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ULTRASONIC INVESTIGATION ON CONCRETE CUBES SUBJECTED TO LOAD-INDUCED CRACKS

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Abstract: Several non-destructive techniques are available to measure the damage of concrete structures subjected to loading, including ultrasonic wave propagation. Generally, in concrete ultrasonic studies, primary waves (P-wave) are mostly used for faster speed and higher penetration depth. Under loading, concrete undergoes micro and macro cracking. The second and third harmonic ratio methods are used extensively in P-wave studies to assess the initial micro-cracks in concrete. In this present investigation, the second and third harmonic ratios are measured by using shear wave (S-wave) to assess the initial damage in concrete. Using shear waves in concrete offers the advantage of minimising backscattering and signal attenuation along the direction parallel to the wave propagation. To study the effect of water-to-cement (w/c) ratio on nonlinear parameters, three w/c ratios, viz, 0.35, 0.45, and 0.55 were chosen. The cracks were induced in concrete by applying compressive loading in a 150 mm cube specimen at a loading increment of 100 kN until failure of the specimen. The experimental results obtained from the S-waves were utilised to investigate the nonlinear parameters β and γ concerning micro and macro damage in concrete with respect to harmonic ratios.

1 INTRODUCTION

Concrete is an extensively utilised construction material primarily employed in reinforced concrete structures. Due to environmental factors and external loads, concrete is highly susceptible to developing micro-cracks. Over time, the application of loads can further exacerbate these micro-cracks. Therefore, regular inspection and monitoring of concrete structures are imperative to manage micro-cracks at an early stage, consequently enhancing the structure's service life. The ultrasonic transmission technique is a reliable and convenient non-destructive testing (NDT) method for assessing the quality and integrity of concrete. This technique involves the generation of actively produced P-waves or S-waves, allowing for the assessment of concrete damage. Aggelis and Shiotani [1] have established the reliability of this method. The study by Demirboğa et al. [2] revealed a strong correlation between their findings and those of Grosse et al. [3]. Additionally, Kumar and Santhanam [4] validated that the changes in signal parameters such as waveform, velocity, and amplitude of the primary wave can offer valuable qualitative and quantitative information on the degree of concrete damage.

Ultrasonic method is broadly classified into two one is linear and another one is nonlinear ultrasonic method. The linear method is more suitable for detecting macro-scale defects rather than micro-scale defects. In linear ultrasonic load, induced stress leads to velocity variation and signal amplitude change. In nonlinear ultrasonic small defects, which is smaller than the wavelength and initial damage, can be detected at the microstructure level [5]. In nonlinear method to measure the stress-induced damage at every load step sideband peak count technique is widely used. The nonlinear ultrasonic technique is more sensitive during loading and tends to vary the material internal structure, and high overload results in permanent damage to the mechanical properties of the material and cannot be reversed [6]. Daponte et al. [7] reported that linear ultrasonics is insensitive to changes in load while, Komlos et al. [8], the capability of longitudinal wave propagation is restricted to detecting defects larger than 100mm in size. In nonlinear material, single-frequency wave propagation generates higher and lower frequency waves.

In nonlinear ultrasonic, the generated high-frequency waves have higher frequencies that are multiplied by integers of the input wave frequency, such waves are called higher harmonics in ultrasonic wave propagation. Higher harmonics can be able to detect small internal defects. Higher harmonics are developed in concrete with micro-cracks in nonlinear wave propagation. Concrete mix proportions with varying water-to-cement ratios and generation of higher harmonics. Shah et al. [9] experiments stated that the 3rd-order harmonics is more sensitive than the 2nd-order harmonics due to loading.

