HEALTH MONITORING OF ROCK BOLTS USING ULTRASONIC GUIDED WAVES

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ABSTRACT. It is necessary to quantify the amount of delamination present in load bearing rock bolts, as small amounts may be deemed acceptable and large amounts may lead to catastrophic failure. In this work, a semi-analytical FEM model is used to calculate the theoretical wave structures for a rod embedded in concrete. A qualitative relationship between percent delamination and wave reflection energy is demonstrated. It is shown that with the proper selection of inspection parameters, it is possible to inspect large lengths (10+ ft.) of embedded rod using an ultrasonic guided wave pulse-echo technique.

Keywords: ultrasonic guided waves, rock bolt, length inspection, delamination detection
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INTRODUCTION

Approximately 200,000 high-strength rock bolts were used in the construction of the five-step ship lock that allows ships to circumnavigate the Three Gorges Dam in the Hubei Province of China. The Chinese government has stated that, when completed, the hydroelectric dam, in addition to providing a significant amount of electricity, will provide flood control and increased river navigability. Because of structural settlement and the tectonic evolution of this area of China, there is an imperative need for the length and bonding evaluation of these embedded rock bolts, both for determining the quality of construction and for health monitoring of the structure in service. Deviations from the pre-embedded bolt length indicate a fracture while delaminations between the bolt and concrete imply a weak bonding condition.

Inspection techniques used in the past include the destructive removal of bolts and nondestructive hammer impact methods. These techniques proved to be time consuming, expensive, and inaccurate. More recently, the application of ultrasonic guided waves has been used to nondestructively evaluate rock bolts. For a good review of the wave mechanics associated with a free-bar, see Rose [1]. Pavlakovic et al [2] provides an excellent review and theoretical wave mechanics analysis of an embedded bar system. It was demonstrated that equally spaced attenuation minima occur for a series of higher frequency *L(0,n)* modes. Beard and Lowe [3] provide an experimental study of rock bolts, or rebar, embedded in epoxy using ultrasonic guided waves. In their study, it was found that

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both high and low frequency tests are necessary for a complete inspection, as many low frequency *L(0,n)* modes are leaky while higher frequency *L(0,n)* modes generally are not; the leaky modes being useful for loss of encapsulation detection. Beard et al [4] also studied tendons embedded in grout using guided wave techniques, demonstrating that attenuation analysis is a viable means of low-leakage detection in short wire specimens. For corrosion detection, Reis et al [5] uses a through-transmission flexural mode inspection technique.

While many of these works have concentrated on the theoretical analysis and experimental techniques for the evaluation of several different embedded-rod systems, there is a need for a long-range debonding characterization method for steel rods embedded directly into concrete. In this work, the propagation of ultrasonic guided waves in a two-layered structure, composed of a solid steel rod and a semi-infinite layer of concrete, is investigated theoretically and experimentally. A Semi-Analytical FEM (SAFEM) model is used to calculate the high-frequency theoretical wave structures for a rod embedded in concrete. In the past, use of traditional FEM has limited these models to low frequency. Utilizing the available theory and numerical SAFEM simulations, a series of experiments, involving longitudinal mode propagation in a simulated rock bolt, was completed. Five specimens were constructed using 3 foot long, ¾ inch diameter steel rods embedded in concrete. It is demonstrated that with the optimum mode, frequency, and transducer, it is possible to perform both rod length measurement and delamination detection using ultrasonic guided waves. Experimental results are in good agreement with theoretical analysis.

THEORETICAL MODEL

In actual applications, the rock bolt system is composed of three layers, a steel rebar, a thin layer of cement as a bond, and a semi-infinite rock embedding the bolt. Considering that the layer of cement is very thin and the material properties are very similar to those of rock, the system was modeled as a two layer axially symmetric system, composed of a solid steel rod and a semi-infinite layer of concrete, as shown in Figure 1. It is worth examining the dispersion curves for longitudinal modes in a free-rod as the general shape and velocity for low frequency will approximately equal that for the rod-concrete system. As can be seen in Figure 2, the multimode characteristics of the wave guide are obvious.

