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Author(s): Chyr, Anthony
Lake, Colton R
Idler, Garrett W
Ulrich, Timothy J. II

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Quantifying Penetration Depth of Damage in Concrete Structures Using Nonlinear Elastic Wave Spectroscopy

Anthony Chyr[1], Garrett W. Idler[2], Colton R. Lake[3], T. J. Ulrich[4]

1. Dept. of Mechanical Eng., University of Utah, Salt Lake City, UT 84112
2. Dept. of Mechanical Eng., Colorado State University, Fort Collins, CO 80523
3. Dept. of Civil Eng., New Mexico Institute of Mining and Technology, Socorro, NM 87801
4. Solid Earth Geophysics (EES-17), Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract The ubiquity of concrete as a building material necessitates the ability to inspect and evaluate its structural integrity, preferably in a nondestructive manner. Of particular interest is the ability to detect and quantify the degree to which surface damage penetrates concrete. This is especially important in the nuclear energy industry where concrete is used as a barrier protecting the primary confinement vessel, such as in dry storage casks, in which case cracks form a path for corrosion. Nondestructive evaluation techniques based on the material's nonlinear parameters are orders of magnitude more sensitive to the presence of damage than linear methods analogous to sonar. Two methods, both subsets of Nonlinear Elastic Wave Spectroscopy (NEWS), were used: Nonlinear Resonance Ultrasound Spectroscopy (NRUS) for evaluation of a sample's bulk nonlinear characteristics, and Time Reversal Elastic Nonlinearity Diagnostics (TREND) for evaluation of a sample's local nonlinear characteristics. These nonlinear characteristics are strong indicators of the presence of damage. Eight concrete samples were cut into two pieces, of the two piece one was thermally damaged for three hours at 500 C. Evaluations of these pieces using NRUS showed a seven times nonlinear parameter increase for the damaged pieces over the undamaged pieces. Using a minimally participating adhesive, samples were glued back together and evaluated using TREND. Results from TREND likewise aligned closely with the expected modeled response.

1 Introduction

1.1 Motivation

As concrete structures continue to age, many structures are reaching their expected life span, and understanding the structural heath of these structures is of increasing importance. In the nuclear industry, dry storage casks are used to contain spent nuclear fuel. These casks are typically made of steel with an outer layer of two to one to one and a half meters of concrete. Thermal damage resulting from heat emanating from the store material and freeze thaw damage from weather on the outside of contains are the primary causes of damage.[1]

Conventional ultrasonic techniques in non-destructive testing have been in use as early as 1942 with the work of F.A. Firestone [2]. While these convention methods, analogous to sonar, have since improved; small material defects such as microcracks continue evade detection. The presence of these small material defects tend to soften the host material, thus reducing its load bearing capacity, in addition to being the source of macroscopic cracks. As such, direct detection through conventional methods may not be viable, as the high frequencies required to achieve the necessary spatial resolution would quickly attenuate within the host material [3]. Methods that interrogate nonlinear material characteristics within the host material on the other hand, such as the softening effect of micro-cracks, have been shown to be orders of magnitude more sensitive to the presence of damage than conventional methods [4], and will be the focus of this paper.

1.2 Background

1.2.1 Damage

<picture of transition halo>

In concrete, the most brittle zone is the interface between aggregate and cement paste. This zone, called the transition halo, is the most porous and crystallized. With increasing temperature, this zone is progressively degraded due to the evaporation of free water and the difference between the thermal expansion of the aggregates and the cement paste. The degradation results in an increase in porosity and microcracks [5]. As the magnitude of strain increases, microcracks are more likely to open, which results in the softening of the elastic moduli and a measurable drop in the elastic wave speed in the material. The presence of microcracks also leads to higher harmonics in addition to an increase in attenuation.

1.2.2 Methodology

Three methods were used to characterize concrete samples with known depths of damage. The first method, call Resonance Ultrasound Spectroscopy (RUS), is a nondestructive interrogation technique that allows the elastic moduli to be characterized. The second and third method, called Nonlinear Resonance Ultrasound Spectroscopy (NRUS) and Time Reversal Elastic Nonlinearity Diagnostic (TREND), are nonlinear techniques where the strain magnitude is varied and the consequences of a drop in wave speed were measured.

RUS uses a transducer and receiver system and a stepped sine input to excite the sample's resonance frequencies. By determining the frequency of the resonance peaks, a stiffness matrix may be constructive given the density and geometry of the sample [6].

NRUS looks at the relationship between the peaks in the frequency response of a test specimen at increasing drive amplitudes. For example, when an ideal bell rings, it has resonant modes that dominate the response, and when the bell is hit it harder, the bell rings at the same modes only louder. Now imagine the same bell, but with a series of cracks running along its side. Hitting the bell lightly results in a similar response of the bell when it was undamaged, but the harder it is hit, the more affect the cracks have on response of the bell. Cracks have been shown to increase the damping of the system, shown as a reduction the amplitude and a widening of the response of the resonant peaks of a sample. Furthermore as the material softens, the wave speed decreases, and the resonance peaks shift toward lower frequencies. NRUS provides a quantization of the amount of damage in a specimen by looking at the shape and location of resonance peaks in the frequency response as a function of the strain magnitude [5].

