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Original Research

A COMBINED ULTRASONIC PROCEDURE TO EVALUATE DAMAGE IN CONCRETE BEAMS SUBJECTED TO STATIC LOAD

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Abstract: Concrete is utilized in a wide range of civil engineering applications specifically in infrastructure projects. In general, as with any construction material, it may be subjected to deterioration over time because of various reasons such as excessive loading and so on. In this research, two reinforced concrete beams on a large scale (length 2400 mm, depth 350 mm, and width 250 mm) are cast and tested under static load using the ultrasonic pulse velocity (UPV) technique consisting of three pairs of transducers (54 kHz, 150 kHz, and 250 kHz). During the loading, the signals are sent and captured through the used transducers at selected loading steps. Two new proposed procedures based on signal peaks in time and frequency domains are used to monitor the crack progress induced in concrete beams under concentrated load. The findings of this study revealed the suitability of the proposed two approaches to detect the propagation of cracks to evaluate damage induced in concrete beams.

Keywords: *Concrete beam; frequency spectra; ultrasonic wave velocity; wave attenuation*

1. Introduction

The gradual aging of infrastructures has received recently more attention from civil engineers and scholars [1-7]. The motive to make the majority of existing structures from reinforced concrete is based on several factors such as economic considerations, raw materials availability, flexible workability, and often arbitrary formability. For safety considerations, it is essential to inspect regularly the integrity of concrete structures on-site by structural inspectors [8-11]. Non-destructive testing NDT techniques are commonly utilized to monitor the quality of structure members, for restoration and repairing purposes, to assess the condition of existing structures, and to monitor the quality of repairs. UPV is one of these NDT methods that are used commonly to evaluate the condition of Concrete elements, both in the field and laboratory conditions.

Recently, the technique has been used in various disciplines such as chemistry, medicine, biology, engineering, and physics [12-14]. Ultrasonics is employed in the civil engineering field for material characterization through non-destructive inspection. In concrete, ultrasonic velocity presents less sensitivity than wave

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attenuation [15-19]. Therefore, attenuation of the wave may be considered a key factor parameter that is required for material characterization. The importance of this parameter is linked to the fact that any reduction in the wave attenuation (wave amplitude) represents an indication of strength loss or degradation of the material's internal conditions [20-21]. However, the use of wave attenuation has some limitations because of challenges in producing reliable measurements at the testing site.

The main goal of this research is to study the potential advantage of a new proposed approach based on wave characteristics to detect the impact of static loading on the integrity of reinforced concrete beams on a large scale. During the loading steps, the UPV method is used with three pairs of transducers (54 kHz, 150 kHz, and 250 kHz) to capture signals at different load steps. The testing data was analyzed using three types of procedures, the first as conventional based on the arrival time and the other proposed two procedures based on signal peaks in time and frequency domains. The investigation includes proposing a damage parameter called damage ratio reference (dr) based on wave characteristics to monitor internal damage in the concrete beams under static load. The research results allow an understanding of the suitability of the new proposed approach to identify the induced damage in compression to the traditional measurements of the **conventional UPV method.**

2. Materials and Methods

2.1 Concrete Beams

Two reinforced concrete beams were cast and tested in the current research study. The total length of each beam was 2.4 m and the dimensions of the cross section had 350 mm depth and 250 mm width. The reinforcement of each beam consists of two bars with 20 mm diameter as the longitudinal reinforcement (compressive reinforcement), and tensile reinforcement of two bars of ϕ 20 mm). The details of a typical concrete beam are shown in Fig. 1.

