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A Vibration and Crack Assessment on Precast Pre-stressed Hollow-Core Floor

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Abstract

Hollow core concrete floors are usually used in high-rise buildings, shopping malls and parking garages due to their sustainability advantage in the construction industry. However, in certain conditions, hollow core concrete floors can be sensitive towards vibration due to long span. The floor vibration issue is crucial and must be managed properly during the building design phase, as addressing this issue becomes significantly more challenging after the structure has been constructed completely. Thus, this study aims to determine the vibration and crack behaviour of precast hollow core concrete floors. 3D finite element models of the floor were developed using SAP2000 software to obtain the vibration parameters of the hollow core concrete floor subjected to vehicle-induced vibration. The specifications of the floor materials are based on the hollow core concrete floor manufacturer, Eastern Pretech, and the acceleration time history from testing was applied to the analysis. Modal analysis and time history analysis were analysed to investigate the vibration behaviour of the hollow core concrete floor. Modal analysis revealed a fundamental frequency of 23.52 Hz for the floor with actual dimensions. The fundamental frequency of the floor was compared to the standard guideline for human vibration sensitivity, which is 10 Hz. Time history analysis was employed to assess floor deformation based on the vibration waves generated by vehicle movement on the floor. The crack assessment analysis on concrete topping of precast hollow core slab in the warehouse flooring system was carried out. The cracks that appeared on the concrete topping were investigated using vibration testing and finite element analysis. Acceleration data from the damaged area was captured and transformed into the frequency domain using ME'Scope to analyse the natural frequency behaviour. The preliminary finite element analysis was performed by SAP 2000 software. Normal attenuation was observed on the surface with a crack at 50 mm, as the pattern of the time series data at this location was similar to other sensor positions. Analysis of the frequency domain of the wave confirmed this observation, revealing a dominant frequency of 23.741 Hz and no abnormal event occurred during testing on the surface crack.

1. Introduction

Historically, traditional concrete floors have rarely experienced vibration problems due to their substantial self-weight. However, recent trends in building construction, such as the use of lightweight concrete and longer spans, have exacerbated this issue. Hollow-core concrete flooring systems, introduced in the early 1900s, are now widely used in high-rise apartments, shopping malls, warehouses, and parking garages. The hollow sections within these floors reduce their self-weight, enabling longer spans. However, this reduced self-weight and increased span length can make hollow-core concrete floors susceptible to vibration issues [1].

The low self-weight of hollow-core concrete floors make them particularly sensitive to forces from 4 Hz to 10 Hz [2]. Fundamentally, humans are sensitive to frequencies that are lower than 10 Hz [3], making it essential to design floors with higher frequencies to mitigate vibration and ensure occupant comfort. Compared to conventional concrete floors, hollow-core floors typically have lower self-weight, increasing their susceptibility to vibration. Heavier floors are generally preferred due to their lower amplitude, higher frequency, and increased damping compared to lighter floor systems [2]. These characteristics contribute to a reduction in the perceived vibration annoyance for building occupants.

The precast pre-stressed hollow-core slab (PPHCS) were installed in an open-space warehouse flooring system, each spanning over 8 meters. This precast system, featuring cast-in-situ topping, reflects a trend towards more slender structures. The PPHCS is often used in the construction of high-rise buildings, shopping malls, warehouses, and industrial buildings due to its high strength performance, which allows for slender and lightweight slab. However, these properties also make it susceptible to excessive excitation and vibration. This excessive vibration can lead to structural fatigue, compromised floor serviceability, and cracking. The excitation sources include both human-induced and machine-induced activities, such as forklift movement within the warehouse. The moving load of a forklift, especially when carrying additional weight, increases the force exerted on the slab during merchandise handling, contributing to floor damage.

Damage to the floor structure can lead to changes in the parameters, including the natural frequency [3]. Cracks on the slab surface cause a reduction in the natural frequency and stiffness of the slab due to significant stress losses [3]-[7]. This flexibility due to cracks can result in a stiffness reduction on the floor system, potentially leading to structural failure. The floor has sustained random fine-line cracks due to moving loads, primarily from forklifts. Structural cracks can occur in beams, columns, and slabs due to design errors or overloading. Both freshly laid and hardened concrete are susceptible to cracking [8], [9].

Various methods for measuring crack depth have been explored in previous studies. One such method employs ultrasonic waves, which can be used to determine crack depth [10]-[13]. A notable technique involves the use of a portable ultrasonic non-destructive digital indicating tester (PUNDIT). In this method, the transducer transmitter and receiver are positioned opposite each other with the crack line in between, maintaining a constant distance from the crack line. Ultrasonic waves are sent from the transmitter to the receiver, and the time taken for these waves to traverse the crack line is indirectly measured. This study aimed to evaluate the impact of transducer distance on crack depth measurement accuracy. The findings indicated that relative inaccuracy decreases when the transducer is placed at a distance equal to 2/3 or 0.67 of the object's thickness.

To ascertain fracture depth and evaluate the impact of transducer distance and reinforcing on the measurement, the ultrasonic pulse velocity (UPV) approach was also employed [11]. By placing the transducer at varying distances, changes in the results were observed. It was found that the presence of reinforcement in the concrete beam led to different crack depths. The study concluded that the relative error diminished as the crack depth increased, and the accuracy of the measurements improved with a greater distance between the transducers.

