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ULTRASONIC EVALUATION OF DAMAGE IN HETEROGENEOUS CONCRETE MATERIALS

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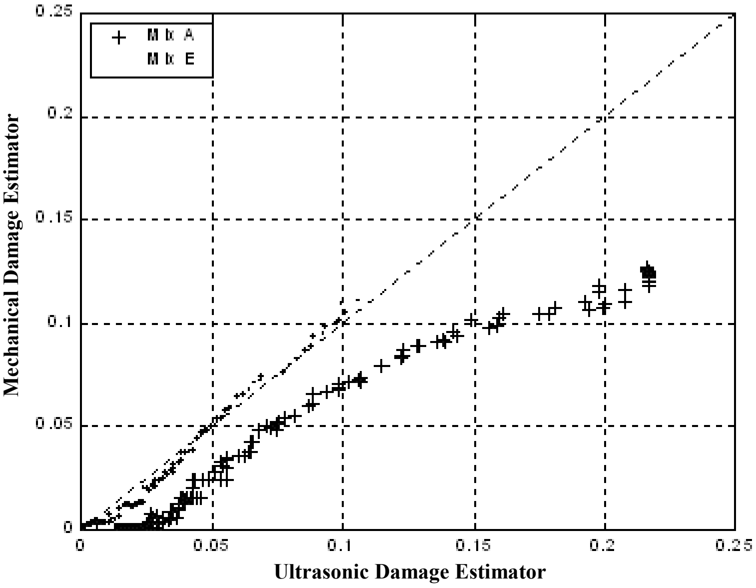
Abstract: *Ultrasonic testing provides non-destructive measurements, which are widely used to evaluate stiffness degradation in existing structures. The purpose of this research is to improve our capabilities to interpret ultrasonic pulse propagation through concrete by formally addressing the heterogeneity of concrete materials. To this end, a numerical simulation model is developed which consists of two-phase concrete meshes comprised of a damaging cement matrix and intact inclusions of elastic aggregates. In addition, a novel technique is used to develop two-phase finite element meshes based on laboratory specimens. Using this approach allows the numerical results to be directly compared with ultrasonic test data. With the described model, we investigate the change of pulse velocity through a coarse concrete specimen, which is subjected to increasing axial compression.*

1 INTRODUCTION

Recently, much progress has been made in the development of nondestructive testing and evaluation techniques for concrete materials, see [Nogueira, 1999]. In general the advantages of such methods are their ability to evaluate *in situ* properties as well as their nondestructive nature. They are based on the propagation of mechanical or electromagnetic waves that are used to assess changes in the material properties due to localized defects and distributed damage. Although various propagation methods exist, the one of high interest due to its low-cost and flexibility has been the ultrasonic method. Ultrasonic testing and evaluation relies on passing a high frequency, low amplitude mechanical disturbance through a specimen and comparing the received pulse to the transmitted pulse. The ultrasonic transmission method, which shall be our focus here, is known as the pulse velocity method according to ASTM Standard C 597. This method relies on the measurement of arrival times and path lengths through the specimen. The corresponding pulse propagation velocity can then be used: (a) to assess the quality of concrete specimen when compared with established reference velocities; (b) to detect changes of the propagation properties to identify the defects in the form of voids or cracks; and (c) to determine the severity of aggregate elastic damage. Pulse velocity data have also been used to approximate the compressive strength of concrete through experimental correlation of strength and stiffness.

Figure 1 [Nogueira,Willam 1999] – Correlation of Mechanical Properties and Ultrasonic Results



Unfortunately, due to the inherent differences of individual concrete mixes, the results from ultrasonic testing provide only a qualitative picture of the change in concrete properties. One of the factors, that affect the value of ultrasonic test results, is the nature of heterogeneities in concrete materials - specifically the type, amount and distribution of aggregate inclusions. The laboratory data in Figure 1 demonstrates this phenomenon. The results show that the pulse velocity method provides excellent correlation between ultrasonic and mechanical measurements of elastic stiffness degradation in mortar (mix E), but it provides poor results for highly heterogeneous concrete materials (mix A). Because of the poor correlation with increasing heterogeneity and coarseness of aggregate, quantitative results from ultrasonic testing may lead to very erroneous conclusions. It is the goal of this paper to address the heterogeneities in concrete materials, and to use finite element analysis to quantify their effects on the velocity of ultrasonic pulse propagation at different damage levels of the uniaxial compression test.

