Subsurface Concrete Damage Detection Using Multifrequency Acoustic Hammer Testing

Xi Huang
Department of Urban and Civil Engineering, Ibaraki University, Nakanarusawa-Cho 4-12-1, Hitachi 316-8511, Japan; email: 22nd302r@vc.ibaraki.ac.jp

Huang Huang
School of Civil Engineering, Henan University of Technology, Zhengzhou 450001, China; email: hhly9527@gmail.com

Mao Kurumatani
Department of Urban and Civil Engineering, Ibaraki University, Nakanarusawa-Cho 4-12-1, Hitachi 316-8511, Japan; email: mao.kurumatani.jp@vc.ibaraki.ac.jp

Zhishen Wu*
International Institute for Urban Systems Engineering, Southeast University, Nanjing 211189, China; email: zswu@seu.edu.cn

ABSTRACT
Subsurface crack detection in coated concrete structures is critical to maintaining their structural integrity. The hammer test, a nondestructive and validated technique, is traditionally employed for subsurface crack detection. However, manual hammer testing is often influenced by the subjective judgments of technicians, and the monotony of automated mechanical hammer patterns results in ineffectiveness in some scenarios. To address these limitations, this study devised a novel acoustic detection method that employs multifrequency hammering to identify the damage concealed beneath concrete with fireproof coating. This approach leverages the distinctive excitation effects associated with various hammering frequencies to transform a monotonous hammer soundwave into a composite sound sequence tailored to specific frequencies. It involves collecting acoustic signals from both healthy and damaged concrete specimens subjected to hammering frequencies in the 1–10 Hz range, followed by an analysis of the evolution of the acoustic characteristics with changes in the hammering frequency. The fundamental acoustic features appropriate for concrete excitation were identified, and a qualitative index based on the variations of these characteristics relative to the hammering frequency was developed. This index enabled the effective detection of concealed concrete damage. The results demonstrated that the response of damaged concrete to varying hammering frequencies was markedly more pronounced than that of healthy concrete, thus confirming the efficacy of the proposed method for detecting subsurface cracks under 10 mm-thick fireproof coatings.

KEYWORDS: damage identification; nondestructive testing; hammering test; coated concrete; subsurface cracks

1. INTRODUCTION

Subsurface-crack detection in concrete structures is crucial to ensuring their structural integrity and safety. Thus, numerous nondestructive testing techniques, such as ultrasonic testing, have been developed. However, these methods are often susceptible to interference from surface coatings applied on the objects being inspected. Therefore, traditional hammer testing is the most widely used technique. However, it is significantly influenced by the subjective judgment of inspectors, particularly when detecting hidden damage under coatings. Therefore, it is imperative to develop an advanced hammer test method that can detect concealed damage and can either replace or augment human judgment.

Recent advances in hammer-detection approaches have attempted to address the limitations of traditional methods and enhance their reliability. Yasuda (2023) highlighted that in human inspections, wherein visual and hammering tests are combined for concrete spalling prevention, the spalling risk is often overestimated owing to low-frequency vibrations that are difficult to detect audibly. They underscored the need for more precise methods beyond auditory evaluations. In response, Sonoda et al. (2023) explored the use of convolutional auto encoders for the quantitative diagnosis of hammering sounds and demonstrated improved anomaly-detection accuracy for deteriorated bridges. Similarly, Alhebrawi et al. (2023) proposed an artificial intelligence (AI)-enhanced approach for automatic crack identification using acoustic impact hammer testing. They showed that mel-frequency cepstral coefficients combined with the support vector machine algorithm could accurately detect deep cracks as small as 0.2 mm wide and 40 mm deep, suggesting that AI integration can significantly improve the detection accuracy for small-scale concrete damage. However, these studies typically relied on manual or mechanical single-frequency hammering and did not enhance the hammering method, particularly for detecting concealed damage beneath coated surfaces.

