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Scientific paper

Effect of Load Pattern in the Generation of Higher Harmonic Amplitude in Concrete Using Nonlinear Ultrasonic Test

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Abstract

Non-destructive testing is used in monitoring health of structures. In this paper, nonlinear ultrasonic test was done to analyze the sensitivity of the fundamental and higher harmonics with the internal damage in concrete. Good sensitivity produces significant quantitative changes in the nonlinear spectral amplitude parameter corresponding to the deviation of load.

In actual conditions, structures have different design strength with varying water cement ratio. In addition, it is experiencing loading and unloading. These are considered as major factors that induce effect in the behavior of ultrasonic test result in concrete. Past researches have only considered increasing application of load with single loading pattern. This study aims to investigate the effect of load application pattern in the generation of higher harmonics.

Ordinary concrete specimens of size 150mm x 150mm x 150mm with water-cement ratio WC40 and WC60 were casted and tested using uniaxial compression machine with two load patterns: a.) single loading pattern from 0% to 100% and, b.) multiple loading/unloading pattern. Ultrasonic test with pitch-catch configuration was conducted at each loading state to record the fundamental and higher harmonic generation in the concrete.

The experimental results showed that there was a good sensitivity for 3rd harmonic amplitude parameter D_A when it was subjected to single loading pattern for both WC40 and WC60. On the other hand, good sensitivity was only observed for 2nd harmonic amplitude parameter D_A when it was subjected to multiple loading/unloading pattern for both WC40 and WC60. This showed that the 2nd harmonic amplitude was consistent and sensitive when repeated load was applied for low and high water cement ratio.

1. Introduction

1.1 Linear and nonlinear ultrasonic test in concrete

Concrete has been predominant in structures. In its early life, concrete usually develops micro cracks between the aggregates and bonding agent. With the application of loads, new micro cracks occur, and early cracks grow further to larger cracks (Stauffer *et al.* 2005). In addition, seismic movement of the structure induce propagation of micro cracks until failure occurs. Thus, concrete inspection at micro level should be done to monitor its serviceability throughout the structure's lifespan.

Non-destructive testing is a widely used method to examine the structural integrity of the concrete structure at micro level. Unlike other materials, concrete is complex. There are a lot of linear ultrasonic testing procedures in concrete from the past. An example of linear ultrasonic test is Ultrasonic Pulse Velocity wherein time of wave traveling a particular distance through the thickness of the concrete are the parameters used to derive the velocity. It is worth noting that in this test, it is

not essential to measure the wave amplitude.

Combination of linear ultrasonic test using ultrasonic pulse velocity (UPV) and rebound hammer was introduced to test on site strength of concrete (Breyse 2012). Another combination of ultrasonic pulse velocity (UPV) and ultrasonic pulse amplitude (UPA) was formulated to predict the compressive strength of concrete (Liang and Wu 2002). With any combination to improve the prediction of strength of concrete, ultrasonic pulse velocity (UPV) is still limited due to its insensitivity to the changes in load (Daponte *et al.* 1995). Other tests like air-coupled impact echo (IE), infrared (IR), and sounding (chain drag) method were introduced to the non-destructive method in concrete (Oh *et al.* 2013). It was emphasized that cracks of size greater than 100mm were the ones detected by longitudinal ultrasonic pulses (Komlos *et al.* 1996). The study further claimed that cracks were practically undetectable especially if it is filled up with fluids.

Another method of non-destructive test is nonlinear ultrasonic test. This provides more promising results due to its sensitivity in damage and crack detection. This test considers harmonic generation which is a phenomenon resulting from interaction between concrete and ultrasonic wave (Zheng *et al.* 1999). Nonlinear ultrasonic waves proved to be sensitively interacting with contact-type defects (Yim *et al.* 2012). This includes the opening and closing of cracks formed when loading and unloading occurs. Ultrasonic waves passing thru dam-

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aged concrete interacts with micro cracks that result to generation of higher harmonics. In particular, harmonic ratio generated from damaged concrete is sensitive to micro structural changes and micro-cracking in the interfacial transition zone (Shah and Ribakov 2009). Variation of concrete mixture also influences the generation of higher harmonics. Increase in water-cement ratio in concrete proved to be increasing with the nonlinear parameter. In previous studies, small crack opening displacement produces large 2nd higher harmonics (Hirose and Achenbach 1993). From previous experiments, third harmonic ratio is more sensitive compared to the 2nd harmonic ratio in a single loading branch (Shah *et al.* 2009). Defect detection using 3rd harmonic generation is also sensitive to damage (Shah and Ribakov 2008). It is also suggested that the amplifier be triggered at high power level in experiments to produce better sensitivity in the higher harmonics generation (Shah *et al.* 2013).

