in its potential to improve the safety and longevity of one-story steel frame structures, prevalent in residential, commercial, and industrial settings. Vibration-based techniques, particularly mode shape curvature analysis, offer a non-destructive, cost-effective, and efficient approach to detecting structural damage. By accurately identifying the damage location, informed decisions can be made regarding repairs, replacements, and maintenance, ensuring structural integrity. Advancing knowledge in vibration-based damage detection techniques enhances the safety, durability, and longevity of critical infrastructure. This paper aims to make a meaningful impact on the field of structural engineering and beyond.

2.0 LITERATURE REVIEW

Structural health monitoring (SHM) is vital for ensuring the safety and reliability of structures. Vibration-based damage detection (VBDD) methods have emerged as a promising approach within SHM, leveraging the dynamic response characteristics of structures to identify and localise damage.

SHM is a widely adopted technique that continuously monitors the health and performance of structures, enabling early detection of changes in geometric properties and preventing unexpected accidents or failures (Modares & Waksmanski, 2013). SHM can be divided into two categories: local and global methods. Local SHM methods focus on specific areas or components of the structure and utilise non-destructive evaluation techniques such as ultrasonic, radiographic, and eddy current tests to detect and assess defects. While these methods effectively detect and localise damage, they face challenges in accurately determining the location of damage and accessing complex or geographically inaccessible areas (Das et al., 2016). In contrast, global damage detection methods offer the advantage of detecting damage throughout the structure without prior knowledge of its location.

VBDD is a global method where the concept rests on the notion that vibration parameters are inherently linked to the physical properties of structures, such as mass and stiffness. Hence, the occurrence of damage induces changes in the structural vibration time response data (Shang et al., 2020; Umar et al., 2021), frequency response (Hassani et al., 2022; Zhan et al., 2022) or modal data (Jayasundara et al., 2020; Martucci et al., 2023; Tan et al., 2019). Natural frequency-based method is a fundamental approach in damage detection, relying on frequency shifts to identify damage. While it offers the advantage of easily measuring natural frequencies, its limitations include the inability to determine the location of damage accurately and its reliability in complex structures (Güemes et al., 2020). Damping-based methods focus on identifying changes in damping matrices for damage detection. Despite the reported successful applications, challenges exist in accurately measuring damping and its sensitivity to various factors such as crack type, slenderness ratio, and stress levels in cracked cross-sections (Bovsunovsky, 2019).

The modal strain energy-based method calculates the fundamental modal strain energy using the elemental stiffness matrix and mode shape component. It has shown effectiveness in localising damage and estimating its severity (Nguyen & Livaoğlu, 2022). However, it was noted that higher modes had limited sensitivity to damage in terms of strain response. The mode shape-based method compares measured modal displacements of damaged and undamaged structures. Techniques such as the Modal Assurance Criterion (MAC) and Coordinate Modal Assurance Criterion (COMAC) have been developed to enhance its performance, providing information on damage occurrence and locations (Altunışık et al., 2017; Doebling et al., 1998). While mode shape analysis is generally resilient to minor damage, it may not effectively detect and quantify small variations in curvature (Tatar et al., 2017).

The mode shape curvature-based method focuses on analysing minor changes in curvature as a reliable indicator of damage. It has shown high accuracy in detecting and pinpointing damage, especially when deflection changes caused by damage are small (Dessi & Camerlengo, 2015; Pandey & Biswas, 1995). mode shape curvature has been used in many to locate damage in cantilever beams (Altunışık et al., 2019; Chinka et al., 2021; Gupta & Das, 2021; Nayyar et al., 2022; Pooya & Massumi, 2021) and numerical model of a bridge (Gomes & Giovani, 2022; Nguyen et al., 2020).

In conclusion, the natural frequency-based method, damping-based method, modal strain energy-based method, mode shape-based method, and mode shape curvature-based method provide unique advantages and challenges. Mode shape curvature-based methods have shown high accuracy in detecting and localising damage. However, further research is required to address limitations and optimise these methods for practical applications.

3.0 METHODOLOGY

This paper involves three main components: experimental testing, finite element modelling, and mode shape curvature analysis.

