© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie

ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Modal Analysis of Corrugated Plate by Finite Element Analysis

Sakhiah Abdul Kudus[1*] Kunitomo Sugiura[2]

[1]Faculty of Civil Engineering,
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA

[2]Department of Civil and Earth Resources Engineering,
Graduate School of Engineering, Kyoto University, Kyoto, 6158540, JAPAN

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2020.12.04.024
Received 01 December 2019; Accepted 20 March 2020; Available online 10 May 2020

Abstract: The use of corrugated steel plates as part of a bridge structure has received worldwide acceptance. Corrugated steel plates are widely utilized as web members of bridge girders for pre-stressed concrete bridges. In the lifetime of such a structure, performance and stability will degrade due to the effects of many factors. This process is usually accompanied by the development of corrosion and loss of thickness in the affected region. This paper aimed to study the vibration characteristics of corrugated web and flanges of bridge girder undergoing corrosion and loss of section problem. The finite element analysis utilizing ABAQUS CAE software has been adapted to model and solve this problem. First, the baseline model of undamaged and healthy corrugated plate was modelled to determine its natural frequency and mode shape. The baseline model results were further used to compare with the damage model. The size of the damage area was fixed, while the position, orientation, and depth of loss of thickness varied for different damage cases. A significant reduction in natural frequency can be observed in the presence of damage to corrugated web bridge girders.

Keywords: Finite element analysis, corrugated plate, natural frequency, modal analysis

1. Introduction

Corrugated steel plate is a good tensile load carrying member in construction. In terms of characteristics, corrugated steel plate has the advantage of high transverse stiffness induced in its corrugation depth, while the narrow-spaced folds in the corrugation profile provide high in-plane stiffness and act as vertical stiffeners [1]. The application of corrugated steel as I-beams and web member bridge girder was widely used. Corrugated plate was first developed used as web member for composite prestressed bridges in the 1980s in France before introduction to Japan [2]. There are couple of criteria that have attracted attention to corrugated plate and increased its utilization. There is a 25% reduction of self-weight in main girders, causing a reduction in dead load. Thus, the ability to expand girder length is expected [3]. Moreover, [4] reported that replacing concrete material with steel corrugated simplified the construction procedure, hence reducing construction time, eliminating the usage of web stiffeners, reducing the number of intermediate diaphragms, and improving the load distribution between the corrugated web and concrete slab.

The corrugated web plays an important role to connect the concrete upper deck with concrete lower deck section and transfer the transverse load. Thus, this structure must be able to sustain a continuous large number of repeated and cyclic loadings, such as those caused by vehicular traffic load and wind loading. Cyclic loads coupled with environmental effects may cause a structure to undergo deterioration or damage like loss of thickness due to corrosion

*Corresponding author: sakhiah@uitm.edu.my

and fatigue cracks, especially at the connection part. The effective damage evaluation and detection of structural damage at earliest possible stage have been interest throughout various engineering field. The damage development should be identified at the earliest possible stage in order to provide fast remediation and ensure the safety and reliability of structure.

Damage detection based on vibration characteristic provide valuable information of global response of structure to identify the local change in the structure. The presence of the structural damage causes significant reduction in structural stiffness, shift of eigenfrequencies, and changes in mode shapes and frequency response function [5]. Modal analysis of a structure provides information on natural frequency and mode shape of the structure. This information is valued information in understanding the dynamic behavior of the structure. Shift of natural frequencies to detect structural damage was proposed by Lifshitz & Rotem in 1969 [6]. Since then, extensive research has been conducted utilizing changes in frequency as a tool to indicating the presence of damage [7, 8].

Structure deterioration, such as corrosion and loss of thickness, affects system behavior because it changes the dynamic characteristics of the structure. The presence of damage such as corrosion changes the material and geometrical properties of corrugated plate, hence causing the vibration characteristics turn to be complicated. The focus of this paper is to study vibration characteristics of corrugated plate undergoing loss of thickness problem using finite element model (FEM) analysis via ABAQUS CAE software. The modal properties from undamaged FEM are referred to as a baseline reference. The size of damage area remains constant, while position, orientation, and depth of loss of thickness was varied for different damage cases. The percentage of thickness reduction indicates that damage severity varies up to 75% based on natural frequency value.