A theory that can be introduced to complex material like concrete is called Nonlinear Mesoscopic Elastic (NME) materials. This results to several important properties such as shift of resonance frequency, generation of higher harmonics, and the phenomenon known as slow dynamics (Johnson and Sutin 2005). These effects are called non-classical non-linear where there are softer regions inside a hard material. Some examples of failure are micro cracks in soft bonding regions between grains. In particular for a concrete specimen, the presence of cement paste which served as a soft bonding region binds with aggregates of different sizes together which served as a hard material in the matrix. If external forces are applied to a concrete specimen, some weak joints may be broken since it is relatively weaker than the coarse aggregates. For weak joints, nonlinear behavior sets in at an earlier stage. For strong joints, it behaves linearly and then nonlinearly at the latter part. This paper aims to consider weak and strong joints of the cement paste between aggregates with the presence of different water cement ratio used. The low water cement ratio of 0.40 considered strong joints with presence of less air voids, while the high water cement ratio of 0.60 considered weak joints with presence of more air voids.

1.2 Nonlinear ultrasonic methods and parameters

Previous works on nonlinear methods include Scaling Subtraction Method (SSM) and Spectral Analysis (Antonaci *et al.* 2010). In this paper, spectral analysis was used to determine the sensitivity of the nonlinear ultrasonic parameters to the damage progression in the concrete cubes. This is to filter time domain waveforms to frequency domain waveforms to analyze the frequency content of the elastic response of the medium and to evaluate the amplitude of the newly generated higher order frequencies and their dependence on the amplitude of the fundamental frequency of excitation. De-

rived from harmonic generation are harmonic ratios. These are nonlinear ultrasonic properties that refer to the ratio between the higher harmonic amplitude and the fundamental amplitude. Harmonic amplitudes are peak amplitudes that can be measured, during the harmonic generation, other than the fundamental one. Harmonic ratio is another parameter utilized to measure nonlinear response of concrete to ultrasonic testing and correlated to development of internal damage in concrete.

The calculation of harmonic ratio is derived using Taylor series expansion to solve for the solution of the nonlinear partial differential equation of motion shown in Eq. 1.

$$\frac{\partial^2 U}{\partial t^2} = c_o^2 \left[1 + \frac{C'''}{C'} \frac{\partial U}{\partial x} + \dots \right] \frac{\partial^2 U}{\partial x^2} \quad (1)$$

where U is the particle displacement with respect to time, t ; x is the propagation distance; C'' and C''' are the 2nd and 3rd order elastic constants and c_o is the velocity of the wave.

Since harmonics are generated when fundamental ultrasonic signals encounter damage, solutions are offered to relate the fundamental amplitude with the generated amplitudes of the higher harmonics in Eqs. 2 and 3.

$$U_2 = -\frac{\Gamma_2}{4} k^2 U_o^2 x \quad (2)$$

$$U_3 = -\frac{\Gamma_2^2}{8} k^4 U_o^3 x^2 \quad (3)$$

where U_2 and U_3 are now the solution for Eq. 1. Γ_2 is $-C''' / 2C''$. The parameters U_2 and U_3 are now the harmonic amplitudes as related to the fundamental amplitude, U_o . To take into account the attenuation (wave loss of amplitude) of fundamental signal when wave encounters damage and the generation of higher harmonics, the calculation for harmonic ratios are presented in Eqs. 4 and 5.

$$\frac{A_2}{A_1^2} = -\frac{\Gamma_2}{4} k^2 x \quad (4)$$

$$\frac{A_3}{A_1^3} = -\frac{\Gamma_2^2}{8} k^4 x^2 \quad (5)$$

where A_1 , A_2 , and A_3 are the fundamental, second, and third harmonic amplitudes taken to be approximately equal to the fundamental, second, and third harmonic displacements (U_1 , U_2 and U_3); k is the wave number.

Harmonic generation will not occur without attenuation as mentioned above. Attenuation is the reduction in intensity in any kind of flux during its travel through a medium. This is an ultrasonic wave response when it propagates through a material in which its energy gets reduced as wave scatters due to the presence of microscopic interfaces. Moreover, internal friction contributes to the attenuation. In other words, attenuation is an energy loss within the material experienced by the sound

Table 1 Design mix of concrete.

TYPE	Maximum Size of Gravel (mm)	W/C (%)	Unit Quantity (kg/m ³)				
			Water	Cement	Sand	Gravel	Water-reducing agent
WC40	20	40	169	422	702	1039	0.84
WC60		60	175	291	812	1021	0.58

wave as it travels through the medium.

