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VIBRATION-BASED DAMAGE DETECTION USING MODAL DATA: AN EXPERIMENTAL VERIFICATION

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Abstract. Dynamic properties are the functions of physical properties. Over the past 20 years, considerable efforts have been made in investigating the relationship between structural damage and modal parameters. Many methods have been introduced ranging from direct methods to application of optimization algorithms. Most of the authors concluded that the dynamic properties are feasible as damage indicators. However, most of the works are validated through analytical models instead of experimental verification. Thus, this study aims to investigate the efficiency of modal curvature and natural frequencies in damage detection through an experimental example of a rectangular hollow section steel beam. Seven damage scenarios are simulated on the specimen using grinder cuts for different damage location and severity. Sensitivity study on the damage index of modal curvature is performed and issues related to the application using modal data are discussed. The results show that natural frequency is a sensitive damage existence indicator. While, the reliability of modal curvature is quite limited and very much depending on the accuracy and precision of measurements.

Keywords: Structural health monitoring; modal testing; modal data

Abstrak. Sifat dinamik adalah fungsi bagi ciri-ciri fizikal. Sejak 20 tahun yang lalu, banyak usaha telah dibuat dalam menyiasat hubungan antara kerosakan struktur dan parameter modal. Banyak kaedah telah diperkenalkan dari kaedah langsung hingga penggunaan algoritma optimuman. Kebanyakan penulis membuat kesimpulan bahawa sifat-sifat dinamik boleh digunakan sebagai penunjuk kerosakan. Walau bagaimanapun, kebanyakan kerja tersebut telah disahkan melalui model simulasi dan bukannya pengesahan uji kaji. Oleh itu, kajian ini bertujuan untuk menyiasat kecekapan kelengkungan mod dan frekuensi tabii dalam pengesanan kerosakan melalui contoh uji kaji rasuk keluli keratan segi empat berongga. Tujuh senario kerosakan disimulasikan pada spesimen dengan menggunakan potongan giling bagi lokasi kerosakan dan keterukan yang berbeza. Kajian kepekaan kepada indeks kerosakan kelengkungan modal

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dilakukan dan isu-isu yang berkaitan dengan penggunaan data modal dibincangkan. Keputusan menunjukkan bahawa frekuensi tabii adalah penunjuk kewujudan kerosakan yang sensitif. Sementara, kebolehpercayaan kelengkungan modal pula adalah agak terhad dan amat bergantung kepada ketepatan pengukuran.

Kata kunci: Pemantauan kesihatan struktur; ujian modal; data modal

1.0 INTRODUCTION

Structural health monitoring (SHM) has emerged as an efficient tool to improve structure's safety and integrity. It can be classified into two categories namely local and global. Local methods exam structure components in precise detail. But these methods require a priori assumption of damage location because they have limited assessment rate. For global methods, structure is monitored as one unit whereby measurements at several locations are sufficient to assess the whole structure.

Damage detection technology such as ultrasonic wave, radiography, eddy-current, magnetic field and thermal field are all considered as local methods. For large scale structure, the local methods seem impractical in term of time and cost. Therefore, the needs of quantitative global damage detection methods that can be applied to large scale structures have led to the research and development of vibration-based damage detection.

The fundamental idea of vibration-based damage detection is by utilizing changes of modal parameters such as natural frequency, mode shape and damping ratio to monitor the physical changes of the structure. It is well proven that structural damage will cause detectable changes in modal parameters. This is because dynamic properties are the functions of physical properties [1].

Vibration-based damage detection technique was initially developed in 1970s by oil and gas industry as the safety strategy for offshore structures. The methodology used was simulation of damage scenarios, examine the changes in natural frequencies and correlate those changes with site measurements. Aerospace community began to apply this technology on space shuttle orbiter body during the late 1970s. As a result, shuttle modal inspection system (SMIS) was introduced to identify fatigue damage in components such as control surfaces, fuselage panels and lifting surfaces [2].