2 EXPERIMENTAL TEST SETUP

At the first stage of this paper we address the preliminary, yet necessary simulation of ultrasonic pulse propagation in a homogeneous linear elastic solid. Specifically, we will show that the finite element models provide reasonable results when compared to theoretical values of elastic wave transmission. The numerical results indicate the level of accuracy that may be expected from subsequent studies of more complicated problems for which there are no analytical solutions available. In addition, the finite element simulation reproduces the laboratory setup so the numerical results may be directly compared to the test data of the test rig shown in figure 2.

Figure 2a [Nogueira, Willam 1999] – Illustration of Experiment Setup

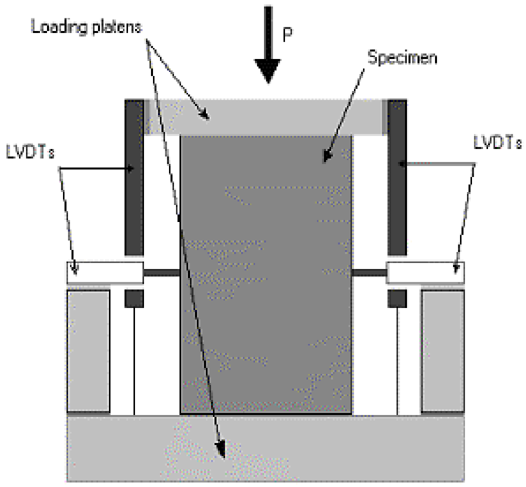
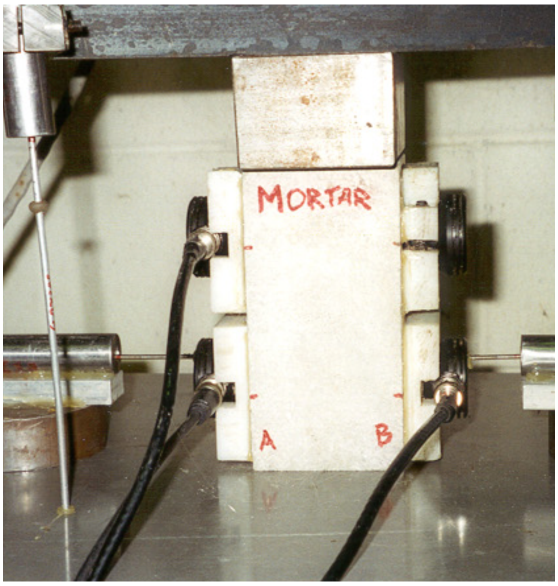


Figure 2b [Nogueira, Willam 1999] – Picture of Lab Experiment



For verification purposes finite element simulations were performed with a homogeneous unstructured mesh in anticipation of subsequent wave transmission studies in heterogeneous materials. The underlying spatial finite element discretization includes element edges not aligned with the wave front that cause numerical dispersion due to numerical pollution at element interfaces. Using a sufficiently fine mesh reduces, but does not eliminate these errors. In short, the homogeneous studies serve to establish the accuracy of the numerical simulation in unstructured meshes in which the element boundaries are miss-aligned from the wave front.

Approximating and scaling the excitation of the piezoelectric transducer provided the temporal model of the input pulse. The pulse model was scaled in order to reduce the dominant frequency of the pulse from 500 KHz to 50 KHz. The lower frequency pulse allows a much coarser resolution in space and time to obtain adequate solution accuracy. Using a 500 KHz pulse would increase the computational effort by two orders of magnitude due to necessary mesh and time step refinement. In addition the lower frequency pulse does not affect the results of the homogeneous elastic test problem, because the elastic propagation velocity is independent of pulse frequency. Pulse attenuation on the other hand varies with pulse frequency. However at this point in our study we shall focus on pulse velocity only.