To determine the size of cracks in concrete constructions ultrasound frequency analysis is recommended to conduct [12]. The pulse-echo method was used in this study to evaluate the depth of cracks in concrete blocks, which were used as test materials. After applying the Fourier transform to the reflected pulse, the frequency spectrum showed the interval of time between two pulses. Three distinct ultrasonic frequencies—2.25 MHz, 5 MHz, and 10 MHz—were used in their experimental investigation to ascertain the best frequency for calculating crack depth. The investigation concluded that surface cracks deeper than 3 mm could not be detected using an ultrasonic frequency of 2.25 MHz, while surface cracks deeper than 6 mm could not be detected using a frequency of 10 MHz. To guarantee accurate results, a higher ultrasonic frequency should be used for short surface fractures and a lower frequency for long surface cracks.

Using ultrasonic shear-horizontal (SH) waves, it was also possible to forecast the depth of cracks in concrete buildings [13]. This work introduced the Ultrasonic Pulse Echo Method (UPE-SH), a novel technique that uses SH waves. It was discovered that SH waves improved the measurement accuracy of crack depth. Two test samples with vertical cracks provided experimental data that were utilised to assess the UPE-SH method's effectiveness. The outcomes showed that the novel approach improved fracture depth measuring accuracy.

Diffuse ultrasonography is another method that can be used to estimate the depth of cracks in concrete beams [14]. The diffuse ultrasonic technique requires the theoretical estimation of the diffuse ultrasonic energy's arrival time, which can be obtained by an analytical or numerical model-based approach [15]. On both sides, transducers at a frequency of 500 kHz were positioned 30 mm apart from the crack line. Estimates of the visible crack depth obtained from visual inspection were compared with the experimental results. From transmitter to receiver, the pulse produced by the pulse generator travelled, and the diffuse waves were examined. Diffusion, dissipation, and peak energy arrival time were among the parameters that were assessed. The findings showed that the core specimen taken from the crack site and the diffuse ultrasonic readings agreed quite well. In the meantime, the eye examination sometimes overestimated the depth of the cracks. As a result, the diffuse ultrasonic approach provided more accurate crack depth estimation.

Using a piezoelectric disc (PZT sensor) as a source of surface wave velocity, automated surface wave measurement was used to evaluate the depth of cracks [16]. The PZT sensor was placed on a concrete slab with a surface fracture in the middle, and accelerometers were used to measure the surface waves it created. The investigation's conclusions showed that the PZT sensor was a trustworthy resource for surface wave velocity and gearbox data used to determine the depth of cracks.

A study on the application of Rayleigh wave measurement (R-waves) to the assessment of reinforced concrete surface cracks was conducted by [17]. Long-range detection is made possible by R-waves' special qualities, which include low attenuation and higher possession than bulk waves. The purpose of this study was to quantify the depth and angle of the cracks. The findings indicated that when the penetration capability of R-waves grew, particularly when the crack depth is smaller than the wavelength, the index of the amplitude appeared to be more accurate in identifying changes in both the degree of inclination and the crack depth.

Monitoring based on vibration is one method used to evaluate fractures in concrete buildings. It is used in structural health monitoring and makes use of vibration data to identify problems within the structure [18], [19]. By assessing the state of the structure, including damage identification, classification, and progressive development, this method is pertinent for determining structural safety [20]. An alternative to the manual visual inspection approach for determining the extent of damage to concrete structures is vibration-based monitoring. It is extensively used in power plants, offshore construction, mechanical, aviation, and civil buildings, as well as cultural heritage locations as bridges [21].

Vibration-based monitoring uses changes in dynamic properties including natural frequencies, mode shapes, and damping ratios to detect structural degradation [22], [23]. Structure-related changes affect certain modal characteristics, including natural frequencies, modal damping, and mode shapes. The most important modal metrics seen in vibration-based monitoring are frequencies and mode shapes. In general, when a building is damaged, frequencies drop. Since mode shapes are more susceptible to damage, frequencies and mode shapes are examined in tandem to determine the location of the damage [24].

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Damage to concrete structures is also can be detected by vibration-based monitoring. Examining variations in natural frequencies, damping ratios, and mode shapes allows for the identification of damage in dam structures and multi-story buildings as suggested by Pereira et al. [25] and Shatilov & Lyapin [26]. This technique has also been used on beams, as shown by a study on fracture detection by Altunışık et al. [27]. Under six damage scenarios in cantilever beams, the study analysed variations in natural frequencies and mode shapes derived from analytical and experimental models. Next, modal testing, modal curvature, and modal flexibility approaches were used to locate cracks in beams.

Non-obstructive testing (modal testing) was used to investigate the crack development on the concrete topping (surface crack) using both ambient test and a forklift-induced excitation. Several design guidelines from The Concrete Society, American Institute of Steel Construction and European Commission [2], [28]-[31] mention the limitations of vibration behaviour, including natural frequency and the critical limit for a floor's natural frequency is 10 Hz. Floors with natural frequencies below this threshold are classified as low-frequency floors, which require analysis of both steady-state and transient responses. Floors with natural frequencies above 10 Hz are classified as high-frequency floors, which only require analysis of transient responses.

