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Cement and Concrete Research 34 (2004) 563–570

CEMENT AND CONCRETE RESEARCH

Actively modulated acoustic nondestructive evaluation of concrete

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Received 24 January 2003; accepted 8 September 2003

Abstract

The need in testing concrete is not only the ability to detect large cracks or flaws but also reliably and efficiently to quantify the residual strength. Current nondestructive testing methods are capable only of discriminating high states of damage. This study lays the foundation for an evaluation method that may be significantly more sensitive than traditional nondestructive evaluation (NDE) to the damage in concrete without high dependency on testing conditions. One promising method of evaluating damage state in concrete is by frequency domain analysis of the stress waves that pass through the material. This study unveils the potential of nonlinear frequency analysis methods for concrete damage detection and evaluation using actively modulated acoustic (AMA) signals. This method actively interrogates the specimen material exaggerating the nonlinearity that exists due to microcracking and deterioration.

Keywords: Concrete; Degradation; Crack detection; Microcracking; Ultrasound

1. Introduction

While concrete structures continue to age and deteriorate due to fatigue and chemical attack, it is important to be able to determine the residual strength of the material before substantial failure occurs. It is possible to repair some extensive damage; however, in most cases, a structure should be evaluated before it becomes a safety hazard. Damage state is a good indicator of the residual strength and durability of a material, so the evaluation of the existing damage state in a material should allow the ascertainment of the structure's integrity for the long term.

The need in testing concrete is not only the ability to detect large cracks or flaws but also reliably and efficiently to quantify the residual strength at all levels of deterioration. At present, there are no robust and reliable methods of doing this; however, the active modulation of acoustic waves seems to be a promising tool for providing good evaluation of the level of damage in all sorts of materials.

This method is an ultrasonic testing method that considers the nonlinear behavior of damaged concrete. The theory was described in the most basic case as acoustic harmonic generation at unbonded, planar interfaces [1,2]. Sutin and Nazarov [3] expanded this to the case of unbonded, rough interfaces providing additional harmonic generation. These harmonics, in the simplest sense, are generated by the cyclical increase and decrease of the contact area of cracks under the stresses of an acoustic wave. This is necessarily dependent on the relative smoothness of the crack interface, the deformability of that interface and the normal stresses induced by the stress wave on the interface. Sutin and Nazarov [3] further suggested that it is possible to modulate the frequency of an ultrasonic wave by forcing cyclical opening and closing of the cracks with another, different wave. The results of studies on Plexiglas with cracks showed consistent displacement of spectral energy away from the ultrasonic probe frequency [4].

This same concept was applied herein to the case of an inhomogeneous material in the form of concrete. The nature of this preliminary study was to assess whether this theory is first valid and then feasible for nondestructive evaluation (NDE) of concrete damage states. Several test procedures were compared side by side to evaluate the validity of the nonlinear actively modulated acoustic (AMA) NDE approach. Both active and passive modulation (spectral analysis of regular dilatational ultrasonic signals) of probe frequencies contain nonlinear parameters; however, results show that active modulation is more sensitive to early concrete damage. This preliminary study has yielded positive results that indicate the strengths of the active modula-

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doi:10.1016/j.cemconres.2003.09.008

tion method. Because of the results presented herein, this testing and analysis procedure will be further developed at Wayne State University (WSU) to improve its reliability and ease of application.

2. Background

2.1. Cracking in concrete

Due to the heterogeneous nature of concrete, stresses are not evenly distributed throughout a concrete structure under load. The result is the formation of small cracks and stress redistribution even at low loads. Fracture mechanics suggests that very small material flaws or interfaces between materials of different stiffness give rise to large stress concentrations [5,6]. Both of these conditions exist in all concretes. Some initial cracks are very small resulting from the presence of processing flaws or material imperfection and subsequently grow where high stress concentrations exist in a member as a result of local tensile or shear stresses. Crack formation and growth begin at low loads in concrete and increase in number (and size) over the whole load capacity range of the material.