Figure 3 – Finite Element Discretization
7 x 14 cm homogeneous specimen

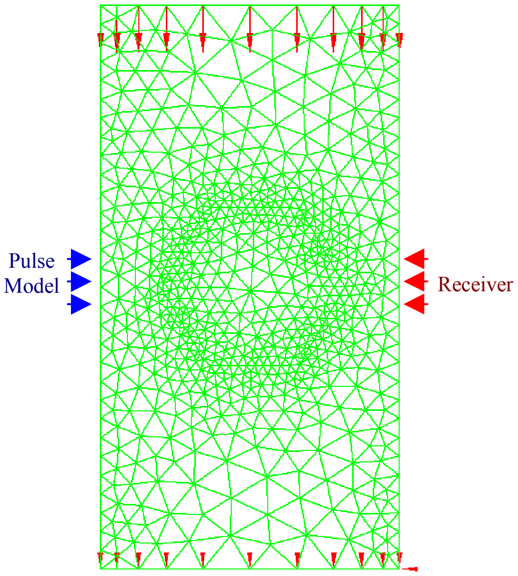
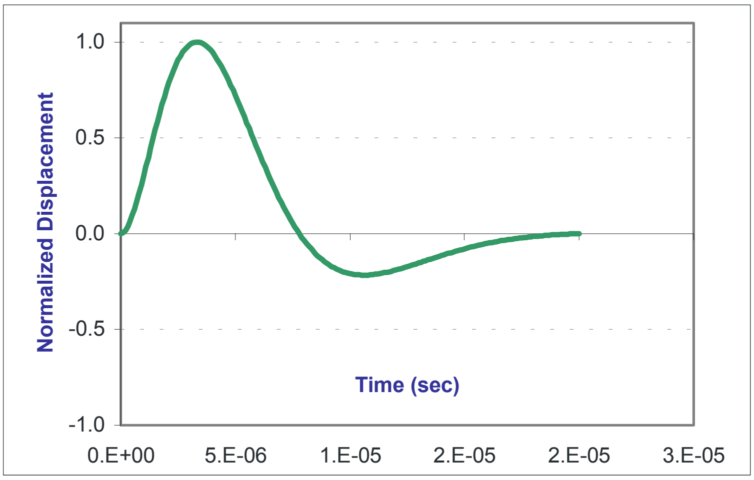


