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Relationship between Crack Depth and Peak Acceleration for Reinforced Concrete Specimens

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Abstract: *Structural Health Monitoring (SHM) plays a critical role in assessing reinforced concrete (RC) structures, where crack depth significantly impacts structural integrity. This study investigates the relationship between crack depth and peak acceleration using 610 mm × 250 mm × 250 mm RC beam specimens with induced cracks (10–150 mm depth). Accelerometers were placed at 100 mm, 200 mm, 300 mm, and 400 mm from cracks, and vibration responses were recorded via impact hammer tests. Results showed that acceleration differences increased with crack depth up to 60 mm for sensors within 300 mm, demonstrating higher sensitivity at closer distances. However, at 400 mm, signal anomalies occurred, likely due to misalignment or attenuation. The findings highlight that optimal accelerometer placement within 100–300 mm enhances crack detection accuracy. This study validates peak acceleration as a practical, time-domain metric for SHM, offering a simplified alternative to complex modal analysis. Strategic sensor positioning is recommended for reliable damage assessment in field applications.*

Keywords: Structural Health Monitoring (SHM); crack depth; peak acceleration; vibration based method

1. INTRODUCTION

Structural Health Monitoring (SHM) has emerged as a vital component in the maintenance and safety management of critical infrastructure, including bridges, tunnels, buildings, and other civil structures. By offering a systematic and continuous approach to assess structural performance, SHM facilitates the early detection of degradation and damage, enabling preventive maintenance and reducing the likelihood of catastrophic failures. This proactive approach not only helps extend the service life of infrastructure assets but also reduces operational downtime and associated costs. SHM systems integrate various sensing technologies and analytical techniques to monitor key performance indicators, thereby enhancing structural resilience and public safety [1].

A central focus of SHM research and application lies in the monitoring of reinforced concrete (RC) structures, which are widely used in modern construction due to their inherent advantages, including high compressive strength, fire resistance, and cost efficiency [2]. RC structures are designed by experience or experimental investigation on existing structures [3]. However, despite their robust mechanical properties, RC structures are susceptible to progressive deterioration over time, driven by environmental exposure, cyclic loading, material fatigue, and shrinkage effects. Among the various forms of degradation, cracking is particularly prevalent and problematic. Cracks may arise from thermal expansion, drying shrinkage, reinforcement corrosion, or mechanical overstress, and can significantly undermine both the safety and serviceability of a structure. They often begin as superficial anomalies but can evolve into deep structural defects if not addressed promptly. As such, crack detection and characterization are fundamental to effective SHM strategies, particularly in infrastructure exposed to dynamic loads and harsh environmental conditions [4].

In this context, crack depth is a critical metric in assessing the severity of structural damage. The depth of a crack directly influences the local stiffness of structural elements, which in turn affects the global dynamic behavior of the system. Deeper cracks often signify more serious structural impairment, as they disrupt stress distribution and diminish the load-carrying capacity of components. These changes can manifest in altered dynamic characteristics such as reduced natural frequencies, modified mode shapes, and altered damping behavior. For example, [5] demonstrated that increasing crack depth in concrete beams correlates with measurable shifts in vibration response, highlighting the importance of incorporating crack depth estimation in SHM programs.

The ability to detect and evaluate cracks non-invasively is crucial in real-world applications, where destructive testing is impractical or impossible. This has led to the widespread adoption of Non-Destructive Testing (NDT) techniques in structural assessment. NDT methods offer a practical and efficient means of identifying surface and subsurface defects without compromising the structural integrity of the tested components. Among these techniques, vibration-based methods have gained prominence due to their sensitivity to stiffness reductions and mass alterations caused by damage. These methods involve subjecting the structure to dynamic excitation typically using impact hammers or shakers and recording the vibrational response using sensors such as accelerometers. Analytical techniques are then applied to extract modal parameters such as natural frequencies, damping ratios, and mode shapes, all of which can serve as indicators of damage presence and severity [6].