Civil engineering community started to develop these techniques during the early 1980s. Basic dynamic properties such as natural frequency, damping ratio and mode shape are the primary parameters used in the investigations. Gradually, method based on changes in modal derivatives such as mode shape curvature, change in flexibilities, change in stiffness, and damage index are used in concrete and steel bridges. Nowadays, damage detection methods integrated with optimization algorithm under consideration of uncertainty are the major fashion.

However, modal curvature is a direct method which emphasized on changes in mode shape values to detect damage. [3] and [4] had compared several of these methods including modal strain energy method, mode shape curvature method, change in flexibilities method and change in stiffness method. Based on both numerical and experimental models, the authors showed that modal curvature is comparatively sensitive and reliable in detecting damages.

Mode shape second partial derivative also known as modal curvature was first introduced by [5]. Through analytical beam models, the authors found that modal curvature is more sensitive compared to modal slope and Modal Assurance Criterion (MAC) & Coordinate MAC. [6] applied the same method to detect damages in pre-stressed concrete bridge. In the study, the authors introduced a term called curvature damage factor (CDF) to sum up the average changes of modal curvature over the entire modes. The authors also concluded that modal curvature of the lower modes is more accurate than those of the higher ones.

Similarly, recent study by [7] had also confirmed the reliability of modal curvature through a numerical slab model. The authors also commented that mode shape of higher order is not accurate to indicate damaged region. Despite of many authors concluded that mode shape curvature method is quite reliable in detecting damages, but most of the studies are verified through numerical example. Hence, an experimental demonstration of vibration-based damage detection is shown in this paper to investigate the efficiency of modal data in damage detection.

2.0 OBJECTIVE

This study investigates the sensitivity of mode shape curvature for the detection of damage location and severity in a laboratory tested rectangular hollow section (RHS) beam. Unlike numerically simulated damage data, where it is noise free, the measured vibration data from real structures inevitability contain noises. Therefore the reliability of modal curvature method in detecting real damage needs to be investigated. Additionally, the changes of frequencies over different damage patterns are also monitored.

3.0 METHODOLOGY

The primary objective of this study is to investigate the reliability of modal curvature to detect damage using experimental data. There are three main stages involved; i) Experimental test; ii) Damage detection using modal curvature method and; iii) Sensitivity study.

In experimental stage, modal test was conducted to obtain the dynamic response of the specimen. A 100×50×5 mm RHS beam with the length of 1900mm was used in the experimental test. In order to simulate different damage level, seven damage scenarios were introduced through grinder cuts with different severities. Modal tests were conducted at each damage level to obtain the modal properties of the damage scenarios. During the test, the responses are passed through signal post-processing software package to extract the required modal parameters such as natural frequencies and mode shapes.

The section properties of the beam are; mass density = 7800 kg/m^3. Poisson's ratio = 300×10^{-3} and Young's modulus = 200×10^{8} kN/m^2. Figure 1 shows the layout of the specimen. Two short steel angle sections were placed at 150 mm from both ends to imply the simply supported condition. For the purpose of sensitivity study, the model is divided into 19 segments with 100mm segment length.