Figure 4 - Model of Transducer Pulse



3 VERIFICATION FROM HOMOGENEOUS EXPERIMENTS

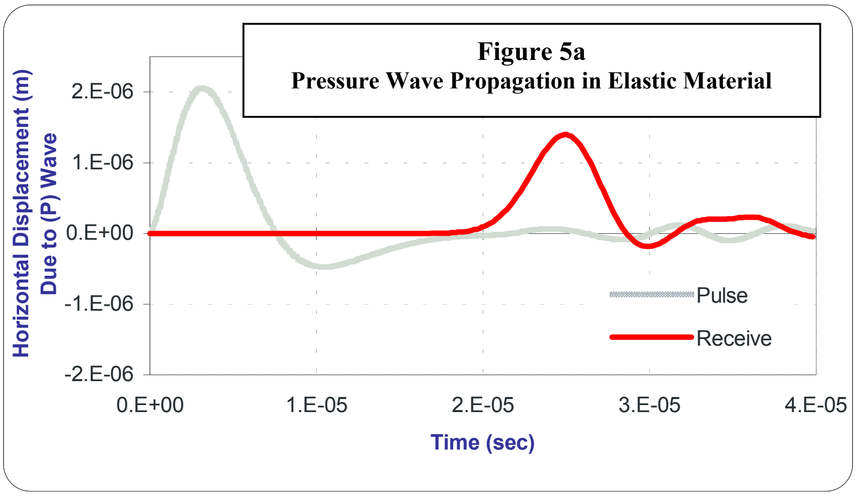


Figure 5a
Pressure Wave Propagation in Elastic Material

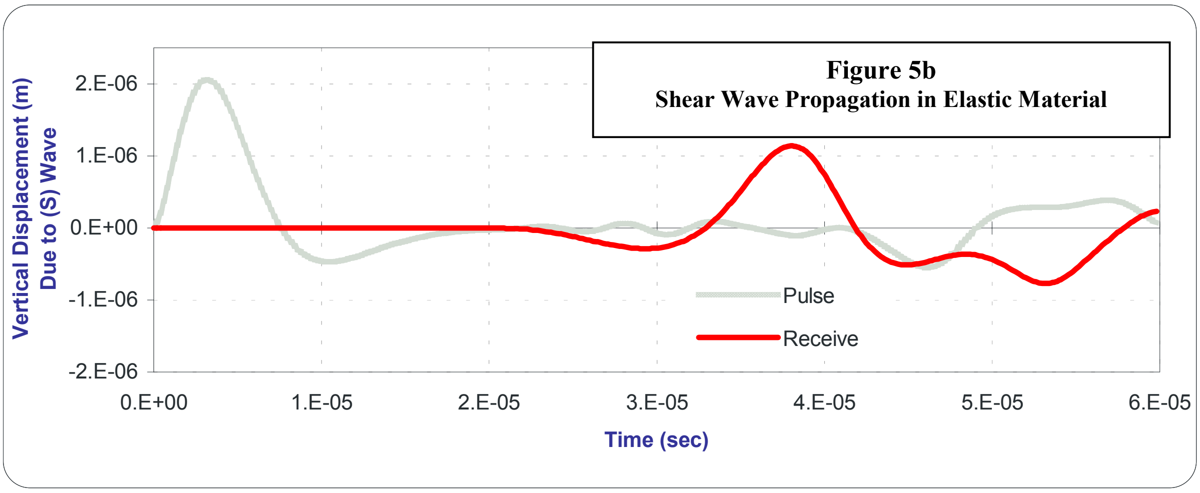


Figure 5b
Shear Wave Propagation in Elastic Material

	Pressure Wave	**Shear Wave**
Finite Element Results	3.210 Km/sec	1.964 Km/sec
Theoretical Quantities	3.227 Km/sec	1.976 Km/sec
Error	**0.54%**	**0.64%**
Notes	The finite element velocities were found by considering the time from zero crossing of the pulse to zero crossing of the receiver. Theoretical body wave velocities were obtained using: $c_1 = \sqrt{\dfrac{E}{\rho(1-\nu^2)}} \qquad \dfrac{c_1}{c_2} = \sqrt{\dfrac{2-2\nu}{1-2\nu}}$ These define the elastic pressure and shear wave velocities under plane stress conditions	

The verification results were obtained using the unstructured mesh shown in figure 3. The Newmark Average Acceleration method with no numerical damping was used for implicit time integration of the finite element equations of motion using consistent mass matrices. The results of other verification runs are summarized below:

Plane Wave Propagation (no volumetric dissipation)

		Pressure Wave	**Shear Wave**
Received/ Transmitted Amplitude	Theory	100%	100%
	Finite Element	98.00%	96.65%
	Error	**2.00%**	**3.35%**

Single Inclusion Reflection Results

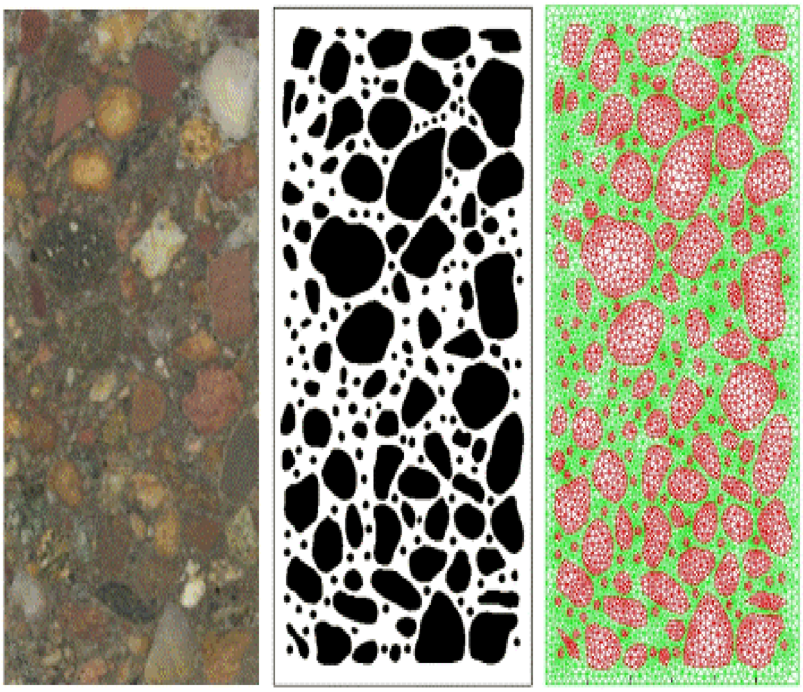
	Contrast Ratio			
	Einc / Ematrix = 0.0	Einc / Ematrix = 0.5	Einc / Ematrix = 2.0	Einc / Ematrix = 8.0
Theory	100%	15.8%	19.1%	50%
Finite Element	97.4%	17.2%	17.2%	47.8%
Error	**2.6%**	**1.4%**	**1.9%**	**2.2%**

In summary, the plane wave simulations in two-dimensional plane stress show that the finite element approach provides high accuracy in simple wave propagation situations that can be evaluated analytically. In other words, numerical dispersion and pollution remains minimal in these simple examples. More importantly, we may anticipate from these verification runs that the finite element approach can be applied to the more complex heterogeneous case in which there are no analytical solutions available. The full-scale heterogeneous runs shall use a significantly finer spatial resolution then the results presented here, this will cause the discretization errors to be smaller then those shown here. In addition the physical scattering effects of material interfaces will be well captured. The resolution properties of the coarse-concrete experiment are summarized later.

