JOURNAL OF STRUCTURAL MONITORING AND BUILT ENVIRONMENT
e-ISSN: 2821-3432

JSMBE

Vol. 4 No. 2 (2024) 1-9
https://publisher.uthm.edu.my/ojs/index.php/jsmbe

Investigation of Crack Depth on Reinforced Concrete Beam Using Vibration-Based Method

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DOI: https://doi.org/10.30880/jsmbe.2024.04.02.001

Article Info

Received: 9 August 2024
Accepted: 26 December 2024
Available online: 31 December 2024

Keywords

Reinforced concrete beam, crack depth, vibration-based method, ambient test, impact hammer test

Abstract

Basic types of damage to a concrete structure include cracks, which can lower the structure's stiffness and load-bearing capacity as well as causing failures and tragedies in buildings under construction. As a result, it's essential to keep an eye on the structural responses in order to assess the health of the buildings, guarantee their operational safety, and identify damage early on. Damage-related changes to the structures' physical characteristics, such as their natural frequency and mode shape that might modify the dynamic response. These parameter changes can be extracted to predict damage detection information, such as the presence, location, and severity of damage in a structure. Thus, in this study, two non-destructive test methods ambient vibration test and impact hammer test were carried out to determine the vibration behaviour of cracked and uncracked of simply supported beams. Moreover, the position of various crack depth from 0mm to 150mm with 50mm interval were determined at the midspan of 0.60m x 0.25m x 0.25m reinforced concrete beams. The result showed, the natural frequency of cracked beam is lower than uncracked beam. Besides, propagation path of wave altered differently with various crack depth. The severity of cracks also can be determined by observing the curve fitting graph where the wave pattern propagate.

1. Introduction

The vibration-based method is one of the types of non-destructive testing (NDT) technique that include vibration analysis, where researchers use it to examine changes in modal characteristics such as natural frequencies, mode shapes, and modal damping values. Vibration tests on damaged and undamaged reinforced concrete beams allow for the assessment of frequency value variations associated with reinforced concrete beam damage from increasing bending force. The dynamic properties of damaged buildings have been linked to the location and extent of damage, even though damage is often a local phenomenon and vibration response is a global feature. The fundamental idea underlying vibration monitoring is that, as dynamic characteristics are functions of a structure's physical attributes, any alteration brought about by damage also affects the dynamic response [1]. The degree, kind, and position of cracks as well as their impact on the structural integrity of the building should all be taken into consideration. Even minor damage has the potential to modify the structure's dynamic response, reducing stiffness and ultimately changing the structure's inherent frequencies and mode shapes.

The reaction to vibrations is utilized in vibration-based structural health monitoring techniques to confirm structural integrity. This enables the prompt evaluation and execution of remedial measures to counteract deterioration, damage, and excessive loads before they threaten the structural integrity or diminish the asset's usefulness. Because stiffness affects a structure's dynamic behavior, vibration-based techniques can identify problems brought on by stiffness losses [2]. Information on the position and depth of the cracks is provided by the frequencies and corresponding mode shape of the structures. Owing to the presence of cracks in the structures, an increase in local flexibility has a negative impact on the overall structure's dynamic behavior. Additionally, this lowers the natural frequency, which modifies the vibration's mode patterns. Finding these variations probably results in the identification of fracture-causing cracks.

Ambient vibration test and impact hammer test are examples of the test that can study the crack behavior in those structures. The process of testing for ambient vibration involves quantifying small structural vibrations brought on by external forces. A micro-tremor, the wind, or road noise are examples of ambient forces. The process is rather quick and straightforward, and it may be applied to an operational structure without interfering with its regular operation. On the other hand, the impact hammer test can use measured frequency response function (FRF) data to predict the dynamic parameters. The sensors and an impact hammer are used in an experimental procedure known as "impact hammer testing," sometimes known as "modal testing," to extract dynamic information. By calculating the decrease in frequency response in each mode because of the structural stiffness in the cracked zones, the degree of damage was determined [3].