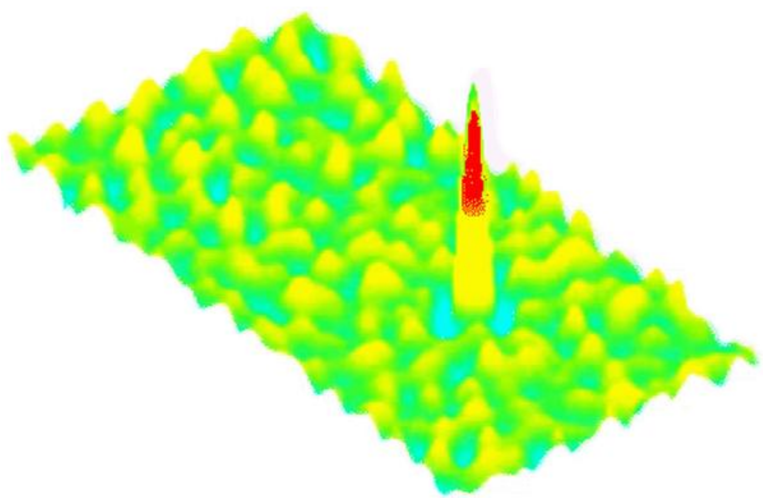


Fig. 1 Surface mapping of time reversed focus. Large peak indicates focus within a aluminum plate from previous work.

TREND employs time reversal to focus energy to a highly localized region of a sample [7], in this region the nonlinearity is most pronounced and quantified. In time reversal, imagine dropping a rock into a pond. The rock creates a series of waves that propagate away from the point of impact. Now imagine placing an array of receiver/transducers around the point of impact, each of which set to record the pressure wave as it pass through the array. After a long period of time, the wave dissipates. If the array of receiver/transducers play the pressure wave in reverse, the back-propagating waves will simultaneously arrive at the original point of impact in phase producing a time reversed focus, a reconstruction of the original wave reversed in time [8]. Using time reversal to create a focused signal at a desired location of measurement, nonlinearity can be quantified in a focused region by comparing the frequency response of the test specimen as drive amplitude increases [9].

1.3 Objective

This series of experiments focuses on employing nonlinear techniques to empirically quantify the amount and location of damage in concrete. Concrete test specimens with a known depth of thermally induced damage were prepared. Three steps were taken to approach the problem. In the first first step, RUS was used to characterize the concrete sample used for testing. These material properties derived from RUS were used to simulate the signal's penetration depth in TREND in addition to allowing finite models to be created used to simulate subsequent tests. In the second step, NRUS testing was used to quantify the bulk nonlinearity in a samples. In the third step, TREND allows for nonlinearity to be characterized in a focused region, and the depth of the damaged region to be deduced.

2 Experimental Procedures

2.1 Specimen preparation

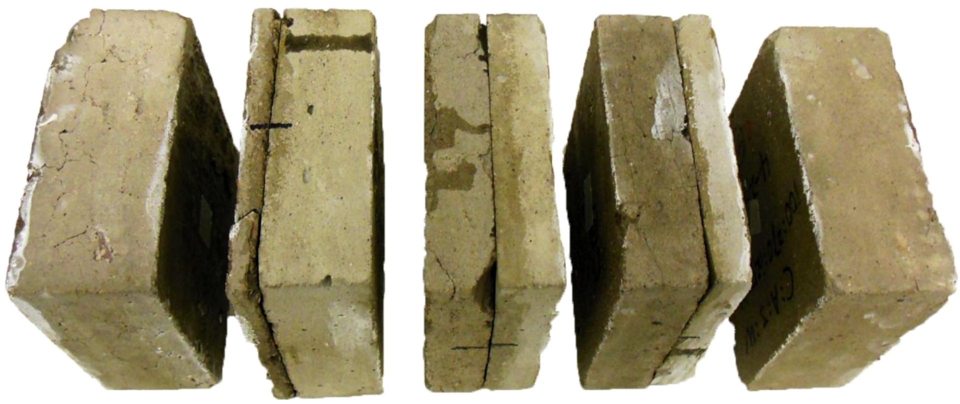


Fig. 2 Concrete specimen samples. From left to right: completely damaged sample, partially damaged sample, half damaged sample, mostly damaged sample, undamaged sample.

Concrete test specimens were prepared using Portland cement with a medium aggregate mixture. Eight blocks were produced with nominal dimensions of 100mm wide by 100mm tall by 50mm deep. Variation in dimensional sizes arose because the pouring process for concrete does not result in tight tolerances and removing the concrete blocks from the mold lead to a small amount of flaking and chipping on exposed surfaces.

Five of the blocks were cut at various thickness to create two pieces with the 100mm wide and 100mm tall but with varying depths. The depths were made to be as close to evenly spaced as possible but some variation due to inaccuracies in the cutting method did occur.