4 HETEROGENEOUS MESH GENERATION

For the purposes of this study, a novel approach was employed to generate the heterogeneous mesostructure of concrete materials. Because of our intention to realistically model the distribution and size of heterogeneities, as well as to compare finite element results with laboratory observations, we selected the laboratory specimen as the basic geometry for the finite element simulation. This was done by first taking photographs of longitudinal cuts of the specimen, then employing image enhancement, along with some manual retouching to arrive at two-phase maps of the composite concrete specimen. These maps were then transformed into finite element meshes with the use of specially developed software. Figure 6 demonstrates the results of these three steps. In addition, random mesh generation was employed to produce meshes used for verification runs. These mesh generation tools are readily applicable to future finite element simulations of heterogeneous materials.

Figure 6 – Mesh Generation



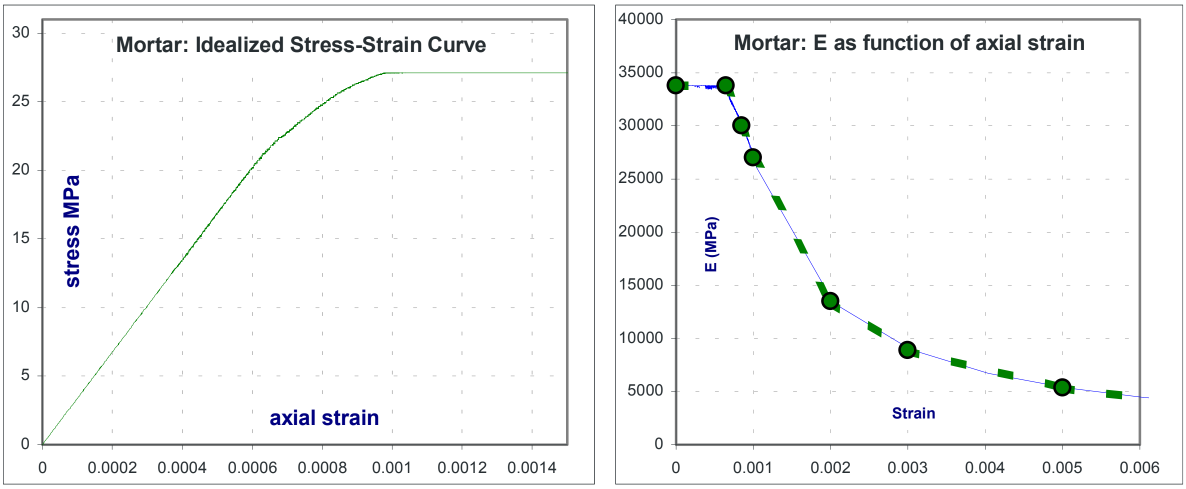
5 DAMAGE MODEL OF CEMENT MATRIX

In preliminary studies several material models, including various elasto-plastic and visco-plastic formulations, were employed to model the cement matrix. However the problem with inelastic models is that it is difficult to quantify the plastic influence on the speed and attenuation of the ultrasonic signal. Additionally, plasticity causes a permanent plastic drift of the pulse, which makes it difficult locate the zero crossing for velocity measurements.

A more transparent material model for the characterization of the ultrasonic pulse is that of elastic damage. With such a model the equations of elastic wave propagation are still applicable and the results are easier to interpret because the plastic drift is eliminated. Additionally, and most importantly, a damage model better captures the physical behavior of the actual cement matrix, which exhibits axial splitting when exposed to uniaxial compression.

For the purpose of this study a simple scalar damage model based on axial strain was employed and incorporated into the commercial finite element code ABAQUS. The damage parameter for the modulus of elasticity was calibrated directly from mechanical laboratory tests of a mortar specimen. It was assumed that the mortar would be homogeneous at the scale of wavelengths considered, and that it was a good model for the cement matrix between the aggregates in the coarse concrete composite. Figure 7 shows the secant modulus of elasticity that was used to calibrate the properties of the cement matrix, assuming that Poisson's ratio remains constant.