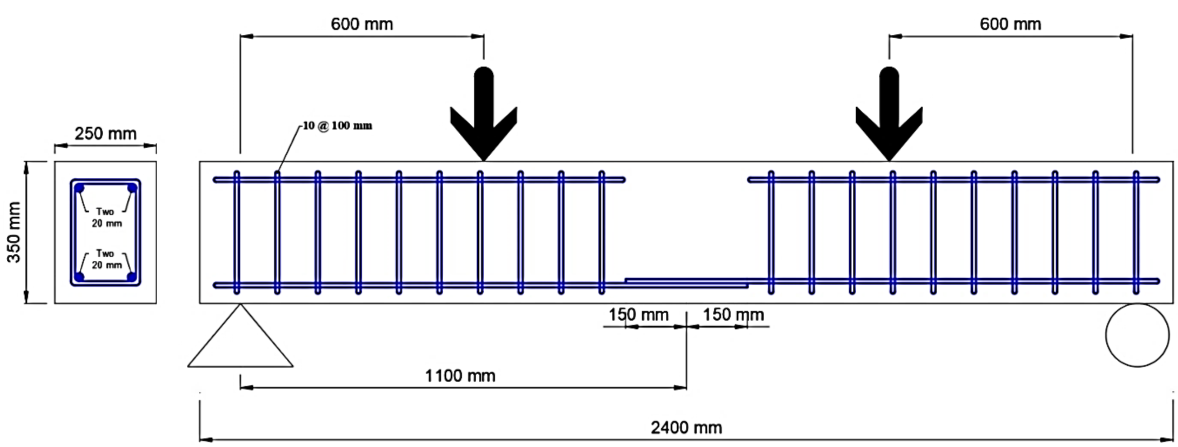

Figure 1. Typical details of the reinforced concrete beam.

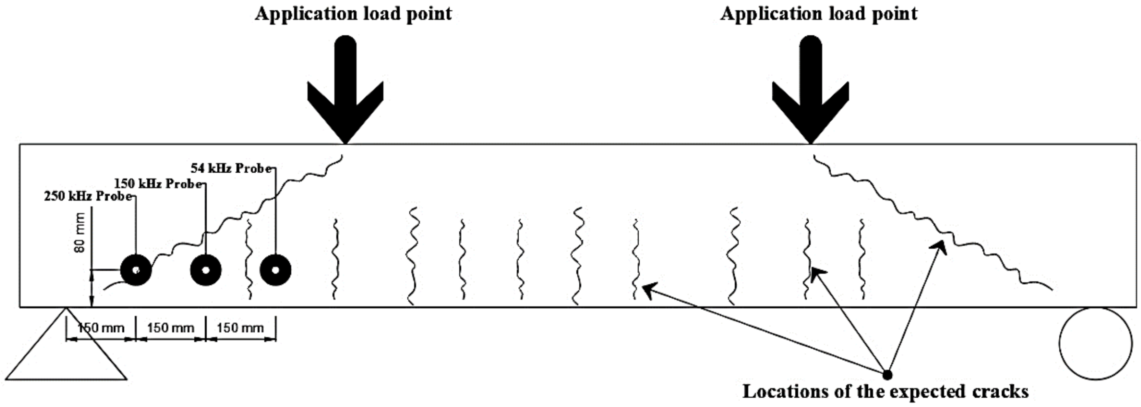

Figure 2. Details of the expected crack locations and the transducer arrangement.

The failure place of the two concrete beams was expected to begin at the locations shown in Fig. 2. Based on that, three different pairs of transducers (54 kHz, 150 kHz, 250 kHz) with different wavelengths were placed near this failure zone from both sides of each concrete beam. The UPV testing equipment consisted of seven components: 1- three pairs of transducers (54 kHz, 150 kHz, 250 kHz); 2- a function-generator; 3- a Piezo driver; 4- oscilloscope; 5- Filter; 6- data acquisition device of 24.0 channels (LDS. Nicolet-Genesis), and 7- laptop computer (Fig. 3).

For each pair of transducers, one transducer is placed on the front side of the beam to transmit the pulse, and the other on the back side to receive the ultrasonic signals during the loading process. To obtain consistent results, square aluminum plates with a thickness of 2 mm were glued to the concrete surface using concrete epoxy then the transducers were glued to these plates using superglue.

The function generator was utilized to generate a square signal, frequency depends on the used transducer 54 kHz, 150 kHz, and 250 kHz, with amplitude (10.0 vpp.) to excite each transducer. The input-output signal data were acquired using a laptop computer with software (Keysight-Bench Vue®) which processes later to calculate the UPVs and other testing parameters.