There were few studies in relating higher harmonic amplitudes with the contacting surface of materials. Recent work showed that the second harmonic generation at the contacting surface of two aluminum blocks was experimentally observed (Murase *et al.* 2014). Only few researches studied nonlinear ultrasonic test in concrete under loading and unloading conditions with strong and weak joints. In this paper, the effect of loading and unloading in concrete was investigated to define the distinction between initial and latter loading branches of degradation. Furthermore, the harmonic ratio (A_2/A_1^2 and A_3/A_1^3) from equations 4 and 5 were not used in this paper, rather the individual harmonic generations A_1 , A_2 , and A_3 were used as a parameter to define the sensitivity with different loading pattern and water-cement ratio.

2. Experimental procedures

2.1 Specimens

A total of 22 cubic specimens of size 150mm x 150mm x 150mm were casted. The water-cement ratio was varied as WC40 and WC60. The concrete contained maximum size of aggregates of 20mm and sand-total aggregate ratio of 45%. The mixture is shown in **Table 1**.

2.2 Experimental setup

After curing, all the specimens were at their mature age, a universal testing machine was used to subject each specimen to compression test. There were two experimental set-up established in this paper. Fourteen concrete cubes were tested in a single loading pattern from 0% to 100%. The remaining eight concrete cubes were tested using multiple loading/unloading pattern as

shown in **Fig. 1**. In this figure, there were four loading branches considered. These had percent load of 0% to 20%, 0% to 40%, 0% to 60%, and 0% to 100%, respectively.

The experimental setup is shown in **Fig. 2**. Specimens were tested by compressive loading. After every loading or unloading, nonlinear ultrasonic testing was used to assess the sample.

The nonlinear ultrasonic test setup is composed of a tone-burst pulser, a high gain broadband receiver, two transducers, and an oscilloscope. The tone-burst pulser supplied voltage amounting up to 1800V with 10 cycles of 100kHz Sine Wave. The pulser-receiver unit has built in modern facilities such as low pass filter set at 3MHz and high pass filter set at 50kHz, and input impedance of 50 Ω .

Transducers, connected to the tone-burst pulser and broadband receivers, were carefully aligned, centered and bonded to the concrete specimen using couplant. A transducer with 100kHz generating frequency capacity was used to transmit the signal from one face of the

Fig. 1 Multiple loading/unloading pattern.

Fig. 2 Compressive testing procedure by loading and unloading setup using nonlinear ultrasonic testing.

specimen. These ultrasonic signals/waves propagate through the damaged concrete. Receiving transducer with 200kHz frequency was placed at the opposite face of the specimen that detected the signal passing through the medium. Ultrasonic signals being transmitted and received were translated through the oscilloscope at each step load. All tested specimens were transmitted with signals at 100kHz fundamental frequency.

2.3 Higher harmonic generation

Higher harmonic waves occur in concrete due to contact of crack interfaces called Contact Acoustic Nonlinearity (CAN) (Solodov *et al.* 2002). This is done through opening and closing of cracks and/or frictional forces acting on the interfaces between cement paste and the aggregates. The higher harmonics generated depends on the behavior of the cracks forming inside when corresponding compressive load is applied (Solodov and Chin 1993).

The transmitted and received frequency domain pass-

ing through concrete is shown in **Fig. 3**. The generation of higher harmonics prove that the concrete material is nonlinear with the presence of its ingredients and micro-cracks.

The results obtained at the receiving transducer were plotted in a time-domain waveform, and then converted to frequency-domain using Fast Fourier Transform (FFT). Afterwards, the amplitudes of fundamental and higher harmonics in frequency-domain were measured.

3. Discussion of results

3.1 Harmonic generation applied to a single loading pattern

After obtaining the time-domain waveform from the receiving transducers in the experimental set-up of single loading pattern, it was then converted to frequency domain. Shown in **Fig. 4** is the frequency spectrum for specimen #1 with water cement ratio of 0.60.

It can be observed that there are formations of higher

Fig. 3 Transmitted and received wave in time and frequency domain through concrete.

Fig. 4 Frequency spectrum of WC 60 specimen #1.

harmonics at 200kHz and 300kHz. The presence of this higher harmonics, when load is increased, signifies the presence of nonlinear interactions in the concrete.