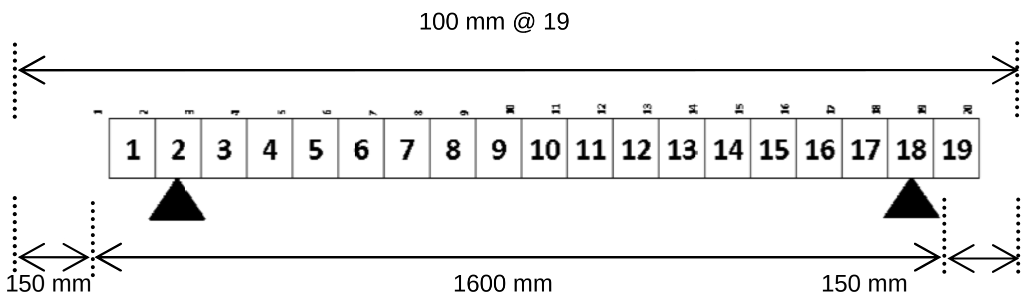


Figure1 Specimen layout

In the test, damage scenarios consisted of several conditions. They are single damage case, multiple damage case, symmetrical damage case and unsymmetrical damage case. Various damage severities are also designed by varying the depth of cuts. Scenario 1 and 2 represent the single damage cases with different damage severities. Both damages are at segment 10 with 5mm and 15mm depths respectively. Scenario 3 represents the unsymmetrical damage condition with 15mm cut at segments 4 and 10. Damages are applied at more locations in Scenario 4 at segments 4, 7, 10, 13 and 16 with 15mm depth respectively. In Scenario 5, the damage severity only at segment 10 is increased to 25mm depth while for Scenarios 6 and 7 the severities of the damage at the five segments are increased to 25mm and 40mm respectively. In this study, four target modes are used for damage assessment. The seven damage scenarios are illustrated in Figure 2.

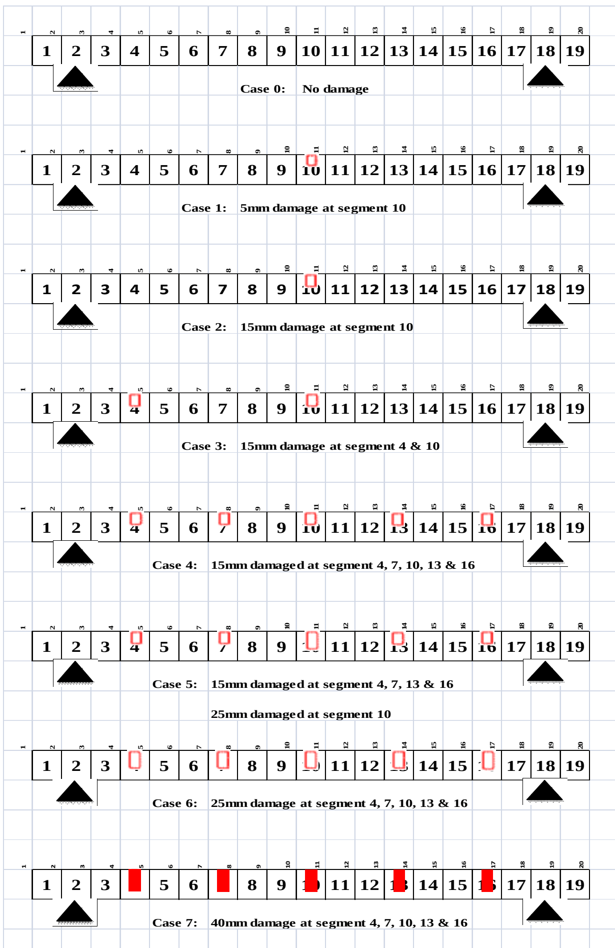


Figure 2 Damage scenarios

In order to validate the experimental data, the RHS beam is simulated in structural analysis software. The beam model is constructed as tube section and its properties are selected from British Steel (BS) table. Two pinned supports and 1.0 factor of self-weight are assigned to the model. Modal calculation is requested in order to obtain the required modal frequencies. Table 1 illustrates a comparison between numerical and experimental natural frequencies for undamaged beam.

Comparing both of the data, it is observed that for mode 1 to mode 4, the variations are relatively small which are 7.6%, 23.9%, 11.0% and 1.5% respectively. The overall difference is about 7.8% only. This indicates that the experimental results are quite reliable. The differences between numerical and experimental data are normally expected due to material nonlinearity for experimental specimen. Moreover, the boundary conditions for both models are not exactly the same. Experimental supports are slightly moveable, while in numerical model the supports are totally fixed. Nevertheless, these differences will not have any effects on the performance of damage detection as long as the system remains unchanged for every damage case. This is because the basis of this damage detection method is based upon relativity between intact and damaged data.