While traditional vibration-based methods provide a comprehensive diagnostic capability, they often require complex data processing and interpretation of multiple modal parameters. In contrast, this study proposes a simplified, yet effective approach by focusing on peak acceleration a readily observable time-domain feature of the dynamic response. Peak acceleration reflects the maximum inertial response of the structure under excitation and can be significantly affected by local damage such as cracks. The hypothesis underlying this work is that the formation and progression of cracks alter the local stiffness of RC beams, thereby diminishing the structure's ability to transmit vibrational energy and reducing the measured peak acceleration at certain points.

This paper aims to investigate the relationship between crack depth and changes in peak acceleration by conducting controlled modal testing on RC beam specimens, both with and without cracks. Using an impact hammer to excite the beams and accelerometers positioned at various distances, acceleration data are collected and processed through ARTeMIS Modal software. The primary objective is to determine whether measurable differences in peak acceleration values can serve as reliable indicators of crack depth and structural damage. By narrowing the focus to time-domain acceleration signals, this study seeks to offer a practical, cost-effective diagnostic method that avoids the complexity of full modal analysis. The findings are expected to contribute to the development of more accessible SHM techniques for early-stage crack detection in RC structures, especially in field applications where rapid assessment is essential.

2. LITERATURE REVIEW

A vital component of structural health monitoring are vibration-based crack detection techniques, which provide a non-destructive way to find and describe cracks in a variety of structures. These techniques identify the existence, location, and extent of damage by analyzing variations in vibrational characteristics, mainly natural frequencies and mode shapes. Modal testing is a popular method in this framework that entails stimulating a structure and assessing its dynamic response in order to identify important modal characteristics.

In vibration-based analysis, modal testing methods like shaker and impact hammer testing are essential instruments. Shaker testing is better suited for larger, more intricate systems, whereas impact hammer testing is usually used for lightweight or compact structures. By measuring the structural response under specified excitation conditions, these approaches are utilized to determine modal parameters such as natural frequencies, damping ratios, and mode shapes [7]. In order to detect alterations in dynamic behavior that can point to structural deterioration, these metrics are essential.

Impact hammer testing has been compared to various non-destructive test (NDT) methods in a number of studies. For example, it has been demonstrated that alternative techniques such as Brillouin Optical Frequency-Domain Analysis (BOFDA) and Fiber Bragg Grating (FBG) sensors offer more thorough insights into the development of both internal and surface cracks, even though impact hammer tests are useful in identifying shifts in natural frequencies and modifications in wave propagation behavior [8]. By identifying micro-level strain changes, these techniques enhance damage localization and characterization and provide supplementary advantages.

It is commonly known that cracks have an impact on the vibrational properties of reinforced concrete (RC) constructions. Natural frequencies diminish as a result of cracks because they reduce structural rigidity. Numerous vibration-based crack detecting techniques are based on this phenomena. When cracks spread, the resonance frequency of RC beams decreases, making it possible to use forced vibration testing to evaluate damage. Their findings support the usefulness of frequency-based monitoring for assessing structural integrity over time. In order to increase the sensitivity of crack identification, wave propagation analysis is frequently used in addition to frequency shifts. This method explains how stress waves interact with structural discontinuities, such cracks, which usually result in wave diffraction and scattering that lower resonance frequencies even more. [9] demonstrated that this approach offers a useful foundation for simulating and evaluating damage-induced changes in dynamic behavior by modeling fractures as straightforward notches.

The mode shape, which characterizes how a structure deforms at particular vibrational frequencies, is another crucial modal feature employed in crack identification. Mode shapes can be utilized to identify damage spots since they are extremely sensitive to changes in local stiffness. In order to investigate this, [10] computed damage indices based on mode shape curvature using Frequency Response Functions (FRFs). According to their research, variations in the curvature of the mode shape provide a trustworthy indicator for determining the location and degree of damage in RC beams.

There is increasing interest in investigating alternate indicators that might provide better sensitivity or practicality in field applications, even if prior research has mostly concentrated on conventional modal parameters like natural frequency and mode shape. Peak acceleration is one such parameter that shows a structure's greatest acceleration response to dynamic excitation. Because it can be measured immediately with accelerometers and may catch fleeting dynamic effects that are not fully reflected in frequency-domain analysis, peak acceleration is desirable. In light of this potential, the current study intends to expand the body of research in vibration-based structural health monitoring by examining the viability and efficacy of employing peak acceleration as a diagnostic tool for fracture diagnosis.