Table 1 Sample characteristics. A denotes the damaged side of the sample. B denotes the undamaged side of a sample

Sample ID		Dimensions			Mass (g)	Density (g/cc)
		x (cm)	y (cm)	z (cm)		
C1	A	10.10	10.27	1.07	240.40	2.17
	B	10.19	10.26	4.05	871.60	2.06
C2	A	10.28	10.23	1.74	393.90	2.16
	B	10.14	10.22	3.05	694.50	2.20
C3	A	10.17	10.18	2.64	580.80	2.12
	B	10.18	10.17	2.35	507.00	2.09
C4	A	N/A	N/A	N/A	N/A	N/A
	B	10.18	10.17	5.08	1152.40	2.20
C5	A	10.25	10.17	5.34	N/A	N/A
	B	N/A	N/A	N/A	N/A	N/A
C6	A	10.17	10.27	3.30	729.70	2.12
	B	10.14	10.16	1.64	342.90	2.03

	A	N/A	N/A	N/A	N/A	N/A
C7	B	10.11	10.13	5.16	1142.00	2.16
	A	10.13	10.24	4.19	904.90	2.08
C8	B	10.10	10.25	0.88	176.60	1.94

One of the uncut blocks and one piece of each of the cut blocks was selected for heat treatment. The selected specimen were heated in a furnace at 500 °C for three hours with a 1 °C per minute ramp during heating and cooling to encourage uniform heating and cooling in the specimen. This was used to develop uniform microcracks throughout the heated specimen for nonlinear testing. The heating process resulted in one fully damaged specimen and five damaged pieces. The damaged pieces were labeled “A” and undamaged pieces were labeled “B” for recognition.

2.2 Testing Procedures

2.2.1 Resonance Ultrasound Spectroscopy Sample Characterization

Resonant Ultrasound Spectroscopy (RUS) was used to characterize each piece of the eight concrete specimens. A stand for holding the block using piezoelectric transducers and a stepped sine signal were used to excite and measure the frequency response of the blocks in the 700 Hz and 20kHz region. RUS uses the resonant response via resonant peak location in the frequency domain and the geometry of the test specimen to determine the elastic tensor for the tested material. The concrete was assumed to be isotropic and the first three peaks of the results were used to get a value for the Elastic Tensor. Many of the damaged specimen did not yield clear peaks because the cracks absorb energy of the signal and introduce small resonances the make the response less clear. Average Elastic Moduli and Poisson’s ratios for the damaged and undamaged states were calculated from the response.

The theoretical frequency response for the specimen was determined using finite element modeling using Abaqus CAE. The theoretical values and the mode shapes were used to verify the peak resonance frequency values from the RUS measurements.

2.2.2 Nonlinear Resonance Ultrasound Spectroscopy

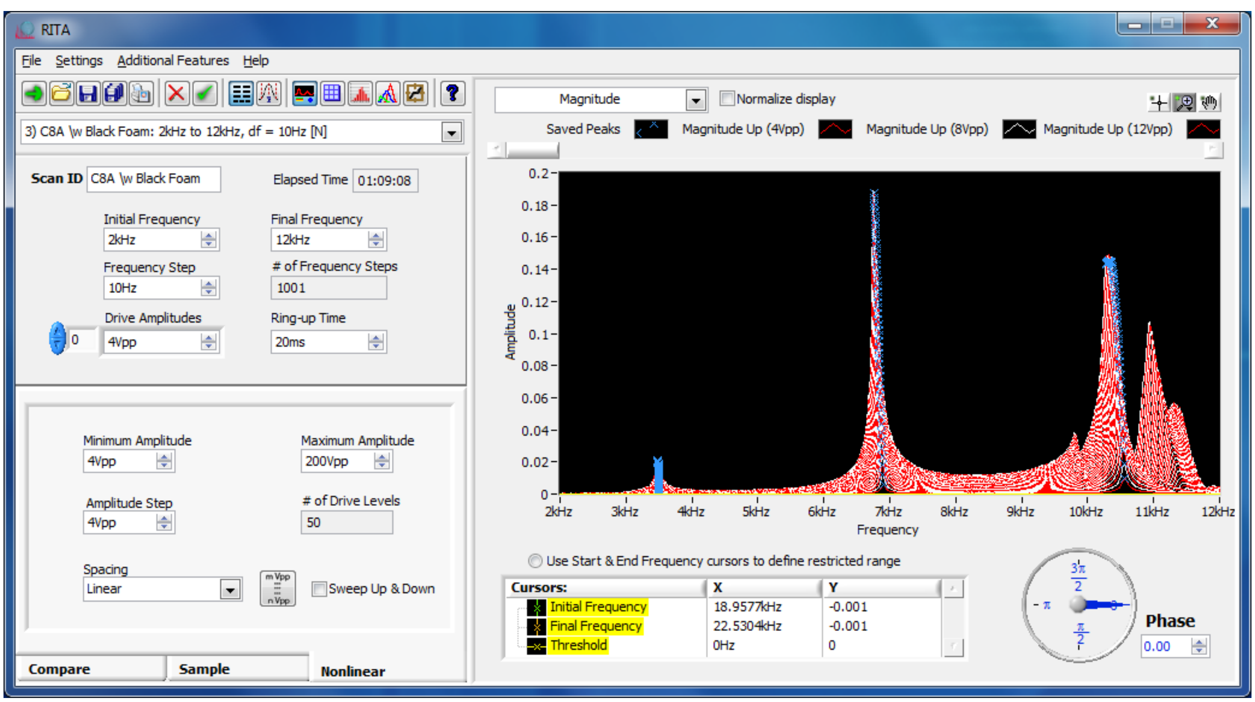


Fig. 3 NRUS measurement. Software interface showing the overlay of forty scans between 4 Vpp to 200 Vpp. Blue crosses indicate peak locations.