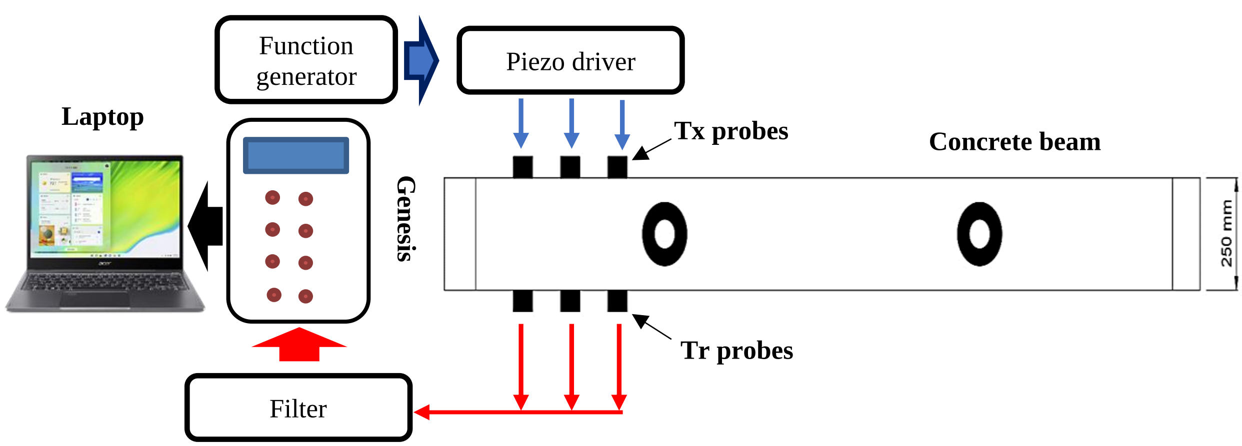

Figure 3. Ultrasonic pulse-velocity testing configuration.

2.3 Damage Evaluation

The UPV test was performed before and during the application of static loading in which at predefined time intervals the signals were acquired and analyzed later. For that purpose, the average ultrasonic pulse velocities for each testing step with all transducers were determined. In addition, three procedures are used to evaluate the damage by accounting for the signal characteristics, one of these is conventional [11,20] and the other is proposed in this research. The first step depends on arrival time to calculate wave velocity to determine the damage progress inside concrete beams under the applied load. On the other hand, the other two procedures are based on a parameter called damage ratio (dr). This index is calculated using the following equation:

$$dr = \frac{E_o - E_d}{E_o}\ (\%) \qquad (1)$$

where: Eo is the signal peak in the time/frequency domain for intact case (no damage). Ed is the signal peak in the time/frequency domain when the damage exists inside the concrete beam. The larger damage ratio value refers to larger damage that occurs in concrete specimens under compression load and vice versa.

3. Results and Discussion

3.1 Damage Evaluation Using UPV Results

Fig. 4 represents the result of UPV versus the applied load during the static compression testing of the two beams using three piezoelectric transducers (54 kHz, 150 kHz, 250 kHz). For all transducers with different wavelengths (λ ≈ 8 cm, λ ≈ 3 cm, λ ≈ 2 cm), the figure shows the lack of ultrasonic velocity (Vp) to capture the cracks propagation inside the two tested beams under continuous compression loading.