Thus, this study devised a novel approach that leverages multifrequency hammering to detect subsurface cracks concealed beneath concrete coatings. The proposed method transforms a monotonic hammer soundwave into a composite sound sequence tailored to specific frequencies, thereby capturing a wide range of acoustic responses from a concrete structure. By analyzing the evolution of the acoustic characteristics with changes in the hammering frequency, fundamental acoustic features appropriate for concrete excitation were identified. These features were then used to develop a qualitative index based on the rate of variation of these characteristics relative to the hammering frequency, thus enabling the effective detection of concealed damages.

2. METHODOLOGY

Variable-frequency hammering is an advanced technique that improves upon traditional manual hammering techniques through intelligent selection and judgment. Huang et al. (2022) developed an automated hammer-testing system for concrete structures. Subsequently, Huang, Huang, and Wu (2023) proposed a variable-frequency hammering method that uses acoustic features to identify the damage type and improves the damage-detection frequency. Thereafter, Huang, Huang, et al. (2023) made further advancements by introducing adaptive excitation frequency matching and an acoustic-feature-based automatic hammering inspection system, thus increasing the accuracy and efficiency of variable-frequency hammering. Wu et al. (2024) then developed a mobile precision detection technology for reinforced concrete structures, enhancing the applicability and mobility of precision detection methods.

By varying the hammering frequency, the variable-frequency hammering technology intelligently selects the optimal excitation frequency to apply the best excitation effect to the object being inspected. This study proposes a multifrequency hammering method based on variable-frequency hammering to improve crack detection in concrete structures with surface coatings. Traditional manual hammer-testing methods or mechanical hammering often relies on single-frequency hammering modes, which often fail to detect hidden damage because of their uniform excitation effects. By contrast, the multifrequency hammering technique uses a series of hammering frequencies to generate a composite sound sequence. As shown in Figure 1, the hammering frequency sequence is customized to cover all frequencies, from low to high. By analyzing the changes in acoustic characteristics with variations in the hammering frequency, the fundamental acoustic features are extracted; then, acoustic characteristics are extracted at various hammering frequencies. Finally, these dynamic acoustic features are used for damage identification.

The multifrequency hammering technique is illustrated in Figure 1 and comprises the following steps:

(1) Continuous Variable-frequency Hammering: This is the first step, wherein the variable-frequency hammering device uses low, medium, and high hammering frequencies to excite the object being inspected. This range of hammering frequencies ensures the comprehensive excitation of the concrete structure, capturing various acoustic responses.

(2) Low-, Medium-, and High-frequency Hammering Soundwaves: Figure 1 shows the soundwaves obtained within 1 s of excitation at different hammering frequencies (low: 2 Hz; medium: 5 Hz; and high: 10 Hz).

(3) Spectral Analysis: Subsequently, the collected acoustic signals undergo spectral analysis, which transforms the time-domain signals into the frequency domain, thus enabling a detailed examination of the frequency components in the hammering sounds.

(4) Fundamental Frequency Extraction: Huang, Kurumatani, et al. (2023) verified that this acoustic feature can be used to effectively detect voids and other types of damage in concrete structures. As a frequency feature, the fundamental frequency is not affected by the number of hammering strokes within 1 s. The fundamental frequency can be extracted using the autocorrelation method as follows:

$$R(\tau) = \sum_{0}^{N-1} x(n) \cdot x(n+\tau), \tag{1}$$

where $R(\tau)$ is the autocorrelation function, $x(n)$ is the signal, and τ is the time lag. The fundamental frequency, f_0, is then determined by identifying the first significant peak in $R(\tau)$.

(5) Dynamic Acoustic Feature Extraction: Previous research on variable-frequency hammering indicated that the changes generated in healthy areas under varying hammering frequencies are minimal. In contrast, the damaged areas exhibit significantly different acoustic characteristics under different frequency excitations. This study used three hammering frequency ranges (low, medium, and high) to obtain dynamic acoustic features from low-to-medium and medium-to-high frequencies. The dynamic feature D_f between two hammering frequencies f_a and f_b is calculated as follows:

$$D_f = \frac{|f_{0b} - f_{0a}|}{f_a}, \tag{2}$$

where f_{0a} and f_{0b} denote the fundamental frequencies of f_a and f_b, respectively.