3. METHODOLOGY

By examining peak acceleration values acquired during modal testing, this study seeks to assess the impact of fractures on the vibrational response of reinforced concrete (RC) beams. A thorough literature assessment was conducted before the experiment started in order to lay the theoretical groundwork and find pertinent modal parameters from earlier research. After that, 610 mm short RC beam specimens, including both uncracked and cracked samples, were cast as part of the sample preparation process. Accelerometers were positioned at different intervals throughout the span to record the structural reaction, and modal testing was performed by excitation of the beams using an impact hammer. In order to examine spatial variations in response, acceleration data were gathered for several sensor positions. The flowchart for this study is as shown in Figure 1.

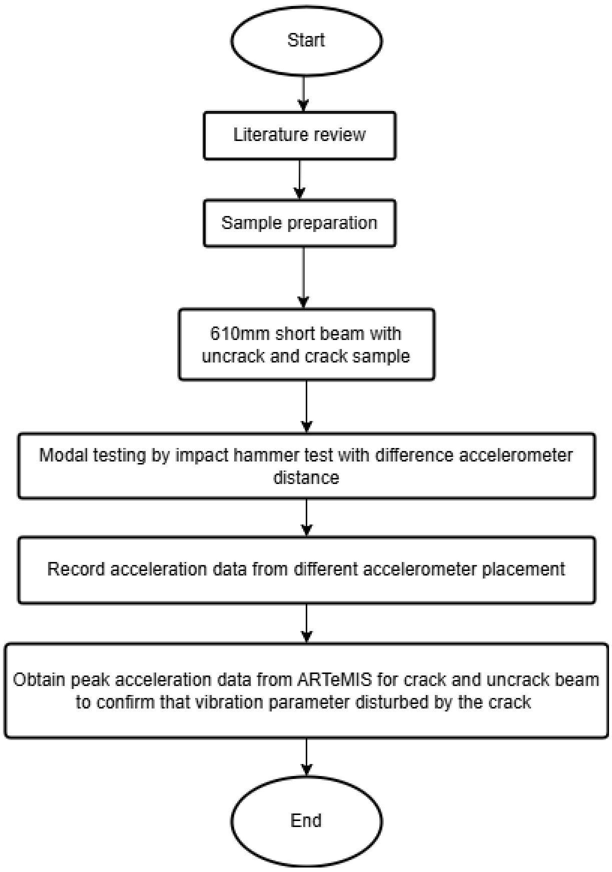

Fig. 1. Flowchart for this study

A total of sixteen reinforced concrete (RC) beam specimens were fabricated for the experimental investigation. Among these, one specimen was maintained as a control sample with no cracks, while the remaining fifteen specimens were deliberately induced with cracks of varying depths ranging from 10 mm to 150 mm, with 10 mm intervals between each depth category. All specimens were designed with uniform dimensions of 610 mm in length, 250 mm in width, and 250 mm in height, as illustrated in Figure 2. The cross-section of the beam is the same typical beam used in a previous study, which is in a square shape [11]. The design and reinforcement detailing of the RC beam followed the guidelines provided in BS EN 1992-1-1: Eurocode 2 – Design of Concrete Structures, ensuring structural consistency across all samples. An example configuration of the induced crack geometry within the RC beam is shown in Figure 2.

Each induced crack had standardized dimensions of 50 mm in length and 10 mm in width, with the depth varying according to the test plan as summarized in Table 1. The crack depths were selected to simulate a range of damage severities, enabling the evaluation of vibration-based detection sensitivity across various structural degradation levels.