3.2 Sensitivity of fundamental and higher harmonic amplitude applied to a single loading pattern

From a study by Daponte *et al.*, amplitude sensitivity analysis was introduced as shown in Eq. 6.

$$D_A = 1 - f(x) / f_{\max} \quad (6)$$

where D_A is the sensitivity of amplitude, $f(x)$ is the amplitude at current load x , $f_{\max}$ is the peak amplitude in the given frequency and loading branch. Sensitivity is

the measurement where there is a significant quantitative change with respect to the load applied.

In this paper, the values of D_A were plotted against percent load. Linear regression was used to show the best fit line that represented the D_A equation as a function of percent load. Shown in Fig. 5 is the sensitivity parameter D_A as a function of load. The definition of good sensitivity used in this paper was marked as 0.80 at 100% load or having a best fit line that had $D_A > 0.008x$, where x is the load percent.

Shown in Fig. 6a and 6b are the average values of sensitivity D_A for each harmonic generation for WC 40 and 60 done in the experiment containing single loading pattern. For WC40, 2nd and 3rd harmonic amplitude be-

Fig. 5 Sensitivity parameter D_A as a function of load.

Fig. 6a Sensitivity parameter D_A for all harmonic amplitude with water-cement ratio of 0.40.

Fig. 6b Sensitivity parameter D_A for all harmonic amplitude with water-cement ratio of 0.60.

haved with good sensitivity having its best fit line $D_A > 0.008x$. On the other hand, the fundamental and 2nd harmonic amplitude was less sensitive compared to the 3rd harmonic amplitude for concrete with WC60. In summary, the 3rd harmonic amplitude gave good sensitivity to monitor damage in concrete with strong and weak joints represented by WC40 and WC60 respectively.

3.3 Sensitivity of fundamental and higher harmonic amplitude applied to multiple loading/unloading pattern

Shown in Figs. 7a, 7b, and 7c are the sensitivity parameter D_A for the fundamental, 2nd and 3rd harmonic amplitude from the 1st loading branch to the 4th loading

branch of concrete with WC40. The best fit line's slope for the fundamental amplitude 1st to 4th loading branch diminishes significantly. As a result, there is less sensitivity at the last loading branch. Similarly, there was a diminishing slope for the 2nd and 3rd harmonics D_A as loading branch increased. The reduction of the slope for both 2nd and 3rd harmonic amplitude was small that kept the best fit line's slope more than 0.80. This was consistent with the single loading branch were 2nd and 3rd harmonic amplitude was sensitive for strong joints represented by WC40.

In Figs. 8a, 8b, and 8c, it shows the sensitivity parameter D_A for the fundamental, 2nd and 3rd harmonic amplitude from the 1st loading branch to the 4th loading branch of concrete with WC60. The best fit line's slope

Fig. 7a Sensitivity parameter D_A for fundamental amplitude with water-cement ratio of 0.40.

Fig. 7b Sensitivity parameter D_A for 2nd harmonic amplitude with water-cement ratio of 0.40.

Fig. 7c Sensitivity parameter D_A for 3rd harmonic amplitude with water-cement ratio of 0.40.

for the fundamental, 2nd and 3rd harmonic amplitude from the 1st to 4th loading branch diminishes. Unlike the concrete with WC40, the 3rd harmonic amplitude for WC60 had significant reduction of slope from 0.024 to 0.0047. This shows that for weak joints with WC60 concrete mixture, the sensitivity of the 3rd harmonic amplitude reduces when repeated load is applied. The 2nd harmonic amplitude however remains to be consistent as the parameter sensitive to the load changes with a slope of 0.0091 at the last loading branch.

3.4 Normalized higher harmonic ratio applied to a single loading pattern

Higher harmonic amplitude in Fast Fourier Transform has no basis for comparison from the undamaged state

of concrete. Normalized higher harmonic ratio is introduced in this paper to set a baseline value. These values are calculated in order to ascertain the effect of loading pattern to the ultrasonic wave propagation in the damaged concrete.

From the frequency spectrum, normalization of amplitude was computed using Equation 7

$$X = 20 \log(A_1 / A_0) \quad (7)$$

where X is normalized higher harmonic ratio in dB, A_1 is amplitudes in volts at a particular step load and A_0 is reference amplitude in volts (undamaged state).

The average normalized higher harmonic ratio for the experimental set-up of single loading pattern from a load of 0% to 100% is shown in Fig. 9a and 9b. Clear

Fig. 8a Sensitivity parameter D_A for fundamental amplitude with water-cement ratio of 0.60.

Fig. 8b Sensitivity parameter D_A for 2nd harmonic amplitude with water-cement ratio of 0.60.

Fig. 8c Sensitivity parameter D_A for 3rd harmonic amplitude with water-cement ratio of 0.60.