To investigate floor vibration behaviour, including deformation behaviour, a finite element analysis (FEA) was carried out. Using recording variations in the floor's inherent frequency and acceleration, the testing results were used to identify the cracks. A 2004 study by Choi & Stubbs [32] formed damage indices with mean strain energy to pinpoint potential damage areas on the structure and employed a time domain response to ascertain the damaged area across a beam structure. In the transverse direction of the cantilever beam, a comparison study using bump testing on both healthy and damaged specimens revealed a decrease in natural frequency and acceleration on the surface hair crack from 21.5 Hz to 15.69 Hz and 0.925 GHz to 0.195 GHz, respectively as mentioned by Elshamy et al. [33]. A notable decrease in natural frequency can be observed from the stiffness reduction caused by the existing crack. There were large discontinuities at the nodal point of the exciting modes, where no vibration was detected, and small discontinuities at the crack area [34].

The study on crack assessment of the PPHCF floor using modal analysis, simulation, and experimentation is presented in this publication. The objectives of this study were to carry out a preliminary inquiry, ascertain the flooring area's vibration behaviour, and use the modal analysis approach to look into the concrete topping cracking. The relationship between crack growth, modifications to modal characteristics (natural frequency, mode shapes), and the floor's vibration response to forklift-induced and ambient excitations will be examined to do this.

2. Vibration Floor Assessment

This study was conducted in the warehouse building where PPHCS was constructed as the flooring system. The PPHSC panels were constructed continuously, spanning 1.2 m between beams. These panels range from 450 mm to 550 mm in thickness and 8 m to 16 m in span length. A 100 mm to 110 mm concrete topping, reinforced with mesh, was poured over the panels. Details of the floor plan layout are shown in Fig. 1.

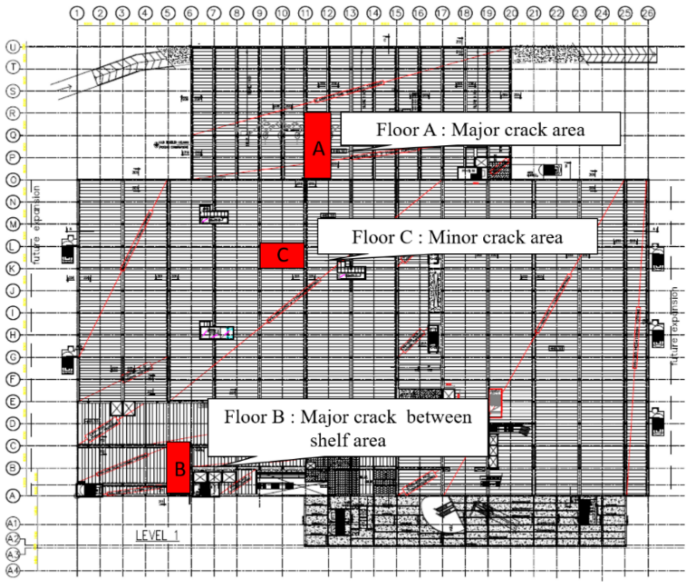

Fig. 1 *Floor plan layout and testing area*

2.1 Modal Testing

Three areas of floors (refer to Fig. 1) were selected to perform the modal testing: (1) the forklift test, and (2) the ambient test. The areas were chosen based on the severity of cracking: Floor A had major cracks, Floor B had major cracking on the walkway between the shelves, and Floor C had minor cracking. A forklift was used to generate moving load forces on the floor, and the acceleration responses were recorded using accelerometers. The forklift truck traversed the floor both parallel and perpendicular to the panels, with accelerometers attached along the floor to capture the acceleration response, see Fig. 2. The forklift made ten passes along the selected area, both with and without loads, maintaining the accelerometers locations consistent with Fig. 2(b). However, due to limited space for the forklift movement, the testing was conducted on Floors A and C.

The ambient test is the simplest assessment to understand the vibration behaviour of the floor. The ambient test aimed to understand the floor's vibration behaviour without any induced excitation forces. During the tests, no excitation forces were created. However, the sources of excitation were limited to the movements of workers within the warehouse during operation hours, as testing could only be conducted then. Accelerometers were placed in the same locations as in the forklift test to record the acceleration response for five (5) minutes.

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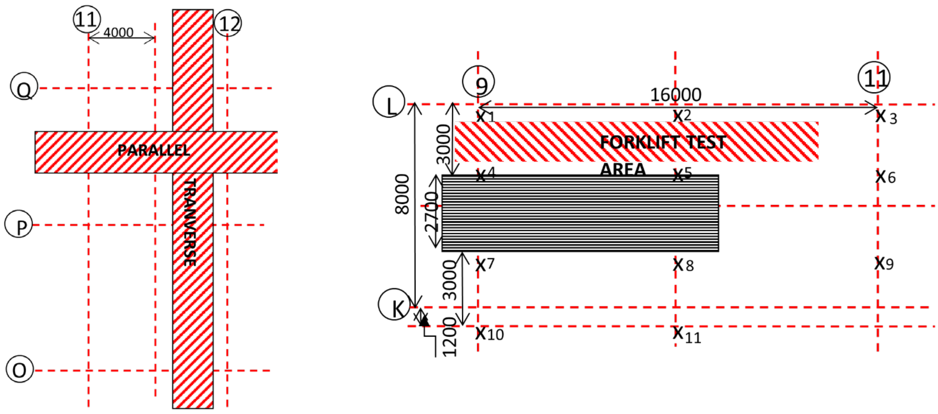
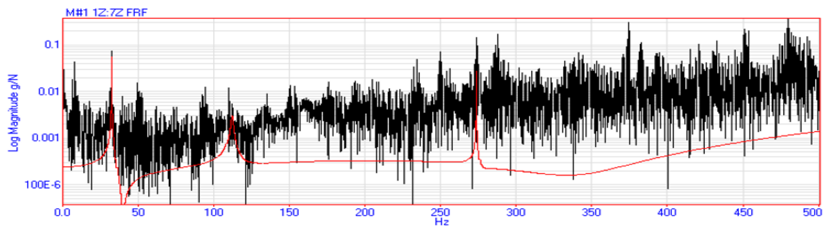