Figure 7 – Damage Parameter Calibration



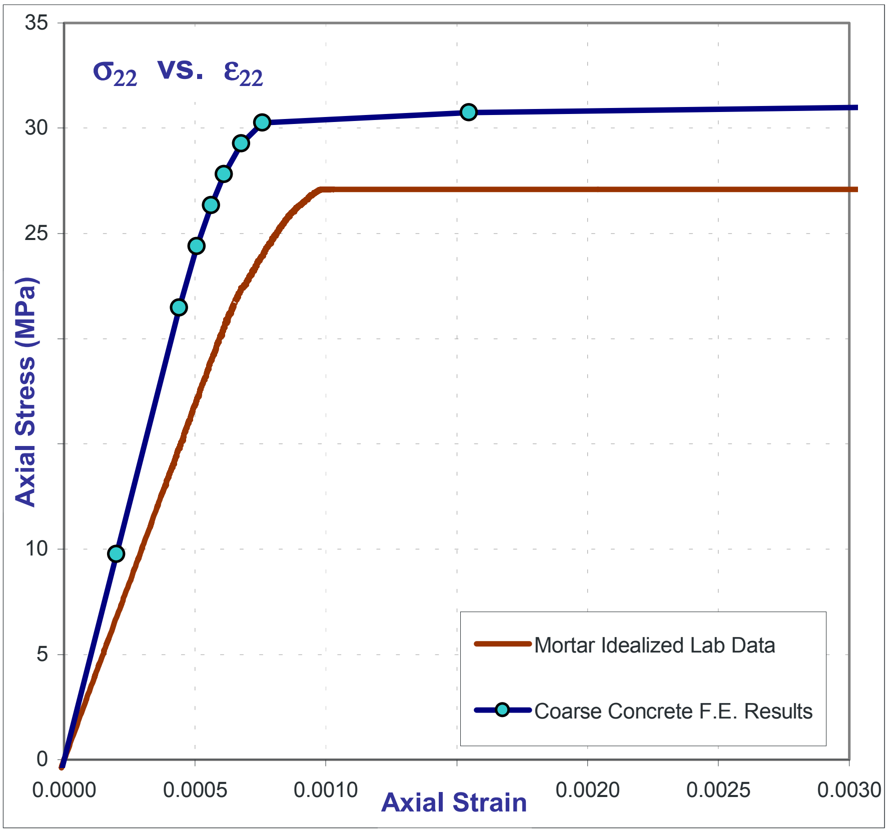
During the entire degradation process it was assumed that the aggregate inclusions behave linearly elastic. The aggregate properties were chosen to be consistent with independent laboratory data since no information was available on the specific aggregate properties used in the concrete samples. The material properties are summarized below.

Material Properties

	Nominal E (MPa)	Density (kg/m^3)	Poisson's Ratio	Nominal P Wave Velocity (km/sec)
Matrix	33800	2400	0.2	3.96
Aggregate	70000	4000	0.2	4.40

Combining the scalar damage model for the cement matrix with the elastic aggregate properties, the coarse concrete mesh shown in figure 6 generated the stress-strain curve in figure 8. As expected, the two-phase specimen is stiffer than the mortar alone, and it exhibits a higher ultimate strength due to the presence of the stiffer elastic aggregate inclusions. Furthermore, the effective stiffness (48.92 GPa) lies within the Hashin-Shtrikman bounds (47.90 – 49.04 GPa) for particulate composites.

Figure 8 – Stress Strain curve for 2-phase Coarse Concrete



7 PULSE PROPAGATION RESULTS

The following results were obtained using the coarse concrete model shown in figure 6. The geometric mesh properties and analysis parameters are summarized below:

Specimen Cross-Section Size: 6 x 15 cm	Number of Elements: 14080
Aggregate/Matrix Area Fraction: f = 0.495	Maximum element size: 0.2 cm
Maximum Aggregate Size: approx. 2 cm	Wavelength: > 6.0 cm (50 KHz wave)
	Analysis Time step: 10^{-6} sec.

The results from the finite element simulations of pulse propagation through the two-phase specimen (figures 9a and 10a) exhibit several interesting features. First, the trend and values of velocities with increasing axial load is very comparable to the laboratory results obtained from ultrasonic testing (figures 9b). These results demonstrate the potential of the proposed approach.

Figure 9a – Finite Element Results
Effects of Axial Loading on Ultrasonic Pulse Velocity in Coarse Concrete Specimen