Table 1 Natural frequencies comparison

Mode	Numerical (Hz)	Experimental (Hz)	Difference (Hz)	Difference (%)
1	96.225	103.5	7.3	7.6
2	375.218	464.8	89.6	23.9
3	811.368	900.4	89.0	11.0
4	1370.208	1390.3	20.1	1.5
Σ	2653.019	2860.3	207.3	7.8

4.0 MODAL CURVATURE METHOD

Damaged cases mode shapes are mass-normalised with respect to undamaged case by multiplying them with modal scale factor which is given by,

$$F = \frac{[A]^T[B]}{[B]^T[B]} \quad (1)$$

where, F = Modal scale factor
A = Mode shape matrix for damaged case
B = Mode shape matrix for undamaged case

(i) Modal curvature (MC) of every node is estimated by central difference approximation which is given by,

$$\text{MC}, \phi''_{n,m} = \frac{\phi_{n+1,m} - 2\phi_{n,m} + \phi_{n-1,m}}{d^2} \quad (2)$$

where, n = Number of node
m = Number of mode
d = Distance between two nodes

Change in modal curvature (MC) of every node is calculated by the differences in mode shape curvatures (CMC) between intact and damaged case,

$$\text{CMC}, \Delta\phi''_{n,m} = \phi''_{n,m} - \phi''_{n,m} \quad (3)$$

where, ϕ'' = Modal curvature for undamaged case
ϕ'' = Modal Curvature for damaged case

Simple formulae for damage index are introduced to summarise the changes in mode shape curvature values. Partial damage index (PDI) of a segment is calculated by averaging the summation of change in modal curvatures (MC) at particular mode to the number of node (N) in the segment,

$$\text{PDI} = \frac{1}{N}\sum_{n=1}^{N} \Delta\phi''_{i,j} \quad (4)$$

where, N = Total number of node

To standardise all the partial damage index, modal curvature index (MCI) of a segment is calculated by summation of ratio of partial damage index (PDI) to its total value,

$$\mathrm{MCI} = \sum_{m=1}^{M} \frac{\mathrm{PDI}}{\sum_{s=1}^{S} \mathrm{PDI}} \quad (5)$$

where, S = Total number of segment
M = Total number of mode

The summation of modal curvature index of a damage case will be equal to the total number of vibration mode that considered in the analysis.

5.0 EXPERIMENTAL RESULT

5.1 Natural Frequency Changes

Table 2 shows the natural frequencies of undamaged and damaged cases, while Figure 3 plots the trend of the frequencies drops for Case 0 to Case 7. The level of damage intensity is increased for each case. For Case 1, the average frequency change is -0.2% and this is followed by -5.0%, -8.1%, -10.9% and -13.2% for Case 2, Case 3, Case 4, and Case 5 respectively. Next, as the damage intensity increased to 25mm at five particular segments, the average change in frequency drops steadily for Case 7 to -9.3%. Lastly, for Case 8, the average change in frequency decreased to -31.7%.

Based on the results, it is observed that the natural frequencies of undamaged case are the highest and their values are gradually decreases as the damage level increases from the least severe Case 1 to the most severe Case 7. This indicates that the natural frequency decreases as the damage severity increases. The frequency reduction trend illustrated in Figure 3 shows that the maximum changes of frequency occurred at mode 4 as compared to the lower modes. This indicates that the higher natural frequency modes are more sensitive to damage compared to lower modes.

Table 2 Natural frequencies

MODE	C0 (Hz)	C1 (Hz)	C2 (Hz)	C3 (Hz)	C4 (Hz)	C5 (Hz)	C6 (Hz)	C7 (Hz)
1	103.5	102.5 -0.9%	87.9 -15.1%	79.1 -23.6%	79.0 -23.6%	76.2 -26.4%	77.2 -25.5%	68.4 -34.0%
2	464.8	458.0 -1.5%	451.2 -2.9%	445.3 -4.2%	430.7 -7.4%	424.8 -8.6%	380.9 -18.1%	320.3 -31.1%
3	900.4	912.1 +1.3%	881.8 -2.1%	881.0 -2.1%	840.8 -6.6%	810.6 -10.0%	741.2 -17.7%	610.4 -32.2%
4	1390.3	1400.3 +0.5%	1400.0 +0.1%	1360.3 -2.7%	1310.3 -6.0%	1290.3 -7.7%	1170.3 -16.0%	985.4 -29.3%
Σ	2860.3	2870.3 -0.2%	2820.3 -5.0%	2760.3 -8.1%	2660.3 -10.9%	2600.3 -13.2%	2370.3 -19.3%	1984.4 -31.7%