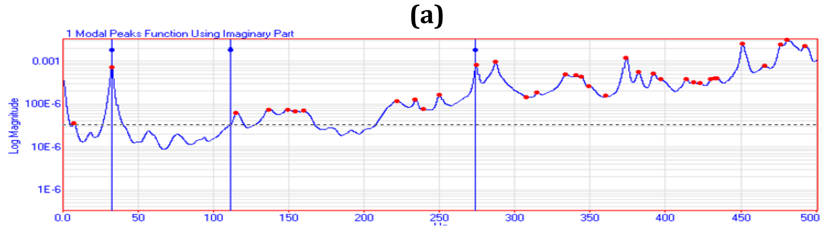
(a) **(b)**

Fig. 2 *Modal testing layout for (a) Floor A; (b) Floor C*

The acceleration responses, initially in the time domain, were converted to Frequency Response Function (FRF) as depicted in Fig. 3(a) before the vibration behaviour could be determined. The curve-fitting method was employed to estimate the vibration behaviour, utilising the ME'Scope software package. The natural frequency of the beam was identified as the highest peak in the FRF graph, as shown in Fig. 3(b).



(a)



(b)

Fig. 3 *Vibration responses (a) FFT spectrum; (b) Modal peak function*

The first three modes of natural frequencies for each test (forklift and ambient) are presented in Table 1. The first natural frequencies from the ambient tests for Floor A, Floor B and Floor C are 28.4 Hz, 29.4 Hz, and 29.8 Hz, respectively. However, the first natural frequencies for the forklift test on Floor A and Floor C dropped to between 12 Hz to 16 Hz. The forklift's weight increases the mass of the floor, and this mass further increases when the forklift carries products within the warehouse, transporting from one location to another location. In this test, only one unloaded forklift was used, resulting a reduction of approximate 50% reduction in natural frequency. During operational hours, several numbers of forklifts operate simultaneously, and these activities are believed to reduce the first natural frequency below 10 Hz. Consequently, humans can perceive the floor's vibration during these activities, potentially contributing to crack formation on the floor. The cut-off frequency for hollow-core concrete floor is 10 Hz, as recommended by CCIP-016) [33] and SCI P354 [2] design guides. Nevertheless, further investigation is needed to understand the behaviour of vibration properties and crack behaviour due to moving loads.

Table 1 *The natural frequency for forklift and ambient test*

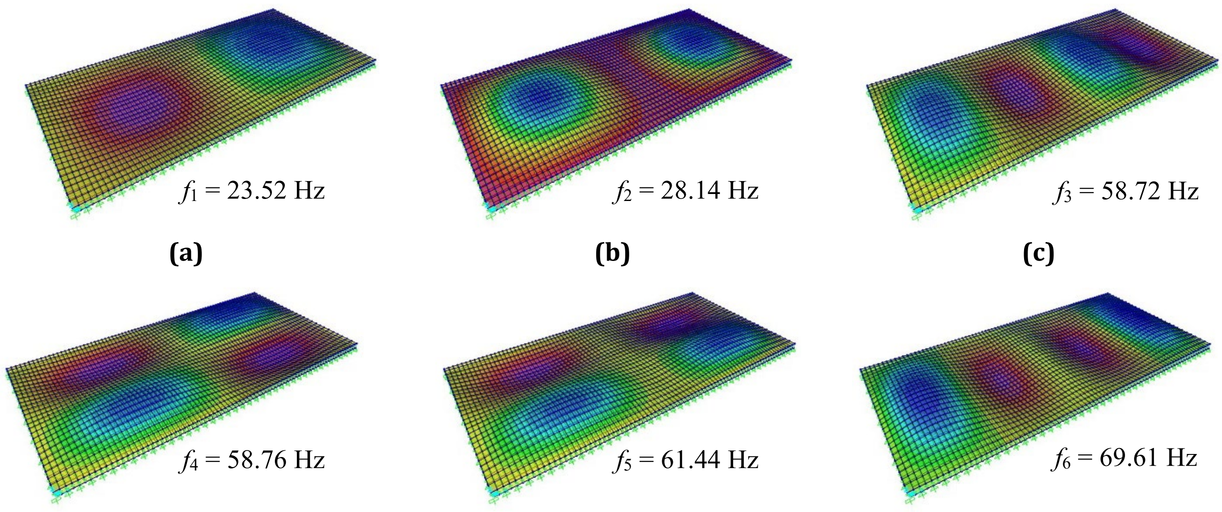
Floor		Forklift Test			Ambient Test		
		Natural Frequency, fn (Hz)					
		Mode 1	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
Floor A	Parallel	16.4	95.5	195.0	28.4	96.94	120.0
	Tranverse	12.2	97.0	148.0			
Floor C		13.3	96.0	193.0	29.8	100.1	168.5

2.2 Finite Element Analysis Modelling

Finite element analysis (FEA) modelling was performed using the SAP2000 software package. The floor model was constructed using 3D frame elements, adhering to actual dimensions of the floor (8 m x 16 m). Due to computational limitations, only one bay of the floor, consisting of six PPHC panels, was modelled. Fixed supports were applied at the four edges of the model, as a simplified boundary condition. The finite element model discretizes the large floor into smaller, simpler elements to achieve more precise results. The model was analysed using modal analysis to determine the natural frequency and mode shape.