(6) Damage Identification: Finally, the extracted dynamic acoustic features are analyzed, and empirical thresholds are obtained through experiments to identify the damage.

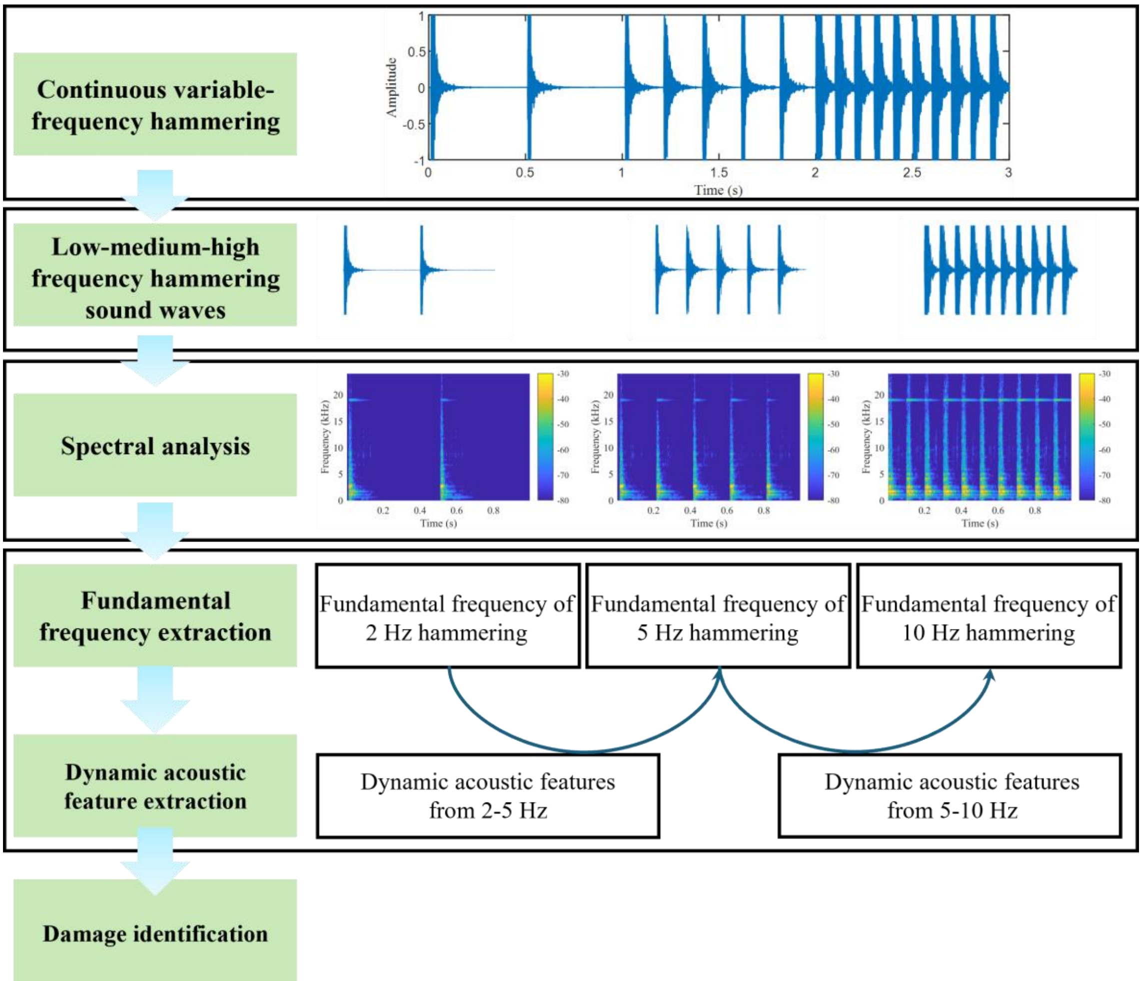

Figure 1 Flowchart of the proposed multifrequency acoustic hammer testing method

3. EXPERIMENTAL SETUP

This study involved two experiments. First, the effectiveness of the dynamic features was verified through experiments on the internal damage in concrete. Subsequently, the effectiveness of these features under the coatings was verified through experiments on cracks in concrete beneath a fireproof coating.

3.1. *Verification of Hammering Dynamic Characteristics*

To verify the applicability of the proposed hammering dynamic characteristics, inspection tests were conducted on concrete beam measuring 420, 60, and 60 mm in length, width, and height, respectively. The concrete beam was