Once each specimen had been characterized and modeled using RUS, a large piezoelectric transducer was mounted directly on each specimen. To mount the piezoelectric actuators, the surface of the concrete was covered in a layer of clear nail polish in order to prevent glue from entering pores in the concrete and changing its dynamic characteristics. A layer of Elmer's All-Purpose glue was then applied to base of the piezoelectric and the transducer was mounted near the corner of the large outside face of the specimen. The glue was allowed 48 hours to dry before use. A small piece of reflective tape was applied to the face of the specimen to reflect light for the laser interferometer measurement system.

NRUS was performed on each specimen using a LabVIEW based software system and a National Instruments data acquisition system. An amplifier with a gain of 20 was used to amplify the input signal to the transducer and a Polytec fiber interferometer was used to get displacement data for NRUS analysis. Scans were conducted on a base two log scale between voltages of 3Vpp and 200Vpp depending on the individual response of the specimen. The tests were always done on the first three resonant peaks to give consistency to the measurements. The software recorded the peak shift and quality factor, inverse of attenuation, for each drive amplitude.

After NRUS characterization of the thirteen specimens was completed, the blocks that had been cut into pieces were glued back together. This created test specimens of the uncut size with a damage layer beginning at a know depth. Once satisfactory data was obtained, the peak shift due to nonlinearities in the concrete was compared to the known depth of damage so determine a correlation between peak shift and damage depth.

2.2.3 Time Reversal Nonlinearity Diagnostic Methods

Time Reversal Elastic Nonlinearity Diagnostic methods were used to quantify the amount of nonlinear response from a concrete specimen in the area of a time reversed focus. Two procedures were carried out. First, each specimen was tested using a 75kHz source signal. Time reversal focuses elastic waves that provide a measurement within one half of the wavelength of the focal point. In the concrete using a 75kHz signal, this results in an estimated measurement depth of 2cm. In order to get results that could be compared between specimen, the strain at the point of measurement must be similar between samples. Since the amplitude of the response varies greatly between specimen, the drive amplitudes were scaled such that maximum response amplitudes for each specimen were within ten percent. Ten drive levels of equal linear spacing between ten percent and one hundred percent of the maximum drive level were used, and the relationship between drive amplitudes were used as metrics for nonlinearity. This method was carried out twice, measuring response from the damaged and undamaged sides. For the second test, four of the eight specimen were selected: one fully undamaged, one mostly undamaged, one mostly damaged, and one fully damaged. In these tests the signal frequency was modulated so that the penetration depth of measurement was varied. Frequencies of 37.5kHz, 50kHz, 75kHz, and 150kHz were selected to measure to a depth of 4cm, 3cm, 2cm, and 1cm respectively. All measurements were taken from the damaged side of each specimen. Once again, ten linear spaced drive levels were used. The maximum strain at the point of measurement needed to remain constant between frequencies so signal frequency and maximum drive amplitude were scaled inversely in order to hold the maximum strain constant.

2.3 Analysis Methods

To determine the amount of nonlinearity in a test, the relationship between the responses of the specimen at varying drive amplitudes is observed. In NRUS testing, the nonlinearity is simply related to two parameters. First, the peak shift as drive amplitude increases can be recorded as a function of the strain magnitude.

$$\frac{f_i - f_0}{f_0} = \alpha\varepsilon \tag{1}$$

Where f_0 is the linear resonance frequency (at low amplitude), f_i is the resonance frequency when drive is at the i^{th} amplitude, α is the nonlinear parameter, and ε is the strain amplitude. This method is based on the understanding that the material softens as damage increases which results in a lower wave speed in the material and subsequently resonance peaks move towards lower frequencies. The second parameter used to characterize nonlinearity in NRUS tests is the change in quality factor (Q) as the amplitude increases. Quality factor is a measurement of how underdamped a system is and is proportional to the inverse of damping. Two different methods were used to determine the nonlinearity of TREND tests. The highest amplitude time response of a test was analyzed to determine nonlinearity. A simple peak shift method (in the time domain) was done using a simple parabolic peak fit. A scaled subtraction method (SSM) was also used, which has been shown to measure second order nonlinearity well.

$$SSM = \int_{t_0}^{t_f} \left(S_1 - \frac{A_2}{A_1} S_2\right)^2 dt \quad (2)$$

Where SSM is the nonlinear parameter of interest, t_0 is the start of the signal, t_f is the end of the signal, S_1 is the reference signal, S_2 is the signal at the amplitude of interest, A_1 is the input amplitude at the reference signal, and A_2 is the input amplitude at the amplitude of interest. This method computes the difference between the measured response at a high amplitude and a low amplitude response that is scaled to reflect the ratio of the two drive amplitudes. A plethora of parameters related to and measures of nonlinearity are available. The methods that were chosen for this preliminary test were chosen based on simplicity and convenience, and future tests would benefit from a study that determine which measure of nonlinearity best measures nonlinearity for this testing method.