The natural frequencies and mode shapes for the three first modes are depicted in Fig. 4. The first natural frequency, corresponding to the first mode shape, was obtained to be 23.52 Hz. The second mode shape behaviour exhibited similar behaviour to the first mode, with a natural frequency of 28.14 Hz. The second mode behaviour was also observed in modes 3 and 4, with natural frequencies of 58.72 Hz and 58.76 Hz, respectively.

A comparison of the modal testing results from the ambient test and the FEA results revealed a difference of approximately 17% in the first natural frequency. However, comparing the first natural frequency from the ambient test (28.4 Hz) with the first natural frequency from Mode 2 (28.14 Hz) showed only 1% difference. The mode shapes in SAP2000 were parallel to and emerged along the panel, resulting in two natural frequencies for each mode, see Fig. 4. The 50% decrease in natural frequency observed in the forklift test results was not captured in the FEA model, as the forklift's weight was not considered during modelling.



(d) **(e)** **(f)**

Fig. 4 *Mode shape of the floor (a) Mode 1; (b) Mode 2; (c) Mode 3; (d) Mode 4; (e) Mode 5; (f) Mode 6*

Subsequently, a time history analysis was carried out to determine the floor deformation under forklift movement. The response data from the forklift tests was assigned to the floor model according to the positions of the accelerometers, as depicted in Fig. 2(b). However, only six data points were used for the analysis, and the resulting relative displacement is shown in Fig. 5. As can be seen in Fig. 5, the maximum relative displacement occurs at the positions of the accelerometer. The floor displacement decreased exponentially with increasing distance from the acceleration points. Nevertheless, in Fig. 5(b) and (e), where the location of the accelerometer is close to the middle of the floor, the wave propagates evenly to the left and right. The highest displacement was

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found close to the mid-span and edges if the floor when all data were included. Thus, forklift movement during operation hours, vibrated the entire floor with critical areas being the middle and edges of the floor.