2. Methodology

The natural frequency of the structure is described by Eq. (1):

$$\omega_n = \sqrt{K/M} \quad (1)$$

where K and M are the stiffness and mass of the structure. The presence of damage in the structure system is usually accompanied with reductions of stiffness or mass. Thus, change of natural frequency can be used as tool to indicate the presence of damage in the structure. The free vibration analyses of intact and damage model cases are conducted on the basis of FEM. The baseline from the intact model will be further compared with several damage scenarios to simulate the damage behavior of the bridge girder corrugated web.

2.1 Geometry of Corrugated Plate

The corrugation profile was modelled in trapezoidal segments. The size of corrugation profile was based on actual constructed bridge girder with corrugate web per work by [9]. Each of the segments was composed of two corrugation sections. The dimensions of the corrugation profile are as described in Fig. 1, Fig. 2 and Fig. 3 illustrate the plan and side view of a corrugated web bridge girder.

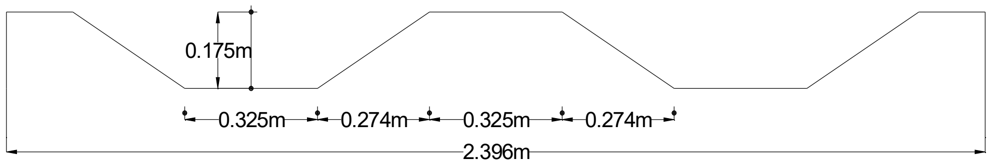


Fig. 1 - Corrugation dimension

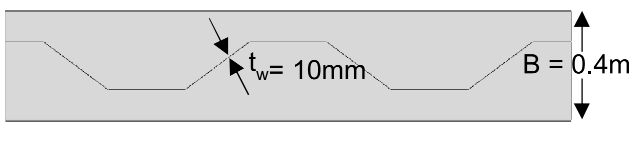


Fig. 2 - Plan view

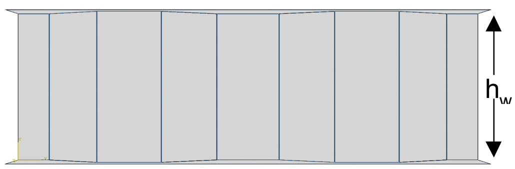


Fig. 3 - Side view

2.2 Finite Element Method

In this study, the corrugated web and flanges model was construct using three-dimensional finite element and ABAQUS version 6.8-1. Eigenvalue analysis was performed to obtain natural frequencies and mode shapes. The Lanczos eigensolver in Abaqus was chosen in this analysis to solve matrices. Both the flanges and corrugated web parts are considered to be in full contact and the tie constraint was defined as connecting both parts. Tie constraints in Abaqus CAE options secure the connecting part to maintain the same displacement.

The material properties of steel considered in this study are: density = 7850 kg/m^3; Poisson's ration = 0.3; and Young's modulus, E = 210 GPa. The flanges and corrugated web are meshed using S4R elements, four node conventional shell elements with reduce integration. The uniform size of elements with 0.01m was set for the whole model, which means 1 element in the thickness direction. Fig. 4 show details meshing of intact model. The boundary condition was set as the simple support of all edges of a corrugated web bridge girder. Translations in the x, y and z directions were retrained.

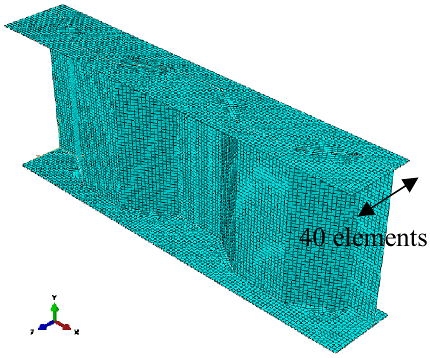
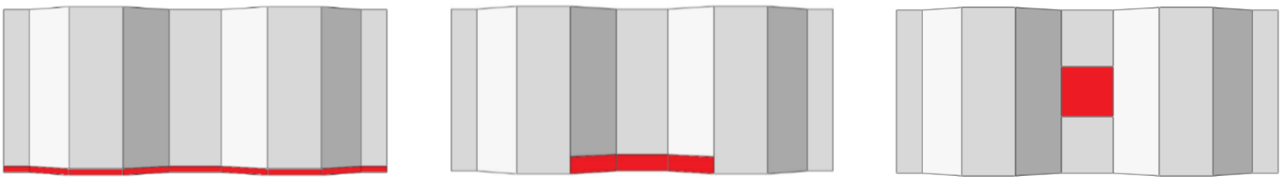