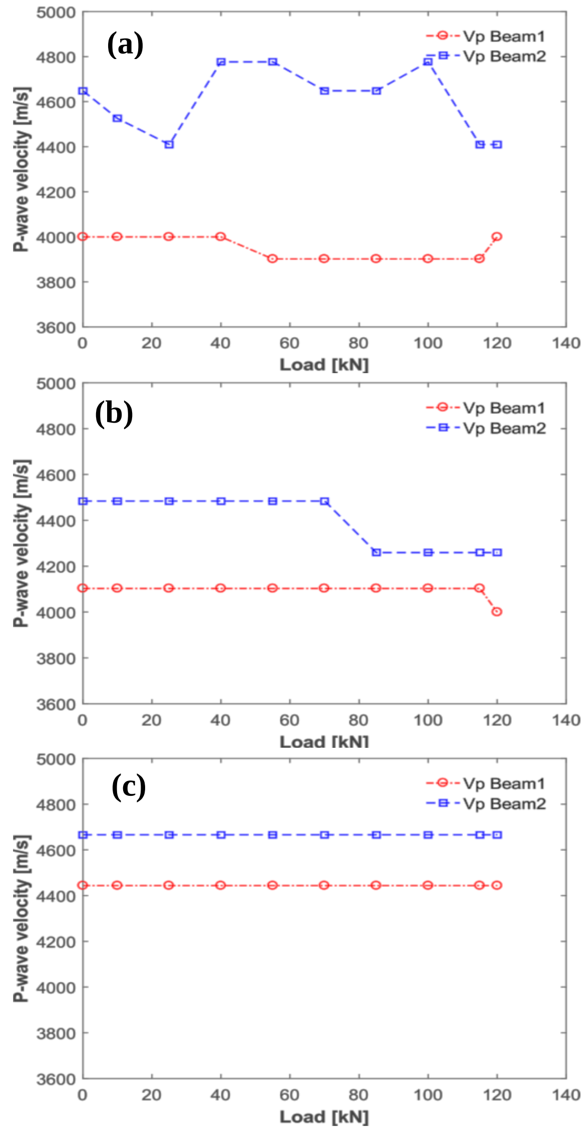

Figure 4. Average P-wave velocities: a Vp of 54 kHz, b- Vp of 150 kHz, c- Vp of 250 kHz.

Also, the observed results did not show a clear trend regarding the interaction with the progressive damage that occurred inside the tested beams. Even the similar testing conditions are applied when testing both concrete beams, it was clear from Fig. 4 that using UPV alone is not enough to capture damage under compression testing. This probably can be attributed to the method used to define the arrival time which is related to the device judgment of the UPV.

3.2 Damage Evaluation using Signal Peaks

The time signals obtained at three load steps- initial, middle, and ultimate (0, 55, 120 kN), for the tested concrete breams using three different ultrasonic transducers (54 kHz, 150 kHz, 250 kHz) are shown in Fig. 5. The reduction percentages in signal energy of 54 kHz probe for the middle and final load step were 10% and 52% in comparison to the signal of initial load step, while for 150 kHz probe, the reduction ratios were higher than 54 kHz probe in the range 37% and 77%. For the 250 kHz probe, the observed reduction ratios were more sensitive to cracks than other probes and were around 46% and 76%. The results of the 150 kHz transducer show that a shorter wavelength can be more efficient in the detection of micro-cracks generated inside concrete medium than the 54 kHz transducer. A similar trend was observed with the results of beam two.

Moreover, the frequency spectra of the time signals captured at predefined three load steps produced are shown in Fig. 6. In this figure, there is also noticed cleared trend in the sensitivity of higher frequency probe to the cracks induced in beams under continuous compression as observed in the time domain for the same signals.

Fig. 7 shows the results obtained after testing the two beams using the proposed two procedures by selecting the signal peaks in time and frequency domains to calculate the damage ratio (dr) for the three piezoelectric ultrasonic transducers used in this study.

