Health monitoring of concrete using rebar-guided ultrasound

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Ultrasonic guided waves are widely used for the inspection of structures such as pipelines, annular tank plates, aircraft wing assemblies, composite radius fillers and wind turbines. They are also attractive for long-term structural health monitoring due to their ability to provide long-range and feature-rich through-structure information from a single transducer location. The use of guided waves in concrete however, has been limited to mainly monitoring setting and curing, mainly due to the heterogeneous nature of the material that could cause a strong attenuation. Recently, there has been much research interest in coated reinforcements as a way of combating corrosion in concrete, and epoxy is an affordable material for such coatings. Here, the effect of epoxy coating on the level of attenuation of the guided waves in reinforcement bars is investigated for a potential new technique for health monitoring of concrete. The attenuation of the fundamental longitudinal rod waveguide mode L (0,1) propagating through a 20-mm diameter mild steel bar surrounded by concrete is investigated using finite element simulations.

Introduction

Concrete is one of the commonly used materials worldwide in the construction industry due to its durability [1]. Civil infrastructures such as power plants, bridges and large buildings are typically built using concrete. It is typically composed of aggregate, sand, cement, water as well as mineral and chemical admixtures [2] To guarantee safe and efficient operation, these structures require regular inspection [3]. The heterogeneous nature of concrete has presented challenges over the years in transferring the various NDT technologies designed for steel testing to the inspection of concrete structures [4]. The heterogeneous nature, the time taken to conduct a test and complex features of the structure presents a challenge during testing and inspection. As a result, guided ultrasonic waves that can cover long distances from a single transducer position are of much interest [5].

Guided Waves

Ultrasonic guided waves are attractive for long-term structural health monitoring due to their ability to provide long-range and feature-rich through-structure information from sparse transducer locations [6]. Guided wave arrays can provide an imaging engine to scan the entire structure and create maps of defective regions. This information can then be used for reaching the defective zones and further inspection using other higher resolution local methods. A combination of the ultrasonic guided wave for inspection in the regions around the concrete reinforcements and ultrasonic bulk waves for volume inspection has the potential to offer a complete solution to monitoring concrete structures.

Non-destructive technologies using Lamb waves have been widely used to inspect composite structures [7]. The effectiveness of ultrasonic guided waves in quantitative defect detection in composites is well documented [8]. Surface-based structural health monitoring techniques use contact surface transducers/piezo-electric actuators/sensors to generate and propagate ultrasonic guided waves through composites [9]. Such methods use omnidirectional wave transduction, resulting in cylindrical (two-dimensional) waves, which decay away from the source, limiting the field of view, especially in inaccessible regions of complex composite structures. Embedded waveguide-based approach has been used to monitor setting, early hardening and defect growth in concrete piles using ultrasonic guided waves [10]. Ultrasonic wave propagation guided through reinforcement has been applied to monitor the solidification and curing behavior of concrete [11-

14]. Several experiments have reported use of ultrasound and acoustic pulse velocity experiments to characterize the setting and early hydration of cement-based materials [15-22].

This investigation seeks to develop an online monitoring system using ultrasonic guided wave technology on the reinforcement bars embedded in concrete infrastructures. The monitoring can be carried out during curing of concrete all through the whole service life of the infrastructure. The sleeved waveguide sensor confines the guided waves in one dimension and at specific opening positions waves leak out and become two-dimensional. These leaky waves are sensitive to defects inside the structure.

Modelling experiment

Numerical (finite element) simulations were carried out to explore the best possible guided wave modes through a 20-mm diameter mild steel bar surrounded by concrete. Five different FE models (axisymmetric) were used and compared:

1. A 3 m long steel reinforcement in air. This was used as the baseline for calculating the attenuation in the other four models.
2. A 3 m long steel reinforcement embedded infinite concrete medium
3. A 3 m long steel reinforcement covered with a 1 mm epoxy coating embedded infinite concrete medium
4. A 3 m long steel reinforcement covered with a 0.1 mm epoxy coating embedded infinite concrete medium
5. A 3 m long steel reinforcement covered with a 0.01 mm epoxy coating embedded infinite concrete medium

Modelling and Simulation Results

The material properties for concrete, steel and epoxy which were used during modeling in the disperse software are shown in Table 1 and the simulation and modelling results are shown in Figure 1. The phase velocity against frequencies for the five models used are plotted in the Figures 1 to 5. The frequency of excitation was chosen to be roughly the same to allow inter-comparison of the attenuation level. It was not possible to go below 160 KHz since the mode of interest L (0,1) did not exist for some of the models. The various velocities corresponding with the frequency of excitation (160 KHz) was used to calculate the signal arrival time at various monitoring points (0.05 m apart) placed along the 3 m long steel reinforcement. The absolute amplitude at these points for each model were picked and compared to the amplitude of the model with 3 m long steel reinforcement in air.