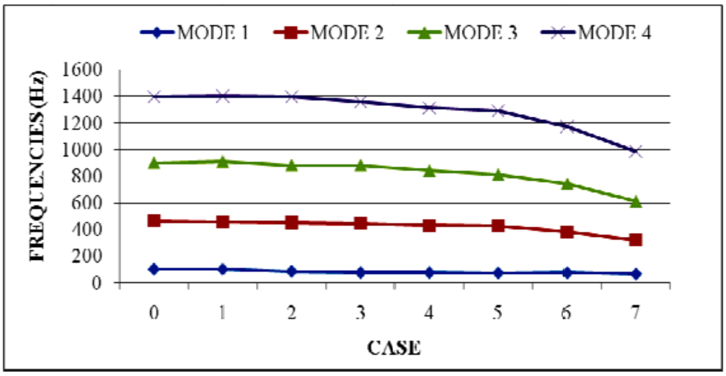


Figure 3 Natural frequencies reduction trend

5.2 Mode Shape Changes

In this stage, several adjustments on the experimental mode shape values are made. Firstly, the entire damage case mode shapes are mass-normalized using modal scale factor with respect to the intact case. The formula is displayed in equation (1). Mass-normalized mode shapes are then filtered using Kalman smoothing method with 3 history points to minimize the experimental noise. By using mathematical software, the values are normalized again to fit their ranges within 0 to 1. This step is to ensure that all the mode shapes are stayed in one standard form before the comparison.

Figure 4 shows the normalized mode shapes from mode 1 to mode 4. In overall, the mode shapes are varying for every damage cases. As presented in the figures, the variation of mode shapes between Case 0 and Case 1 is the smallest. This difference is about the same for Case 2 and Case 3, where the variation of mode shape between damaged cases and intact case is quite small. Larger variations of mode shapes are observed in Case 7 and Case 8 as the damage intensity dramatically increases. From these observations, mode shape values are able to provide preliminary information regarding the presence of damage. However, changes in mode shape provide insufficient information to determine the location and severity of the damage. Thus, the following subtopic presents the direct application of modal curvature to localize damage regions.

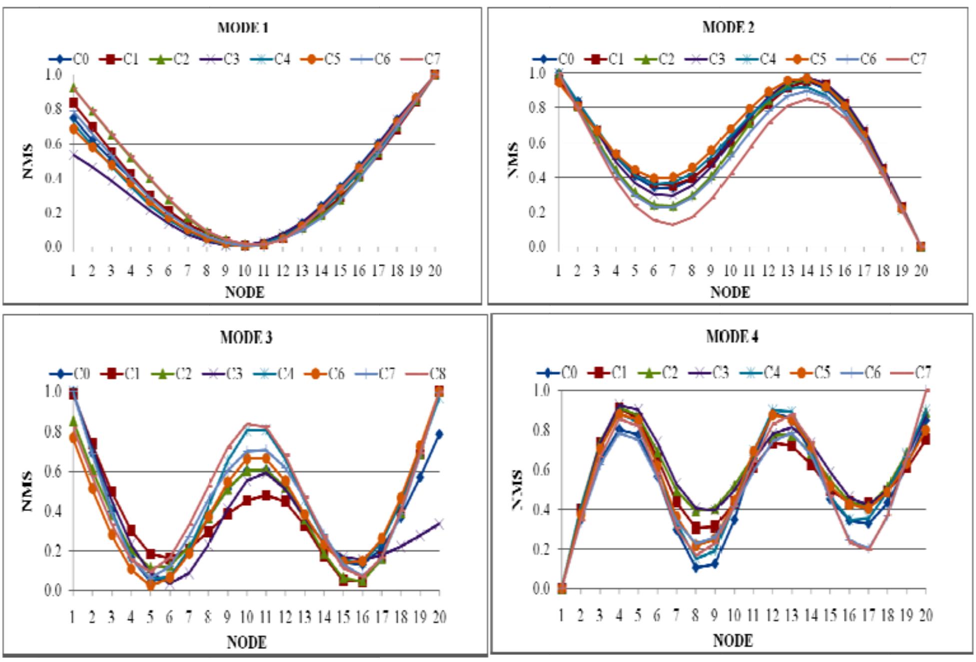
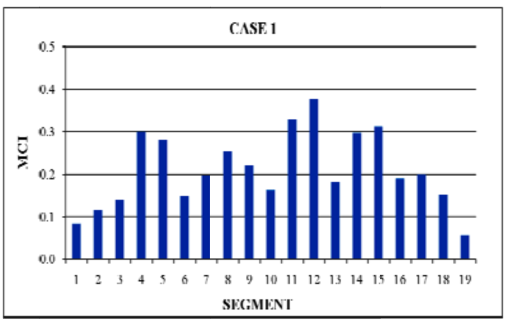