As discussed in Hayashi et al [6], the key feature of the SAFEM, which makes it a semi-analytic approximation, is the expression of the longitudinal displacement field by the

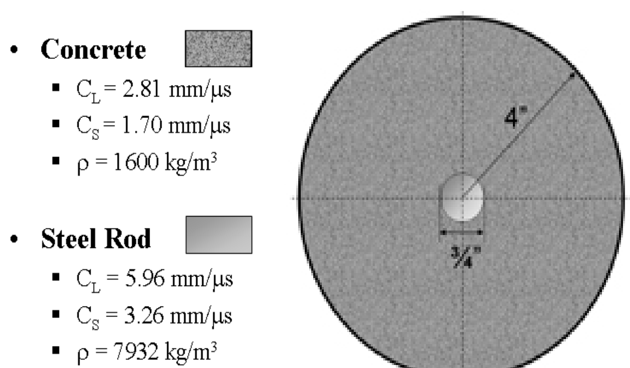
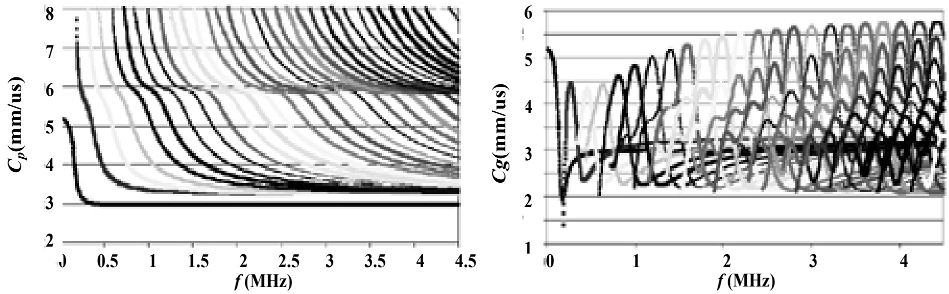


FIGURE 1. Cross section of theoretical and experimental model of bolt-concrete system. Material properties for each material are listed on left. It should be noted that the material properties of concrete can vary greatly depending on material sources and mixing ratios and the above values were used for the benefit of numerical simulation only.



(a) Phase velocity (b) Group velocity

FIGURE 2. Phase and Group velocity dispersion curves for a ¾" steel rod. Dispersion curves for a rod-concrete system would show similar shapes.

orthogonal function $e^{i\xi}$. This feature is what provides computational efficiency over traditional FEM and allows the modeling of higher frequency modes.

Figure 3 shows an example of the radial particle displacement for a high frequency mode being excited at 5 MHz. Assuming axisymmetric loading, there is no displacement at the center of the rod. This is illustrated in the figure. Also, it can be seen that for this particular mode, there is an energy peak at the rod-concrete interface. A review of wave structures would show that at this particular frequency/mode combination, a majority of the displacement energy is concentrated in the axial direction and thus the radial displacement at the interface is miniscule in comparison and will contribute little to leakage. In a similar fashion, low frequency wave structures will show large energy concentrations at the interface and thus will be susceptible to leakage. These features can be utilized for length measurement and the detection of delaminated regions at the rod-concrete interface. Beard [3] obtained similar results for an epoxy-rod system. In general, the smaller acoustic impedance between the rod and concrete, as opposed to a rod and epoxy, will mean more energy leakage in the rod-concrete system. This suggests that inspection of long lengths of rock bolt embedded in concrete using pulse-echo methods may prove difficult.