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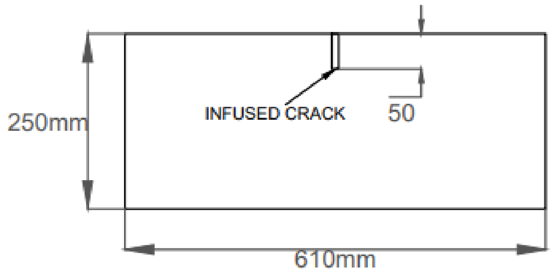


Fig. 2. Example of configuration of the induced crack geometry

Table 1. Dimension for difference crack depth

Specimen	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Crack depth, D (mm)	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Crack width, W (mm)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Crack length, T (mm)	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Modal testing is employed to evaluate the peak acceleration of vibrating structures. One commonly used approach is the instrumented impact hammer test, in which a hammer strike induces free vibration in the structure. This vibration produces amplitude peaks in the response spectrum, each corresponding to distinct modal frequencies. Damping characteristics, or modal loss factors, are typically derived from these peaks using the 3 dB bandwidth method in conjunction with identified modal frequencies [12].

The ARTeMIS Modal program was used to process the time-domain acceleration data collected during the impact hammer tests. While ARTeMIS is best known for modal analysis (extracting natural frequencies, damping ratios, and mode shapes), it also allows for a thorough evaluation of raw acceleration data. In this investigation, the program was utilized to extract peak acceleration values from the time-history data of each sensor position. These peak values were then evaluated to determine the effect of fracture depth on the dynamic response of the RC samples.

In this study, an impact hammer equipped with a force transducer was used to deliver excitation, while accelerometers mounted on the RC specimens captured the resulting vibrations. These signals were recorded using a data logger, as illustrated in Figure 4. The recorded data were then analyzed using the ARTeMIS software suite to determine the specimens' acceleration.

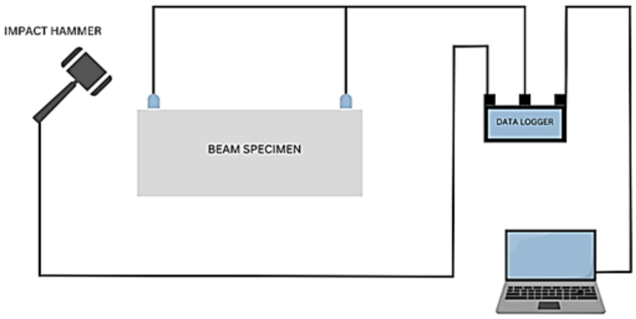
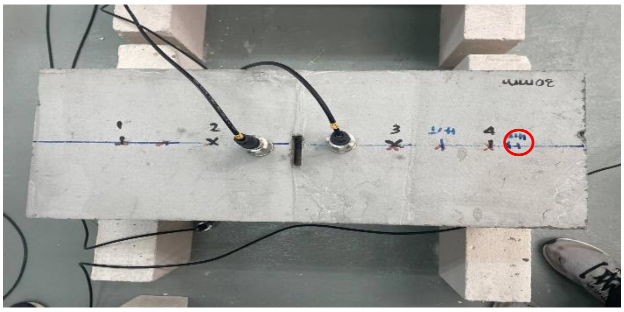
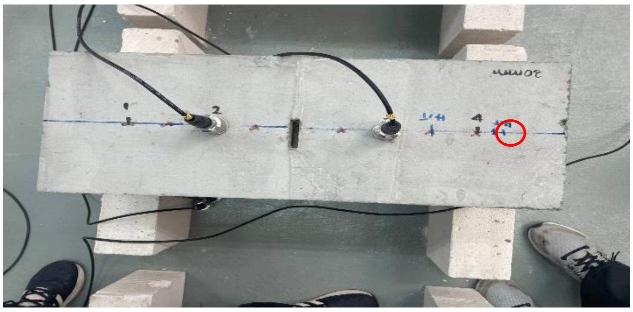


Fig. 3. Layout of the impact hammer.