Concrete failure is initiated by wing crack propagation under compressive loading [7] or by tension crack propagation under flexural [8,9] or shear loading [10]. Unstable propagation of a critical tensile crack accounts for the failure of brittle solids under tension. However, under compressive loading, microcracks in the solid come under a local tensile field at their tips causing initiation of "wing cracks." The extension of wing cracks under such a local tension has been demonstrated to be unstable initially and becomes stable as the crack length increases [7,11]. Under compressive loading, a critical stress is required to initiate crack growth: it depends on the initial crack length and orientation, on the coefficient of friction and on the stress state. The cracks then grow in a stable way until they start to interact; interaction increases the stress intensity driving crack growth and leading to instability and finally failure [12].

It is therefore important to have the ability not only to identify internal flaws but also more importantly to determine any reduction in the integrity of the concrete as a result of those flaws [13]. The development of a nondestructive test procedure for rapid characterization of the residual strength of a concrete member is the first focus of this effort.

2.2. Testing methods

Presently, several methods are used to estimate the present (residual) strength of concrete structures including core testing, surface hardness testing and ultrasonics. Major drawbacks include insensitivity to the early damage state of the structure and great difficulties in correlation to residual strength and durability. As the count density of small flaws grows due to damage, the structure's resistance to further damage decreases although its ultimate strength may not be significantly changed initially [14,15]. When there is a dense accumulation of small fractures, they begin to interact rapidly, allowing the formation of large cracks under relatively small load increases [12]. It is only after this stage that any of the current testing methods can reliably detect a problem [16], but at that point, it is often too late or too costly to repair the structure [13,15].

2.2.1. Core sampling

The most accepted method of determining the residual strength of concrete and from that of the damage state is by taking core samples and performing standard strength tests and/or petrography [15,17]. This method is hardly a nondestructive method and may not be acceptable for cosmetic reasons. It also has the disadvantage that deterioration cannot be evaluated as a function of time. Finally, the compressive strength of the selected core sample is not necessarily representative of damage that may affect durability [17,18].

2.2.2. Pulse-echo and through-pulse

Pulse-echo is an arrangement for ultrasonic testing using a pulsed stress wave, which propagates through the material until it hits a reflective surface and returns to the point of origin where it is detected and recorded. A reflective surface is any surface between two media in which the acoustic impedance of each medium is not the same. This could be a flaw, an inclusion or void or the opposite border of the material being tested. It is obvious that the larger the reflective surface is in comparison with the primary wave beam generated by the transducer, the more energy will be reflected back toward the source and less energy will pass on. Hence, flaws will significantly reduce the total energy at the receiver while also spreading it out over time [19,20]. Through-pulse testing is an arrangement of two transducers such that the ultrasonic signal propagates through the material. Flaws either reduce the energy by attenuation or increase the signal path by reflecting the signal.

The minimum flaw size detectable by ultrasound in a continuous homogeneous medium is about four times the wavelength of the signal. In heterogeneous concrete, however, the noise developed by the interface between constituents will obviously mask the signal of any flaw less than the maximum size of the aggregate, and even then, statistical meaning must be achieved. Additional information may be obtained using velocity analysis.

2.2.3. Pulse-velocity

Currently, the standard ultrasonic analysis method for concrete testing uses ultrasonic pulse-velocity [16]. Pulse-velocity is defined as the speed at which a pulse signal propagates through a medium. Usually, it is determined by initializing a signal at one point on a sample and recording the travel time that it takes for that signal to reach another point. If the path length is known, then the velocity can be calculated [21]. Unfortunately, this travel time has been shown to have negligible sensitivity to microfracturing (and thus damage state) in concrete and only begins to change around 80% of the compressive capacity when large fractures form [15]. According to ASTM standard C 597-97, the pulse-velocity may be related to the dynamic modulus of elasticity, dynamic Poisson's ratio and density. Because these three parameters are not very sensitive to the presence of microcracks, they only register appreciable difference when interacting microcracks start to form macrocracks [16]. This change may start to take place around 60% of the ultimate compressive strength but only becomes substantial when loaded beyond 80% of the compressive capacity.