segmented into 21 sections of 20 mm in width. As shown in Figure 2, the damage to each area was categorized into four types: “healthy” (no damage), “surface damage” (surface cracks), “internal damage” (internal cracks), and “compound damage” (both surface and internal cracks). An automatic hammering device was used to inspect each area along the beam length.

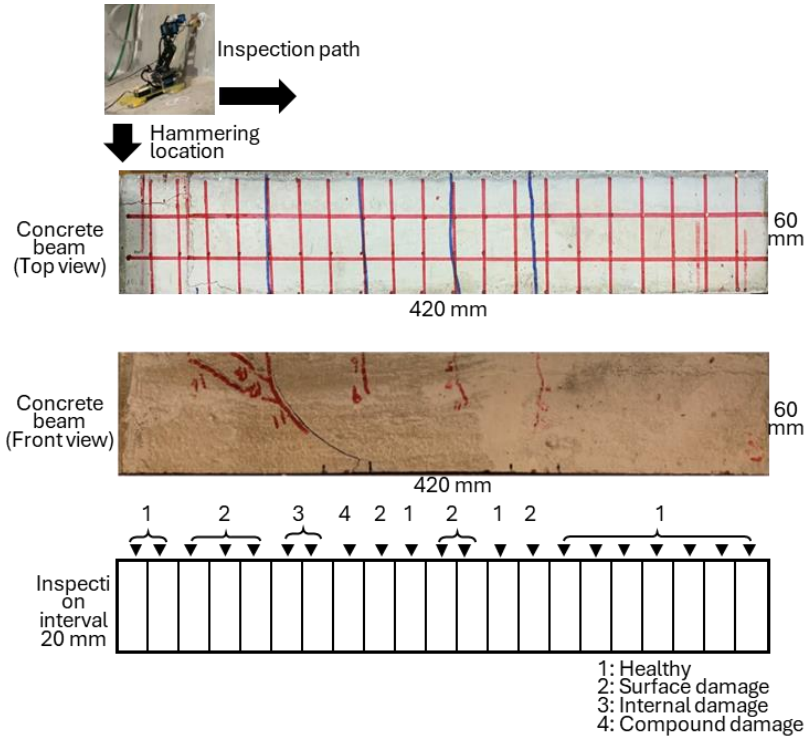

Figure 2 Layout of the specimen used for internal damage detection

3.2. *Detection of Hidden Damage under Fireproof Coatings*

To verify the damage detection in concrete with fireproof coating, a 400 mm-long, 500 mm-wide, and 100 mm-thick specimen was designed. Crack damage appeared after loading tests, as shown in Figure 3. A 10 mm-thick fireproof coating was then applied to the surface. For the tests, the specimen was divided into 100 × 100 mm grids, and each grid section was subjected to hammering.