Fig. 4 - Meshing of bridge girder corrugated web

2.3 Damage Case Simulation

In this this study, six damage cases were numerically simulated in web members. Damage was varied in terms of both orientation and position. There are three scenarios of horizontal damage orientation and another three scenarios of vertical damage orientation with three different level of cut depth. The damaged area was modelled by decreasing its flexural stiffness. Reduction of flexural stiffness was achieved by reducing the thickness of elements in damaged region. The damage area, which is 3.85% of the corrugated web area, was set constant for all 10 damage cases. Detailed descriptions of damage cases scenarios and specified regions are shown in Fig. 5 and Fig. 6.

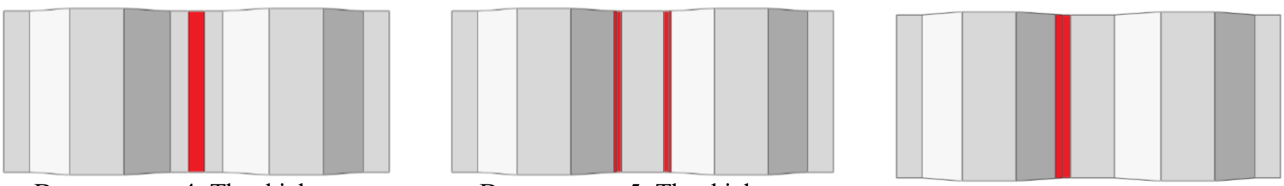


Damage case 1: The thickness reduction was considered horizontally at whole bottom part of corrugated plate

Damage case 2: The thickness reduction was considered horizontally at bottom, center part of corrugated plate

Damage case 3: The thickness reduction was considered horizontally at center panel of corrugated web

Fig. 5 - Distribution of thickness reduction of corrugated web plate in horizontal orientation



Damage case 4: The thickness reduction was considered vertically at center part of corrugated plate

Damage case 5: The thickness reduction was considered vertically at both ends center parts of corrugated plate

Damage case 6: The thickness reduction was considered vertically at near center part of corrugated plate

Fig. 6 - Distribution of thickness reduction of corrugated web plate in vertical orientation