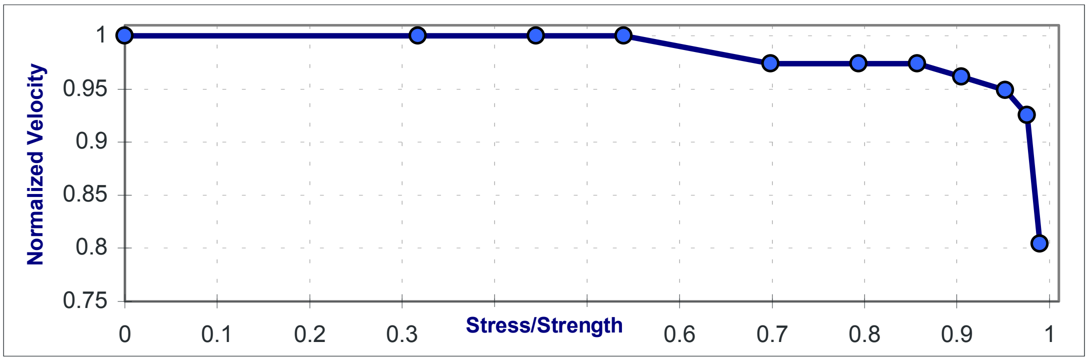
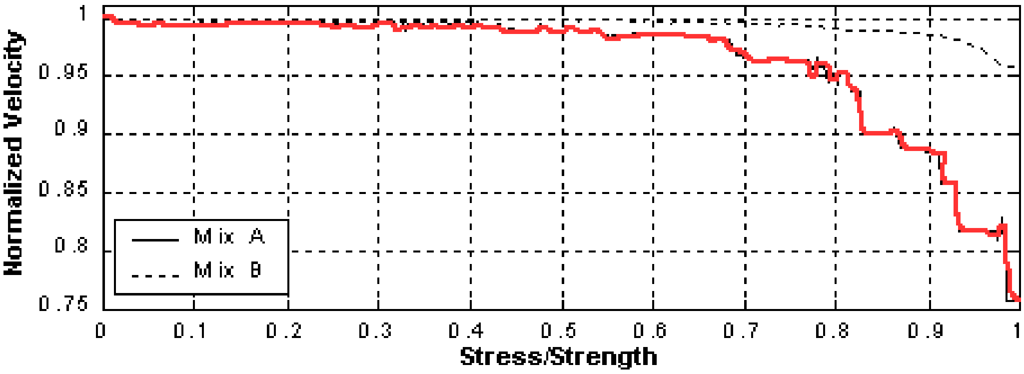


Figure 9b [Nogueira, Willam 1999] – Laboratory Results
Effects of Axial Loading on Ultrasonic Pulse Velocity
(Coarse Concrete being studied is marked in RED)



As anticipated, the pulse attenuation results do not coincide well with laboratory results, see figure 10. Several aspects of the analysis cause this deficiency. First, the lower frequency wave used in the numerical analysis has a long wavelength as compared to the maximum size of the heterogeneities in the specimen (6.0 cm vs. 2.0 cm). Thus the small heterogeneities do not induce significant scattering and do not affect attenuation. Regions of stress concentrations in the specimen, even under peak load, remain of approximately the same dimension as the largest aggregates - see figure 11. Thus the increased compressive load level has little effect on the wave attenuation. In addition, the finite element damage model does not include discrete micro-cracks and voids, which are present in the physical concrete specimen and cause attenuation. Finally, the elastic damage model used does not have an ability to dissipate mechanical energy, which occurs in real concrete via crack formation and slip. However, this effect is very subtle and accounts for less then 1% of wave attenuation [Gaydecki, Burdekin, *et. al.*, 1992].

Additionally, the noticeable increase in amplitude at moderate load level is worth consideration. Several explanations for this phenomenon are possible. First, as stress concentrations begin to develop under axial compression the contrast between wave speeds in neighboring regions increases, this has a tendency to induce scattering. However the higher frequencies are scattered more strongly than the lower ones. At moderate stress levels it is likely that scattering affects mainly frequencies above the dominant frequency of the pulse, resulting in a received signal with reduced high frequency *interference,* which results in a higher apparent amplitude. The shape of the received pulse supports this theory. Another possibility is that the heterogeneities, at this load level, create a mild channeling effect. This theory has been supported by previous results obtained from randomly generated heterogeneous meshes. Finally, it is worthwhile mentioning that a small increase in received pulse amplitude observed at low load level is evident in the laboratory results as well. A realistic explanation is that under moderate axial loading the initial micro-cracks close in the concrete specimen, which accelerates the propagation of the pulse. However, this generally accepted explanation of initial compaction is not applicable to the finite element simulation. Conversely, the suggested causes of the phenomenon seen in the finite element results are certainly feasible in the physical concrete specimen.

Figure 10a – Finite Element Results
Effects of Axial Loading on Ultrasonic Pulse Attenuation in Coarse Concrete Specimen