Therefore, it becomes crucial to keep an eye on how the structure's reaction characteristics evolve to ensure structural integrity, performance, and safety. Due to the local flexibility the crack introduces, cracks in a structural part, whether they originate from inherent faults in the material or the result of fatigue or load concentration, can lower natural frequencies and alter the forms of vibration modes [4]. Thus, in this study, investigation against various crack depths on reinforced concrete beam based on vibration-based method were carried out using ambient vibration test and impact hammer test to study its vibration behavior.

2. Methodology

This study aims to determine the vibration behaviors of reinforced concrete beams with and without cracks that are simply supported and to determine the crack depth using those vibration-based methods. The structure of the beams was constructed in the laboratory first before the testing started. Four beams with dimensions 0.60m x 0.25m x 0.25m were constructed. Bending of bar and links were then carried out. Polystyrene was act as cracks after scooped out from concrete. Curing is the process of hardening that begins immediately after the concrete is poured. It is usually complete after 28 days. Thus, the testing will be started as well as after 28 days. Two vibration tests were then conducted to determine the vibration behaviors of beams, which are ambient vibration test and impact hammer test. The natural frequency and wave propagation of peak acceleration can be determined after conducting the test and analyzing the data using Me' Scope software. Me' Scope software fits curves to determine the frequency, damping, and mode shape. The time histories were processed using ME' Scope, which was also utilized to compute the FRFs between the excitation and response signals and determine the structure's modal parameters using curve fitting of the FRFs. All the results were tabulated in Excel spreadsheet and formed the graph to find out the correlation between wave parameters.

2.1 Prior Preparation Before Formwork

Before entering the formwork stage, there were many materials needed to prepare first as shown in Figure 1 to 4. For instance, purchasing reinforcement bars, links, plywood board and binding wires. After that, the reinforcement bars and links need to be measured and cut for desired distances using measuring tapes and markers before bending it using bar bending machine. Then, the reinforcement bars and link will be bonded using binding wires.

Cutter was then be used to cut the polystyrene into three sizes which the depth in 50mm,100mm, 150mm, whereas the thickness and width were fixed which are 5mm and 50mm. Polystyrene acted as crack in beam where those were fixed in the middle of the formwork using cement and scooped out after concrete using metal ruler.

After all these things have been done, then were proceed to formwork stage. The plywood board and timber wood were cut using radial cutting saw and screwed together using drill kit in wood fabrication laboratory before entering the concreting stage.

Fig. 1 *Measuring the reinforcement bars using markers and bending it using bar bending machine*

Fig. 2 *Binding the reinforcement bars and links using binding wires*

Fig. 3 *Cut out the polystrene for later stick in the formwork*

Fig. 4 *Cut out the polystrene for later stick in the formwork*

2.2 Detailing of the Beam

The dimension of the beam is 0.60 m length, 0.25 m width and 0.25 m thickness with concrete cover of 38mm. The reinforcement bars will be 12mm diameter and link diameter will be 6mm. The reinforced concrete beam will be designed to be Grade 25. The mixed ratio of C25 concrete is 1:1:2, consisting of one part cement, one part fine aggregate or sand, and two parts coarse aggregate.

Fig. 5 *Detailing and concreting of beam*

3. Theory Equation of Healthy Beam

In theory, the value for natural frequency in healthy beams can be evaluated using the specified formula. A formula involving Timoshenko beam theory was used to calculate the natural frequency in healthy beams that are properly without crack [5]. The formulas (1) and (2) proved that the theory that natural frequency drops as crack depth increases is true.

$$\boldsymbol{W_n = \alpha^2 \sqrt{\frac{EI}{A\rho L^4}}} \quad (1)$$

$$f_n = \frac{1}{2\pi} W_n \quad (2)$$

where,

W_n= natural frequency in rad/sec
α = Shear correction factor
E = Young's Modulus of Elasticity
I = Moment of inertia
A = Cross sectional area
ρ = Density of material
L = Length of structure
f_n = natural frequency in Hz

4. Testing of Beam

Before carried out the test, the gridlines were plotted on the beam along the length of the beam as shown in Figure 5 to create a point where the accelerometers will be placed. The tests needed four sets of gridlines which were 30mm, 40mm, 60mm and 120mm intervals between accelerometers to be carried out. From the left side, the starting two points have different distance compared to others which are 40mm for 30mm interval gridlines whereas a point placed differently which is 80mm for 40mm, 60mm and 120mm interval gridlines.