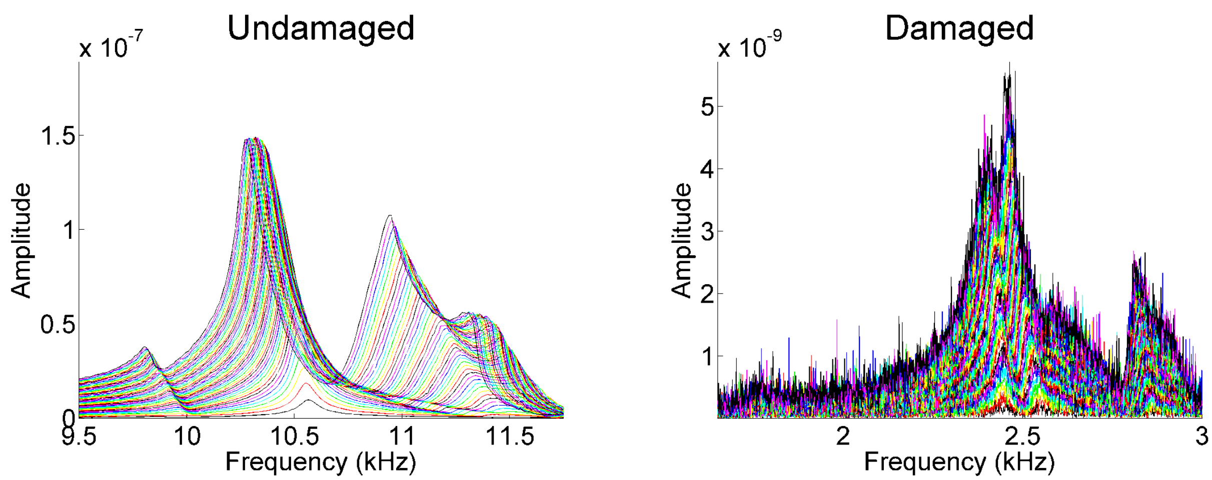
3 Results

Through the iterative process of RUS, the Young's modulus and Poisson's ratio for the concrete samples were obtained. The average Young's modulus and Poisson's ratio were 19.3 GPa and 0.13 respectively for the undamaged concrete with errors below 3%. Due to the attenuation from the damage, RUS could not be used to get Young's modulus and Poisson's ratio for the damaged samples. Based on the resonant peaks found during NRUS tests on damaged samples, which could be done because of the higher drive amplitudes, and iteratively changing values in a finite element model, a Young's modulus between 2 to 6 GPa and a Poisson's ration around 0.1 was approximated for the damaged samples. The values for the moduli are presented in Table 1.

Table 2 Young's modulus and Poisson's ratio for undamaged samples.

	C1	C2	C3	C4	C5	C6	C7	C8	μ	σ
E (GPa)	18.6	20.9	17.6	19.9	—	18.7	18.2	21.4	19.3	1.4
ν	0.089	0.107	0.105	0.168	—	0.102	0.117	0.226	0.131	0.49

There were several reasons why it was difficult to obtain the Young's modulus and Poisson's ratio for the damaged samples. The frequency response modes shifted to much lower frequencies, to a range that was so low that it possibly might have no longer been in a linear region of our measurement system. The frequency mode peaks became distorted. In plots of the frequency response of the damaged samples, the peaks became more tightly packed and less defined, likely due to the sides of the micro and macrocracks interacting and creating local resonances. In contrast, undamaged frequency response graphs are cleaner. The peaks are spaced further apart and are much more defined. Fig. 4 presents a comparison of a damaged frequency response and an undamaged frequency response. Note the lower response amplitudes, less spacing between peaks, and apparent noisiness of the damaged sample compared to the undamaged sample.



(a) (b)

Fig. 4 Frequency response of damaged and undamaged sample. (a) Undamaged sample indicates resonance near 10.5 kHz with minimal noise. (b) Damaged sample indicates resonance near 2.5 kHz.

When NRUS experiments were performed on the samples, it is easily seen that there is a difference between damaged and undamaged concrete in terms of strain and frequency shift. As shown in Fig. 2, as increasing strain is induced in the specimen by a piezoelectric transducer, a frequency shift occurs. This frequency shift depends on the concrete and the amount of damage within the concrete. The nonlinearity in the response of a sample increases as the strain increases due to higher drive amplitudes, and frequency shift will increase correspondingly. This shift is higher in damaged samples than undamaged samples due to more nonlinearity in the response. [7]