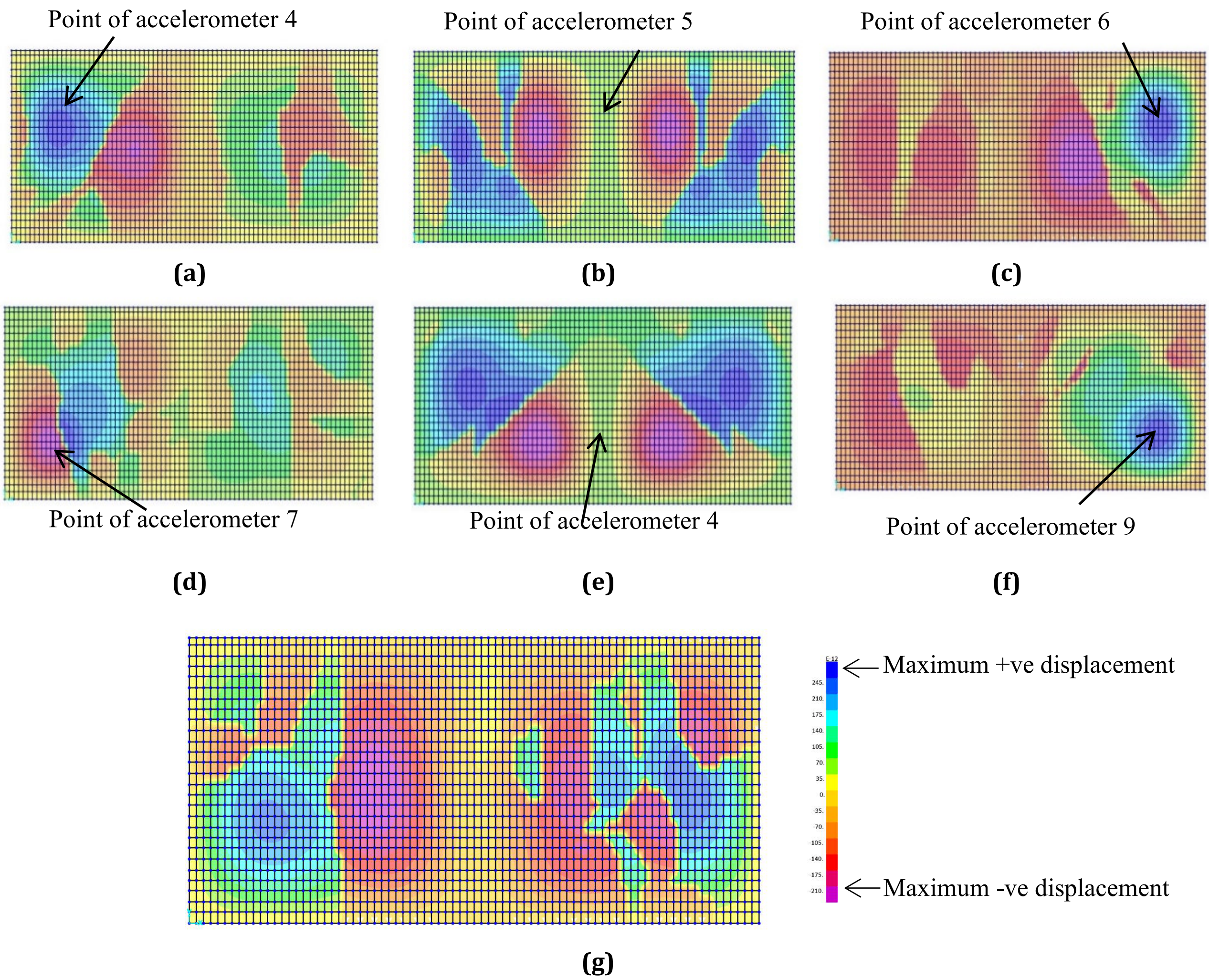


Fig. 5 *TH analysis results for accelerometer: (a) 4; (b) 5; (c) 6; (d)7; (e) 8; (f) 9; (g) combine all data*

3. Crack Assessment

The PPHCF floor was reported to be facing cracking issues after a few months after installation work. Hairline cracks appeared on the surface, impacting the floor's appearance, refer to Fig. 6. Despite treatment, the cracks continued to form and spread over the floor. While the cracks originated in the concrete topping of the PPHC, there was concern that they could extend deeper into the floor. To investigate the behaviour of these cracks, accelerometers were placed on top of the existing cracks with a 50 mm spacing between them, as depicted in Fig. 7.

Fig. 6 *Cracks were developed on the floor*

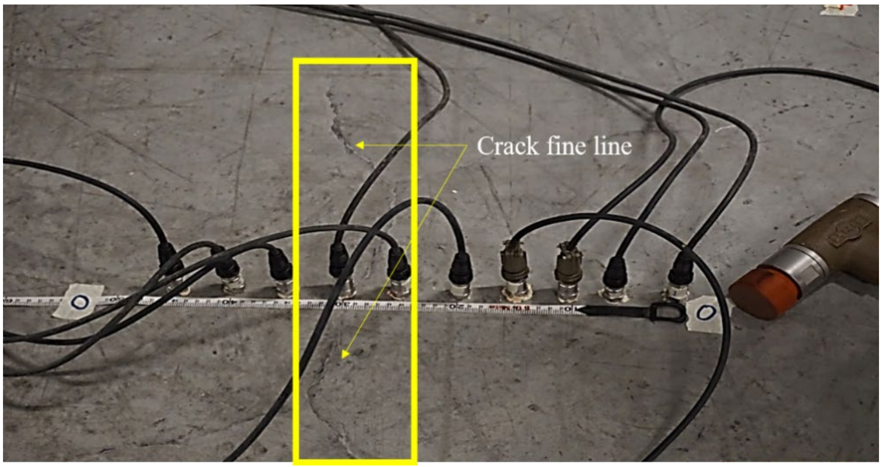
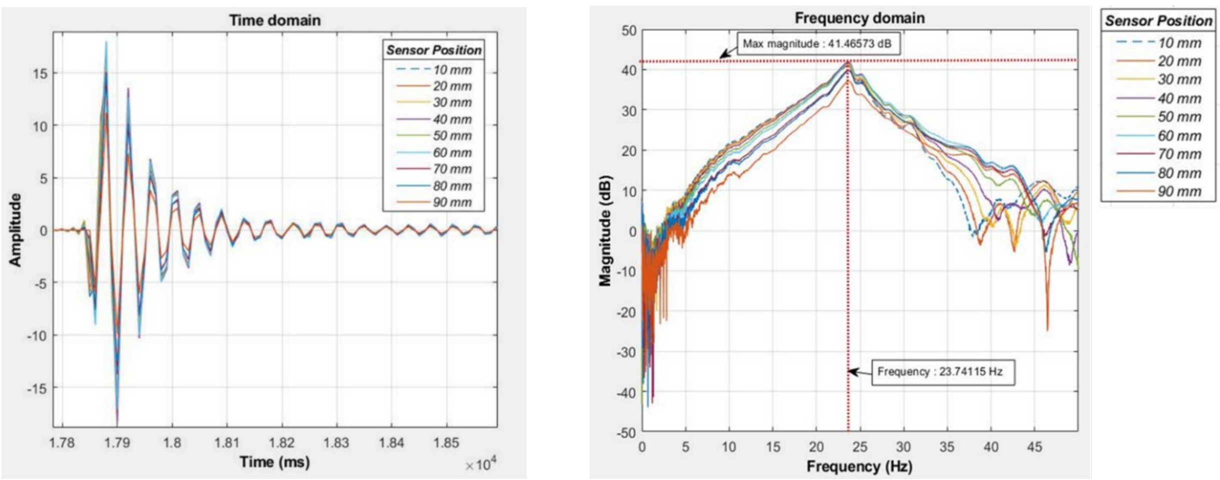


Fig. 7 *The testing setup for crack depth assessment*

Fig. 8 shows the attenuated time series data from each sensor. When sound travels through a medium, its intensity diminishes with distance. In idealised materials, sound pressure (signal amplitude) is reduced only by the spreading of the wave. In this case, the wave travels on the surface of the concrete. The data indicates normal attenuation on the surface with a crack at 50 mm, as the pattern of the time-series data at this location is similar to other sensor positions. This is confirmed by analysing the frequency domain of the wave (Fig. 8(a)). The dominant frequency was 23.741 Hz, and no anomalies were observed when testing on the surface crack, as shown in Fig 8(b). All sensor position exhibits the same dominant frequency, suggesting that the material quality remains consistent, even in the presence of the surface crack.