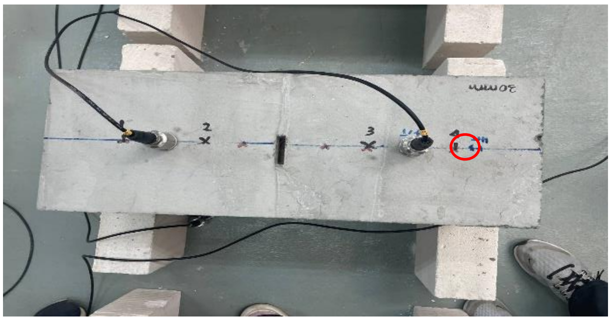
The testing was repeated ten times to find the average value for the parameter. The distance between each accelerometer is different, as shown in Table 2. The distance is calculated from the centre of the specimen and then to its left or right. The placement of accelerometers in the lab is presented in Figure 5, where the red circle in each figure shows the hammer point which is 60mm from the nearest accelerometer.



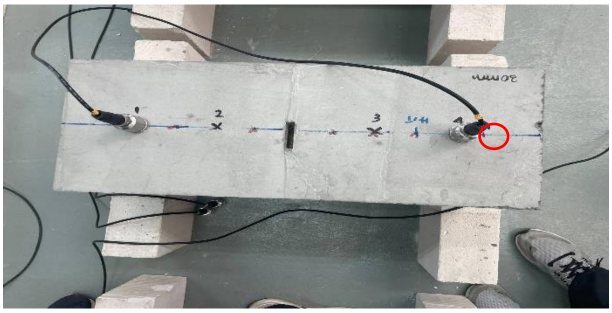
(a)



(b)



(c)



(d)

Fig. 4. Accelerometer placement with a distance of (a) 100mm (b) 200mm (c) 300mm (d) 400mm.

The vibration-based data collected from the experiments was processed and analyzed using ARTeMIS software, a specialized tool for structural health monitoring through vibration analysis. ARTeMIS enables the acquisition, processing, and interpretation of data from accelerometers and other vibration sensors. By comparing vibration measurements over time, ARTeMIS is capable of detecting irregularities and evaluating the condition of various structures such as buildings, bridges, and mechanical systems. Figure 8 shows an example of raw data that was collected using accelerometers. It is a time domain data which shows acceleration (m/s^2) versus times (s). The peak data in the graph shows the time that the hammer delivered impact to the specimen with a maximum acceleration of 5.429E-2 m/s^2 and a minimum acceleration of -6.587E-2 m/s^2. The Root Mean Square (RMS) acceleration is a statistical measure that quantifies the total level of vibration in a system, returning a single result that indicates the average magnitude of the acceleration over a given period. RMS acceleration is calculated by calculating the square root of the average of the squared acceleration data. The RMS value for this accelerometer is 3.110E-2 m/s^{2,} including the median and mean values of the data. In addition, variance is the measure of the distribution of the data, skewness is a measure of the distribution's asymmetry, whereas kurtosis is the measure of the tailenders of a distribution. The peak acceleration data between accelerometer 1 and accelerometer will be differentiate in order to find the difference. The example layout of the data that been collected is as shown in Figure 6.

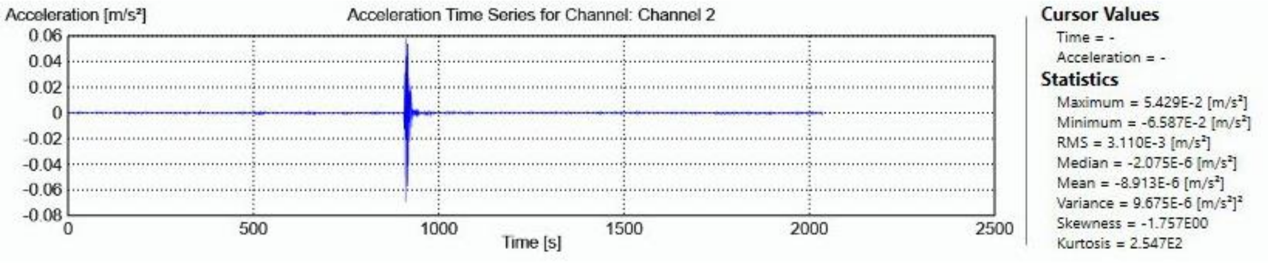


Fig. 5. Acceleration data from ARTeMIS software.