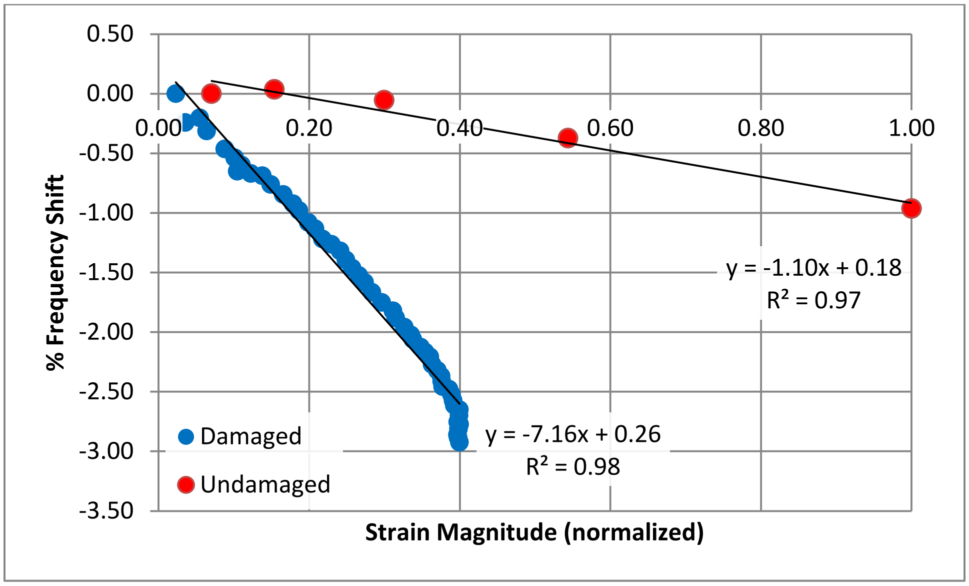


Fig. 5 NRUS percent frequency shift vs. normalized strain magnitude of sample C3 for the damaged and undamaged side. Linear regression of response produces the nonlinear parameter α.

In TREND experiments, when the signal is time reversed and then focused, it is measured as what appears to be a sine wave with a window in the time domain. In Fig. 3, the ten different responses from the ten drive amplitudes can be seen. Close inspection shows a shift to the right at higher amplitudes of the peaks because the material is softening so the waves are arriving at a later time. The max peak at each drive amplitude is found using a parabolic peak fit.

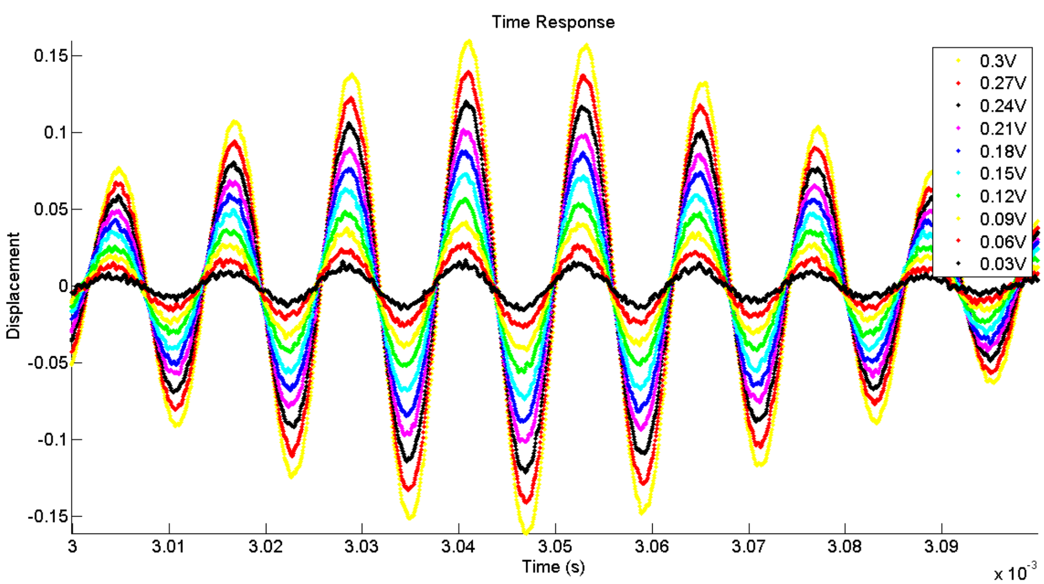


Fig. 6 TREND time response of a 75 kHz signal at various drive amplitudes.

The Scaled Subtraction Method (SSM) is used as another quantifier of nonlinearity between the different drive amplitudes. The difference between two scaled signals based on their drive amplitude is quantified. The entire focused time signal is used for the characterization and its result is shown in Fig. 4.

