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# Parametric study and modeling of PZT based wave propagation technique related to practical issues in monitoring of concrete curing

Yee Yan Lim [a,*], Kok Zee Kwong [b], Willey Yun Hsien Liew [c], Ricardo Vasquez Padilla [a], Chee Kiong Soh [d]

[a] School of Environment, Science and Engineering, Southern Cross University, PO Box 157, Lismore, NSW 2480, Australia
[b] Civil Engineering Program, Faculty of Engineering, University Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[c] Mechanical Engineering Program, Faculty of Engineering, University Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[d] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

## HIGHLIGHTS

- Practical issues related are investigated through parametric study and modeling.
- FE modeling of WP technique is found to be useful alternative to the experiment.
- Effect of temperature and humidity on WP technique is experimentally studied.
- A semi-analytical model is used to generate strength calibration chart for concrete.

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## ABSTRACT

This paper presents a series of investigative studies, mainly parametric and numerical, into various issues related to the practical application of the wave propagation (WP) technique in monitoring of concrete curing using smart material (PZT). This paper is an extension of a range of experimental studies presented in the authors' recent publication. Coupled field finite element (FE) simulation of the PZT-structure interaction in WP technique is conducted on mortar and concrete specimens. Identification of the pressure wave (P-wave) and the surface wave (R-wave) velocities simulated in the FE model is attempted. Results are found to be matching closely with the experiment. The verified FE model, together with the theoretical model are then used to perform parametric study on selected factors related to the practical application of the technique, in particular those uncontrollable in the experiment, including the dynamic modulus of elasticity, the Poisson's ratio and the damping coefficient. Further experimental and analytical studies on the effect of varying temperature and humidity are also presented. A semi-analytical model previously proposed by the authors is finally adopted to generate a strength calibration chart for concrete with different coarse aggregates. The theoretical and FE models are proven to be useful alternatives to the experiment, which can be used in future design and optimization of the PZT based WP technique in monitoring of concrete curing.



## 1. Introduction

Accurate predictive models are essential for understanding an engineering problem domain and the behaviors of various structural systems. The developments of theoretical or analytical models with closed form mathematical equations are generally useful in providing strong physical insights into a particular engineering problem. However, their practical applications are often limited by their simplicity. Numerical models such as finite elements (FE) models are excellent alternative to the analytical models. Finite element method (FEM) enables the analyst to numerically evaluate a sufficiently close approximate solution for an engineering problem when analytical model is unavailable.

In the past two decades, various analytical and FE models have also been developed and studied in the field of smart piezoelectric based structural health monitoring [12,3,2,34] for both electromechanical impedance (EMI) technique and wave propagation (WP) technique. Some of these studies are reviewed in the following sections.

* Corresponding author.
*E-mail addresses:* yee.lim@scu.edu.au (Y.Y. Lim), wyhliew@ums.edu.my (W.Y.H. Liew), ricardo.vasquez.padilla@scu.edu.au (R.V. Padilla), csohck@ntu.edu.sg (C.K. Soh).

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### 1.1. Modeling of EMI technique

The EMI technique employs a single smart piezoceramics transducer (PZT), acting as collocated actuator and sensor. The mechanically attached PZT transducer is dynamically excited by an alternating voltage. The vibrational force generated by the PZT patch under the converse piezoelectric effect can be transferred to the host structure. The corresponding structural response at different excitation frequency will modulate the electric current (admittance signatures) across the PZT patch. These admittance signatures carry information pertinent to the vibratory characteristics, such as stiffness, density and damping ratio of the host structure.

Thus far, various EMI based analytical models simulating the PZT–structure interactions have been developed by researchers such as Liang et al. [18], Giurgiutiu and Zagrai [10], Bhalla and Soh [5], Annamdas and Soh [2], Lim and Soh [22], and Gresil et al. [12].

On the other hand, the coupled field FE model is found to exhibits exceptional robustness [24], capable of simulating damage [22,8]. In comparison to most of the previously studied models, either purely analytical through impedance-based modeling or semi-analytical through FE-based impedance modeling, the coupled field FE models are able to accurately simulate minor resonance peaks [36] and exhibit higher accuracy in both magnitude and resonance frequency, especially in the higher frequency range (>60 kHz) [23].

Wang et al. [33] formulate a 3-D electromechanical impedance model that characterized the interaction between an embedded square PZT transducer and the host structure based on the effective impedance. The model is experimentally and numerically verified using a smart concrete cube with embedded square PZT transducer. A new methodology to monitor the compressive strength of concrete based on the effective mechanical impedance is proposed.