3.1 Experimental Testing

A one-story steel frame structure was prepared and set up with fixed-end conditions in the D04 structure laboratory, Faculty of Civil Engineering, University Teknologi Malaysia. The structure is made up of rectangular steel plates. The structure has a span and height of 1000mm, consisting of beams measuring 36mm × 6mm and columns measuring 48mm × 6mm in cross-section. As illustrated in Figure 1, modal testing was conducted on the structure to assess its dynamic characteristics. Fibre optic cables were utilised to connect the impact hammer and accelerometers to the signal analyser, ensuring efficient transmission of data. The hammer used has a sensitivity of 1.82 mV/N, while the accelerometer's sensitivity value is 10.28 mV/ms-2. The modal testing procedure commenced with an initial phase conducted on the intact structure, serving as a reference baseline. Excitation was applied at the predetermined points on the structure, as depicted in Figure 2, using an impact hammer, and the response was measured using accelerometers. These points were spaced at regular intervals of 100mm apart. The collected data was processed using the SIRIUS system and DEWEsoftX software, enabling Fast Fourier Transform (FFT) analysis. The recorded frequency response function (FRF) data in DEWEsoftX was then exported to Microsoft Excel for further analysis and visualisation. The experimental approach involving the intact frame formed a crucial part of the paper, which subsequently focused on inducing damage in the structure and analysing its effects. By intentionally introducing controlled damage as outlined in Table 1, the study aimed to investigate the behaviour of modal data in a one-story steel frame structure. The sample damage cases, depicted in Figures 3 (a) and (b), provided visual representations of the sample damage scenarios studied. The analysis of the vibration data provides valuable insights into the modal behaviour of the structure. Moreover, the vibration data facilitated the detection and localisation of the induced damage within the structural system, contributing to a deeper understanding of its effects.

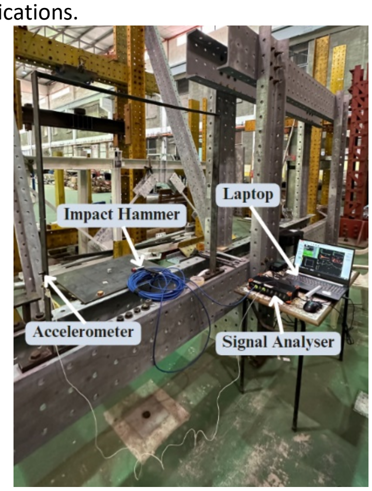


Figure 1 Modal testing setup

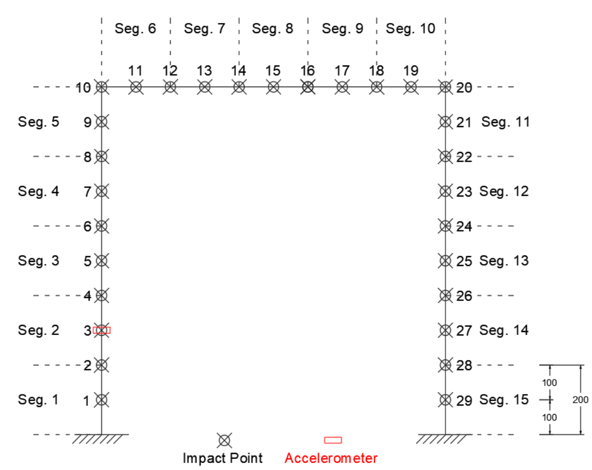


Figure 2 Impact point and segment on the one-story steel frame structure

Table 1 Damage cases

Damage Case	Segment Number	Depth of Single Cut	Number of Cut
1	2	15	3
2	2	15	5
3	2	15	7
4	4	15	7
5	9	15	7

(a) (b)

Figure 3 Damage on the structure (a) 3 cuts with a depth of 15 mm (b) 5 cuts with a depth of 15 mm

3.2 Finite Element Modelling

A numerical model was developed to validate the measured data from the experiment using Abaqus, a powerful finite element analysis software. Finite element analysis was employed to analyse the one-story steel frame structure, utilising 3D deformable solid elements to capture its three-dimensional behaviour. To ensure the reliability of numerical simulations, a mesh convergence study was conducted. The finite element analysis model demonstrated successful convergence, as illustrated in Figure 4, affirming the suitability of the meshing approach for the analysis. The structure was meshed using a global mesh size of 0.05, as illustrated in Figure 5. The meshing pattern demonstrates how the structure is discretised into smaller elements to facilitate the numerical simulations. Furthermore, the finite element modelling incorporated material properties obtained from a tensile test to represent the material behaviour accurately. Figure 6 illustrates the stress-strain curve derived from the tensile test. These properties included a mass density of 7670 kg/m³, Young's modulus of 202.61 GPa, and Poisson's ratio of 0.265. The supports at the columns were defined as fixed in all three DOFs. The experimental findings of the intact frame were validated using this numerical model to ensure that the vibration data of the structure closely matched the experimental results.