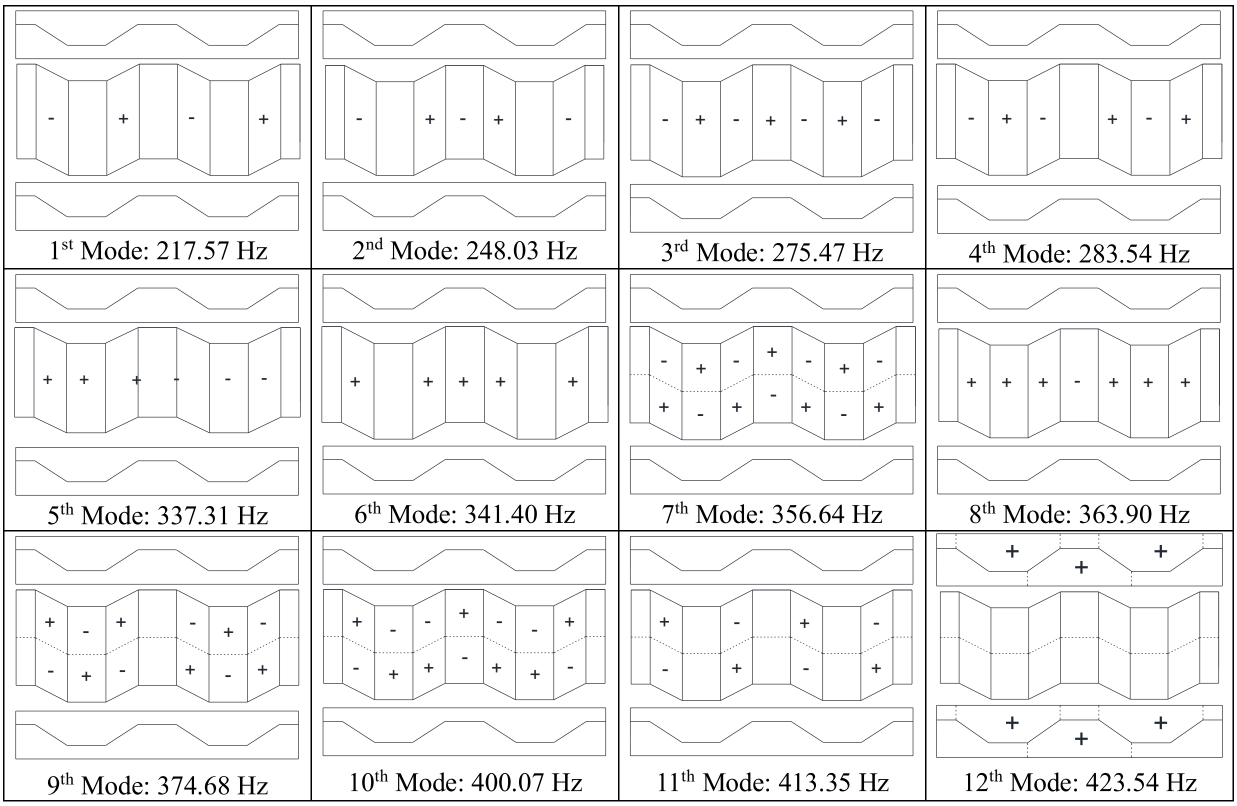
The horizontal damage orientation in this study is to indicate corrosion problem of this structure. Normally, the bottom part of a structure suffers more due corrosion because this part is highly contaminated with chloride, air-borne salt and salinity which cumulated on structure surface and been wash away especially during rainfall and at the end, its stuck in this lower section region cause significant deterioration in this part. On the other hand, vertical or longitudinal damage orientation was simulated to indicate poor connections between the two adjacent sides of plate panel in the corrugation section.

The thickness of corrugated web, which is 10mm for the baseline model, was reduced to 7.5mm to indicate 25% thickness reduction in the specified damaged region, with 5.0mm for 50% thickness reduction and 2.5mm for 75% thickness reduction. Variation in thickness reduction was used to represent the level of severity of damage, where higher thickness reduction shows that the affected area is severely damaged.

3. Results and Discussion

Based on the concept that damage alter the physical properties of the structures, which are geometrical properties and mass properties, it was expected from the results that due to the introduction of damage to the bridge girder corrugated web, the significant change of natural frequency and mode shape of the structure take place. The different position of loss of element section and damage orientation are also factors that contribute to the amount of reduction of natural frequency. Further investigation into first few modes of vibration is important, because this mode contains high vibration energy of the system compared to subsequent modes. The first 20 mode shapes and corresponding natural frequencies were extracted from modal analysis, as shown in Fig. 7 which also shows the mode shapes for both flanges and corrugated web for undamaged model. The signs '+' and '-' indicate the deflection profile of the corrugated plate and used to understand the vibration phenomena of corrugated plate. The sign '+' or '-' means that the plate panel deflected the same movement both in direction out of plane. In the first eleven modes, vibration was dominant in the corrugated web and there was no vibration observed in the flange part, while the occurrence of damage in the flange's region may not have had a significant influence on the structure.

In the first mode, the vibration occurs in four alternate plate panels and no vibration occurs in another three-plate panel together with end section of corrugated plate. The vibration caused this alternate plate to move up and down independently, separated by nodal lines for each plate panel. In the second mode shape, there is an additional panel vibrated as compared to the 1st mode, where the additional vibration was observed in the middle of corrugated web with just a small amplitude of vibration. In the third mode, all the plate panel of corrugated web vibrate independently up and down in out of plane deformation with almost the same amplitude. The nodal line can be clearly observed in the 3rd mode, where a nodal line acts as a boundary to distinguish the vibration of each plate panel. On the other hand, the vibration of mode 4 is dominant at both ends and near the center region of the corrugated web. There is no vibration observed in middle panel of corrugated web plate. In mode 5th, the vibration pattern switches a little bit, where the maximum amplitude points from the center plate panel changes to its boundary line. In this mode, the highest amplitude of vibration is located in the second plate panel from both ends.