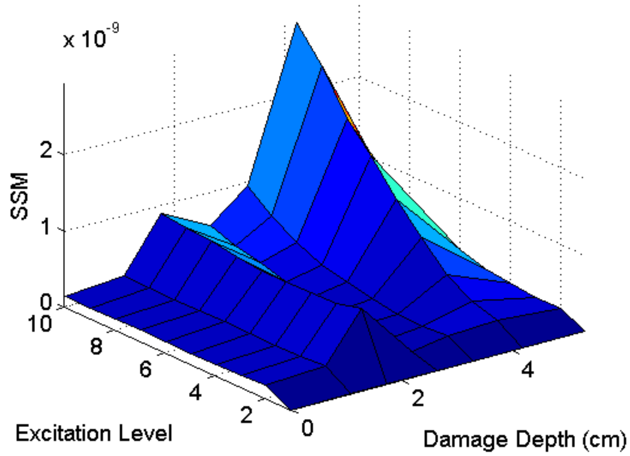
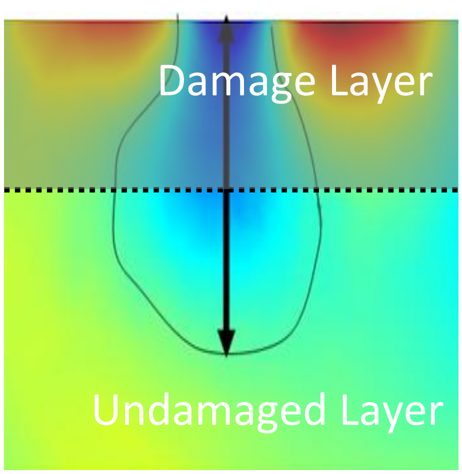
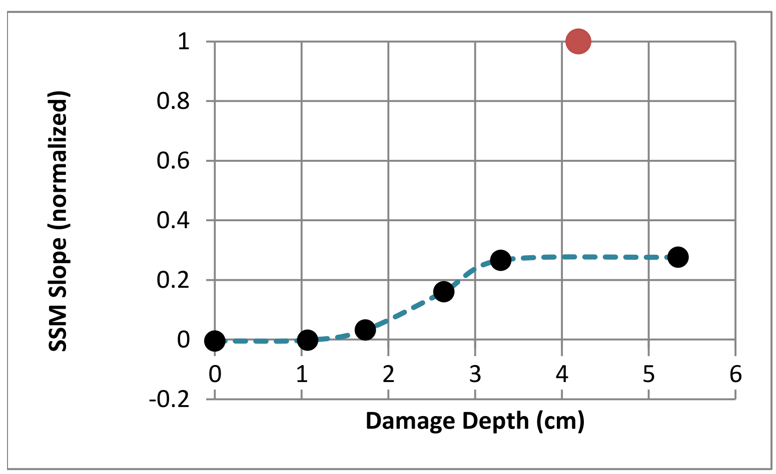


Fig. 7 SSM vs. excitation level and damage depth for all samples.

To find a correlation between SSM results and damaged depth, the slope of the SSM was plotted against the damaged depth. Other than one data point which will be dismissed as an outlier and is probably not accurate due to experimental error, as explained in the discussion section, the resulting graph shows exactly what would be respected as the damaged depth is changed. When the damage depth is zero, a totally undamaged sample, the SSM changes only a small amount because there is only a small amount of nonlinearity in an undamaged sample. An increase in the SSM's slope is seen as the damage depth is increased, because an increasing amount of microcracks are present in the area of the time reversed focus that the SSM is quantifying. The increasing trend continues until the damage depth exceeds the depth of the focus, and then the SSM slope levels off because the amount of nonlinearity in the region is not changing. Fig. 5 shows this result.





(a) (b)

Fig. 8 Comparison of penetration depth and slope of SSM. (a) Simulated signal's penetration depth of the increase strain region for sample C2 [cf. 9]. (b) Slope of the SSM as a function of the excitation level vs the depth of damage within the sample. Red point indicates improperly cut sample C8.

Error was characterized for the correlation between the slope of the SSM as a function of strain magnitude. As expected, for the first three samples where the majority of the region influenced by the signal's focus were highly linear and the results correlation was within the noise floor.

Table 3 Characterization of error for the slope of the SSM as a function of drive level. Samples with a damage depth of 0 through 1.75 are within the noise floor.

Damage Depth (cm)	SSM Slope	r	ρ @ 95%	p-value
0	-0.0016	-0.46	[-0.86, 0.29]	0.21
1.07	0.006	-0.24	[-0.78, 0.50]	0.54
1.74	0.012	-0.55	[-0.89, 0.18]	0.12
2.64	0.057	0.96	[0.81, 0.99]	0
3.3	0.094	0.91	[0.62, 0.98]	0.0006
4.19	0.35	0.99	[0.95, 1.00]	0
5.34	0.097	0.97	[0.86, 0.78]	0

4 Discussion

The primary purpose of RUS tests were to characterize the samples for use in nonlinear testing. The development of an elastic tensor based upon the placement of the resonant peaks of the sample being testing depends on clean peaks being found during the test. The nondamaged samples were easy to characterize because the frequency response had a high signal to noise ratio and peaks were well defined. A peak fitting algorithm was easily used and low RMS error was attained. The RMS error around 1.5% was attained for most samples, and the highest RMS errors were around 3%. In the damaged samples, the attenuation increased dramatically and it became exceedingly difficult to locate peaks. Fitting techniques resulted in bad peak fits and the error resulting from determining a stiffness matrix for the damaged material so high that RUS testing on damaged samples was abandoned. Approximation of the elastic constants for the damaged concrete was estimated based on high amplitude response from NRUS tests and iteratively changing the elastic moduli of a finite element model until rough agreement between results and the model could be attained.

The lack of clean data for damaged samples had an effect on NRUS measurements also, but because of the test setup, much higher excitation amplitudes were achievable and peak fits were possible, although not very attractive. The change in the peak placement was monitored as well as the quality factor, which is inversely related to attenuation. A comparison between a damaged and an undamaged sample show that the peak shift of a damage sample was seven times greater than the peak shift of a damaged sample, but its variation also was seven times greater.