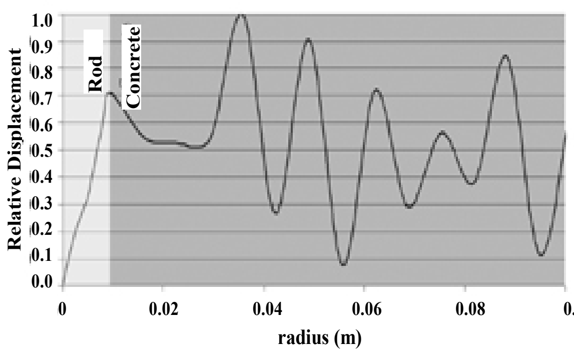


FIGURE 3. **S**emi-**A**nalytical **F**inite **E**lement **M**ethod approximation of the radial displacement of a rod-concrete system for a mode excited at 5MHz. Notice the displacement peak at the interface of the rod and concrete. If compared to axial displacement, the radial displacement would prove almost negligible.

EXPERIMENTAL INVESTIGATION

Experimental Set Up

The experimental set up is shown in Figures 4 and 5. A pulse-echo arrangement was used with a 1000V Matec Explorer II tone-burst system. Two normal beam piezoelectric transducers with center frequencies of 1MHz and 2MHz were used to generate waves. For experimental studies, five specimens were constructed using 3 foot long, ¾ inch diameter steel rods embedded in concrete. To simulate delaminations between the steel rod and concrete, sections of the rod were wrapped with negligible thicknesses of high-density polyethylene to prevent bonding. Each specimen had a different amount of simulated delamination, measured as 0%, 25%, 33%, 50% and 75% of the entire rod length. In addition, a sixth, un-embedded rod was used in air to simulate a 100% delamination.

Length Measurement

The experimental length measurement results are shown in Figures 6(a) and 6(b). Transducers with center frequencies of 2MHz and 1MHz, respectively, were used for the measurements. Results shown in Figure 6(a) show the presence of 3 back-wall echoes (BWE), suggesting that the selected wave mode can travel 18+ feet before being lost in the noise. Even longer range inspections could be completed by increasing amplifier gain. It can also be seen, in this figure, that there is little amplitude difference between a completely bonded interface and a 33% delaminated specimen at a frequency of 1.8 MHz. This was found to be true for most frequencies above 1 MHz. The results in Figure 6(b) illustrate that different frequencies and modes have different dispersion characteristics with a trend toward higher frequencies having slower energy transport velocities.

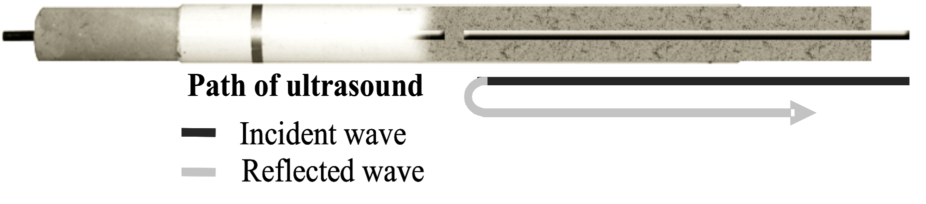


FIGURE 4. Picture/illustration of test specimen. Two rods can be seen in the image. The outer white layer is PVC tube and is considered to have no effect on the wave propagation characteristics as it is far removed from the rod and is not bonded to the concrete.