2.2.4. Pulse-amplitude

A second method of pulse analysis for damage state is by amplitude (or energy) analysis methods. This is dependent on the attenuation of the material. Ideally, one measures the amount of attenuation of the signal in the material and compares it with the expected attenuation or the undamaged material attenuation to estimate the state of damage. Attenuation depends on three parameters as follows: scattering, absorption and geometric factors. Scattering comes from small discontinuities like grain boundaries or aggregate interface. Absorption is from dislocations or elastic damping, and geometric factors can be described by diffraction, beam spread or coupling losses [20].

This method is potentially more sensitive than pulse-velocity [13]. However, this method is strongly dependent on coupling for reliability [13,16]. The difficulty is in the fact that contact ultrasonic methods have poor repeatability in coupling conditions. It is also obvious that if the structure's load history is unknown (it has not been continuously monitored), there is no baseline for comparison of amplitude or energy domains. The final problem with this method is the additional requirement of skilled analysis.

2.2.5. Acoustic emission

Another method of damage state analysis is by monitoring acoustic emissions. As cracks begin to form, failure at localized tension zones releases energy in the form of acoustic emissions. These can be recorded and analyzed using various methods to estimate the rate of crack formation and propagation as well as the type of cracks forming. The health relative to the state of the structure when monitoring began can be ascertained in the area monitored by the transducers. However, in concrete, the emissions attenuate quickly; therefore, unless cracks form very near to the transducers, they must have very high initial energy that comes only from the formation of a large crack.

2.2.6. Nonlinear NDT

Both pulse-velocity and pulse-amplitude methods may be termed "linear acoustics." The effects of properties such as scattering, reflection and absorption on the phase and/or amplitude of a signal are analyzed in linear acoustic methods while the frequency is assumed to remain constant. Nonlinear acoustics investigates the effect that damage, flaws and other such properties have on the modulation of the frequency of a signal as it propagates through the material [22]. This damage results in a nonlinear relationship between stress and deformation (equation of state) of the material where the degree of nonlinearity depends on the level of damage. The elemental case affecting interactions between elastic acoustic waves and the damage state (i.e., microcracks) of concrete is a single microcrack. The most basic way to consider a crack-like defect is as a planar interface where there is no adhesion between two semi-infinite elastic materials [2]. Under acoustic interrogation due to dilatational waves, as the compression phase passes through the defect, the two sides of the interface are in direct contact. Similarly, the tensile phase passes through the defect, yet because there is no traction across the interface, the two sides separate and the contact becomes zero, thereby forming harmonics.

A more complex model modifies the planar interface to be a nonuniform interface. In this case, a rough surface is in contact with another surface and the changes in local stresses will either increase the contact area or decrease it. In the presence of an acoustic signal, this results in modulation of the signal amplitude with respect to frequency [3,22].

2.2.7. Frequency analysis

One promising method currently used for damage evaluation is frequency domain analysis of the stress waves that have propagated through the material. Cracks and deterioration in concrete modulate the frequency domain of stress wave much more than undamaged concrete does. This can be attributed to the count density of cracks or microcracks that make up the majority of the damage. The expected result of analyzing the frequency response of a signal through a damaged area is a shift of the spectral energy away from the frequency of the probe signal [13,22,23]. The fundamental frequency becomes less defined and other harmonics develop. This method has been used successfully to detect distributed damage and has been proven to be more effective for concrete damage detection than most linear acoustic methods [13]. Frequency analysis is not terribly new for testing metals; however, in concrete, it is only recently that this method has been applied [13].

Any method of acoustic nondestructive testing that relies on frequency analysis of a signal that is modulated by its interaction with flaws that are otherwise passive may be considered to be a passively modulated acoustic method. The biggest problem that was discovered during testing with passively modulated frequency analysis is the difficulty in distinguishing the modulated energy from the probe fundamental energy to quantify the distortion. For example, if the transducer puts out an energy signal consisting of a bandwidth covering 100 Hz and if 80% of the energy is lost in attenuation, then there remains only 20% of the original energy. If one-tenth of the signal energy is modulated as a small offset down the frequency scale by 10 Hz, similar to the theory explained previously, then the resulting spectrum would show the fundamental frequency band with a small (very small) hump for about 10 Hz off the low-frequency side of the fundamental band. The small shift of energy across the fundamental bandwidth also results in a small loss at the high end. In that case, only the outside portions of the frequency band of the signal are modulated in such a manner that damage can be discerned by spectral analysis. The use of a very narrow band tone burst signal may increase the size of the hump, but the fundamental will still be proportionately larger than the frequency offset. Therefore, a large magnitude offset by passive modulation still requires high levels of damage.