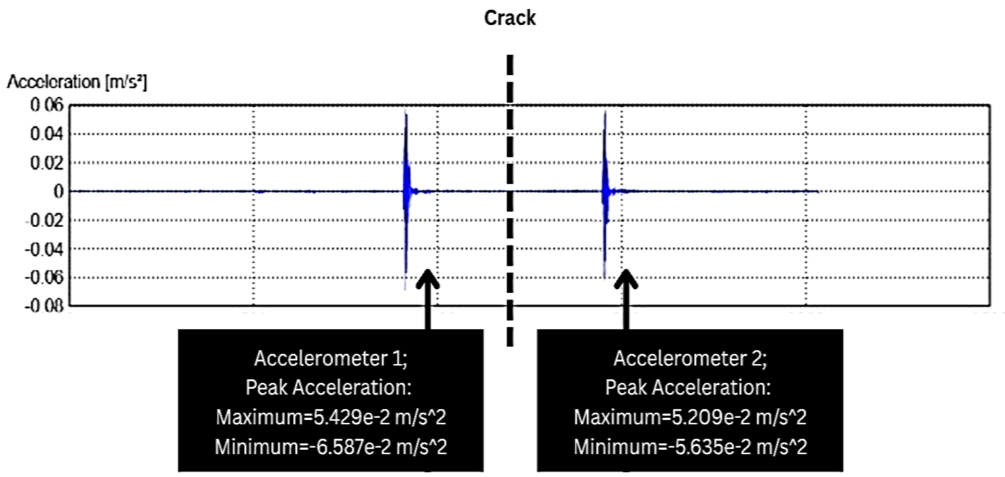


Fig. 6. Example layout of acceleration data from accelerometer 1 and 2 from 40mm crack depth experiment.

4. RESULT AND DISCUSSION

The graph shows in Figure 7 depicts the link between acceleration difference and crack depth for sensor placements at different distances (100, 200, 300, and 400 mm) from the crack. A general pattern is observed for sensor distances of 100 mm, 200 mm, and 300 mm, with the acceleration difference increasing as the fracture depth approaches 60 mm. This suggests that sensors placed closer to the crack are better at detecting vibration signals caused by crack propagation. The increased sensitivity at shorter distances is most likely owing to a higher signal-to-noise ratio, which improves the capacity to discern structural anomalies from background vibrations. This result aligns with the findings of [13], who concluded that closer sensor location greatly increases crack detection accuracy by assuring clearer and more stable signal gathering.

At the 400 mm sensor distance, an anomaly is found in which the acceleration difference lowers suddenly at 50 mm fracture depth before rising again at 60 mm. This inconsistency could be due to difficulties that become more noticeable with increased sensor distance, such as signal attenuation or misalignment-related distortion. Accelerometer misalignment, particularly when it comes to spacing or orientation, can have a substantial impact on measurement accuracy. [14] demonstrate how such misalignment might alter the beam pattern in acoustic vector sensors. This distortion occurs when the sensitive axes of the accelerometers are not properly aligned, resulting in inaccuracies in directional sensitivity and overall responsiveness of the sensor system. At larger distances, even minor misalignments can result in phase variations or directional inconsistencies, causing particular vibration components to be underrepresented or masked, as demonstrated at the 50 mm fracture depth at 400 mm.

This supports the broader conclusion highlighted by [15], who emphasized the necessity of optimum accelerometer positioning during vibration testing. Inappropriate sensor placement might result in inadequate or erroneous data, reducing the reliability of the dynamic response analysis. Despite this anomaly, the overall pattern across all distances is similar, with a rising acceleration difference with crack depth. This implies that, while the underlying structural reaction to cracking is coherent, sensor positioning has a significant impact on the precision and clarity of the measurement. For successful structural health monitoring, sensors must be carefully calibrated and strategically placed.