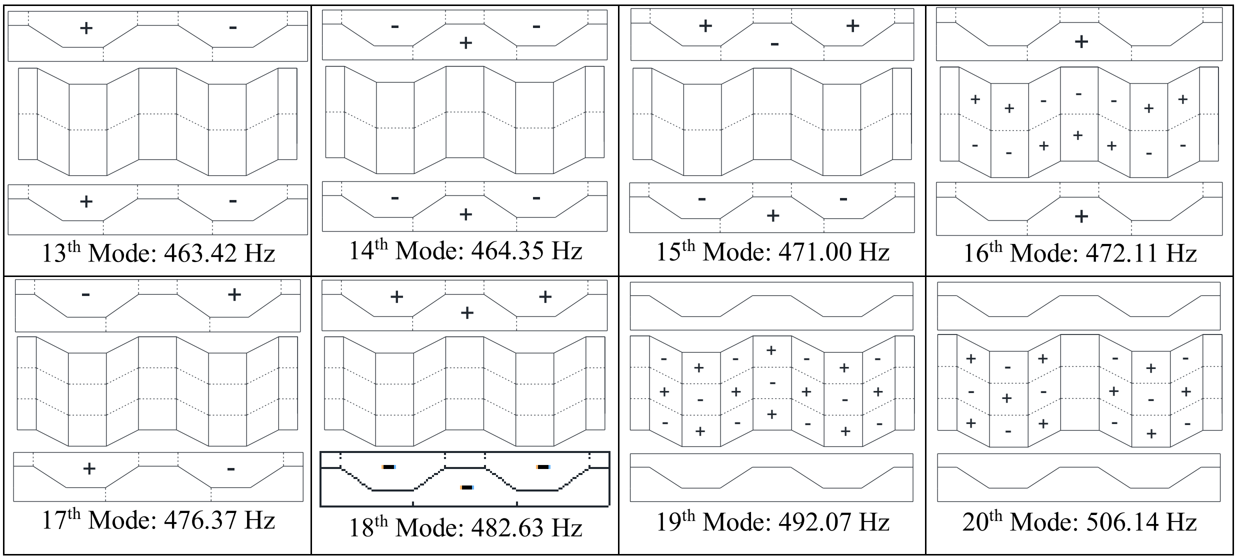


Fig. 7 - Mode shape and natural frequency of intact model

Whereas in sixth mode, the maximum amplitude point was located at the center of corrugated web section and there is also small amplitude of vibration in another four adjacent panels. In the 7th mode, the corrugated web was divided into 14 distinct part and each of this part vibrate independently with three plate panel in middle region vibrate with higher amplitude. The vibration pattern almost the same until mode 11. In contrary, in mode 12, the vibration starts to become dominant in both flanges, with no vibration observed in web section. The flanges move up and down in the marked region. The same vibration pattern was observed from mode 12 to mode 18, where the vibration dominant in flanges part and the amplitude of vibration in web is almost zero except for mode 16. In that mode there is higher amplitude of vibration in the center of web. In mode 19 and 20, no vibration take place in flange part and the vibration is dominant only in web region. The nodal line divided corrugated web into 21 distinct regions, in which each plate panel has three independent vibration patterns. The vibration mode shape provide user understanding of right position to placed exciter and receiver for monitoring purpose. User should avoid location where there is no occurrence of vibration and as in this case, the flange region should be avoided since there is no vibration observe in flanges part. Mostly, the vibration dominant in the corrugated web. The presence of damage in the structure will cause alteration in the mode shape, causing deflected mode shape curvature in the damage region.

Fig. 8 shows graph of percentage of natural frequency reduction due to 25% of thickness reduction in damaged region. In the first fundamental mode, the frequency change does deviate a great deal between each case and there is less than 0.9% frequency deviation observed in this first mode. The following mode does not show any drastic frequency change. The introduction of 25% of thickness reduction does not give much deviation of natural frequency from baseline model. A clearer observation of frequency change was expected in more severe and large damage cases, indicating a higher percentage of thickness loss.