2.3. Active nonlinear wave modulation

Because the level of modulation in passive signals is dependent on the amount of damage and the amplitude of cyclic opening and closing of cracks, one might force the cracks to deform in a controlled fashion. Contact areas of cracks could be further excited by a second stress wave, hence leading to improved modulation of the probe signal and therefore sensitivity to the presence of damage. Hence, any acoustic testing and analysis methods that depend on that active perturbation could be called AMA methods.

In addition to analyzing the frequency spectrum of modulated stress waves (just like the passive modulation techniques), advanced nonlinear acoustics simultaneously employs a secondary wave to effectively agitate the material through which the primary wave passes [4,18,22,24]. The result is a modulated through-signal with readily recognizable sidebands, which indicate the extent of flaws [22]. The expected location of the sidebands is the probing frequency plus and minus the frequency of the modulating wave. Such a difference immediately removes the problem of separating the amplitude of the modulated energy from the probe energy because the location is generally known. Secondly, because both energies are concentrated in known frequencies, they can be easily compared across the range of damage.

Defects may not always be planar contact type cracks that occur in a plane normal to wave propagation. However, Sutin and Nazarov [3] and Sutin and Donskoy [22] claim that the orientation of the crack toward the direction of propagation is insignificant in the presence of active modulation because the outcome of active modulation is elemental stiffness modulation. Additionally, voids and inclusions also act as modulators.

3. Experimental program

This active modulation concept was applied to concrete at WSU. Several test procedures were compared side by side to evaluate the validity of the nonlinear AMA NDE approach.

3.1. Sample preparation

A batch of mortar cylinders was created and allowed to cure and then thoroughly dried so that in all testing to follow we would have consistency. The mortar cylinders, measured 2-in. diameter and 4-in. in height, were made of cement/water/sand (1:0.45:4.17 by weight). These samples were cured 28 days in water. After curing and drying, all of the samples were trimmed to square. Several of these cylinders were tested for compression strength, with the average results shown in Fig. 1. This figure also shows the forces used to initiate microcracking of different degrees in several additional samples. The degree of microcracking in each case is estimated in relation to the average strength of the samples. The initiation of microcracking in concrete under static loading (although some cracking preexists due to shrinkage, etc.) typically occurs around 30% of the ultimate capacity. The count density of cracking increases until the formation of macrocracks at a force near 80% of the capacity. Therefore, each of the cylinders loaded as in Fig. 1 has a different and proportionate degree of microcracking.

3.2. Test procedure

The virgin cylinders were first tested using the standard ultrasonic pulse-velocity tests using through-pulse techniques. They were then retested for ultrasonic attenuation by measuring the average peak amplitude of ultrasonic through-pulse signals. Finally, they were tested by measuring the frequency shift and distortion similar to the studies

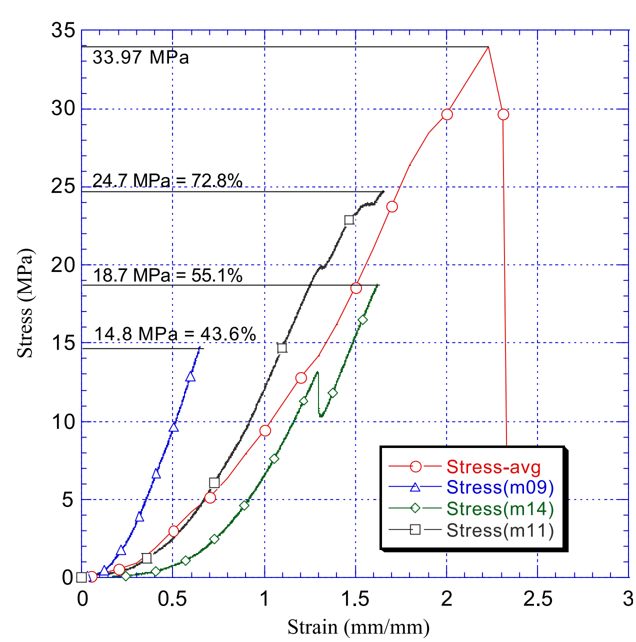

Fig. 1. Load diagram for the set of mortar samples sent to LANL.