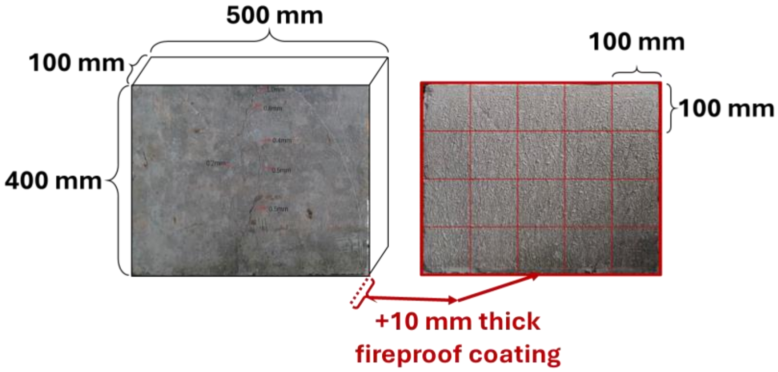

Figure 3 Layout of the specimen with fireproof coating

4. RESULTS AND DISCUSSION

4.1. *Damage Identification Based on Fundamental Frequency Features*

The damage identification based on the fundamental frequency features is illustrated in Figures 4–6. A horizontal coordinate system was established based on Figure 2, and the fundamental frequency features obtained by hammering each 20 × 20 mm grid were extracted onto the coordinate system as a heatmap. Evidently, all single hammering frequencies of 2, 5, and 10 Hz show pronounced responses in the 60–120 mm range. However, healthy areas without damage appear chaotic and are not clearly distinguishable. Additionally, the vertical cracks at 220–240 and 260–280 mm exhibit different behaviors across the hammering frequencies, resulting in inconsistent effects. Additionally, the multiscale identification results under single hammering frequencies are relatively dispersed, converging toward a specific type of damage (60–120 mm).

As shown in Figures 7 and 8, the changes in the fundamental frequency features based on the 2–5 and 5–10 Hz ranges were extracted onto the horizontal coordinate system as a heatmap. Evidently, the variations in the fundamental frequency features obtained from variable-frequency hammering converge toward both the internal and surface cracks. In Figure 8, surface cracks at 60–120 mm and vertical cracks at 220–240 and 260–280 mm are identifiable, whereas the internal extension cracks at 100–160 mm exhibit slight convergence, clearly distinguishing the healthy area at 180–200 mm.

These results demonstrate that the detection results vary among different excitation frequencies, and fixed mechanical hammering frequencies do not guarantee optimal detection effectiveness. Dynamic features also show different effects; those from 5–10 Hz reveal the damage distribution more comprehensively than those from 2–5 Hz.

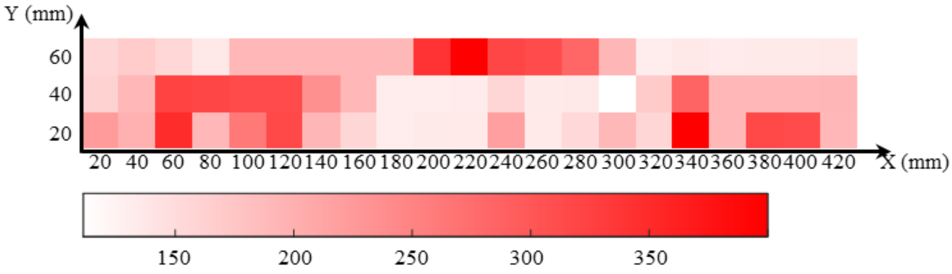

Figure 4 Fundamental frequency detection results under 2 Hz single-frequency hammering

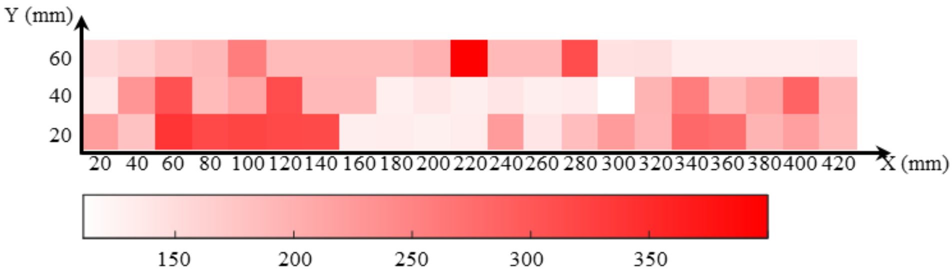

Figure 5 Fundamental frequency detection results under 5 Hz single-frequency hammering