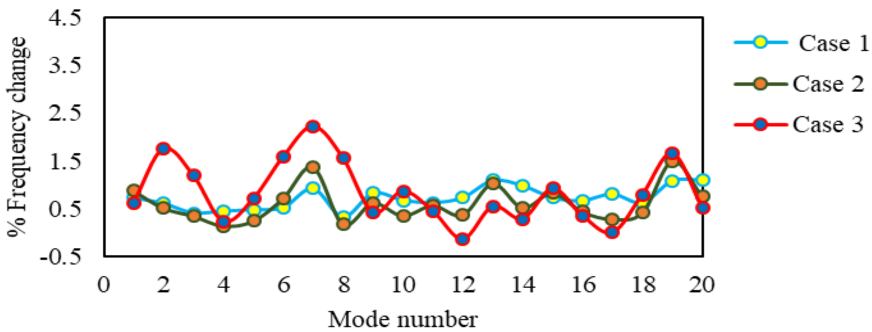


Fig. 8 - Reduction of natural frequency for first 20 modes due to 25% thickness reduction in horizontal damaged cases

The switch of natural frequency due to cut-off of 25% thickness in vertical damaged orientation is discussed in Fig. 9. From the results obtained, damage case 5 shows the highest frequency change, mainly in mode 5 and mode 13 with values of 4.01% and 3.95%, respectively. The location of damage case 5, which is located at both ends of the center plate panel, was the main factor causing the higher frequency change since this location is dominant vibration spot in corrugated web based on deflected mode shape for damage case 5.

Above all, the vertical damage orientation has a higher impact on the corrugated web for 25% of thickness reduction although the affected region area is same for vertical and horizontal damage orientation. This shows that the position of damage and its orientation do contribute to alteration of natural frequency.

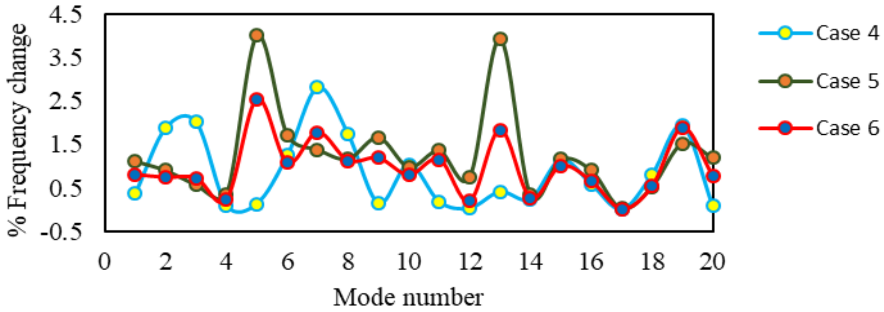


Fig. 9 - Reduction of natural frequency for first 20 modes due to 25% thickness reduction in vertical damaged cases

The greatest deviation of mode shape was expected to occur around the damage region and this information is valuable information for user to locate the location of damage in structure [10]. Fig. 10 graphically depicts the deviation of natural frequencies for 75% thickness reduction. In this case, damage case 2 contributes to dominant case of natural frequency change, with the highest mode deviation is observed in the mode 7. Mode 14 does not show significant alteration in frequency for damage case 3, since the location of damage in this mode was located in a passive region where no vibration is observed.

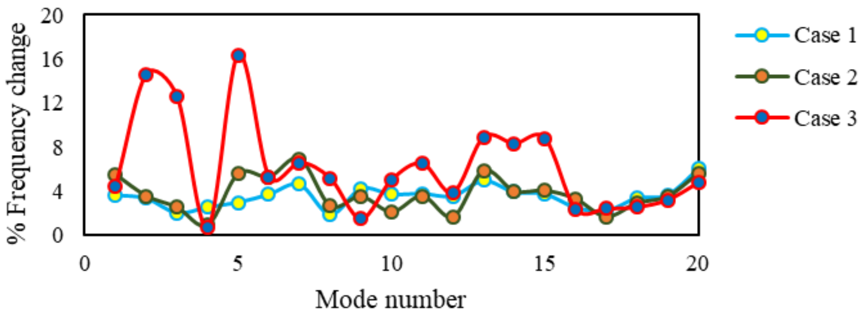


Fig. 10 - Reduction of natural frequency for first 20 modes due to 75% thickness reduction in horizontal damaged cases

Fig. 11 indicate the graph reduction of natural frequency for first 20 modes for 75% thickness reduction in designated vertical damaged cases. From the observation, the existence of damage case 4 does not give significant effect on the integrity of a corrugated web, even for cases of higher severity at 75% thickness loss. This was related to position of damage case 4 which located in passive region where there is less and almost zero vibration. Thus, the presence of this damage does not cause significant changes in either natural frequency and mode shape of the corrugated web.