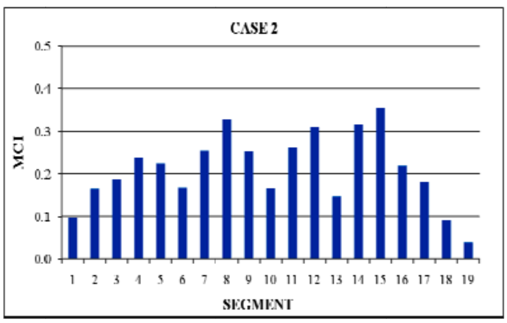
Figure 4 Mode shapes variation trend

5.3 Modal Curvature Index

Two damage index formulae are introduced in this sensitivity study namely partial damage index (PDI) and modal curvature index (MCI). Briefly, the PDI summaries changes of modal curvature at one particular mode, while MCI summaries the changes of modal curvature over the entire modes. These indexes directly indicate the damage severity at every segment. Figure 5 shows MCI damage predictions using modal curvature method.

The degree of variation of modal curvatures between damage and undamaged beam are indicated by the MCI value. In Case 1, the highest MCI values are occurred at segments 11-12 however, the actual damage is located at segment 10. For damage Case 2, the damage severity is increased at the same segment from 5mm to 15mm. Again, the result seems inaccurate where the damage is wrongly predicted at segment 8 and segment 15. The same situation also observed in Case 3 where the damage locations are inadequately predicted. The actual damaged segments for Case 3 are segments 4 and 10 while the predicted are distributed among segments 2-3-4, segments 7-8, segments 11-12 and segments 14-15-16. Cases 4, 5 and 6 show the same situation where the modal curvature method is still unable to provide a reliable result even though the severities of the damages are high.