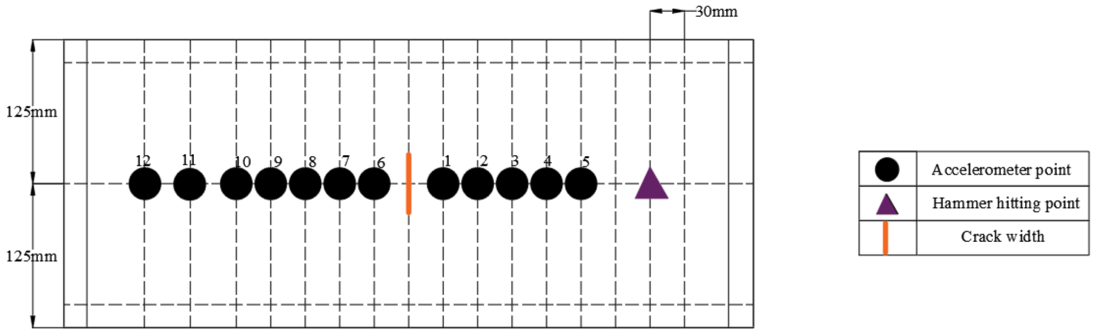
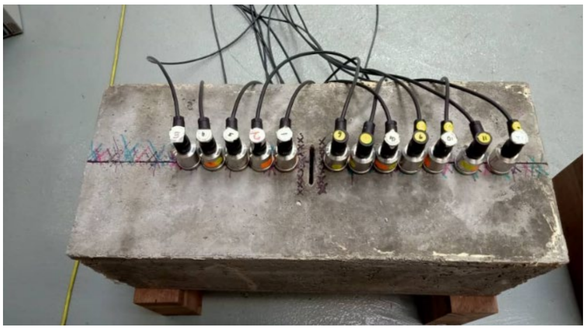


Fig. 6 *Position of accelerometers on beam surface*

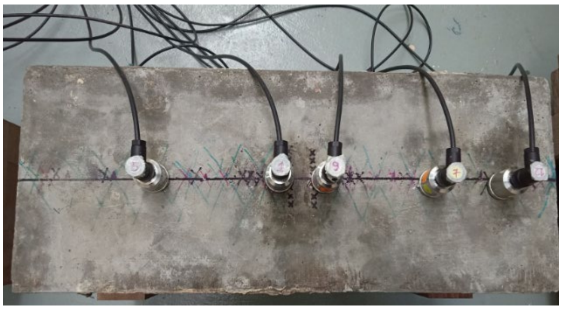
To start the ambient vibration test, the accelerometers were place on the surface of the beam according to the position that has been decided which were starting from gridlines 30mm until 120mm. The sensitivity of the accelerometers were 101.8 mV/g and the signal recording time set to 10 s. Cables will be used to link each accelerometer to the data logger. The connection of the accelerometers to the data logger was according to the number of channels. Next, the computer and data logger will be connected so that the vibration wave can be recorded. The Me' Scope software that installed in the computer will process a frequency response function (FRF) that the data logger sends. The modal parameters like wave propagation, natural frequency of beam were recorded. The natural frequency will be tabulated in the table. The same steps were repeated to the beams that have various crack depths on the surface of the beams. For the impact hammer test, an impact hammer was used as a vibration excitor and the testing was same as ambient test before.