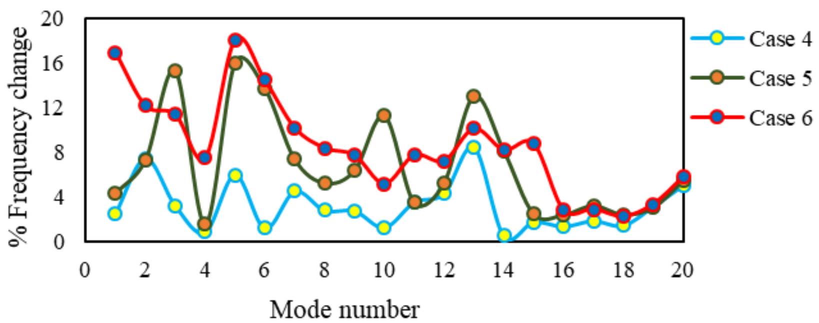


Fig. 11 - Reduction of natural frequency for first 20 modes due to 75% thickness reduction in vertical damaged cases

4. Conclusion

Vibration measurements provide advantages to forecast the extent of damage in structure from modal parameters obtained during analysis. This information will help give early warnings to maintenance team in the event of failure. Incipient failure, if any, can be predicted earlier at the stage in which frequency value drops significantly. The present study focuses on the identification of presence, location, and orientation of damage in a corrugated web bridge girder using two main parameters from eigenvalue analysis, which are natural frequency and mode shape. The observation from the results shows that:

- The curvature of mode shape can be used to indicate the presence and further determine the location of damage.
- Percentage decrease of natural frequency of damaged corrugated plate can be used to indicate the severity of damage and the effect of the presence of damage in the structure.
- By increasing the loss of thickness section, the reduction of natural frequency increases. Vertical damage orientation has a stronger effect on the corrugated web structure compared to horizontal damage orientation.
- All things considered, it is reasonable to conclude that the existence of damage leads to a significant reduction and change in frequency, which strongly depends on location of the damage and its orientation.

Acknowledgement

The authors wish to acknowledge the Ministry of Higher Education Malaysia and Universiti Teknologi MARA, Shah Alam for supporting this publication process via research grant RACER/1/2019/TK01/UITM/2.

References

[1] Metwally A. E. & Loov R. E. (2003). Corrugated steel webs for prestressed concrete girders, materials and structures. Materiaux et Constructions, 36, 127–134.

[2] Ikeda S. & Sakurada M. (2005). Development of hybrid prestressed concrete bridges with corrugated steel web construction. Proceedings of the 30th Conference on Our World in Concrete and Structures, Singapore.

[3] Mutsuyoshi H., Hai N. & Perera S. (2013). Development of modern prestressed concrete bridges in Japan, Jupiter Civil Saitama, 38, 18–25.

[4] Cheyrezy M. & Combault J. (1990). Composite bridges with corrugated steel webs - achievements and prospects. IABSE Reports, 60, 479–484.

[5] Su Z. & Ye L. (2009). Identification of Damage Using Lamb Wave. Heidelberg: Springer.

[6] Lifshitz J. M. & Rotem A. (1969). Determination of reinforcement unbonding of composites by a vibration technique. Journal Composite Materials, 3(3), 412–423.

[7] Kudus S. A., Suzuki Y., Matsumura, M. & Sugiura K. (2018). Vibration-response due to thickness loss on steel plate excited by resonance frequency. IOP Conference Series: Earth and Environmental Science, 140(1), 012123.

[8] Kudus S. A., Suzuki Y., Matsumura M. & Sugiura K. (2018). Damage assessment based on modal analysis of pipe structure. Jurnal Teknologi, 80(5). 10-20.

[9] Hassanein M. F. & Kharoob O. F. (2013). Behavior of bridge girders with corrugated webs: (I) real boundary condition at the juncture of the web and flanges. Journal of Engineering Structures, 57, 554-564.

[10] Kudus S. A., Suzuki Y., Matsumura M. & Sugiura K. (2018). Damage assessment based on sensitivity of modal parameter in plated structure. Malaysian Construction Research Journal, 24 (1), 65-82.