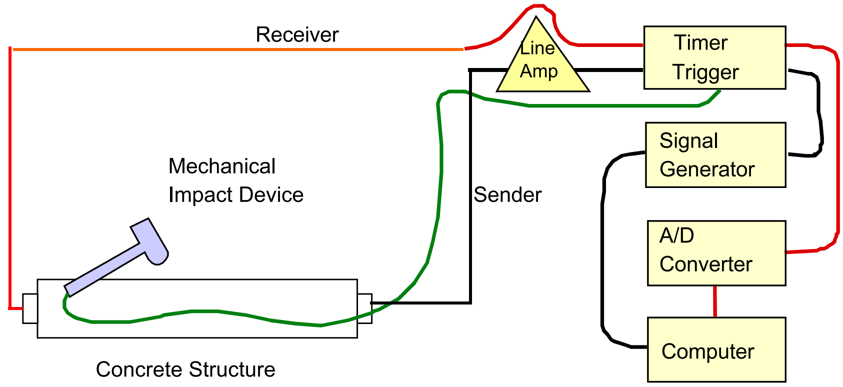

Fig. 2. Schematic diagram of the testing setup used for AMA testing.

reported in the literature [13,23]. The same samples were then damaged by applying compressive forces to them as described above; then, the ultrasonic tests were repeated on them. These damaged samples were split into two similar series for further testing. The first set of concrete samples was sent to Los Alamos National Laboratory (LANL) to be tested by Dr. Sutin. The other series was tested at WSU. This provided us with a higher level of reliability for testing the validity of the AMA technique.

The setup was similar in all ultrasonic testing cases and can be seen schematically in Fig. 2. The impact hammer was only used for the active modulation testing. The tests all consisted of passing an ultrasonic signal from a 100-kHz piezoelectric transducer through the sample to be received by a matching 100-kHz transducer. In all cases, the transducers were acoustically coupled to the sample using a thin layer of petroleum jelly. The transducers were oriented with the receiver face up on the counter top, coupled to the bottom of the sample, and the sender on the top. An isolated clamp was then used to keep the transducers from slipping when tested using the AMA method. A photograph of the testing setup is shown in Fig. 3.

3.3. Signals

In AMA nonlinear testing, two waves were introduced into the test object simultaneously. The frequency and initial energy of the probe wave was chosen to assure that the received signal is useful (i.e., voltage output of the receiver is much greater than the line noise). Both conditions depend on the equipment used and the properties of the test material. One major concern was that the frequency used for the probe signal could not be near the resonance frequency of the object; otherwise, the resonance would mask signal information. Transducers were mounted on the sample as shown for the ultrasonic testing (Fig. 3). For the probe signal, a “continuous” sinusoid generated by an analog waveform generator and amplified by a 20 × gain high-voltage amplifier was used.

The modulating wave was required to be of much lower frequency than the probe frequency and could be of any type that would be useful including impact, impulse or tone. However, the duration of the modulating wave needed to be sufficient that all areas of interest were affected by the wave at the same time as the probe wave was passing. Active stress waves were formed by impact (Fig. 4) because of the simplicity of generating a strong, low-frequency stress wave by the use of a tuned impact hammer. Fig. 5 shows the recorded signals. The time-variant signal is only used to make sure that the waves are of similar amplitude and general shape, thereby reducing the possibility of erroneous records. For example, the sample end near the sending transducer was tapped lightly such that the maximum magnitude of the received signal was about four times the magnitude of the probe signal alone for every specimen. Fig. 6 shows the transformed