Zhao et al. [10] conducted a study that induced cracks with varying damage scales in concrete specimens to simulate different damage conditions. In nonlinear materials, ultrasonic wave propagation induces an acoustic nonlinear response, which can be characterised by the nonlinear parameters 'β' and 'γ.' These parameters, β and γ, measure the degree of distortion of the ultrasonic waveform as it propagates through the material. The changes in β and γ in ultrasonic waves provide a measure of the material's nonlinearity and, consequently, allow for estimating the accumulation of damage in the material [6]. To understand the regularity of nonlinear parameters β and γ on micro and macro damage in concrete. The linear and nonlinear ultrasonic measurements are carried out extensively by P-wave. P-wave has a low signal-to-noise ratio and it is more sensitive to air voids and in turn, affects the velocity. Due to the above limitations, the nonlinear parameters may be affected. In S-wave, the signal-to-noise ratio is high and propagates only in solids. S-wave is more sensitive to the development of solid structures. Not many studies were attempted on S-waves on nonlinear ultrasonic measurements. This study will give insight into nonlinear ultrasonic measurement in both the P-wave and S-wave.

The primary objective of this research is to investigate the patterns and trends of the second and third harmonic ratios concerning multiscale damage, employing both P-wave and S-wave. Concrete specimens were cast and tested with varying load intervals till failure to study the harmonic ratio. Throughout the loading process, the concrete specimens undergo multiscale damage, ranging from micro to macro scales, and the nonlinear parameters β and γ are employed to assess the extent of damage using both P-wave and S-wave. Additionally, this study investigates the influence of w/c ratio on nonlinear ultrasonic measurements.

2 GENERATION OF HIGHER ORDER HARMONICS IN ULTRASONIC WAVE PROPAGATION [10]

In linear ultrasonic measurements, the amplitude of the heterogeneous medium remains small, and the stress-strain relationship follows a linear pattern. Consequently, the velocity and amplitude in linear measurements exhibit insensitivity to the presence of microcracks. However, in nonlinear theory, the stress-strain relationship deviates from linearity. In the present investigation, the time-domain signals are transformed into frequency-domain waveforms to analyse the elastic response of the solid medium, specifically concrete. By examining this response, the amplitudes of fundamental and higher harmonics (first, second, and third order) are derived in the frequency domain. The generation of higher harmonics is influenced by the formation of cracks within the solid medium when subjected to external loading [9]. Nonlinear parameters, β and γ, are computed as the ratios between the higher amplitude and the fundamental amplitude obtained from the generated harmonics. These nonlinear parameters serve as indicators of the internal damage within the concrete. The harmonic ratios effectively correlate and assess the extent of internal damage in concrete.

In the one-dimensional nonlinear wave equation (1), the solution can be expressed as stated in reference [10, 12 and 13].

$$u = u_o - u'$$

$$A1\cos(kx - \omega t) + \frac{A_1^2 k^2 x\beta}{8}\cos(2kx - 2\omega t) + -(1)$$

In the nonlinear wave equation, where u_0 represents the linear solution, and u' represents the nonlinear solution. The amplitudes A_1 and A_2 are associated with the fundamental wave and the second harmonics, respectively. The wave number is represented by 'k', where k = ω/c, with ω being the angular frequency, and C denotes the wave velocity. Additionally, β represents the second-order nonlinear parameter. The interaction between the fundamental wave and its second harmonic counterpart within the context of the nonlinear wave equation (2) and (3) is characterised by the relationship between A_1 and A_2.

$$\beta = \frac{8A_2}{A_1^2 k^2 x} - - - - - (2)$$

$$\beta = \frac{A_2}{A_1^2} - - - - - - (3)$$

It is essential to note that the value of β, the second-order nonlinear parameter, is influenced by the factors such as material damage degree, wave number and wave propagation distance. The wave number controls the excitation source and propagation distance is kept constant. In a similar manner, when expanding the stress-strain equation to the third order, a distinct third-order nonlinear parameter can be defined as follows. The third-order nonlinear parameter captures additional nonlinear effects in the material stress-strain relationship and proves valuable in understanding the material's behaviour under a more complex loading protocol.

$$\gamma = \frac{32A_3}{A_1^3 k^4 x^2} - - - - (4)$$

$$\gamma = \frac{A_3}{A_1^3} - - - - - - - - (5)$$

3 EXPERIMENTAL PROGRAMME

3.1 Concrete specimens

In the present experimental programme concrete cube specimens of size 150×150×150 mm have been prepared. Three water-cement (w/c) ratios of 0.35, 0.45

and 0.55 were used and the concrete mixture proportions are listed in Table-1 In each w/c ratio six specimens (total of 18 specimens) were cast for the experimental work. The average compressive strength for 0.35, 0.45 and 0.55 are 49, 47 and 33 MPa respectively.