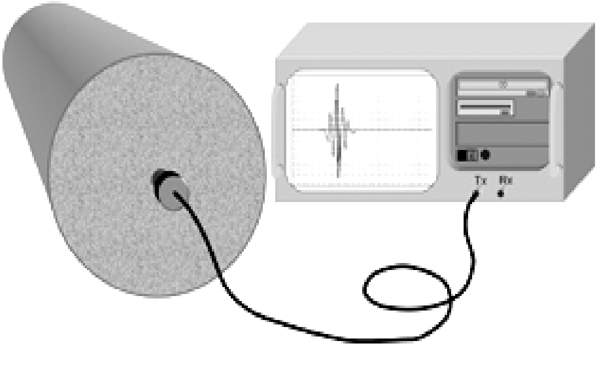
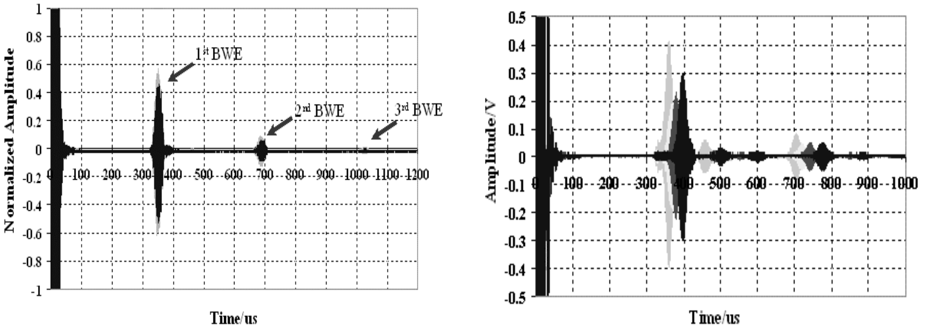


FIGURE 5. Illustration of experimental pulse-echo setup using a 1000V Matec Explorer II tone-burst system. Transducer center frequencies varied between 1 and 2 MHz.

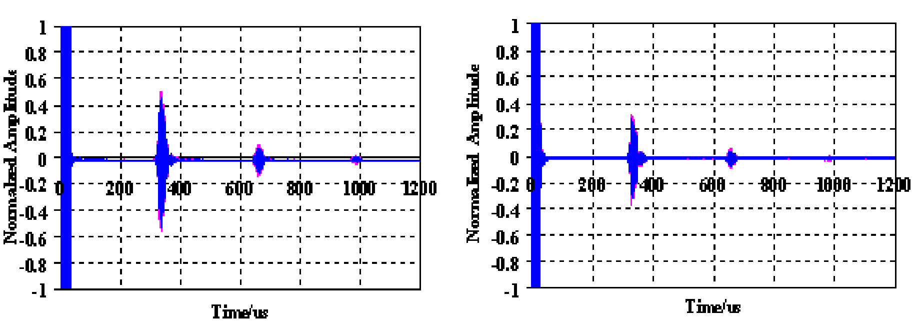


(a) 2MHz transducer (b) 1MHz transducer

FIGURE 6. Several experimental results obtained using pulse-echo measurements at different frequencies. (a) Waveform at 1.8MHz, grey for no delamination, black for 1/3 delamination (b) Echoes at 1.58, 1.38, 1.18 and 0.98MHz from left to right