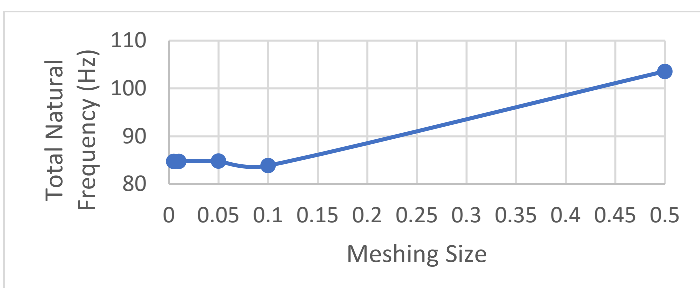


Figure 4 Meshing Convergence Study

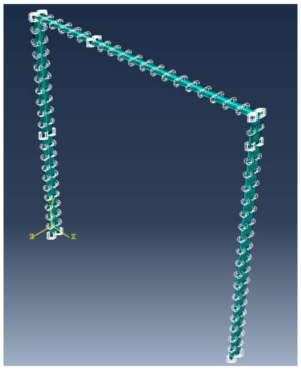


Figure 5 Meshing Configuration in Abaqus

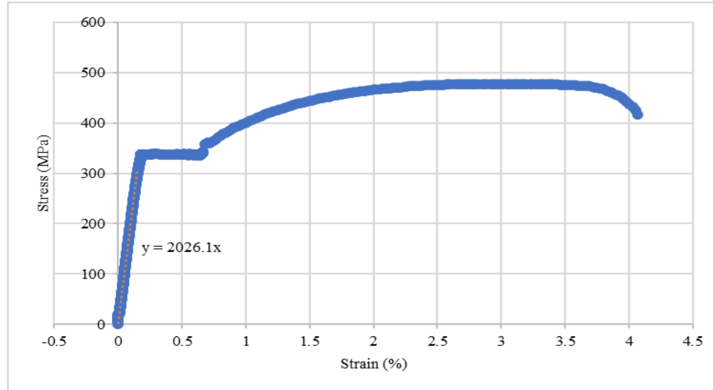


Figure 6 Stress Strain Curve

3.3 Mode Shape Curvature Analysis

This section presents the methodology for analysing mode shape curvature in a one-story steel frame structure. The analysis involves several steps, including mode shape extraction, mode shape normalisation, mode shape curvature calculation and damage detection algorithm.

3.3.1 Mode Shape Extraction

Mode shape extraction is a crucial step in obtaining the spatial distribution of displacements associated with each natural frequency of the structure. It provides valuable insights into the dynamic behaviour and deformation patterns of the structure. In this context, the recorded frequency response function (FRF) data in DEWEsoftX is exported to Microsoft Excel for further analysis and visualisation.

The peaks observed in the FRF data serve as indicators of the vibration modes, and the corresponding frequencies associated with these peaks represent the natural frequencies of the structure. By identifying these peaks and their frequencies, a comprehensive understanding of the vibrational characteristics of the system can be effectively achieved. Furthermore, the magnitudes recorded at all nodes in the FRF data provide valuable insights into the mode shapes of the structure. The distribution of these magnitudes across the nodes reveals the spatial pattern of displacements associated with each vibration mode.

3.3.2 Mode Shape Normalisation

Mode shape normalisation is an essential step in the analysis of mode shapes. Normalisation brings mode shapes to a scale within [-1, 1] range, ensuring consistent magnitudes and allowing fair comparison of mode shapes. Normalisation enhances the interpretability and applicability of mode shapes across test conditions.

3.3.3 Modal Scale Factor

Modal scale factor relates to the scaling of the entire dynamic response of the structure based on the modal properties. This takes into account the modal participation factors, which indicate the extent to which each mode contributes to the overall response. The following equation serves as a demonstration of this concept.

$$MSF = \frac{[\varphi_D]^T[\varphi_I]}{[\varphi_I]^T[\varphi_I]} \tag{1}$$

where $[\varphi_I]$ is the mode shape matrix for the intact case and $[\varphi_D]$ is the mode shape matrix for the damaged case.

3.3.4 Mode Shape Curvature

Mode shape curvature involves determining the curvature distribution along the structure, which is obtained by taking the second derivative of the mode shape function with respect to the spatial coordinates. The resulting curvature values provide information about the local bending and deformation characteristics of the structure. Numerical technique of central difference approximation is used to calculate the mode shape curvature and can be represented by the equation:

$$\varphi_i'' = \frac{\varphi_{i+1} - 2\varphi_i + \varphi_{i-1}}{d^2} \tag{2}$$

where φ_i is the mode shape at node i and d is the distance between two successive nodes.