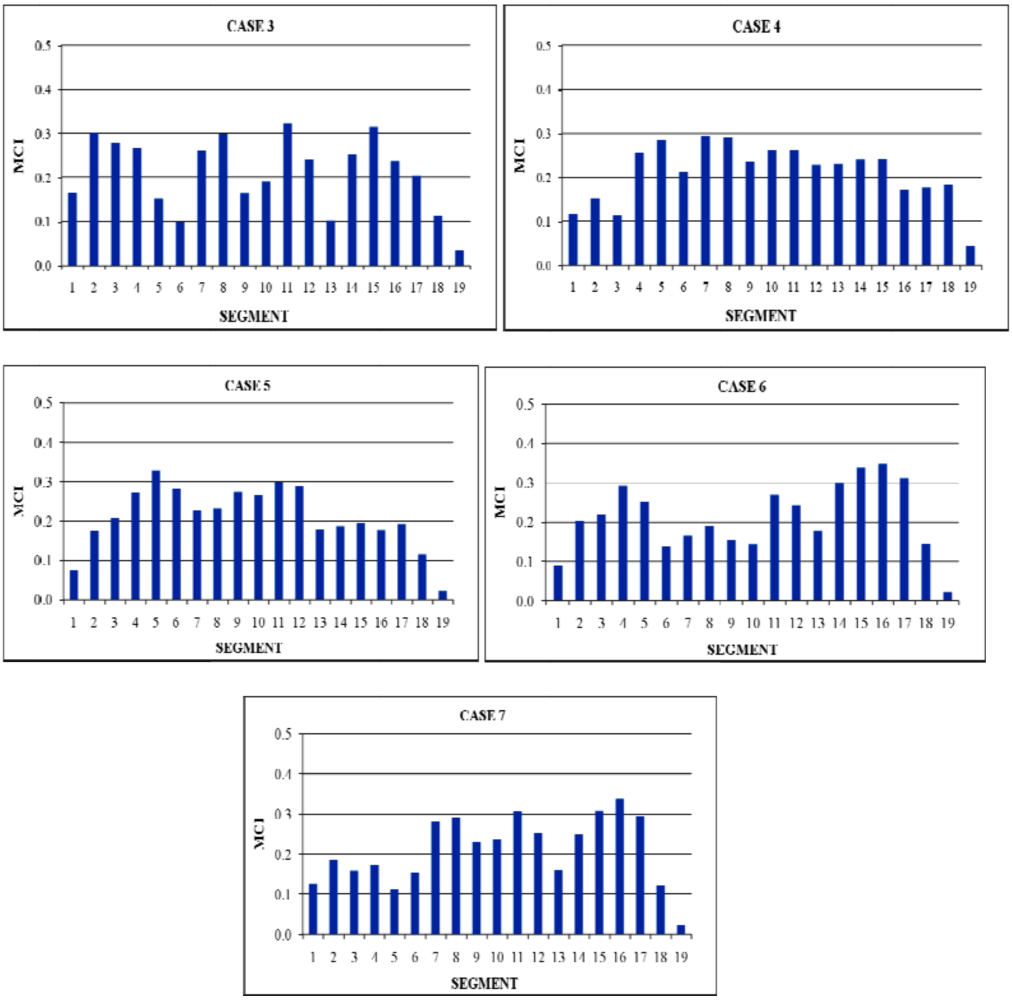


Figure 5 MCI damage predictions

Based on the results, it is marked that the natural frequencies provide damage information correctly. However, since it is a global parameter, natural frequency is not capable to tell a unique solution to locate damage region. For instance, frequency is unable to detect symmetric damage in a symmetric structure. On the other hand, results obtained using Modal Curvature method is unsatisfactory. This is not reconciled with the result obtained using numerical model observed in many other studies for instance, in [5], [7] and [8].

In vibration test, mode shape has relative larger error than the natural frequency, which explains the situation where natural frequency performs better than modal curvature for the same data measurement. Major concern is regarding the measurement errors which include imprecise placement and orientation of sensors and errors that are resulted from signal processing and the identification approach. Random error which is part of measurement errors such as corrosion of specimen, temperature difference, air moisture, sound waves and other environmental factors would be normally expected in any vibration test. Besides that, frequency response functions (FRF) are relatively sensitive and easily contaminated due to support free vibration.

Although the experiment is carried out in precise manner, the original placement of sensors and specimen are still subjected to change due to the vibration of cutting process and steps of roving the sensors. The difficulties to detect real damage are also noticed by [6] for the bridge assessment. The authors concluded that techniques for improving the quality of the measured mode shapes are highly recommended. Since the modal curvature method depends on mode shape curvature values, the existence of noises may easily change the mode shape slope and their curvature hence resulting in false damage identification.

6.0 CONCLUSION

This study verified the efficiencies of natural frequency and modal curvature for damage identification through an experimental beam. The Modal Curvature formulations and procedure of mode shape normalizations are also summarized in detail. Based on the experimental verification, the following conclusions are drawn. Natural frequency can fairly indicate the damage existence and severity but not the location. Modal curvature did not show the promising result compared to numerical simulations. In fact, the efficiency of modal curvature is relatively sensitive to noise and very much depending on the precision of measurements.

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