TREND testing became an exercise in interpreting data. Strain at the focus of the signal had to be normalized between tests so that nonlinearity could be compared between tests, but a continuous iterative approach to scaling drive amplitudes that resulted in similar strain values was not perfectly accurate. Many uncontrolled variables could have had an effect on TREND results. Two methods for using TREND to determine the depths of damage in a material were planned for the experiment. When the signal frequency is held constant, the volumetric region of the test specimen that is being examined for nonlinearity is held constant. [8] The damaged layer can then be moved in and out of this region, in our case by changing to blocks with differing depths of damage, to quantify the the nonliearity in a region. A second method can be used that varies the signal frequency resulting in a changing volumetric region that is being examined for nonlinearity. Using this technique, the damage depth might be held constant, and the change in nonlinearity as the region of interest enters the known damaged area might be evaluated. [9] Only the first testing method was done during this set of experiments.

TREND was the most helpful in accomplishing the overall goal of quantifying damage depth in concrete. By being able to focus the energy from each transducer to a specific spot where the laser is located nonlinear characteristics are evaluated at a focused time and location. TREND shows the most promise in being able to be used to determine severity and depth of damage in concrete structures. TREND’s characteristics lend itself to becoming a viable option for creating a portable device that can be mobile and used for spot measurements on a permanent structure.

The concrete samples that were created for testing in this experiment were prepared based on a small amount of knowledge of previous tests that were used to characterize similar nonlinearities in materials. Throughout the testing procedure, more was learned about how the concrete could have been prepared differently to lead toward better results. The epoxy that was used to combine damaged and undamaged pieces for combined testing had been shown in other tests to respond to resonance tests in a very linear manner. In this series of experiments, the glue bond appeared to have an unforeseen affect on nonlinear testing that needs to be characterized more deliberately in future tests. One sample, C8, came from sample prep with geometric irregularities. When the sample was cut in two pieces, the cut surface had a large shelf on it as if the cut had been half made and then backed out and finished at a different depth. This does not affect the RUS and NRUS results because all tests were conducted with the samples separated, but when the pieces were glued together for TREND testing, the glued layer was very different from the glued layers on other blocks because the pieces did not match up well. In TREND testing, the C8 sample had a much higher SSM result than any other specimen, and so the C8 sample was excused as an outlier due to it variation in sample prep compared to the rest of the samples.

The process that was used to thermally damage the concrete resulted in such dried out concrete that it began flaking and breaking up much more easily than desired. This weakening of the material affected to removal of transducers for NRUS testing, and also could have affected the localized measurements of TREND in an uncontrolled way. In real world applications, microcracking resulting from thermal damage or freeze/thaw damage tends to produce a gradient of damage throughout the material, rather than a finite boundary layer between damaged and undamaged portions of a structure. Developing a testing mechanism that creates a gradient of damage rather than a piecewise representation of damage theoretically will respond better to a localized measurement technique like TREND so that discontinuities do no skew average characteristics of a sample.

For the TREND experiments, a higher ratio between signal and noise could have greatly helped the reliability and repeatability of our testing method. Future tests using this method would benefit from larger amplifiers and a more transducers. This test was approached as proof of concept, and a weak correlation between damage and measured nonlinearity was accepted. For future tests, an increase in the number of tested samples and repeated measurements will result a quantization of dependability and repeatability of these nonlinear testing techniques.

References

[1] Richtor, Burton, Darleane Hoffman, Raymon Juzaitis, Sekazi Mtingwa, Ron Omberg, Joy Rempe, and Dominique Warin. *Report of the Fuel Cycle Subcommittee of NEAC*. <Date??>

[2] Firestone, Floyd A. Flaw Detecting Device and Measuring Instrument. Floyd A. Firestone, assignee. Patent 2280226. 27 May 1940.

[3] Joshi, Narayan R., and Robert E. Green. "Ultrasonic Detection of Fatigue Damage." *Engineering Fracture Mechanics* 4.3 (1972): 577-83.

[4] Johnson, Paul A. "The New Wave in Acoustic Testing." *Materials World* (1999): 544-46.

[5] Payan, C., TJ Ulrich, PY La Bas, and M. Guimaraes. "Quantitative Linear and Nonlinear Resonant Inspection Techniques for Characterizing Thermal Damage in Concrete." *Acoustics 2012* (2012): 1-6.

[6] Migliori, Albert, and John L. Sarrao. *Resonant Ultrasound Spectroscopy: Application to Physics, Materials Measurements and Nondestructive Evaluation*. Tech, 1996. Print.

[7] Fink, Mathias. "Time Reversal of Ultrasonic Fields: Parts I." *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* 39.5 (1992): 555-78. Web.

[8] Anderson, Brian E., Michele Griffa, Carene Larmat, Timothy J. Ulrich, and Paul A. Johnson. "Time Reversal." *Acoustics Today* Jan. 2008: 5-16.

[9] Payan, C., TJ Ulrich, PY La Bas, and M. Guimaraes. "Probing Materials Damage at Different Depths by Use of Time Reversal Elastic Nonlinearity Diagnostic: Application to Concrete." *Acoustics 2012* (2012): 1-6.