3.3.5 Damage Detection Algorithm

The damage detection algorithm utilises the mode shape curvature information to identify and locate structural damage. It compares the curvature patterns obtained from the undamaged and damaged states of the structure to detect deviations caused by damage. The algorithm involves the following steps:

3.3.5.1 Change in Mode Shape Curvature

The algorithm calculates the absolute change in mode shape curvature by comparing the intact curvature data with the damaged curvature data.

$$\Delta\varphi_i'' = |\,(\varphi_i'')_I - (\varphi_i'')_D| \tag{3}$$

where $(\varphi_i'')_I$ represents the intact mode shape curvature and $(\varphi_i'')_D$ represents the damaged mode shape curvature at node i.

3.3.5.2 Partial Damage Index

A partial damage index for a segment is a measure of the severity of damage within a specific segment of the structure. It provides information about the relative magnitude of damage in that particular segment compared to the entire structure.

$$PDI_s = \frac{1}{N}\sum_{n=1}^{N}(\Delta\,\varphi)_i'' \tag{4}$$

where N represents the total number of nodes in a segment.

3.3.5.3 Total Damage Index

The algorithm computes the Total Damage Index (TDI) by quantifying the partial damage indices across multiple modes. The TDI represents the overall level of damage or deterioration in the structure.

$$TDI_s = \sum(m=1)^M \frac{PDI_s}{\sum_{s=1}^{S} PDI} \tag{5}$$

where S represents the total number of segments in a mode, and M represents the total number of modes.

4.0 RESULTS AND DISCUSSION

The results obtained from both finite element modelling and experimental testing are discussed herein. The findings contribute to the understanding of modal behaviour in the presence of damage and highlight the effectiveness of mode shape curvature analysis for damage detection in one-story steel frame structures.

4.1 Finite Element Modelling

Table 2 showcases the natural frequency data obtained from both finite element analysis and experimental measurements for a one-story steel frame structure. In this study, the focus was primarily on analysing the intact condition of the structure, disregarding any instances of damage. By comparing the results obtained from the finite element analysis and experimental measurements, it was observed that the variation between the two data sets was minimal, with a difference of less than 3% for the first four modes. This close alignment between the experimental and numerical data provides strong evidence of the success of the experiment and the reliability of the experimental setup.

Table 2 Natural frequency obtained from the finite element analysis and experimental measurements

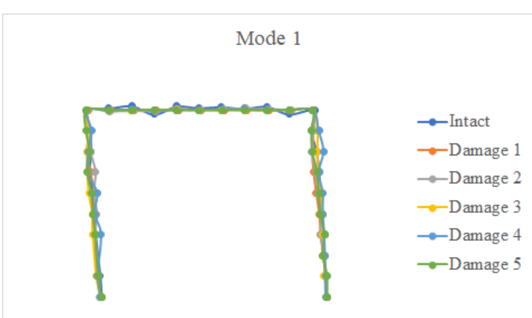
Mode Shape	Natural Frequency (Hz)		Difference (%)
	Finite Element	Experiment	
1	4.8269	4.6875	2.89
2	18.622	18.359	1.41
3	29.355	28.613	2.53
4	32.020	31.250	2.40

4.2 Behaviour of Modal Data

Understanding the behaviour of modal data in both intact and damaged one-story steel frame structures is crucial for assessing the effects of damage on the structural dynamics. Modal data, including mode shapes and natural frequencies, provides valuable insights into the vibrational characteristics and response of a structure.

Mode shapes are visual representations of structural deformations at specific modes of vibration. In intact condition, the mode shapes exhibit clean and regular patterns, indicating a well-defined vibrational response. However, in damaged structures, irregularities or deviations from the expected mode shapes can be observed. Figure 7 illustrates the plot of the mode shape obtained from the undamaged and damaged one-story steel frame structure during the experimental investigation.

The natural frequencies, which represent the rates at which a structure naturally vibrates in different modes, also exhibit distinct behaviours in intact and damaged structures. This pattern is evident in the results presented in Table 3 and Figure 8. The presence of damage introduces changes in the stiffness distribution and alters the structural dynamics, thereby leading to a decrease in the natural frequencies (Yang & Le Wang, 2009). Figure 9 demonstrates this phenomenon by comparing the total natural frequencies between intact and damaged structures. In essence, the pattern exhibits a gradual decline in total frequency with increasing the level of damage.