Table 1: Concrete mix proportions

W/c	Cement	Sand	CA	Water	Superplasticiser (% of Cement)
0.55	309	921	981	170	0.6
0.45	378	865	981	170	0.6
0.35	485	774	981	170	0.6

3.2 Experimental test setup

The experimental work involved using the Ultrasonic Pulse Velocity Tester (PUNDIT+) from Proceq. Two types of transducers, P-wave, and S-wave, were employed in the study. The P-wave transducer (transmitter and receiver) had a frequency of 54kHz. On the other hand, the S-wave transducer (transmitter and receiver) was a spring-loaded dry point contact (DPC) type with a frequency of 40kHz. One of the advantages of using the DPC transducer is that it eliminates the need for a couplant, and its spring-loaded mechanism can adjust automatically even on surfaces with undulations. For the P-wave measurements, a sampling rate of 0.5µsec was employed, while for the S-wave measurements, the sampling rate was set at 0.1µsec.

3.3 Loading protocol

After attaining maturity, the concrete specimens were subjected to compressive loading in a compression testing machine of capacity 3000kN. All the specimens were tested under single load pattern from 0 to 100% (till failure and the loading interval is 100kN. Every 100kN, the test was paused to take the ultrasonic measurements. Figure.1 shows the typical experimental test setup adopted for the all the test specimens. The ultrasonic P- and S-wave transducers were placed and aligned center of the specimen and bonded with couplant and receiver is placed opposite to the transmitter. The ultrasonic signal is propagated through the concrete after attaining the desired stages of loading.

Figure 1: Experimental test setup.

4 TEST RESULTS

4.1 Wave velocity in cracked concrete

The wave velocity under compressive loading till failure is evaluated by using P and S wave, the results from the P and S waves under various load stages are discussed. The wave velocity variation under different stages of loading in both the wave propagation are shown in Figures 2 and 3. It is observed that the wave velocity is constant till the formation of macro cracks.

During loading the crack width is increased. There is a significant reduction in wave velocity in both the cases. The wave velocity measurement can detect the macro scale damage and very insensitive to detect micro scale degree of damage. The crack width and number of cracks increased in the concrete specimen due to loading, where the micro crack is transformed to macro crack. At that stage the wave velocity tends to decrease. This similar in trend is exhibited in all the w/c ratio.

From the shear velocity plot, the decrease in velocity is not less than 10%. The sudden decrease in velocity variation is observed during the transition of micro to macro cracks. In micro-cracks, the wave propagates as same as that of uncracked concrete, this may be due to the lesser crack width in micro cracks. In the case of macro cracks, the crack width is more, where the wave propagation takes more time to reach the receiver.

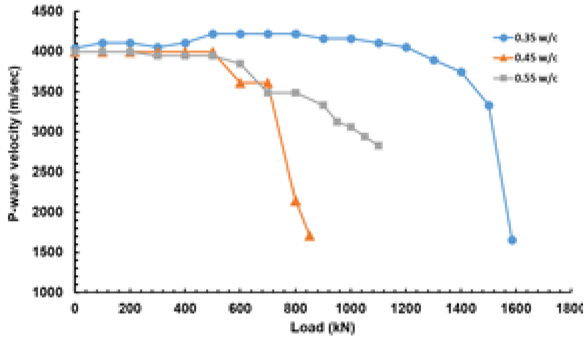

Figure 2: P-wave velocity variation at varying load stages of cracked concrete.