(a)

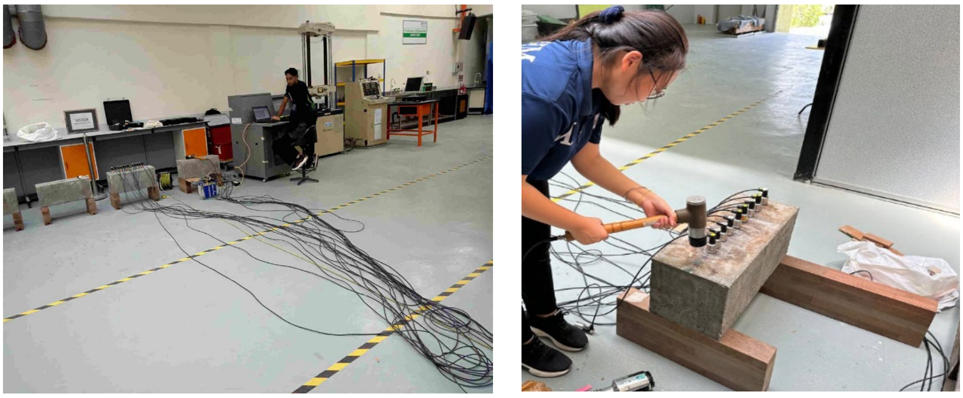
(b)

(c)



(d)

Fig. 7 *Position of accelerometers for gridline distance (a) 30mm; (b) 40mm; (c)60mm; and (d) 120mm*



(a) **(b)**

Fig. 8 *Ambient (a) and impact hammer test (b) in laboratory*

5. Finding and Discussion

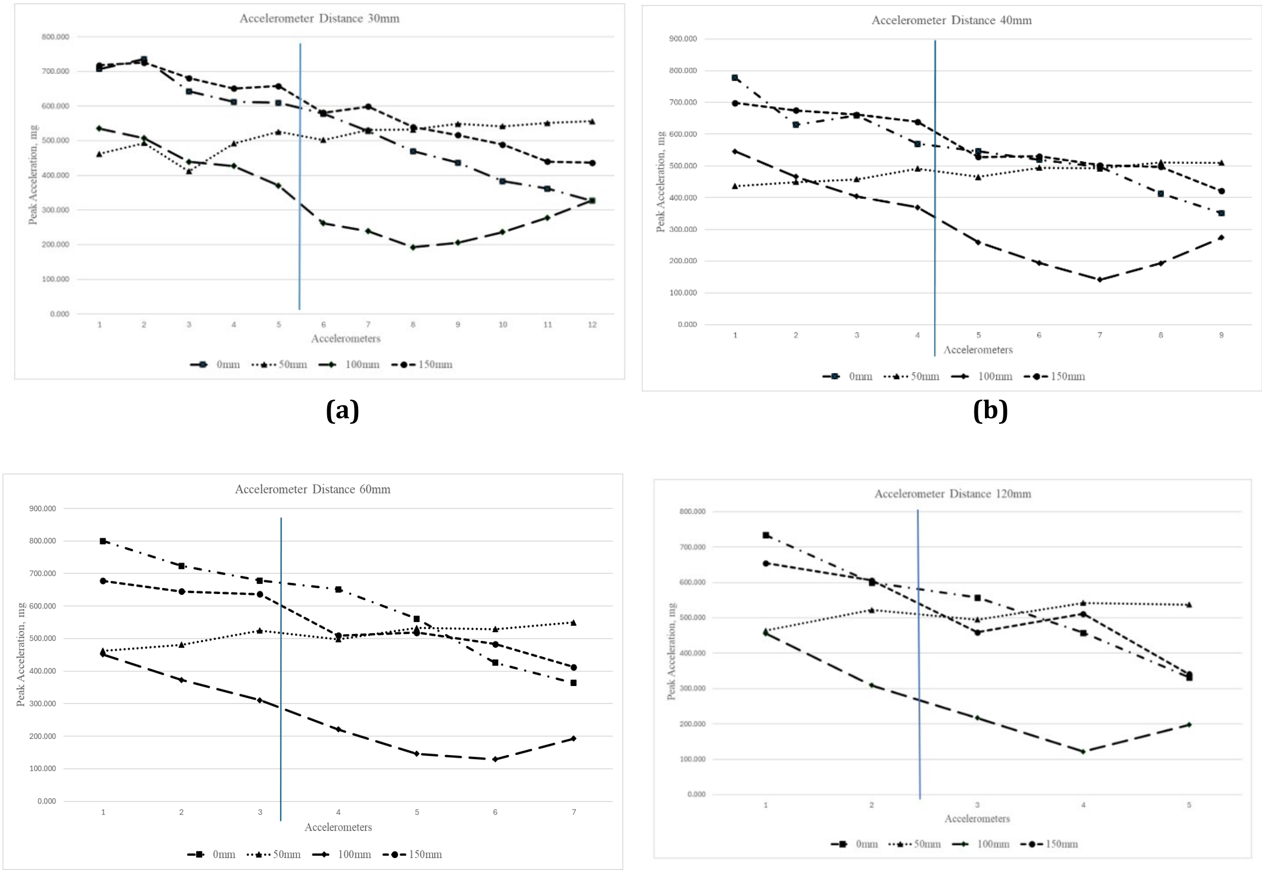
The wave parameters like acceleration and natural frequency data were obtained from the IMS Famos and ME' scope software. Correlation between acceleration and natural frequency with various crack depths were drawn out.