Lu et al. [25] recently developed a novel EMI based model for strength development monitoring of cementitious materials. They overcame the shortcoming of lack of physical model in the conventional EMI based technique by introducing the concept of "Smart Probe". A 3-D coupled field FE model is also established to predict the admittance spectrum of the Smart Probe embedded in cementitious material [26].

Up to date, various analytical based models simulating the PZT-structure interaction has been developed. However, most of these models focus on metallic structures such as aluminum and steel. Literatures on concrete structures are fairly limited.

### 1.2. Modeling of WP technique

In the field of WP technique, surface bonded PZT transducer actuates the host structure through "in-plane strain coupling" [37]. Its strong planar actuation predominantly generates Lamb wave or R-wave (surface wave). Lamb wave is usually dominant in thin metallic structure whereas R-wave is common in thick structure, such as concrete. In thick structure, weaker pressure wave (P-wave) is also simultaneously excited. These waves travel radially outwards on the plane at which the PZT transducer is attached. Recently, WP technique finds its application in concrete structures, extending into concrete hydration and strength monitoring [13,16]. Kong et al. [16] have successfully investigated the three states (fluid state, transition state, and hardened state) of very early age concrete based on classification of the received electrical signal. Kong and Song [17] conducted a comparative study to investigate the performance of monitoring the very early age cement hydration process by using P-wave and shear wave (S-wave).

Similar to the EMI technique, modeling performed and studied in this area, thus far, focused mainly on metallic structures. Moulin et al. [28] present a modeling approach that couples the normal mode expansion method with the FEM to predict the surface displacement of Lamb waves in a composite plate excited from a source. The source of the Lamb waves is generated from both surface bonded and embedded piezoelectric transducer. The applicability of the model is validated with experimental study.

Giurgiutiu [8] presents a model of one-dimensional plane harmonic Lamb waves tuning mechanism with piezoelectric transducer. Assuming perfect bonding conditions, the interfacial shear is concentrated at the ends (i.e. pin-force model). The harmonic displacement and strain field is obtained by using the residual theorem to evaluate the integral of the inverse Fourier transform. A solution for a generic expression of the interface shear stress distribution is obtained. Lamb wave modes tuning curves with varying frequency are derived and verified against experimental results.

Giurgiutiu [9] presents a series of 1-D and 3-D modeling involving piezoelectric generated guided waves propagating in thin metallic strip. Both conventional FE and coupled field FE modeling are conducted. In the conventional simulation, prescribed harmonic displacements are applied to nodes located at the opposite ends of the piezoelectric transducer. Axial waves ($S_0$ mode) and flexural waves ($A_0$ mode) are separately simulated and studied. Effectiveness of both types of waves in detecting cracks is compared. The coupled field FE modeling is considered as a more complete analysis as the coupling between piezoelectric transducer and the host structure is simulated. Sensor's electrical signatures could be directly produced. Good agreements between both analyses are generally found.

Song et al. [31] conduct FE study to simulate the generation and the reception of R-wave in the concrete structure. They show that the R-wave induced by the piezoelectric actuator can be detected by the sensor in spite of a fairly large distance. The FE simulation result has been experimentally validated. The authors conclude that the R-wave excited by surface bonded PZT transducer generated stronger actuation and thus a more effective sensing, in comparison to the embedded transducer.

Lim et al. [19] propose a WP based semi-analytical concrete strength evaluation model. Classical wave equations are used in conjunction with the P-wave and R-wave acquired from the WP technique to predict the physical properties of concrete, namely the dynamic modulus and the Poisson ratio. The WP technique is proven to be capable of predicting the strength of mortar and concrete with different water-to-cement ratio throughout the curing process. The performance of the PZT based WP technique is also found to be comparable to other conventional techniques, including the rebound hammer, the ultrasonic pulse velocity and the EMI techniques. Tian et al. [32] developed a simple and effective absorption attenuation model of stress waves in concrete based on the Rayleigh damping model.

Kijanka et al. [15] present a three-dimensional temperature-dependent model of surface-bonded PZT on Lamb wave propagation. The effect of temperature on Lamb wave actuation, propagation and sensing is investigated. Actuation and sensing properties of PZT for various temperatures are studied through the electric field analysis. It is found that the temperature-dependent physical properties of PZT, bond layers and host structures significantly affected the amplitude and phase of Lamb wave responses.

In this paper, a complete coupled field FE simulation into the WP based PZT – concrete structure interaction is performed. Both P-wave and R-wave are identified from the sensor's electrical signatures. Selected experimental results for verification are initially reported in the studies recently conducted by the same authors [20]. Parametric studies are then conducted using both FEM and theoretical wave equations. Experimental and analytical studies