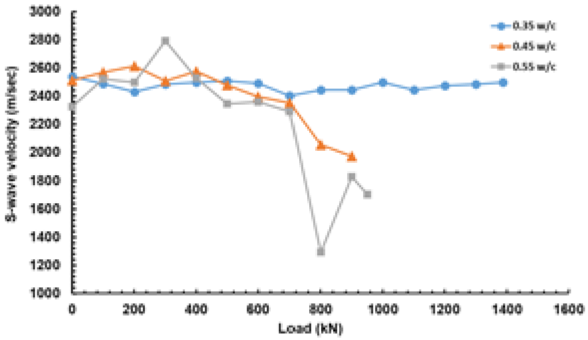

Figure 3: S-wave velocity variation at varying load stages of cracked concrete.

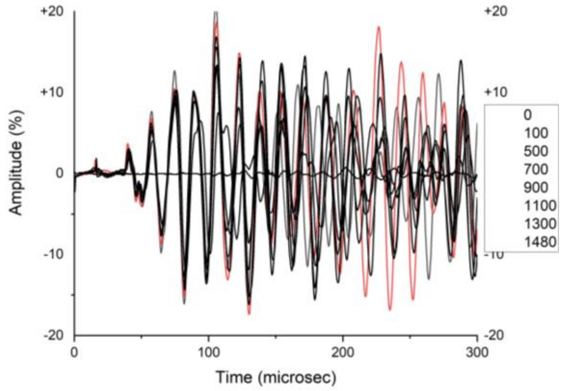

Figure 4a: Time versus amplitude of the received signal

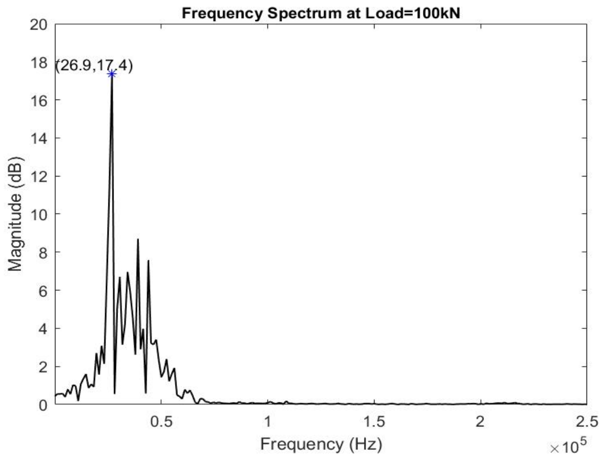

Figure 4b: Typical frequency spectra of the received signal.

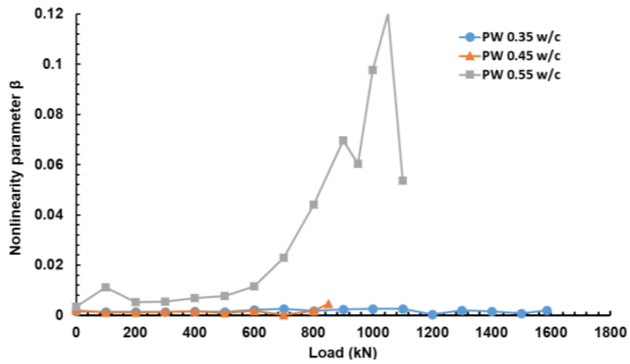

Figure 5a: Nonlinear parameter β versus load.

4.2 Nonlinear parameters (β and γ) in a concrete specimen subjected to loading

The captured time domain waveform at various stages of loading is in Figure 4a and the typical frequency spectra are shown in Fig. 4b. The nonlinear parameters β and γ for both the P and S waves are shown in Figures 5a, 5b, 6a and 6b respectively. Due to the heterogeneous nature of concrete, the inherent micro defects distributed randomly in the β and γ values obtained from loading at a point on the specimen is diverse.

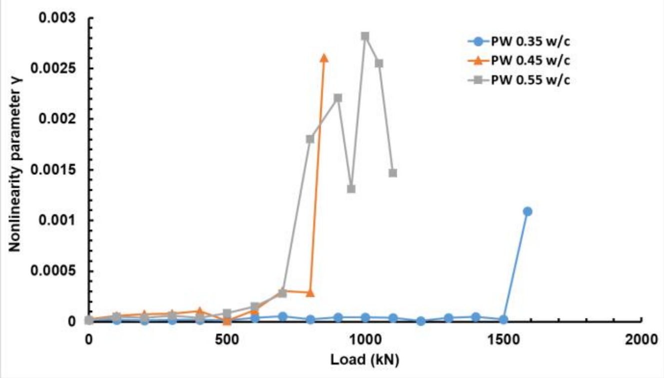

Figure 5b: Nonlinear parameter γ versus load.