Table 1: Material properties of steel and concrete used for modelling in Disperse

Material Property	**Rebar**	**Concrete**	**Epoxy**
Modulus E, (GPa)	210	29.569	3.5
Density, (kg/m^3)	7932	2200	1200
Longitudinal Attenuation (db/m)	0.003	0.2	-
Shear attenuation (db/m)	0.008	0.5	-
Longitudinal velocity (m/s)	5960	4100	2610
Shear velocity (m/s)	3260	2300	1100
Poison's Ratio	0.2865	0.2703	0.33

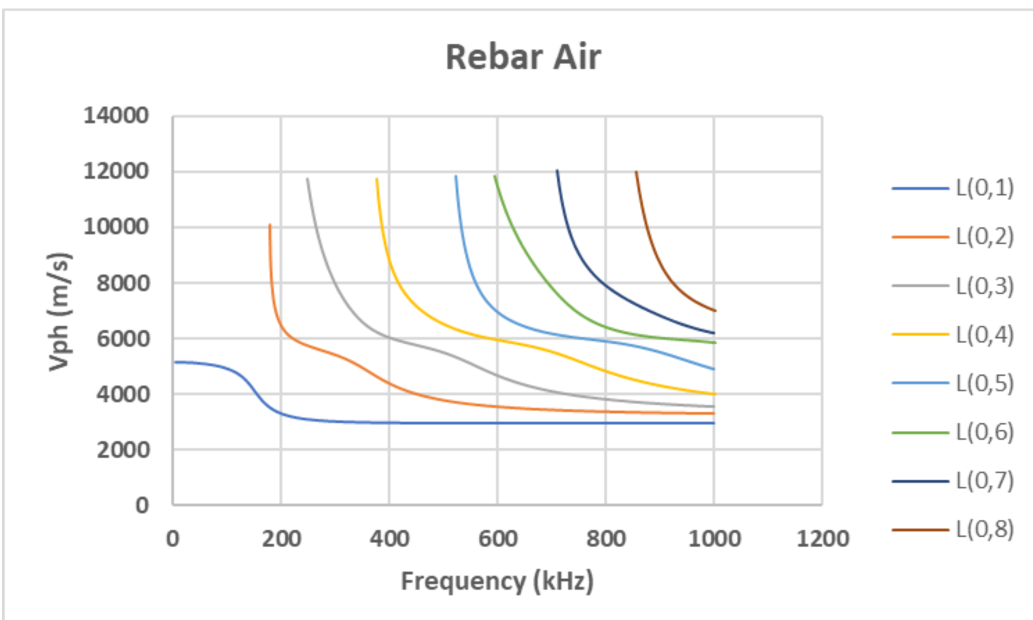

Figure 1: Disperse plot for Rebar in Air

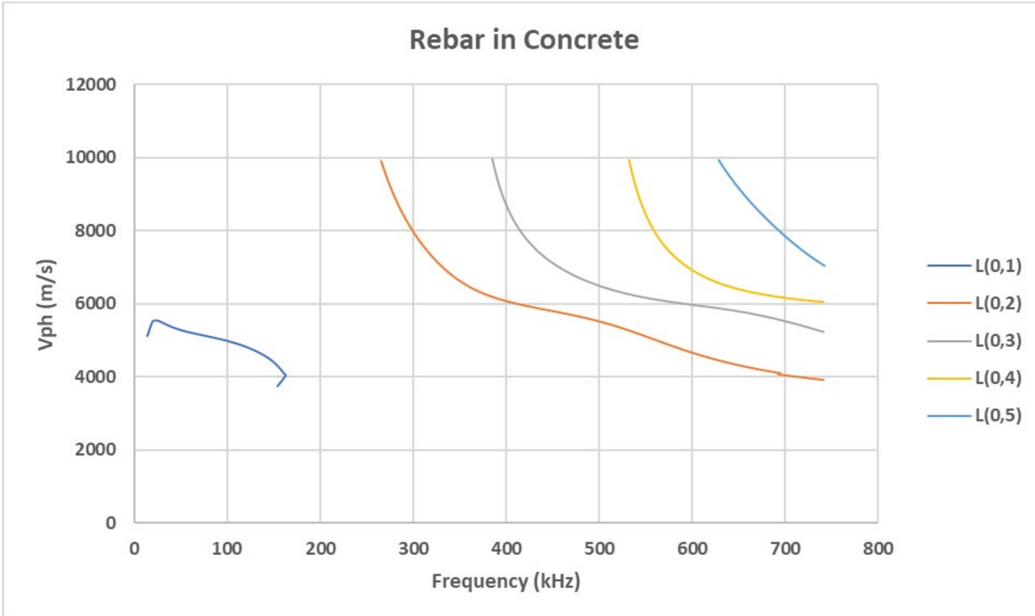

Figure 2:: Disperse plot for Rebar in Infinite Concrete

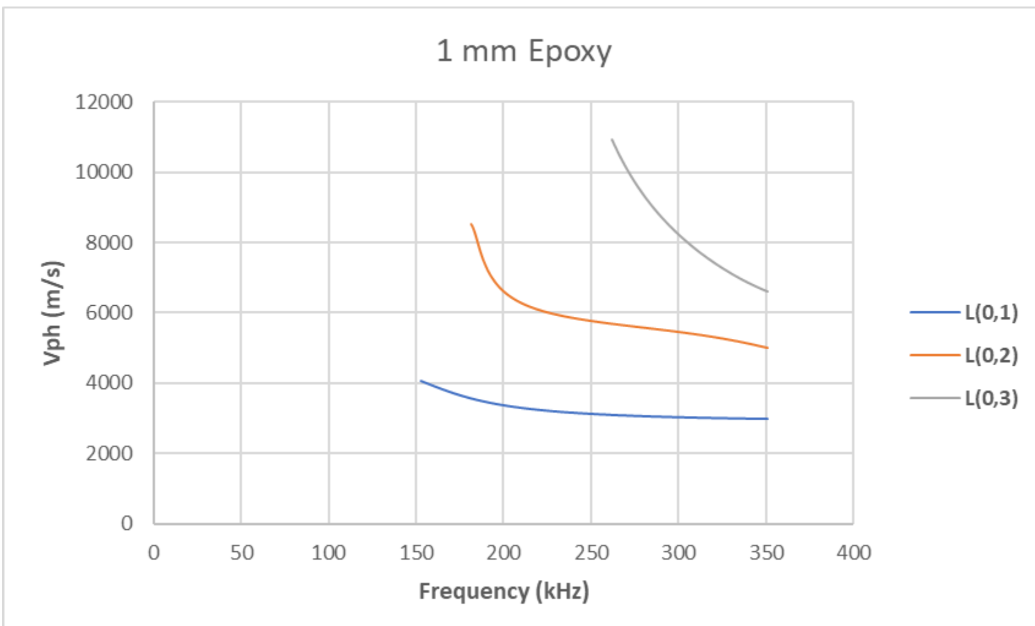