(a) **(b)**

Fig. 8 *The testing results (a) Time domain; (b) Frequency domain*

4. Conclusions

This paper presented a study on the vibration behaviour and crack assessment of precast pre-stressed hollow core floors using modal testing and finite element analysis. The findings indicate that moving loads from vehicles can reduce the natural frequency of the floor. Humans are sensitive to vibration when the natural frequency drops below 10 Hz, which may lead to structural issues. The simulation of moving loads revealed that the mid-span and edges of the floor experience greater movement in wave propagation. Consequently, cracks are more likely to appear in these areas. However, the observed fractures were confined to the concrete topping and did not compromise the structural integrity of the floor.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *NH Abd Ghafar, Zack Lim;* ***data collection:*** *NH Abd Ghafar, Lyn Dee Goh, Zack Lim;* ***analysis and interpretation of results:*** *NH Abd Ghafar, Noridah Mohamad, Seyed Jamalaldin;* ***draft manuscript preparation:*** *NH Abd Ghafar, Lyn Dee Goh. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Johansson, P. (2009). Vibration of Hollow Core Concrete Elements Induced by Walking. [Master Thesis, Lund Institute of Technology, Sweden]

[2] Smith. A., Hicks. S., Devine, P. (2009). *Design of floors for vibration: a new approach (SCI P354)*. Steel Construction Institute (SCI), Berkshire.

[3] Yan, Y. J., Cheng, L., Wu, Z. Y. & Yam, L. H. (2007) Development in vibration-based structural damage detection technique, *Mechanical Systems and Signal Processing*, *5(21)*, 2198–2211, https://doi.org/10.1016/j.ymssp.2006.10.002

[4] Yan, Y. J. & Yam, L. H. (2004) Detection of delamination damage in composite plates using energy spectrum of structural dynamic responses decomposed by wavelet analysis, *Computers & Structures*, *82(4-5)*, 347–358, https://doi.org/10.1016/j.compstruc.2003.11.002

[5] Kaouk, M., Zimmerman, D. C. & Simmermacher, T. W. (2000) Assessment of Damage Affecting All Structural Properties Using Experimental Modal Parameters, *Journal of Vibration and Acoustic*, *122(4)*, 456–463, https://doi.org/10.1115/1.1310328

[6] Chondros, T. G., & Dimarogonas, A. D. (1998) Vibration of a Cracked Cantilever Beam, *Journal of Vibration and Acoustic, 120(3),* 742–746, https://doi.org/10.1115/1.2893892

[7] Cawley, P. & Ray, R. (1988) A Comparison of the Natural Frequency Changes Produced by Cracks and Slots, *Journal of Vibration and Acoustic*, *110(3)*, 366–370, https://doi.org/10.1115/1.3269527

[8] Nama, P., Jain, A., Srivastava, R. & Bhatia, Y. (2015) Study on Causes of Cracks & its Preventive Measures in Concrete Structures, *Journal of Engineering Research and Applications, 5*(*5*),119-123.

[9] Amini, K., Jalalpour, M. & Delatte, N. (2016) Advancing concrete strength prediction using nondestructive testing: Development and verification of a generalizable model, *Construction and Building Materials*, *102*(*1*), 762-768, https://doi.org/10.1016/j.conbuildmat.2015.10.131

[10] Suhariyanto, S., Arystianto, D. P. & Raharjo, B. A. (2021). The effect of transducer distance on the concrete crack depth measurement using PUNDIT, *IOP Conference Series: Materials Science and Engineering*, *1073(1)*, 012-014, https://doi.org/10.1088/1757-899X/1073/1/012014

[11] Baehaki, Andi, M. & Yohanes, G. R. (2019) Experimental study of crack depth measurement of concrete with ultrasonic pulse velocity (UPV), *IOP Conference Series: Materials Science and Engineering, 673(1),* 20-47, https://doi.org/10.1088/1757-899X/673/1/012047

[12] Her, S-C. & Lin, S-T. (2014) Non-destructive evaluation of depth of surface cracks using ultrasonic frequency analysis, *Sensors (Switzerland)*, *14*(*9*), 17146–17158, https://doi.org/10.3390/s140917146

[13] Lin, S. & Wang, Y. (2020) Crack-Depth Estimation in Concrete Elements Using Ultrasonic Shear-Horizontal Waves, *Journal of Performance of Constructed Facilities, 34(4)*, https://doi.org/10.1061/(ASCE)CF.1943-5509.0001473

[14] In, C. W., Arne, K., Kim, J. Y., Kurtis, K. E. & Jacobs, L. J. (2017) Estimation of Crack Depth in Concrete Using Diffuse Ultrasound: Validation in Cracked Concrete Beams, *Journal of Nondestructive Evaluation, 36(4),* https://doi.org/10.1007/s10921-016-0382-4