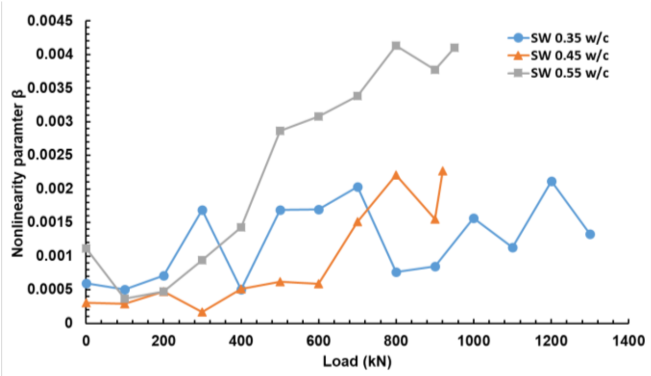

Figure 6a: Nonlinear parameter β versus load.

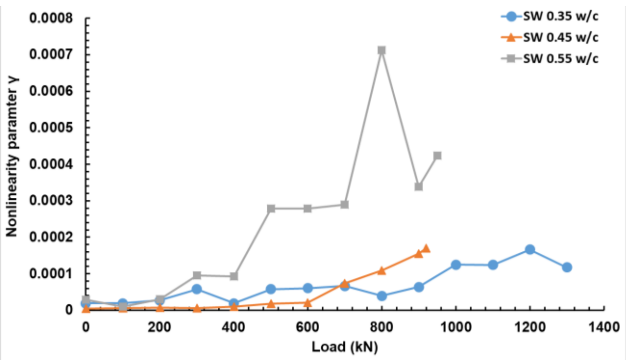

Figure 6b: Nonlinear parameter γ versus load.

At higher load level the macro scale damage is formed in the concrete specimen; the wave does not propagate into the concrete when the crack width increase. In the second and third harmonics, the amplitude variation is small compared to first-order harmonics. The first order is affected due to attenuation and scattering due to the heterogeneous nature of concrete and cracks due to loading. Owing to this, an increase in β and γ values at the macro scale crack occurred in concrete during loading. The higher the load level, the larger corresponding β is calculated in P-wave and S-wave.

The β value varies at a certain load level, indicating that even for a concrete specimen, the values of β vary at different load stages. The main reason is that the concrete composition and loading induce micro-crack initially and macrocracks later. The application of loading played a significant role in the behaviour of nonlinear properties of heterogeneous materials like concrete, the interface between the aggregate and paste creates frictional forces that lead to the development of higher harmonics. It is observed from Figure 5 a & b and 6 a & b, higher the load higher is the harmonics in both P and S wave propagation. Higher load amplifies the fundamental harmonics. The increase of A_1 is larger than the A_2 and A_3, Fig. 7a and 7b. The magnitude of A_2 is higher than A_3