Figure 3: Disperse plot for Rebar in concrete with 1mm epoxy layer

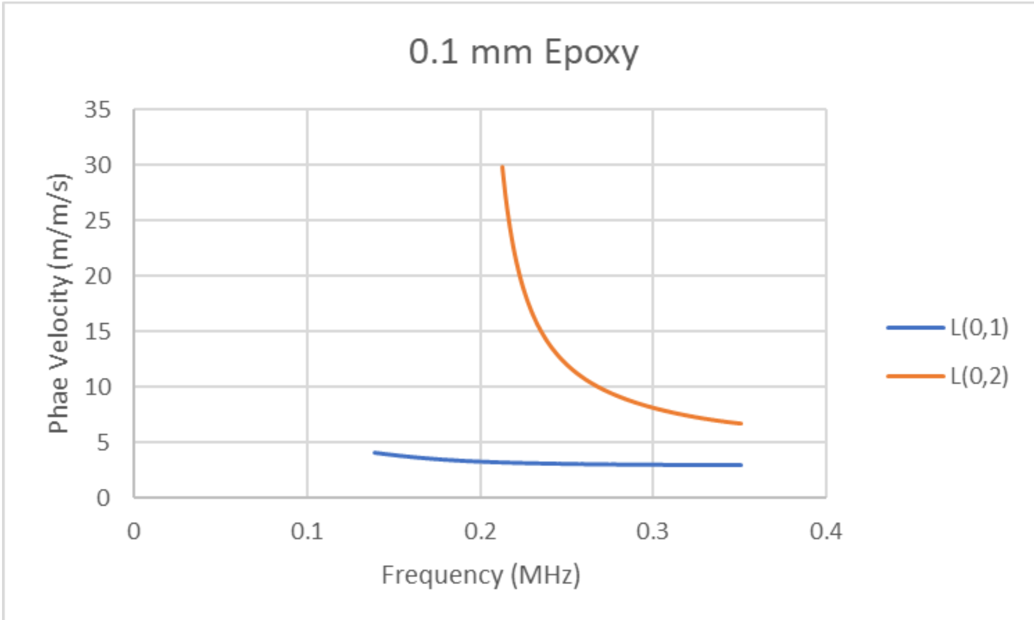

Figure 4:Disperse plot for Rebar in concrete with 0.1mm epoxy layer

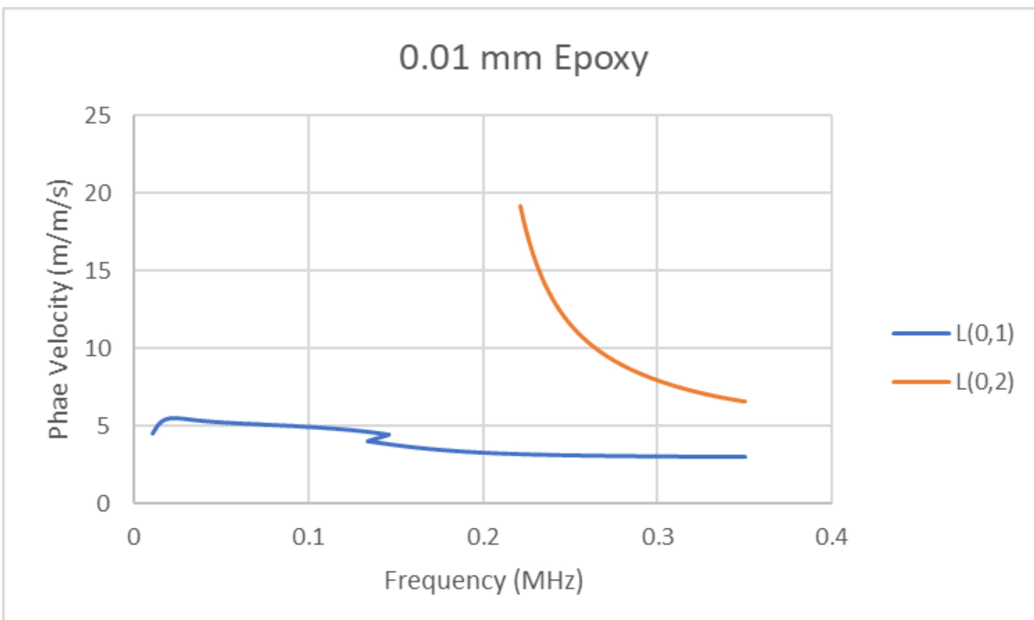

Figure 5: Disperse plot for Rebar in concrete with 0.01mm epoxy layer

Figure 6 shows a comparison of the signal amplitudes along the reinforcement bar for the various models used. The simulation results, it was observed that the model with the 0.1 mm epoxy provided the highest level of ultrasonic isolation as less attenuation levels were observed.

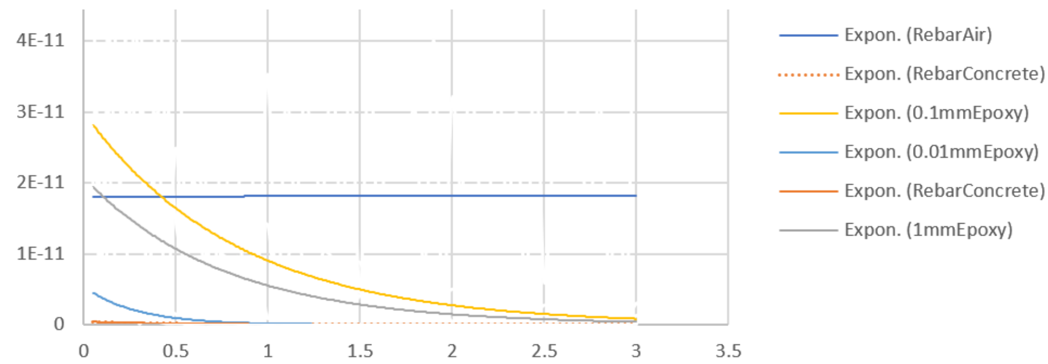

Figure 6: Best line of fit of maximum amplitude against distance

Conclusion

The work shows the potential of development of guided waves in online structural health monitoring of reinforced concrete structures. Ultrasonic guided waves can offer an advantage over other available test methods since they can travel over a longer distance a single transducer position. Experimental validation of waveguide concepts generated by simulation is in progress and if successful, it will have the potential of online monitoring large reinforced concrete infrastructures from just a few locations.

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