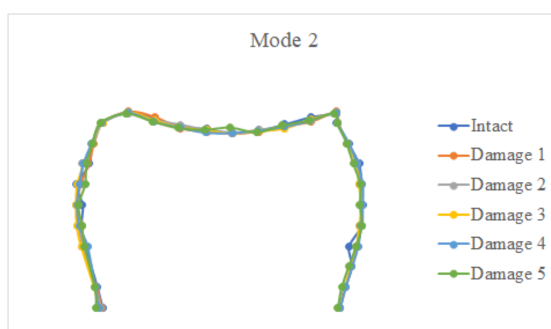


Figure 7 Mode shape plot obtained from experiment

Table 3 Natural frequency obtained from experimental measurements

Case	Natural Frequency (Hz)				Total Frequency (Hz)
	Mode 1	Mode 2	Mode 3	Mode 4	
Intact	4.6875	18.359	28.613	31.250	82.910
Damage 1	4.5898	18.262	28.613	31.152	82.617
Damage 2	4.5898	18.262	28.613	31.152	82.617
Damage 3	4.5898	18.262	28.613	31.055	82.520
Damage 4	4.4922	17.871	28.418	31.055	81.836

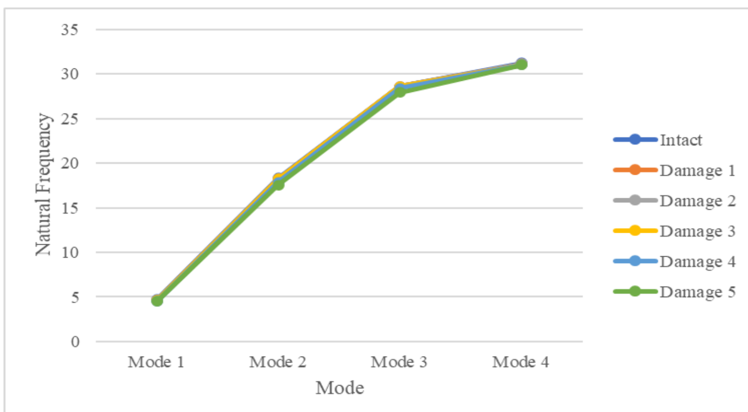


Figure 8 Plot of natural frequency versus mode shape

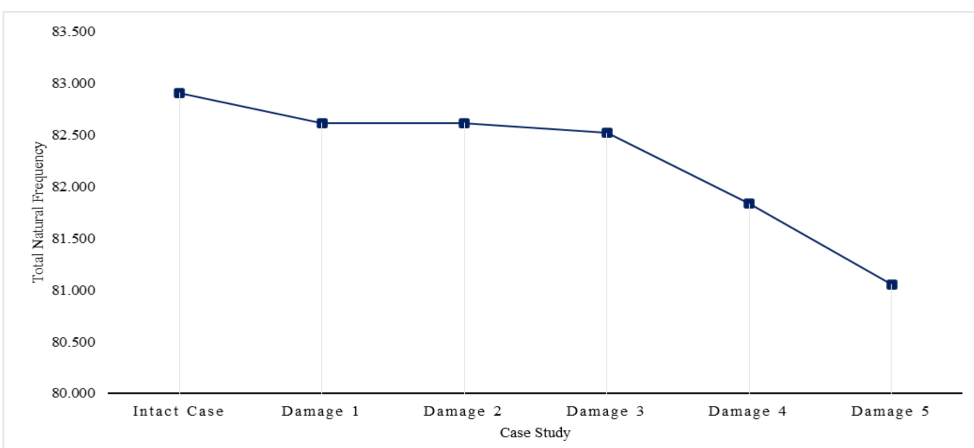


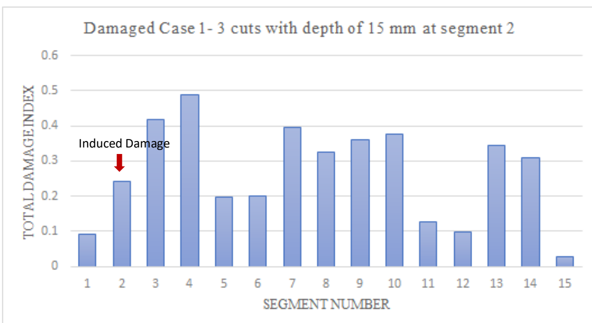
Figure 9 Comparison of total natural frequencies between intact and damaged structures

4.3 Mode Shape Curvature

Mode shape curvature analysis facilitates the visualisation of variations in curvature along the structure, thereby highlighting regions characterised by concentrated bending or curvature. This information is particularly important in identifying regions that undergo significant changes in vibrational response or are more susceptible to damage. By examining the mode shape curvature, critical areas for further investigation and structural assessment can be identified. By utilising this information, the development of a TDI becomes possible, which allows for visualising and quantifying the extent of damage of a segment within a structure. This plot serves as a visual representation of the TDI values associated with different segments within the structure. Figure 10 illustrates the plot of the TDI and Table 4 presents the outcomes of the damage identification performance in detecting induced damage across different segments of the structure.