5.1 Wave Propagation of Peak Acceleration

Based on the results that have been recorded, it can be shown that the peak acceleration for the uncracked beam decreases from the hammer hitting point, point 5 to point 12 for all gridlines distance which are 30mm, 40mm, 60mm and 120mm as shown in Figure 9. There is no obvious change for the wave. The decrease in acceleration during an impact hammer test on an uncracked beam is a result of energy dissipation through various damping mechanisms inherent in the material and stiff structural design of the beam. These mechanisms convert kinetic energy into other forms, gradually reducing the amplitude of vibration and the acceleration of the beam over time. Plus, the structure is stiffer without cracking, which makes the wave deflect slower.

Other than that, from Figure 9, there is an increasing pattern for cracked beams which are 50mm, 100mm and 150mm. For 50mm and 100mm cracked beam, it showed the most obvious increasing pattern which the acceleration increases gradually whereas for 150mm cracked beam, it showed slight increases only for those all-gridline distance. This changing condition can be explained by when a beam is cracked, the stiffness of the beam decreases, which affects how it responds to applied loads. In a deeper crack, there's less material resisting deformation, so the beam is less stiff. When a load is applied to the cracked beam, it deflects more easily, causing higher accelerations at the crack location.

Furthermore, the position and severity of crack depth also can be analyzed out. From Figure 9(a), it shown that all increasing pattern was starting after or around point 6, means the crack exists there. Same goes to Figure 9(b), all increasing pattern was starting after or around point 5, starting after or around point 4 in Figure 9(c) and starting after or around point 3 in Figure 9(d). While for the severity of crack, it can show that the peak acceleration value for 150mm cracked beam are higher than 50mm cracked beam for all gridline distance except for 120mm gridline distance. This means that more accelerometer is needed for conducting the test to analyze the wave propagation pattern. For instance, the peak accelerometer for 50mm cracked beam is 502.05mg while 150mm cracked beam is 580.67mg at point 6. Thus, we can induce that higher peak acceleration means higher the crack depth there. The exception happened at 100mm cracked beam where the increasing pattern were starting far away from the crack position. This may be due to different reasons like the impact load was non consistent, human error or instrument error like the accelerometer or wires have problem or even caused by environmental factors. The condition when higher acceleration peaks mean higher cracked depth has been proved with previous study, the analysis of acceleration signals in wavelet transform helps to study the severity of crack with the aid of wavelet coefficient peak value. It showed that the value of wavelet coefficient peak is increasing with increase of crack size [6]. The increasing depth of crack means more defects and less stiffness makes it more easily reflected and hence acceleration.