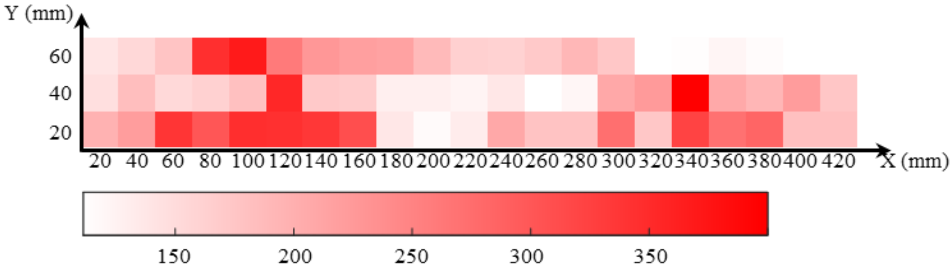

Figure 6 Fundamental frequency detection results under 10 Hz single-frequency hammering

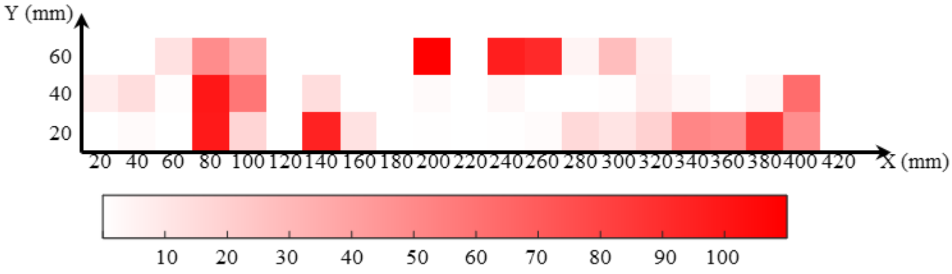

Figure 7 Dynamic feature results from 2 Hz

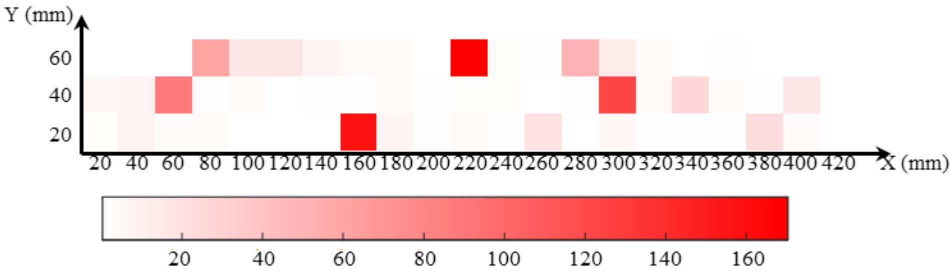

Figure 8 Dynamic feature results from 5–10 Hz

4.2. *Detection of Concrete Cracks under Coatings*

The detection results based on dynamic features are shown in Figure 9. A horizontal coordinate system was established based on Figure 3, and the detection results obtained by hammering each 10 × 10 cm grid were extracted onto the coordinate system as a heatmap. Evidently, the areas without damage are almost transparent. In contrast, significant damage can be observed at 30 cm. The previously undamaged area at (400, 400) shows damage, which is hypothesized to be caused by the extension of the internal cracks on the right side of the original crack during loading. Similar results can be observed for the (400, 100) and (400, 200) planes.