The ability to successfully detect and localise damage in other segments, such as Segment 4 and 9 validates the effectiveness of the approach used. However, there were no successful detections in Segment 2 for any of the cases. Despite the increased severity of damage, the absence of a peak damage index and the emergence of an unforeseen alternating pattern in the TDI at Segment 2 can be attributed to the fixed support's tendency to constrain the displacement and movement of the structure in that specific segment. Due to its stabilising nature, the fixed support effectively restricts excessive deformation, thereby mitigating potential damage in that segment (Khan et al., 2020). As a result, the response and damage may be relatively lower compared to other segments of the structure.

Moreover, false damage detection in other segments has been observed when utilising mode shape curvature in TDI as a method for damage detection and localisation. This occurrence can be attributed to the susceptibility of mode shape curvature data to noise, resulting in inaccurate curvature values (Shokrani et al., 2018). These inaccuracies lead to false indications of damage in segments where, in reality, no damage is present while also hindering the accurate assessment of damage severity.



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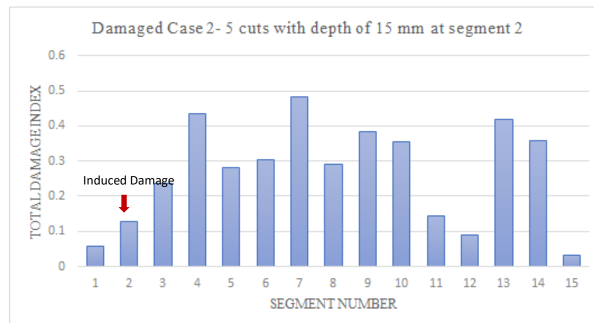

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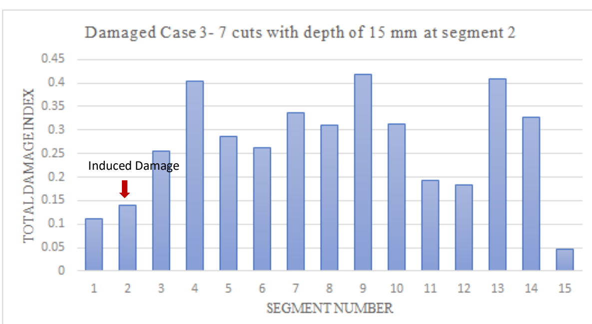

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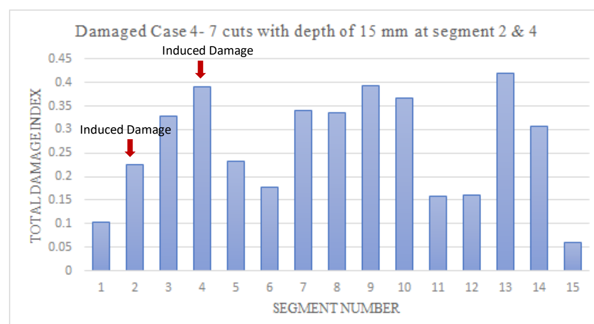

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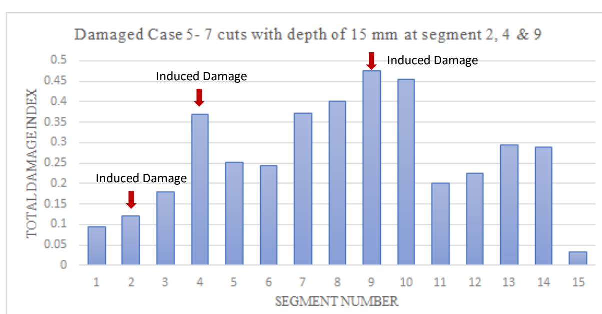

(e)

Figure 10 Total damage index plot for (a) Damage case 1 (b) Damage case 2 (c) Damage case 3 (d) Damage case 4 (e) Damage case 5