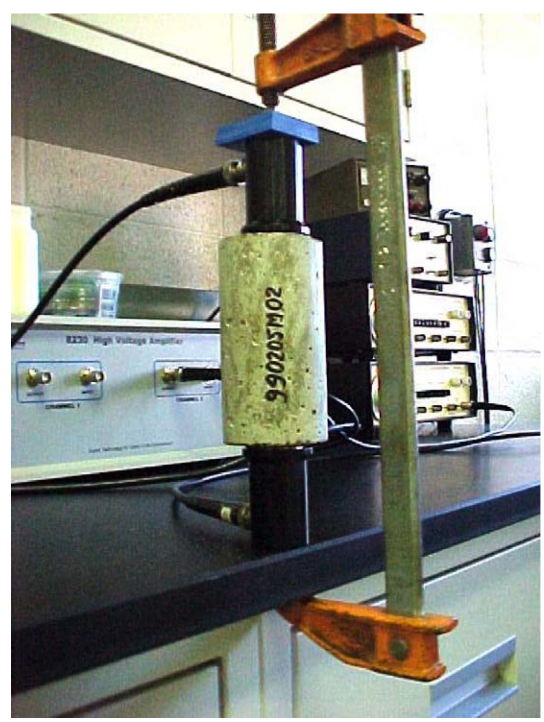

Fig. 3. Picture of the setup for ultrasound testing.

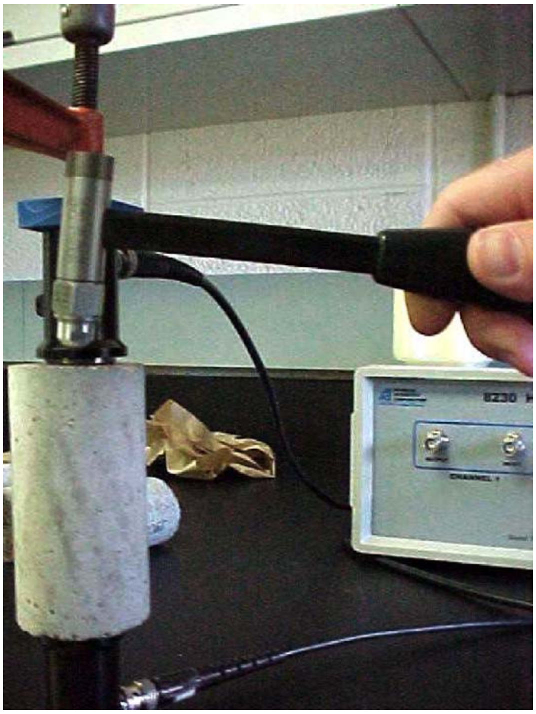

Fig. 4. Picture of the use of a modally tuned impact hammer to perturbate damage in the concrete for AMA testing.

frequency spectrum of the above signals for a small range of frequencies near the central frequency of the receiver. The sidebands can be seen progressively larger as the concrete has more microfracturing.

The signal was acquired and recorded by a 12-bit A/D computer board, windowed using the Blackman window and transformed into the frequency domain using the chirp-z

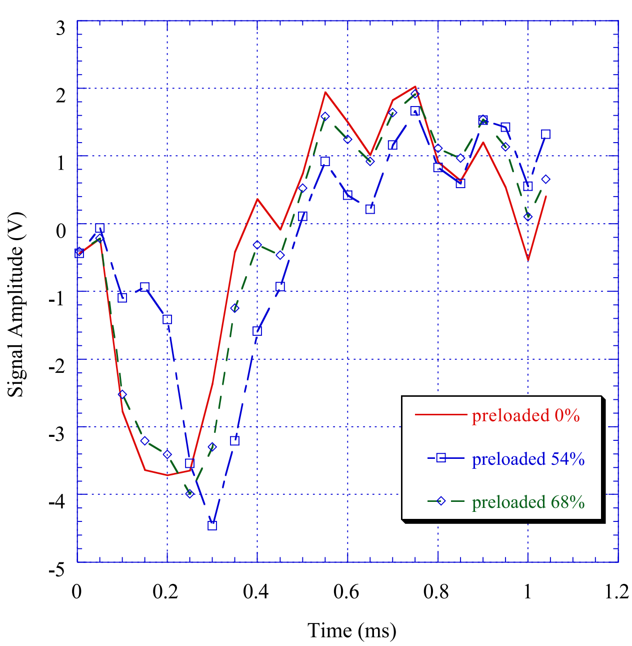

Fig. 5. Time domain signals from several AMA tests.