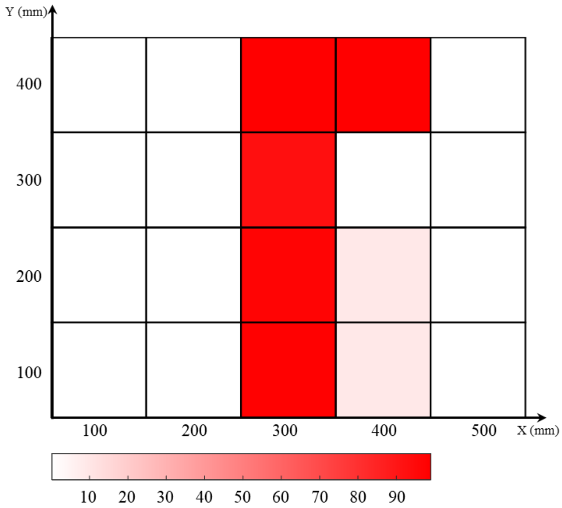

Figure 9 Crack detection results for coated specimens

5. CONCLUSION

Based on the variable-frequency hammering detection technology, this study developed a dynamic acoustic feature-based damage-detection technique using multifrequency hammering. The relationship between the internal damage and dynamic features was investigated, and a method for detecting damage in concrete with coatings was established. The main conclusions of this study can be summarized as follows:

(1) Generally, the hammering acoustic data change with the movement of the measurement points. By comparing each measurement point with its own variations and analyzing the changes in the acoustic characteristics of concrete damage at different frequencies, dynamic acoustic features were obtained. Compared with the hard-to-capture thresholds of damage presence or absence using single mechanical hammering frequencies, the dynamic features can capture the damage with a higher sensitivity.

(2) The experimental results confirmed the effectiveness of the dynamic acoustic features obtained through variable-frequency hammering excitation for internal damage detection. Additionally, this study confirmed that the dynamic feature detection method based on multifrequency hammering can identify crack damages in concrete with 10 mm-thick fireproof coating.

However, these tests were conducted in a laboratory environment and were not affected by field engineering issues, such as noise and damage detection in complex terrain environments. In the future, we will focus on integrating techniques such as machine learning to quantify concealed damage based on dynamic features.

ACKNOWLEDGEMENTS

This research was funded by the National Key Research and Development Program of China (Grant number: 2019YFC1511103).

REFERENCES

Alhebrawi, M.N., Huang, H. and Wu, Z. 2023. Artificial intelligence enhanced automatic identification for concrete cracks using acoustic impact hammer testing. *J. Civ. Struct. Health Monit.*, 13(2): 469–484.

Huang, H., Huang, X., Wu, Z., Alhebrawi, M.N. and Liang, Z. 2023. Adaptive excitation frequency matching and acoustic-feature-based automatic hammering inspection system. *Int. J. Struct. Stab. Dyn.*, 23(16n18): 2340038.

Huang, X., Kurumatani, M., Huang, H. and Wu, Z. 2023. Detection of delamination in concrete using acoustic-based variable-frequency hammering tests. In *Proceedings of the 12th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-12)*, Hangzhou, China: ISHMII.

Huang, X., Huang, H. and Wu, Z. 2023. Development of a Variable-Frequency Hammering Method Using Acoustic Features for Damage-Type Identification. *Appl. Sci.*, 13(3): 1329.

Huang, X., Huang, N.A. and Wu, Z. 2022. Development of an automated hammer testing system for concrete structures. *Int. J. Sust. Mater. Struct. Syst*, 6(1): 32–45.

Sonoda, Y., Lu, C. and Yin, Y. 2023. Basic research on usefulness of convolutional autoencoders in detecting defects in concrete using hammering sound. *Struct. Health Monit.*, 22(4): 2231–2250.

Yasuda, N. 2023. Hammering sound of concrete with defects and spalling risk. *Tunn. Undergr. Space Technol.*, 131: 104789.

Wu, Z.-S., Hou, S.-T., Huang, X. and Huang, H. 2024. Development of mobile precision detection technology for reinforced concrete structures. *Eng. Mech.*, 41(1): 1–16.