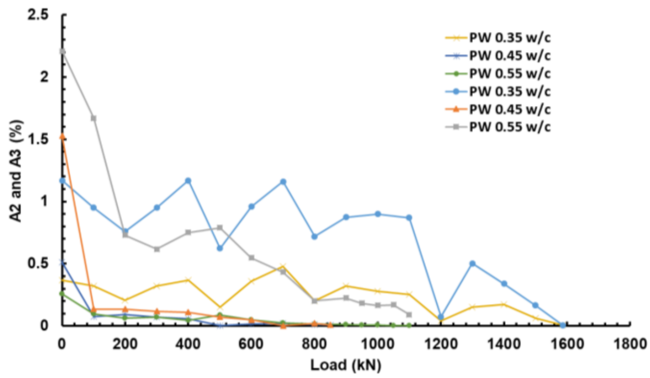

Figure 7a: Second and third harmonic amplitudes after loading

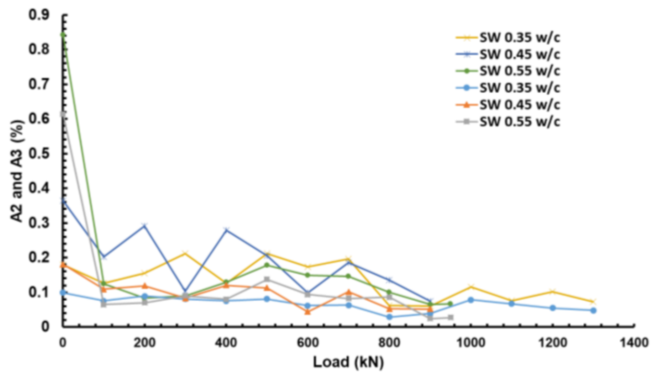

Figure 7b: Second and third harmonic amplitudes after loading

The nonlinear parameter γ was analysed in a similar manner, and identical conclusions are drawn. The value of γ also increases with the advancement of the load stage. This implies that as the load stage progresses, the value of γ tends to rise. The value of γ increases as the loading in second harmonics advances. The variation rate in the ratio of third-order harmonics is higher than in the ratio of second-order harmonics. The third-order harmonics have a more significant impact on the value of γ than the second-order harmonics.

Recent studies compared the second and third harmonic ratios showed consistent behaviour and display similar damage evolution in concrete. However, the third harmonic ratio, γ, appears more sensitive [13, 14 and 15]. The harmonic ratio generated from damaged concrete demonstrates sensitivity to microstructural changes and microcracking in the Interfacial Transition Zone (ITZ) [14]. Furthermore, variations in the concrete mixture can also influence the generation of higher-order harmonics. An increase in the water-cement ratio positively correlates with the nonlinear parameter's increment.

5 DISCUSSIONS

The load-induced ultrasonic experimental result gives more understanding of the degree of damage in concrete specimens subjected to compressive loading. The nonlinear parameters β and γ values are vary with the load stages, from the β and γ values the stages of micro and macro level of damages is evaluated. The nonlinear parameter β in S-wave is more sensitive to damage compared to the P-wave. This may be due to the 100% excitation of shear wave compared to P and Rayleigh waves. It is observed from the Figure. 5b and 6a 2nd order harmonics of S-wave is the 3rd order harmonics of P-wave under loading. This shows that the S-wave is more sensitive to damage than the P-wave.

Higher w/c ratio in both the P and S waves shows higher order harmonics generations. The observed behaviour can be attributed to a weak interface between the aggregate and cement paste phase, which generates higher-order harmonics. The primary source of nonlinearity is mainly the interfacial transition zone between the aggregate and mortar.

The increase in load leads to higher harmonics and indicates nonlinear interaction in the concrete. The loading protocol played a significant role in the behaviour of nonlinear properties of heterogeneous materials like concrete, the interface between the aggregate and paste creates frictional forces that lead to higher harmonic generation.

6 CONCLUSIONS

In this experimental investigation, the ultrasonic method explored the effect and reliance of nonlinear parameters on concrete damage induced by loading until failure. The study yields the following conclusions:

1. The experimental results demonstrate that the values of β and γ significantly depend on the applied loading. The rise in γ indicates higher sensitivity to micro-damage.
2. The experimental findings indicate that the third harmonic (γ) exhibits higher sensitive to loading in comparison to the second harmonic (β).
3. Particularly, shear wave propagation of the 2nd and 3rd harmonics exhibit higher sensitivity to loading. An increase in loading during shear wave propagation leads to a higher rate of increment in the nonlinear parameter, and it is similar to the P-wave behaviour.
4. Furthermore, the results indicate that the uniaxial loading is more sensitive to a higher water-cement ratio in both wave propagations.
5. Based on the experimental investigation

results, S-wave propagation can be effectively employed to assess the nonlinear parameters. The S-wave shows higher sensitivity to damage compared to the P-wave.

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