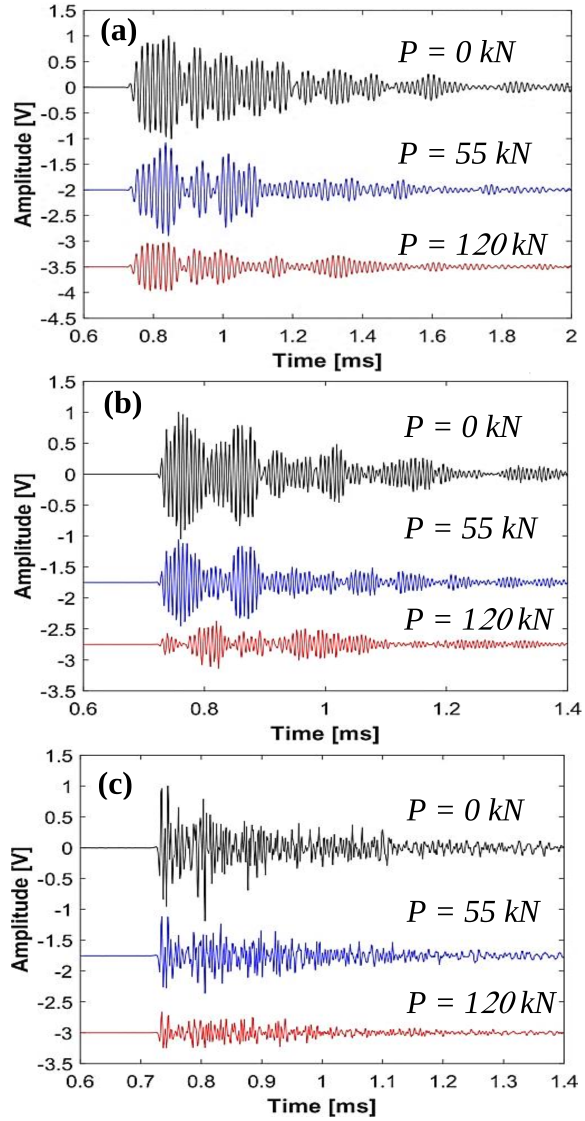

Figure 5. Typical time signals: a signal of 54 kHz, b- signals of 150 kHz, c- signals of 250 kHz.

Also, it can be seen that the frequency spectrum can be used effectively to recognize the crack propagation inside concrete beams subjected to static load. This is useful to identify the damage in concrete early which can be used to evaluate the health of concrete under certain conditions.

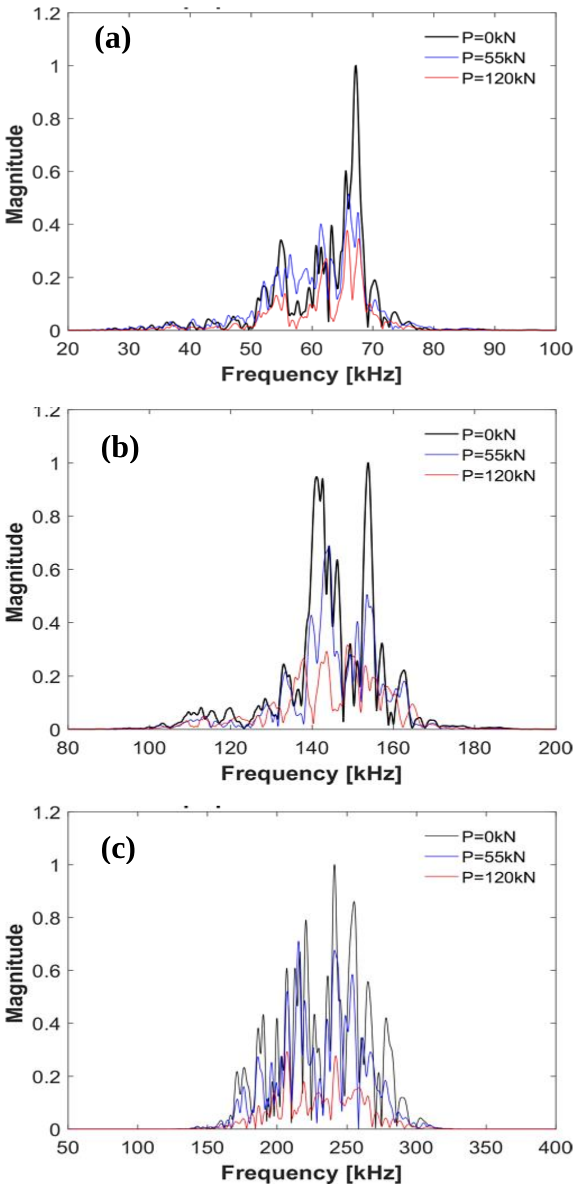

Figure 6. Typical spectra of signal: a- spectra of 54 kHz, b- spectra of 150 kHz, c- spectra of 250 kHz.

Figure. 7. shows that the signal peaks in the frequency domain of the 54 kHz probe are more sensitive to cracks than peaks in the time domain. On the other hand, the signal peaks for both beams in time and frequency domains for 150 kHz and 250 kHz probes show almost similar sensitivity to detect crack propagation under subjected compression load (Fig. 7. b & c).