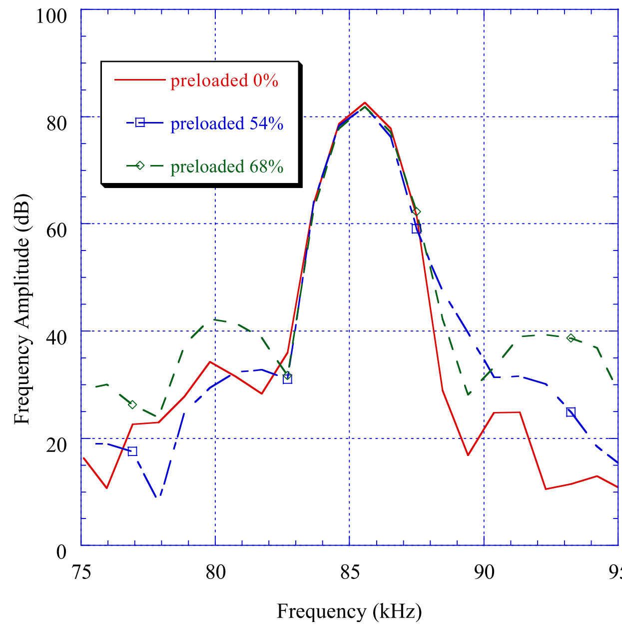

Fig. 6. Frequency domain signals from several AMA tests.

transform for better resolution near the fundamental frequency. Because the majority of the impact energy was contained in the range between 0 and 10 kHz, only the transform range $\pm$ 10 kHz around the probe frequency was considered for comparison. This range was averaged on a normalized decibel scale. The results, therefore, can be easily compared from one sample to the next. The larger the magnitude of the average, qualitatively, the more internal microcracking there is.

The procedure for identifying the frequency modulation entailed a transformation of the received time domain waveform into the frequency domain. Frequently, this is done with the Fourier transform, which requires a very large even-numbered data sample to achieve a meaningful resolution. In our analysis, we used a chirp-z transform covering the frequencies of interest only. Often, in concrete, testing short waveforms are received because of the attenuation characteristics of the material and because of time considerations. Alternative transformation algorithms have been developed to reduce the required sample size for time-frequency transformations while maintaining or increasing the frequency resolution but are not within the scope of this paper.

3.4. Preliminary results

A series of concrete samples was loaded to 0%, 35%, 44%, 52%, 55%, 68% and 73% (Table 1) of the ultimate compressive strength to induce different internal damage. These were later split into two groups for testing at separate facilities. Conventional linear acoustic methods (pulse-velocity and amplitude attenuation) and nonlinear acoustic methods (active and passive) were applied to the samples before and after the induction of internal damages. For comparison purposes, sensitivity factors that attempt to normalize the capability of testing methods for damage evaluation were proposed by Daponte et al. [13]. For pulse-velocity, the sensitivity factor (to damage) was defined as

$$D_v = 1 - \frac{x}{x_o}$$

where x and x_o are the velocities through the damaged and undamaged specimens. For amplitude attenuation, the variable D_a was calculated in the exact same manner as D_v, where x and x_o in this case are the relative amplitude values. For frequency analysis, D_f is the sensitivity of the total harmonic distortion in the frequency domain of a signal to the damage state in the samples

$$D_f = 1 - \frac{THD_o}{THD}$$

where THD is the total harmonic distortion of the sample in question and THD_o is that of the undamaged sample. The total harmonic distortion is defined as the root mean square of the signal without the fundamental frequency band of the transducer divided by the root mean square of the fundamental. In reality, this is simply a mathematical expression of the relative amounts of energy recorded in the fundamental band and the rest of the frequency spectrum.

A graphical representation of the test results is shown in Fig. 7. As expected, D_v is rather insensitive to the degrees of damage until near 80% of the ultimate compressive strength; D_a is somewhat better. A standard passive spectral analysis ($D_{f(passive)}$) shows further improvement. All of these are shown to be somewhat dependent on the damage state of the concrete. Sellec et al. [23] already indicate that none of these is very reliable for evaluating distributed damage. Deviations in each of the first three cases were relatively large. Also note that in the case of amplitude measurements in the contact case it is very difficult to get repeatable coupling.