[15] Seher, M., In, C. W., Kim, J. Y., Kurtis, K. E. & Jacobs, L. J. (2013) Numerical and experimental study of crack depth measurement in concrete using diffuse ultrasound, *Journal of Nondestructive Evaluation, 32(1),* 81–92, https://doi.org/10.1007/s10921-012-0161-9
[16] Kee, S. H. & Nam, B. (2015) Automated Surface Wave Measurements for Evaluating the Depth of Surface-Breaking Cracks in Concrete, *International Journal of Concrete Structures and Materials*, *9*(*3*), 307–321, https://doi.org/10.1007/s40069-015-0110-y
[17] Lee, F. W., Chai, H. K. & Lim, K. S. (2016) Assessment of reinforced concrete surface breaking crack using Rayleigh wave measurement, *Sensors (Switzerland)*, *16*(*3*), 337, https://doi.org/10.3390/s16030337
[18] Brownjohn, J. M. W., de Stefano, A., Xu, Y. L., Wenzel, H. & Aktan, A. E. (2011) Vibration-based monitoring of civil infrastructure: Challenges and successes, *Journal of Civil Structural Health Monitoring*, *1*(*3–4*), 79–95, https://doi.org/10.1007/s13349-011-0009-5
[19] Farrar, C. R., & Worden, K. (2007) An introduction to structural health monitoring. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, *365*(*1851*), 303–315, http://www.jstor.org/stable/25190443
[20] Boscato, G., Fragonara, L. Z., Cecchi, A., Reccia, E. & Baraldi, D. (2019) Structural Health Monitoring through Vibration-Based Approaches, *Shock and Vibration*, *2019*(*380616*), 1-5, https://doi.org/10.1155/2019/2380616
[21] Döhler, M., Hille, F. & Mevel, L. (2018) Vibration-based monitoring of civil structures with subspace-based damage detection, *Intelligent Systems, Control and Automation: Science and Engineering*, *92*, 307–326, https://doi.org/10.1007/978-3-319-68646-2_14
[22] Das, S., Saha, P. & Patro, S. K. (2016) Vibration-based damage detection techniques used for health monitoring of structures: a review, *Journal of Civil Structural Health Monitoring*, *6*(*3*), 477–507, https://doi.org/10.1007/s13349-016-0168-5
[23] Fan, W. & Qiao, P. (2011) Vibration-based damage identification methods: A review and comparative study, *Structural Health Monitoring*, *10(1)*, 83–111, https://doi.org/10.1177/1475921710365419
[24] Yang, Y., Zhang, Y. & Tan, X. (2021) Review on vibration-based structural health monitoring techniques and technical codes, *Symmetry*, *13*, 1998, 1998, https://doi.org/10.3390/sym13111998
[25] Pereira, S., Magalhães, F., Gomes, J. P., Cunha, Á. & Lemos, J. V. (2021) Vibration-based damage detection of a concrete arch dam, *Engineering Structures*, *235(4)*, 112032, https://doi.org/10.1016/j.engstruct.2021.112032
[26] Shatilov, Y. Y. & Lyapin, A. A. (2018) Vibration-based damage detection techniques for health monitoring of construction of a multi-storey building, *Materials Science Forum*, *931*, 178–183, https://doi.org/10.4028/www.scientific.net/MSF.931.178
[27] Altunışık, A. C., Okur, F. Y., Karaca, S. & Kahya, V. (2019) Vibration-based damage detection in beam structures with multiple cracks: modal curvature vs. modal flexibility methods, *Nondestructive Testing and Evaluation*, *34(1)*, 33–53, https://doi.org/10.1080/10589759.2018.1518445
[28] Murray, T. M., Allen, D. E. & Ungar, E. E. (2016) *Design Guide 11: Vibrations of steel-framed structural systems due to human activity*, American Institute of Steel Construction.
[29] Pavic, A. & Willford, M. (2005) *Vibration serviceability of post- tensioned concrete floors. Appendix G, Technical Report 43, 2nd edn.*, The Concrete Society.
[30] Willford, M. & Young, P. (2006) *A design guide for footfall induced vibration of structures - CCIP-016*, The Concrete Centre.
[31] Feldmann, M., Heinemeyer, & C., Lukić, M. (2010). *Human-induced vibration of steel structures (Hivoss)*, Publications Office, https://data.europa.eu/doi/10.2777/79056
[32] Choi, S. & Stubbs, N. (2004) Damage identification in structures using the time-domain response, *Journal of Sound and Vibration*, *275*(*3–5*), 577–590, https://doi.org/10.1016/j.jsv.2003.06.010
[33] Elshamy, M., Crosby, W. A., & Elhadary, M. (2018) Crack detection of cantilever beam by natural frequency tracking using experimental and finite element analysis, *Alexandria Engineering Journal*, *57*(*4*), 3755–3766, https://doi.org/10.1016/j.aej.2018.10.002
[34] Asnaashari, E. & Sinha, J. K. (2014) Crack detection in structures using deviation from a normal distribution of measured vibration responses, *Journal of Sound and Vibration*, *333(18),* 4139–4151, https://doi.org/10.1016/j.jsv.2014.04.057