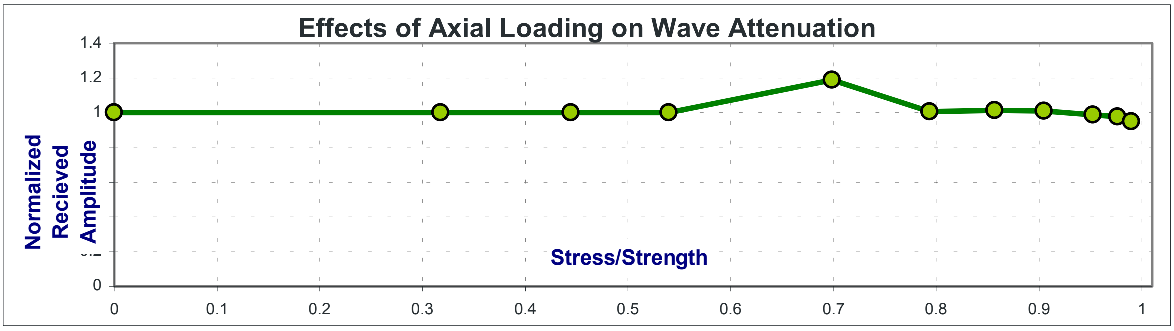


Figure 10b [Nogueira, Willam 1999] – Laboratory Results Effects of Axial Loading on Ultrasonic Pulse Attenuation (Coarse Concrete being studied is market in RED)

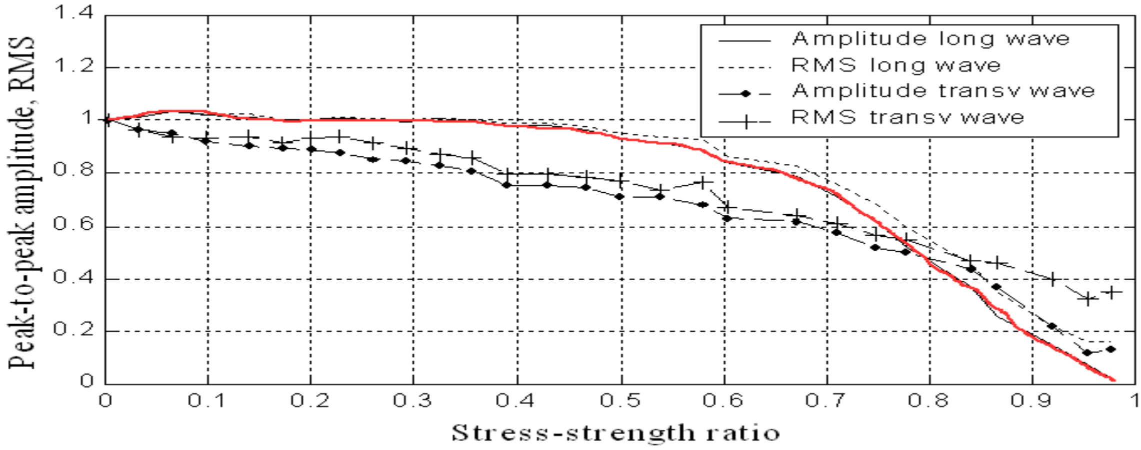
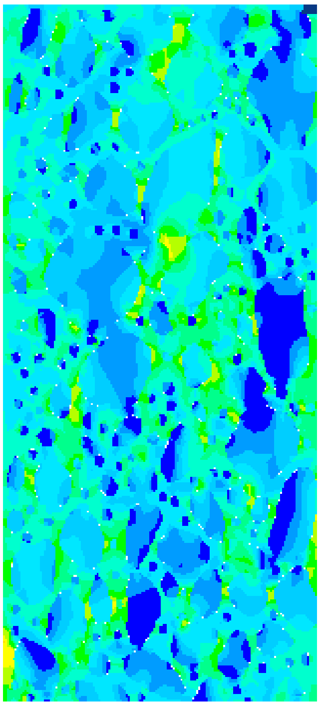


Figure 11 – Stress Contour of Coarse Concrete Specimen Near Peak Load



(Blue regions are regions of high stress)
(Yellow are regions of low stress)

7 CONCLUSIONS

This research demonstrates the significance of the finite element model-based simulation for studying the effects of heterogeneities on ultrasonic wave velocities. Comparisons with ultrasonic test data illustrate the accuracy of the present approach for modeling a highly coarse concrete specimen under increasing axial compression. At this point a broader study, including various classes of heterogeneous concrete mixes, is necessary to extract quantitative results and to apply these to current ultrasonic evaluation procedures. Mesh generation capabilities developed will be fundamental in these future studies.

Present studies briefly considered the effects of heterogeneities on pulse attenuation. Although, as presently configured, the described approach does not capture the attenuation trend seen in laboratory tests, it is likely that changing the frequency and wavelength of the modeled pulse to match the one used in the laboratory test (or vice versa) will improve the attenuation result. This is the direction that deserves our principal attention.

Furthermore, consideration of the shear wave propagation concurrently with the pressure wave propagation will allow the calibration and use of more sophisticated and more realistic isotropic damage models of the bulk and shear behavior.

8 ACKNOWLEDGMENT

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