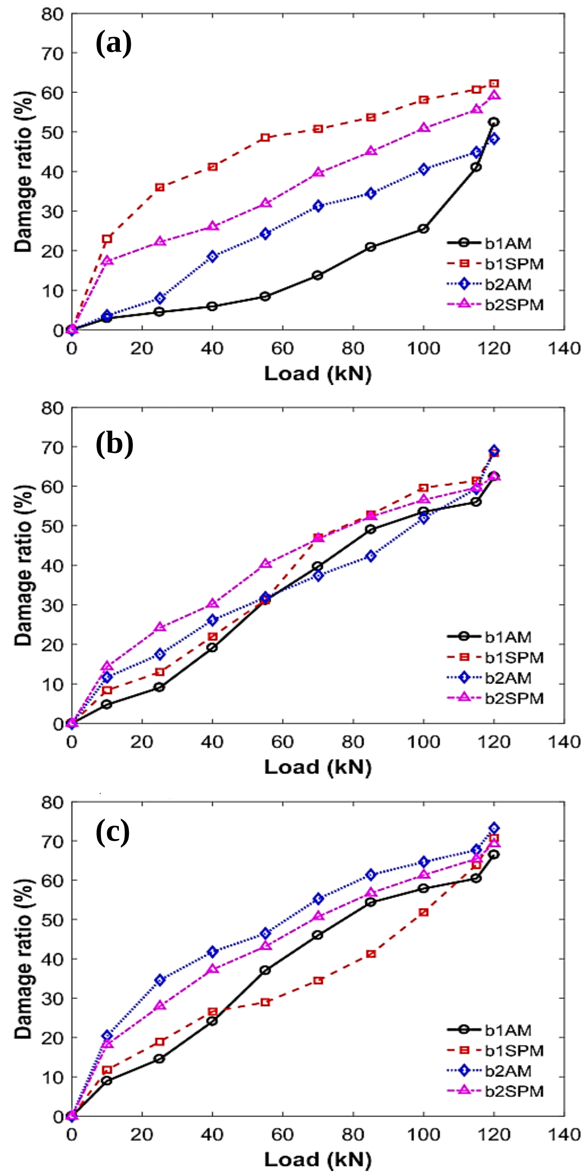

Figure 7. Comparison between damage ratios: a- damage ratios of 54 kHz, b- damage ratios of 150 kHz, c- damage ratios of 250 kHz. b1AM represents peak amplitude in the time domain. b1SPM represents peak amplitude in the frequency domain for beam b1

This trend may be attributed to the closer values of wavelengths of both probes (λ ≈ 3 cm and λ ≈ 2 cm) which are better for capturing cracks than the wavelength of the 54 kHz probe (λ ≈ 8 cm).

4. Conclusions

Different approaches based on the UPV testing method including two new proposed procedures are used to evaluate its potential to detect damage propagation in two concrete beams on a large scale subjected to continued static load. During the loading, UPV is used with three pairs of transducers (54 kHz, 150 kHz, and 250 kHz) to capture signals at different load steps. The testing data was analyzed using three types of procedures, one is conventional based on the arrival time, and a proposed two procedures based on signal peaks in time and frequency domains. The investigation includes proposing a damage parameter called damage ratio reference (dr) based on wave characteristics to monitor internal damage in the concrete beams under static load. The wave velocities calculated from the obtained results for beams show no important variation as the cracks propagate inside the beams because of compression load. Unlikely, the results of signal energy and damage ratios of all probes for both beams based on the signal peaks in the time and frequency domains indicated that there is a significant reduction observed as a consequence of the crack propagation induced inside concrete by loading. The findings of this study prove the suitability of the new two proposed approaches to enhance the sensitivity of the UPV measurements to monitor the concrete integrity subjected to static load.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Sabah H. Fartosy proposed the research problem and performed the testing.

Sabah H. Fartosy and Narmeen A. Abdalqadir performed the computations.

All authors discussed the results and contributed to the final manuscript.

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