Table 4 Outcomes of the total damage index identification performance

Segment	Case 1 Induced Damage	Case 1 Detection Result	Case 2 Induced Damage	Case 2 Detection Result	Case 3 Induced Damage	Case 3 Detection Result	Case 4 Induced Damage	Case 4 Detection Result	Case 5 Induced Damage	Case 5 Detection Result
2	3 cuts	No	5 cuts	No	7 cuts	No	7 cuts	No	7 cuts	No
4	-	-	-	-	-	-	7 cuts	Yes	7 cuts	Yes
9	-	-	-	-	-	-	-	-	7 cuts	Yes

4.0 CONCLUSIONS

This paper concludes that mode shape curvature analysis has mixed effectiveness in detecting and localising damage. While successful detection and localisation were achieved in some segments, no successful detections were observed in one segment for any of the cases. Additionally, false damage detection and an unexpected alternating pattern emerged in the TDI with increasing damage severity were observed in certain segments. These findings suggest that utilising mode shape curvature for damage detection may have limitations and should be carefully interpreted. Further paper and refinement of the methodology are needed to enhance the reliability and accuracy of damage detection using mode shape curvature analysis.

This paper has made significant contributions to the field of structural health monitoring to improve the safety, durability, and longevity of one-story steel frame structures. Findings conforming to the objectives of this study can be summarised as shown:

1. The natural frequency data obtained from finite element analysis closely align with experimental measurements, confirming the reliability of the experimental setup.
2. Deviations from regular mode shapes and decreases in natural frequencies have been observed in damaged structures, providing clear indications of the presence of damage.
3. The effectiveness of the TDI has been demonstrated in detecting and locating damage across various segments of the structure. However, it is worth noting that no indications of damage were found in Segment 2. Furthermore, a decrease in the TDI was observed in Segment 2, contrary to what would be expected with higher damage severity with higher TDI. This emphasises the importance of considering factors such as fixed supports or other influences that may affect the response and vulnerability of different segments within the structure.
4. Some segments have shown false indications of damage has been observed. These findings highlight the need for careful interpretation of results and consideration of potential sources of noise or other factors that may impact the accuracy of the damage detection process.

Acknowledgements

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References

[1] Altunışık, A. C., Okur, F. Y., and Kahya, V. 2017. Modal parameter identification and vibration-based damage detection of a multiple cracked cantilever beam. *Engineering Failure Analysis*, *79*: 154–170.

[2] Altunışık, A. C., Okur, F. Y., Karaca, S., and Kahya, V. 2019. Vibration-based damage detection in beam structures with multiple cracks: modal curvature vs. modal flexibility methods. *Nondestructive Testing and Evaluation*, *34*(1): 33–53.

[3] Bovsunovsky, A. P. 2019. Efficiency of crack detection based on damping characteristics. *Engineering Fracture Mechanics*, *214*: 464–473.

[4] Chinka, S. S. B., Putti, S. R., and Adavi, B. K. 2021. Modal testing and evaluation of cracks on cantilever beam using mode shape curvatures and natural frequencies. *Structures*, *32: 1386-1397*

[5] Das, S., Saha, P., and Patro, S. K. 2016. Vibration-based damage detection techniques used for health monitoring of structures: a review. *Journal of Civil Structural Health Monitoring*, *6*(3): 477–507.

[6] Dessi, D., and Camerlengo, G. 2015. Damage identification techniques via modal curvature analysis: Overview and comparison. *Mechanical Systems and Signal Processing*, *52–53*: 181–205.

[7] Doebling, S. W., Farrar, C. R., Prime, M. B., and Shevitz, D. W. 1998. A summary review of vibration-based damage identification methods. *Shock and Vibration Digest*, *30*(2): 91–105.

[8] Gharehbaghi, V. R., Noroozinejad Farsangi, E., Noori, M., Yang, T. Y., Li, S., Nguyen, A., Málaga-Chuquitaype, C., Gardoni, P., and Mirjalili, S. 2021. A Critical Review on Structural Health Monitoring: Definitions, Methods, and Perspectives. *Archives of Computational Methods in Engineering. 29*(4): 2209–2235.

[9] Gomes, G. F., and Giovani, R. S. 2022. An efficient two-step damage identification method using sunflower optimization algorithm and mode shape curvature (MSDBI–SFO). *Engineering with Computers*, *38*(5): 1711–1730

[10] Güemes, A., Fernandez-Lopez, A., Pozo, A. R., and Sierra-Pérez, J. 2020. Structural Health Monitoring for Advanced Composite Structures: A Review. *Journal of Composites Science 2020, 4*(1): 13.

[11] Gupta, S. K., and Das, S. 2021. Damage detection in a cantilever beam using noisy mode shapes with an application of artificial neural network-based improved mode shape curvature technique. *Asian Journal of Civil Engineering*, *22*(8): 1671–1693.