(a) **(b)** **(c)** **(d)**

Fig. 9 *Graph of accelerometer distance for various crack depth (a) 30mm; (b) 40mm; (c) 60mm; (d) 120mm in impact test*

5.2 Natural Frequency

After all the data has been recorded and analyzed in graph, the result showed that almost of the natural frequency decreases as the crack depth increases for both tests except for 40mm gridline. For instance, in the 30mm gridlines of the ambient test, the natural frequency drops from 99.72 Hz to 62.86 Hz as proved in previous study which a vibration-based method was utilized to evaluate the vibration serviceability of the bridge. The findings observed that stiffness decreases which causes the natural frequency to decrease [7].

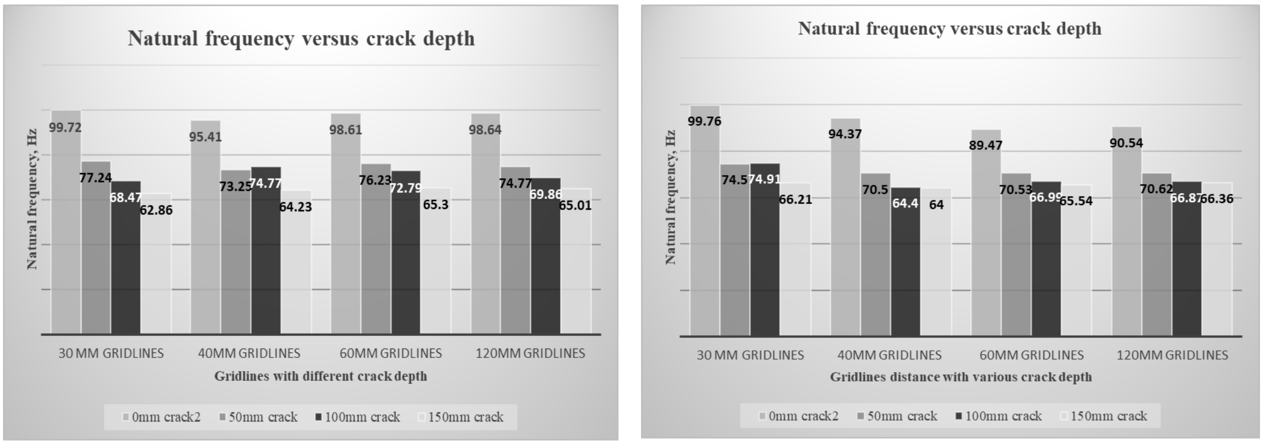
Same goes to impact hammer test except for the 30mm gridlines in Figure 10. The exception may be caused by the impact load being too heavy that caused by human error or instrument error which detect abnormally. The decreasing phenomena can be seen in 60mm gridlines distance, the value of natural frequency drops from 89.47 Hz to 65.54 Hz where test on the crack depth 50mm, 100mm and 150mm. This condition was proven by previous study where the findings also indicate that frequency reduces as crack depth increases across the beam using impact hammer test [8]. The reason why natural frequencies are inversely proportional to crack depth is because when a crack forms in structure, it creates a weakened area in the structure. This weakened area is less resistant to deformation compared to the surrounding intact material. As the crack deepens, the effective stiffness of the structure decreases because the cross-sectional area available to resist deformation decreases. Consequently, the structure vibrates at a lower natural frequency due to its reduced ability to resist deformation.

Table 1 *Natural frequency for various gridlines distance in both test*

Gridlines distance, mm	Crack depth, mm	Natural frequency, Hz		
		Theory	Ambient test	Impact hammer test
30	0	109.76	99.72	99.76
	50		77.24	74.50
	100		68.47	74.91
	150		62.86	66.21
40	0	109.76	95.41	94.37
	50		73.25	70.50
	100		74.77	64.4
	150		64.23	63.0
60	0	109.76	98.61	89.47
	50		76.23	70.53
	100		72.79	66.99
	150		65.30	65.54

Table 2 *Natural frequency for various gridlines distance in both test (continued)*

Gridlines distance, mm	Crack depth, mm	Natural frequency, Hz		
		Theory	Ambient test	Impact hammer test
120	0	109.76	98.64	90.54
	50		74.77	70.62
	100		69.86	66.87
	150		65.01	66.36