In contrast, active modulation ($D_{f(active)}$ in the graph) reveals very good sensitivity to the state of damage. The values of sensitivity for the AMA method used in the graph were calculated as the magnitude of the fundamental peak of the spectrum divided by the average magnitude of the first sidebands. An example of the signal and analysis results for an actively modulated signal can be seen in Figs. 5 and 6, respectively. Two series of similar cylinder samples were tested, one at LANL and one at WSU, using the AMA method with comparable results as tabulated in Table 1. However, because a decibel is a relative measure of intensity and the two test series were performed and analyzed at separate facilities with some differences in experimental setup, the values of the results differ somewhat. From these results, it can be seen that early detection of microcracking that forms around 30% of the compressive strength can be achieved if damaged concrete is actively interrogated using more than one waveform. The current results appear to be very promising. Nevertheless, there remains work in the area of refinement of active modulation methods. This method of analysis has only to be fully developed.

Table 1
Frequency analysis results of AMA signals for both sets of mortar samples

	Tested by Dr. Sutin at LANL				Tested at WSU		
Sample ID	m08	m09	m14	m11	m02	m04	m01
Loading portion of max (%)	0	44	55	73	0	52	68
Average level of side components (dB)	− 63	− 60	− 51	− 34	− 57	− 52	− 45

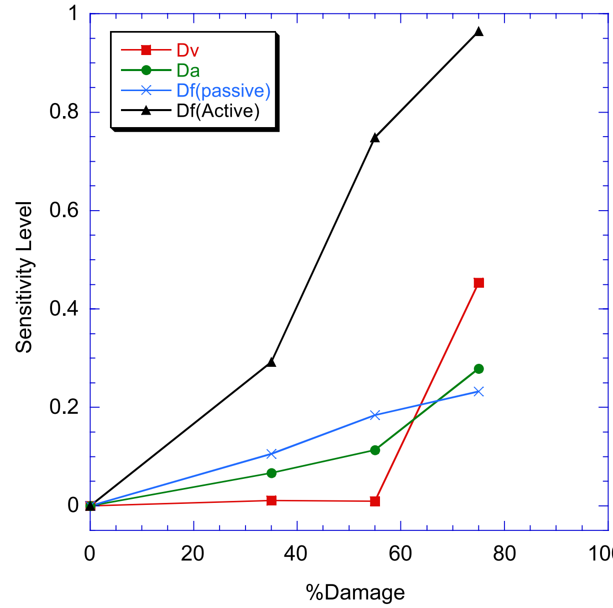

Fig. 7. Graph of the relative sensitivity of several nondestructive testing methods to levels of damage in concrete.

4. Further remarks

The ultimate goal of this project is to develop AMA technique for strength assessment of concrete structures. If successful, this technique will not require prior records of baseline acoustic information of the concrete structures or loading history of the structure. These features are important for any vital NDE technique because, more than likely, aging structures do not have such records available. In addition, this technique can be applied directly in the field nondestructively without a need to take core samples. Finally, it should be noted that damage in concrete could also be due to environmental effects such as freeze-and-thaw or deleterious deicing agents. These damages might not be the same as that due to loading. Such environment-induced damage will be investigated in the future.

5. Conclusions

The need in testing concrete for residual strength is not so much in the ability to detect high levels of damage only but in being able to reliably and efficiently quantify all ranges of damage. At present, there are no robust and reliable methods of doing this; however, the active modulation of acoustic waves seems to be a promising method for providing good evaluation of the level of damage in all sorts of materials including concrete. In this study, several test procedures were compared side by side to prove the validity of the AMA nonlinear approach. Both actively and passively modulated acoustic analyses of probe frequencies represent nonlinear parameters; however, by our tests and the theory involved in the procedure, active modulation is more sensitive to concrete damage. Further study into the exact correlation and thus quantification of the above results is needed before this method can be useful. Additionally, more study is needed to determine the optimal and most robust application of the above method.

Acknowledgements

The authors thank the staff of the Department of Civil and Environmental Engineering of Wayne State University for their help in this study. The authors also thank Dr. A. Sutin for introducing active modulation to us and for providing much valuable guidance. Finally, we thank the reviewers who provided very useful suggestions.

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