Fig. 9a Average normalized 2nd harmonic ratio amplitude.

Fig. 9b Average normalized 3rd harmonic ratio amplitude.

Fig. 10a Average 2nd harmonic amplitude with loading/unloading pattern.

Fig. 10b Average 3rd harmonic amplitude with loading/unloading pattern.

trend showed that it is decreasing with an increasing load. The maximum difference for the average normalized 2nd harmonic ratio of undamaged state at 0% and the damaged state at 100% was -15.96dB for WC40 and -9.50dB for WC60. The difference for the average normalized 3rd harmonic ratio of undamaged state at 0% and the damaged state at 100% were -20.79dB for WC40 and -14.79dB for WC60. It showed that the normalized 3rd harmonic ratio is sensitive to damage since it contained higher numerical value for better assessment of internal damage. This behavior was also observed from the previous sensitivity measurement D_A that the 3rd harmonic amplitude was highly sensitive to changes in load.

3.5 Normalized higher harmonic ratio applied to a loading/unloading pattern

The time-domain waveforms from the receiving transducers for the loading/unloading branch were recorded. It was then converted to frequency domain. Shown in **Fig. 10a** and **10b** are the normalized harmonic ratios for WC40 and W60. For WC40, all higher harmonic amplitudes were sensitive to loading and unloading pattern. This was evident with the significant variation with respect to changes in load. For WC60, the 2nd harmonic amplitude was sensitive to the loading and unloading pattern compared to WC40.

The normalized 3rd harmonic ratio of WC60 was insensitive due to weak regions represented by weak cement paste or more voids in a heterogeneous material

consisting of aggregates. From studies (Solodov *et al.* 2011), the 3rd harmonic amplitude was sensitive to contact friction. In WC60, there was less contact friction when repeated load was applied producing less sensitivity at the latter loading branches.

3.6 Level of damage measurement for loading/unloading pattern

In the loading/unloading pattern, two damage level measurements are introduced - total damage and the incremental damage. The total damage has a baseline of zero decibels when there is no stress experienced in the concrete at step load 0 as shown in **Fig. 11**. On the other hand, the incremental damage is the normalized harmonic ratio from zero load of any loading branch to the step load considered within the particular loading branch. The total damage of WC40 using normalized 3rd harmonic ratio is -22.37dB from step load 0 to 16, while the incremental damage at the last loading branch from step load 12 to 16 is -8.23dB.

The 2nd harmonic amplitude proved to be more consistent and sensitive than 3rd harmonic amplitude for all water cement ratio when repeated load is applied. The total damage or difference of normalized 2nd harmonic ratio from undamaged for WC40 and WC60 are -24.99 dB and -22.37dB, respectively. Shown in **Fig. 12** are the incremental damages of normalized 2nd harmonic ratio considering only the last loading branch for WC40 and WC60 were -10.88dB and -9.89dB, respectively.

Fig. 11 Total damage and incremental damage for WC40 at the last loading branch.

Fig. 12 Normalized 2nd and 3rd harmonic ratios for the incremental damage at the last loading branch.

4. Conclusions

From literatures, 3rd harmonic amplitude was sensitive to internal damage. In this paper, it was investigated that the loading pattern played an important role in the behavior of nonlinear properties in strong and weak joints when subjected to load or repeated load. In reality, the concrete structure is assumed to be pre-loaded by its own weight or any initial loading condition subjected to it. Careful analysis of amplitude sensitivity was studied and the diminishing effect of harmonic generation was taken into consideration.

The experimental results showed that there was a good sensitivity for 3rd harmonic amplitude D_A when it was subjected to single loading pattern for both WC40 and WC60. On the other hand, good sensitivity was observed for 2nd harmonic amplitude D_A when it was subjected to multiple loading/unloading pattern for both WC40 and WC60.

Furthermore, results showed that the single loading pattern produced 3rd harmonic amplitude that was sensitive for both WC40 and WC60. The damage measurement using the largest difference of normalized 3rd harmonic ratio from undamaged to damage state was -20.79dB and -14.79dB, respectively. On the other hand, the difference of normalized 2nd harmonic ratio was -15.96dB for WC40 and -9.50dB for WC60.

For the loading/unloading pattern, it produced differ-

ent behavior on its harmonic generation. Second harmonic amplitude was used to measure the damage. The total damage or difference of normalized 2nd harmonic ratio for WC40 and WC60 was -24.99dB and -22.37dB, respectively. The incremental damage of normalized 2nd harmonic ratio considering the last loading branch for WC40 and WC60 was -10.88dB and -9.89dB respectively.

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