(a) **(b)**

Fig. 10 *Graph of natural frequency versus crack depth in ambient test (a) and impact hammer test (b)*

6. Conclusion

In conclusion, the ambient vibration and impact hammer test for four beams with various crack depths were successfully conducted. The vibration behavior of wave propagation for cracked and uncracked beam were studied. The wave parameters like acceleration and natural frequency were analyzed out. The results showed that those parameters and crack depth have a strong relationship. For instance, the peak acceleration varied for different crack depth. Changing peak acceleration pattern at crack location helped us to detect where the crack exists and its severity. But peak acceleration just gives us guidance only as the circumstances can be changed by others factor also like the static load. Whereas natural frequency more truly showed out that which the beam more stiffness and severe as the theory equation have been proved that. Those increasing peak acceleration conditions happened in crack location was because of the stiffness of the beam. When stiffness of beam decreases, the beam less resistance to deformation hence easier for the vibration wave to travel faster and less natural frequency across the crack depth. To illustrate more, the severity of crack depth can be determined based on the curve fit graph by evaluating the value of natural frequency out. However, further research needs to be carried out for the better accelerometer location and distance to be placed on structure that need to be tested as some of the data need to be further investigated as vibration wave in structure is much complicated and can affected by various factors and many conditions that affect wave parameters.

Acknowledgement

The authors acknowledge the support from Universiti, Tun Hussein Onn Malaysia throughout this project.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

References

[1] Limongelli, M. P. et al. (2021). Vibration Response-Based Damage Detection. Retrieved from https://doi.org/10.1007/978-3-030-72192-3_6
[2] Yang, Y., Zhang, Y. & Tan. X. (2021). Review on Vibration-Based Structural Health Monitoring Techniques and Technical Codes. Retrieved from https://doi.org/10.3390/sym13111998
[3] Meruane, V. et al. (2022). Damage Detection in Steel–Concrete Composite Structures by Impact Hammer Modal Testing and Experimental Validation. Retrieved from https://www.mdpi.com/1424-8220/22/10/3874
[4] Golewski, G. L. (2023). The Phenomenon of Cracking in Cement Concretes and Reinforced Concrete Structures: The Mechanism of Cracks Formation, Causes of Their Initiation, Types and Places of Occurrence, and Methods of Detection—A Review. Retrieved from https://doi.org/10.3390/buildings13030765
[5] Sawanta, S. U., Chauhan, S. J. & Deshmukh, N, N. (2017). Effect of Crack on Natural Frequency for Beam Type of Structures. Retrieved from https://www.researchgate.net/publication/318578751_Effect_of_crack_on_natural_frequency_for_beam_type_of_structures?enrichId=rgreq08a04d78619f9b5c41a21549e8913c6bXXX&enrichSource=Y292ZXJQYWdlOzMxODU3ODc1MTtBUzo1MzMzMzkwODU5OTYwMzJAMTUwNDE2OTM1NTU4OA%3D%3D&el=1_x_2&_esc=publicationCoverPdf
[6] Vaidya. T & Chatterjee.A, (2015). Wavelet Analysis of Acceleration Response of Beam Under the Moving Mass for Damage Assessment. Retrieved from https://www.academia.edu/87473530/Wavelet_Analysis_of_Acceleration_Response_of_Beam_Under_the_Moving_Mass_for_Damage_Assessment?uc-sb-sw=111477807
[7] Saidin, S. S. et al. (2023). Vibration-based approach for structural health monitoring of ultra-high-performance concrete bridge. Retrieved from https://doi.org/10.1016/j.cscm.2022.e01752
[8] Chinka, S. S. B., Putti, S. R. & Adavi, B. K.(2021). Modal testing and evaluation of cracks on cantilever beam using mode shape curvatures and natural frequencies. Retrieved from https://virtualsim.nuaa.edu.cn/file/up_document/2021/06/wvZZ0T2652bj4sNe.pdf