[12] Hassani, S., Mousavi, M., and Gandomi, A. H. 2022. Damage detection of composite laminate structures using VMD of FRF contaminated by high percentage of noise. *Composite Structures*, *286.115243*

[13] Jayasundara, N., Thambiratnam, D. P., Chan, T. H. T., and Nguyen, A. 2020. Damage detection and quantification in deck type arch bridges using vibration based methods and artificial neural networks. *Engineering Failure Analysis*, *109*: 104265.

[14] Khan, M. W., Din, N. A., and Ul Haq, R. 2020. Damage detection in a fixed-fixed beam using natural frequency changes. *Vibroengineering Procedia*, 30(4):38-43

[15] Martucci, D., Civera, M., and Surace, C. 2023. Bridge monitoring: Application of the extreme function theory for damage detection on the I-40 case study. *Engineering Structures*, *279*: 115573.

[16] Meruane, V., Yanez, S. J., Quinteros, L., and Saavedra Flores, E. I. 2022) Damage Detection in Steel–Concrete Composite Structures by Impact Hammer Modal Testing and Experimental Validation. *Sensors 22*(10): 3874.

[17] Modares, M., and Waksmanski, N. 2013. Overview of Structural Health Monitoring for Steel Bridges. *Practice Periodical on Structural Design and Construction*, *18*(3): 187–191.

[18] Nayyar, A., Baneen, U., Ahsan, M., Zilqurnain Naqvi, S. A., and Israr, A. 2022. Damage detection based on output-only measurements using cepstrum analysis and a baseline-free frequency response function curvature method. *Science Progress*, *105*(1): 1–25

[19] Nguyen, D. H., Nguyen, Q. B., Bui-Tien, T., De Roeck, G., and Abdel Wahab, M. 2020. Damage detection in girder bridges using modal curvatures gapped smoothing method and Convolutional Neural Network: Application to Bo Nghi bridge. *Theoretical and Applied Fracture Mechanics*, *109*: 102728.

[20] Nguyen, Q. T., and Livaoğlu, R. 2022. Modal strain energy-based updating procedure for damage detection: a numerical investigation. *Journal of Mechanical Science and Technology*, *36*(4): 1709–1718.

[21] Pandey, A. K., and Biswas, M. (1995). Experimental verification of flexibility difference method for locating damage in structures. *Journal of Sound and Vibration*, *184*(2), 311–328.

[22] Pooya, S. M. H., and Massumi, A. 2021. A novel and efficient method for damage detection in beam-like structures solely based on damaged structure data and using mode shape curvature estimation. *Applied Mathematical Modelling*, *91*: 670–694.

[23] Shang, Z., Sun, L., Xia, Y., and Zhang, W. 2020. Vibration-based damage detection for bridges by deep convolutional denoising autoencoder. *Structural Health Monitoring*, *20*(4): 1880–1903.

[24] Shokrani, Y., Dertimanis, V. K., Chatzi, E. N., and N. Savoia, M. 2018. On the use of mode shape curvatures for damage localization under varying environmental conditions. *Structural Control and Health Monitoring*, *25*(4): e2132

[25] Tan, Z. X., Thambiratnam, D. P., Chan, T. H. T., Gordan, M., and Abdul Razak, H. 2019. Damage detection in steel-concrete composite bridge using vibration characteristics and artificial neural network. *Structure and Infrastructure Engineering*, *16*(9): 1247–1261.

[26] Tatar, A., Niousha, A., and Rofooei, F. R. 2017. Damage detection in existing reinforced concrete building using forced vibration test based on mode shape data. *Journal of Civil Structural Health Monitoring*, *7*(1): 123–135.

[27] Umar, S., Vafaei, M., and C. Alih, S. 2021. Sensor clustering-based approach for structural damage identification under ambient vibration. *Automation in Construction*, *121*: 103433.

[28] Wu, R., Zhang, H., Yang, R., Chen, W., and Chen, G. 2021. Nondestructive Testing for Corrosion Evaluation of Metal under Coating. *Journal of Sensors*, 2021(2):1-16

[29] Yang, Z., and Le Wang. 2009. Structural Damage Detection by Changes in Natural Frequencies. *Journal of Intelligent Material Systems and Structures, 21*(3): 309–319.

[30] Zhan, P., Qin, X., Zhang, Q., and Sun, Y. 2022. Damage identification in beam-like structure using strain FRF-based damage index and artificial neural network. *Mechanics of Advanced Materials and Structures*, *30*(12): 2458–2476.