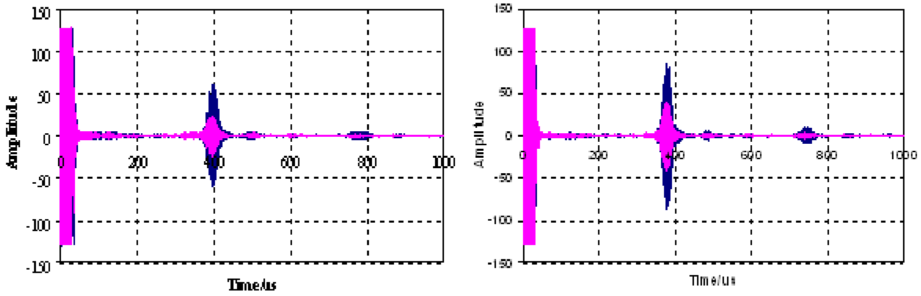
Delamination Detection

Six specimens were used to investigate the possibility of delamination detection using a pulse-echo arrangement. Experimental results are displayed in Figures 7 through 9. Figures 7(a) and 7(b) show the waveforms at excitation frequencies of 2.6MHz and 2.8MHz respectively. It can be seen that these particular high frequency modes are not sensitive to the presence of the delamination, as there is very little change in signal amplitude. Figure 8 illustrates the effect of the delamination on lower frequency modes. Figure 8(a) shows, approximately, a six decibel gain in signal amplitude because of the 1/3 length delamination. An experimental relationship between attenuation and percent delamination is given in Figure 9. For comparison, linear trend lines were fit to the data. It is seen that the slope of the trend lines decrease as frequency increases, again suggesting that higher frequencies are less affected by the delamination. For lower frequencies, there is an obvious decrease in attenuation with increase in percent delamination. A significant change in slope is seen between the 1.38MHz and 1.58MHz trends. It is hypothesized that this is the range of the frequency spectrum in which the ultrasound begins to lose sensitivity to delamination. A trend line for a frequency above 1.58MHz would have an even smaller slope, showing attenuation due to material losses only. Note that in Figures 6(b) and 9, the increment in scanning frequency is 0.2MHz. Experimentally, this was determined to be the frequency separation between attenuation minima.



(a) 2.6MHz (b) 2.8MHz

FIGURE 7. Waveforms typical of those obtained above 2MHz. There is almost no contrast between the delaminated specimen and the completely bonded specimen. Grey for no dela. and black for 1/3.



(a) 0.97MHz (b) 1.17MHz

FIGURE 8. Waveforms typical of those obtained below 1.6MHz. The delamination produces a gain in signal amplitude of approximately 6dB. Grey for no delamination and black for 1/3 delamination.

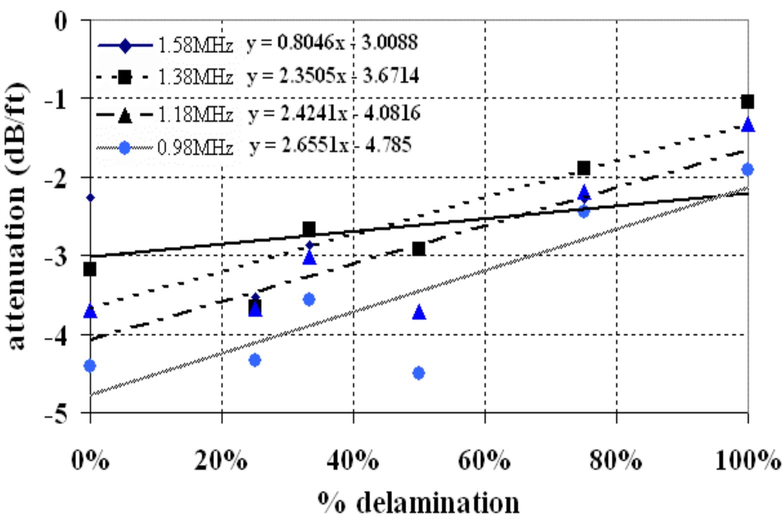


FIGURE 9. Comparison of attenuation and percent Delamination. There is a clear relationship showing an increase in wave amplitude as the amount of delaminated area increases.

CONCLUSIONS

1. Guided waves can be used efficiently, both for measuring the length of a rod embedded in concrete and for estimating the amount of delamination between a steel rock bolt and concrete.

2. Transducer choice is critical. When determining the length of an embedded rod, guided wave modes at higher frequencies must be used. Lower frequencies are better for estimating delamination. A transducer with a center frequency of 1MHz or higher is suitable for length determination, and any transducer with a center frequency larger than 2 MHz is not suitable for delamination estimation for these specimens.

3. At higher frequency, the energy focuses in the center of the rod and there is little energy leakage into the concrete. However, when using a lower frequency, large

amounts of energy leak into the concrete due to the large displacement at the interface. Further experiments will need to be conducted to characterize the delamination quantitatively. Many more specimens with different percentages of delaminated area are needed.

4. Further work will be done to distinguish individual modes among the many present longitudinal modes. In order to determine the exact length, there is a need for accurate velocity and the time of flight information at any given frequency, and therefore it is necessary to determine the mode and velocity of the received echo.

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