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NONLINEAR ULTRASONIC AND ACOUSTIC EMISSION INVESTIGATION OF CONCRETE DAMAGE

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Structural health monitoring is very important in today's modern world. Infrastructures experiences man-made and natural disasters that needs more precise and accurate assessment during post event. Material that is commonly used in structures is concrete. Concrete can be assessed in many different ways where factors to be considered in the test are cost, time, and the idle period during assessment. One way of having a better and economical test is the use of non-destructive test. In this dissertation, ultrasonic test and acoustic emission test are applied to evaluate the integrity of concrete specimens. The thesis comprises of two main concrete materials considered for testing, the unreinforced concrete and the reinforced concrete. The unreinforced concrete was designed having a specimen size of 150mm x 150mm x 150mm cube. The method of testing was uniaxial compression load. On the other hand, the reinforced concrete was designed having specimen size of 100mm x 100mm x 400mm beam. The method of testing was four-point loading test. In addition, there were three chapters: Investigation of unreinforced concrete cubes, investigation of reinforced concrete beams, and modeling of data collected from experiments.

In the first section of unreinforced concrete cubes, effect of load pattern in the generation of higher harmonics using Nonlinear Ultrasonic test was investigated for low and high water cement (WC) ratio. From literatures, 3rd harmonic amplitude was sensitive to internal damage. 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. 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 (D_A) for 3rd harmonic amplitude 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 different 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.

In the second section of unreinforced concrete cubes, Nonlinear Ultrasonic test was done for concrete with varying aggregate size. Two damage level assessment using normalized 2nd harmonic ratio was investigated. The total damage level had a baseline at step load 1 (undamaged state) while the incremental damage level had a baseline when the load is zero or minimal load at step loads 1, 3, 7, and 13 depending on the loading branch where it belongs.

The total damage produced by mortar was -8.52dB at the last loading branch which was relatively lower than all the other specimen type, -11.22dB for well-graded aggregates, -12.41dB for small aggregates, and -26.00dB for large aggregates. This showed that when the specimen is more heterogeneous with the presence of large particles, it will produce bigger value of normalized 2nd harmonic ratio due to the increase in interfacial transition zone that led to more formation of micro-cracks.

The incremental damage produced by mortar in every step load was consistently increasing compared to the other types were no specific trend was observed. This showed the complexity of concrete being a heterogeneous material produced different crack formation from one loading branch to another.

In the third section of unreinforced concrete cubes, damage progression using acoustic emission (AE) test through convex hull visualization was undertaken. This progression of damage inside concrete is very important to assess the health condition of structures. One promising tool in assessing damage is the use of AE test. From AE experiments, AE hits and AE locations were calculated. These parameters were then used to visualize damage progression using computational geometry particularly convex hull algorithm.

From the three different mixtures namely mortar, ordinary concrete, and fiber-reinforced concrete, it was found out that the progression of convex hull volume for all mixtures significantly increases on or before 20% compressive load. This indicated that the progression of AE hits in space represented by convex hull volume spreads very fast in low compressive force. After 20% load, the behavior of the change in the progression of volume of convex hull was minimal.

In addition, it was found out that the total AE hits for the three different mixtures increases linearly. With the fiber-reinforced concrete having the least total number of AE hits due to its resistance from crack formation inside the mortar matrix or the Interfacial Transition Zone (ITZ) region. The concentration of AE hits (K/X)% or the number of AE hits inside convex hull over the total number of AE hits decreases when load is increased. This showed that formation of AE inside the convex hull is very low at initial stage of the compressive load. On the other hand, when compressive load is near failure, the formation of AE hits inside the convex hull volume formed is increased.

In the first section of reinforced concrete beams, contact and non-contact ultrasonic non-destructive test in reinforced concrete beam was studied. This section focused on two types of specimens and testing under nondestructive test. Contact ultrasonic test with varying WC of 40 and 60 under compression load showed that normalized peak to peak amplitude gave good agreement and was sensitive with the load for concrete cubes. High WC gave larger value of peak to peak amplitude. The second type was reinforced concrete beams under four-point bending test with varying WC of 40 and 60. Additional parameters were considered to explore the sensitivity of the contact and non-contact ultrasonic test. These were neutral axis index and ultrasonic wave path. It showed that the higher WC produced good sensitivity in non-contact ultrasonic test while low WC gave good sensitivity with load for contact ultrasonic test since it had its ultrasonic wave path passing the concrete compression zone.

In the second section of reinforced concrete beams, computational geometry using convex hull algorithm was used to determine the maximum volume formed by the AE hits inside the eighteen concrete beams with varying water-cement ratio and reinforcements. The volume of the convex hull gave good relation to the force applied in four-point loading test. High WC had higher convex hull volume formation compared to low WC due to its ductility where the movement of AE hit spreads wider. The volume of convex hull generated was proportional to the load from 0% to 60%, but had insignificant progression after 60% load. This proved that the convex hull volume progression in compression zone had direct relation to the load applied to the beam.

In the first section of modeling using unreinforced concrete cubes, optimum feed-forward backpropagation artificial neural network (ANN) models were used to compare four types of concrete mixtures with varying water cement ratio (WC), as ordinary concrete (ORC) and concrete with short steel fiber-reinforcement (FRC). The models showed promising results comparing four types of mixtures for the concrete cubes ORC WC40, ORC WC60, FRC WC40, and FRC WC60. Prior to ANN modeling, statistical Spearman's rank correlation was used to reduce the input parameters in the ANN model. In general, different types of concrete produced similar top five input parameters that had high correlation to compressive stress. These were average strain (ε), fundamental harmonic amplitude (A1), 2nd harmonic amplitude (A2), 3rd harmonic amplitude (A3), and peak to peak amplitude (PPA).

Optimum model was chosen for each WC model having the least mean square error, the highest Pearson correlation coefficient, and the soundness of the behavior for the input parameters in relation to the compressive stress of concrete. Optimum ANN model showed that increasing WC produced delayed response to stress at the initial stages, followed by abrupt response after 40%. This was due to the presence of more voids for high water cement ratio that activated Contact Acoustic Nonlinearity (CAN) at the latter stage of loading path. In addition, FRC showed slow response to stress than the ORC. This indicated the resistance of short steel fiber that significantly produced delayed stress increased against the loading path. In addition, residual errors of WC40 and WC 60 for the training, validating, and testing data gave a good measurement on the accuracy of optimum ANN model in predicting non-linear relationship of the parameters presented to determine the stress in concrete.

In the second section of modeling using reinforced concrete beams, sensitivity of ultrasonic test and neutral axis index in damage detection of reinforced concrete beams using artificial neural network was explored. Few research explored the use of ultrasonic testing in RC beams. This research used experimental database with varying WC content and reinforcing bars to train, validate, and test ANN to model the complex nonlinear relationship of the five parameters A1, A2, A3, PPA, and NA in predicting the load it experienced under four-point bending test. In addition, classification of sensitivity was done were A2 and NA proved to be sensitive for all WC and reinforcing bar content. It showed that the range of sensitivity of A2 increased when reinforcing bar decreased, while the range of sensitivity of NA decreased when reinforcing bar decreased. These two parameters showed good agreement with the load applied to the RC beam.