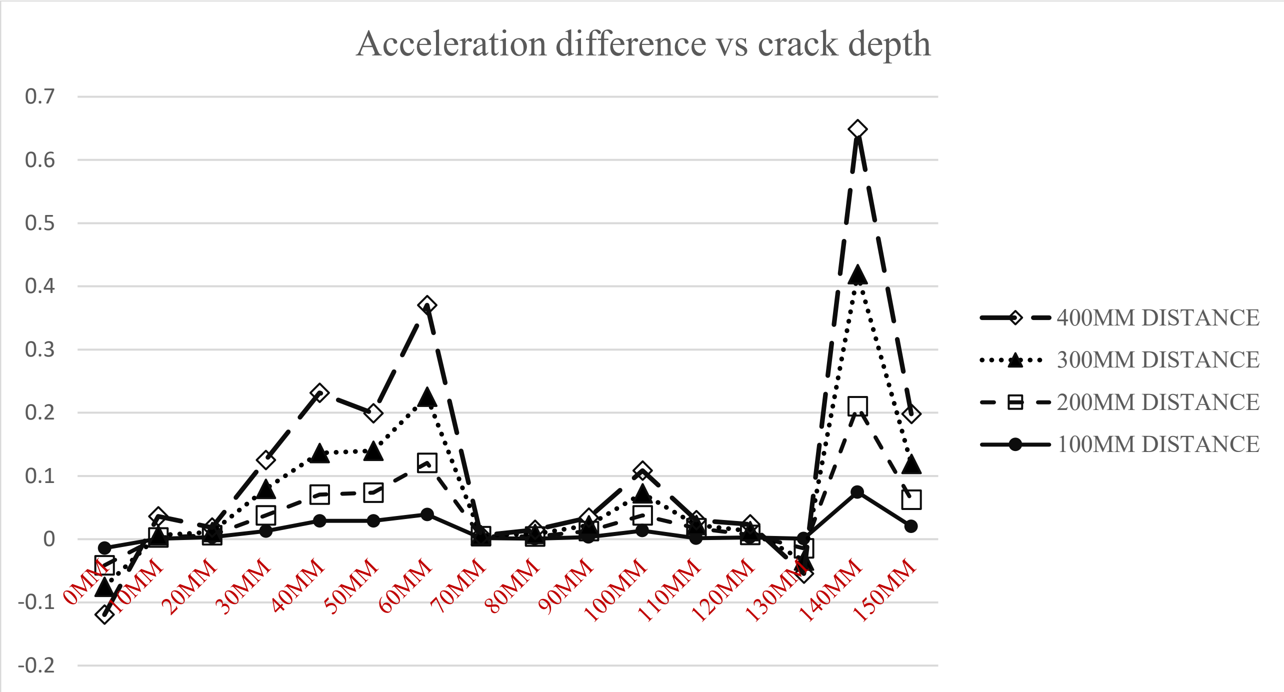


Fig. 7.Acceleration difference vs crack depth graf.

5. CONCLUSION

This study examined the relationship between crack depth and changes in peak acceleration response in RC beams, with particular emphasis on how the distance of accelerometers from the crack influences measurement sensitivity. The experimental results provide valuable insights into vibration-based structural health monitoring (SHM) techniques, offering practical guidance for optimizing sensor placement in real-world applications.

The key findings reveal a correlation between crack depth and acceleration difference, particularly when accelerometers are positioned at closer distances (100–300 mm) from the crack. At these ranges, the acceleration difference exhibited a consistent increase as crack depth approached 60 mm, demonstrating that sensors placed nearer to the damage site captured more pronounced vibrational anomalies. This enhanced sensitivity is attributed to stronger signal transmission and reduced noise interference at shorter distances, which aligns with previous research emphasizing the importance of proximity in crack detection.

However, the study also identified limitations when accelerometers were placed farther away (400 mm). At this distance, the acceleration difference showed an unexpected drop at 50 mm crack depth before rising again at 60 mm. This anomaly suggests that signal attenuation, sensor misalignment, or wave scattering effects may distort measurements at extended ranges. Such inconsistencies highlight the challenges of relying on distant sensors for precise crack assessment, reinforcing the need for careful calibration and strategic placement in SHM **systems.**

Based on these results, it is recommended to position accelerometers within 100–300 mm of the crack for effective structural health monitoring (SHM). This range balances sensitivity and practicality, avoiding the limitations observed at greater distances. Future studies could explore advanced signal processing techniques or multi-sensor arrays to mitigate alignment issues and further improve crack detection accuracy in field applications.

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