Simulation of Ultrasonic Response to Early Corrosion in Reinforced Concrete

Farah Aina Jamal Mohamad[1], Anita Ahmad[1*], Ruzairi Abdul Rahim[1], Sallehuddin Ibrahim[1], Juliza Jamaludin[2], Noorhazirah Sunar[1]

[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
[2]Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, Bandar Baru Nilai, 71800, Nilai, Negeri Sembilan, Malaysia

Corresponding author* email: anita@utm.my
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ABSTRACT

Corrosion of steel reinforcement is a major cause of deterioration in reinforced concrete (RC) structures. It often starts at the steel–concrete interface and progresses silently, without any visible signs of damage, until significant deterioration has occurred. Early detection is therefore crucial to enable timely maintenance and extend service life. This study investigates the feasibility of using ultrasonic techniques to detect early-stage corrosion in RC through finite element (FE) simulations. A two-dimensional model was developed in COMSOL Multiphysics, with a steel rebar embedded within a concrete block. Early corrosion was represented as a thin annular layer with reduced stiffness and density surrounding the steel bar, and three cases were simulated: intact steel, 1 mm corrosion layer, and 2 mm corrosion layer. The simulation results showed that thicker corrosion led to reductions in wave amplitude, delays in arrival time, and distortion of the waveform, which indicates changes in acoustic impedance and scattering at the degraded interface. These findings demonstrate the potential of ultrasonic-based methods for detecting corrosion at its earliest stages and provide a foundation for developing more sensitive structural health monitoring techniques for RC infrastructure.

Keywords: early-stage corrosion, FE simulation, reinforced concrete, ultrasonic

1. Introduction

Reinforced concrete (RC) is widely used in civil infrastructure, including buildings, bridges, and pavements, due to its high compressive strength and cost-effectiveness [1]. However, the embedded steel reinforcement is susceptible to corrosion, particularly when exposed to moisture, chlorides, or carbonation [2], [3]. Corrosion leads to the formation of rust products that expand in volume, which causes internal stresses, cracking, and delamination of the surrounding concrete. This progressive deterioration reduces the load-carrying capacity and service life of RC structures. Globally, corrosion-related damage in civil infrastructure is estimated to cost about 3–4% of the annual gross domestic product, and in the United States alone, direct corrosion-related maintenance costs exceed USD 276 billion annually [4], [5]. As corrosion initiates internally and progresses slowly, visible signs of deterioration often appear only after significant damage has occurred. Therefore, early detection is critical to enable timely intervention, reduce maintenance costs, and ensure the long-term safety of RC infrastructure.

Various nondestructive testing (NDT) techniques have been explored to monitor the condition of RC structures, such as half-cell potential measurement, ground-penetrating radar, acoustic emission, and ultrasonic testing [6], [7]. Among these techniques, ultrasonic-based methods have gained significant interest due to their ability to assess internal conditions without causing damage to the structure. Ultrasonic waves are highly sensitive to changes in material properties and interfaces, which makes them suitable for detecting cracks, voids, and delamination. Recent advances in sensor technologies, such as piezoelectric transducers and fiber optic sensors, have enabled the use of active ultrasonic sensing for structural health monitoring (SHM) in RC systems [8]–[10].

Despite these developments, most existing studies focus on detecting corrosion at advanced stages, where significant section loss, visible cracks, or delamination have already occurred [11]–[13]. In these cases, ultrasonic signals commonly exhibit clear reductions in velocity and amplitude due to the presence of large voids and discontinuities. However, during the early stage of corrosion, the steel–concrete interface undergoes subtle degradation and the formation of micro-voids, which cause only minor changes in the acoustic impedance. These early-stage changes are much more challenging to detect, and the ultrasonic response mechanisms associated with them remain poorly understood.

Finite element (FE) simulation has emerged as a powerful approach to investigate ultrasonic wave propagation in complex and heterogeneous concrete materials. Several studies have used FE modelling to examine wave scattering, reflection, and attenuation patterns in intact and damaged RC [14]–[16]. However, many of these works rely on complex post-processing techniques to interpret the ultrasonic signals, and only a limited number have attempted to numerically characterize the interaction between ultrasonic waves and corrosion-induced interface degradation at an early stage.

To address this gap, this study aims to numerically investigate the ultrasonic response of reinforced concrete structures subjected to early-stage corrosion at the steel–concrete interface using finite element simulations. A two-dimensional RC model was developed in COMSOL Multiphysics to simulate the propagation of ultrasonic waves through both intact and corroded specimens. Early corrosion was represented as a thin, degraded interfacial layer surrounding the embedded steel rebar. Two piezoelectric sensors were positioned on opposite sides of the concrete to actively generate and record the ultrasonic signals. The simulation results provide insights for assessing the feasibility of using ultrasonic techniques for early-stage corrosion detection.

2. Methodology

A two-dimensional finite element model was developed in COMSOL Multiphysics 6.0 to investigate the propagation of ultrasonic waves through reinforced concrete subjected to early-stage corrosion at the steel-concrete interface. The simulation employed the Pressure Acoustics, Solid Mechanics, Electrostatics, and Electrical Circuit physics modules under a time-dependent study. The Pressure Acoustics interface modeled wave propagation in the concrete medium, while the Solid Mechanics interface represented elastic behavior in the steel rebar and the concrete's solid phase. The Electrostatics and Electrical Circuit interfaces were coupled to simulate the electrical excitation and piezoelectric response of the ultrasonic transducers. These physics modules were bidirectionally coupled through displacement and pressure continuity boundaries to replicate the actuation and sensing process of an active ultrasonic measurement system.

The model geometry, as illustrated in Figure 1, consisted of a rectangular concrete block with a centrally embedded steel rebar, representing a simplified section of RC structural components. The concrete block was modelled with overall dimensions of 150 × 150 mm, while the steel rebar was represented as a smooth circular rod of 12.7 mm diameter. Surface ribs on the rebar were neglected to reduce computational complexity and focus on bulk wave behavior. Two piezoelectric sensors were defined in the model. The first one generated the ultrasonic pulse, while the second one at the bottom recorded the received wave signals.

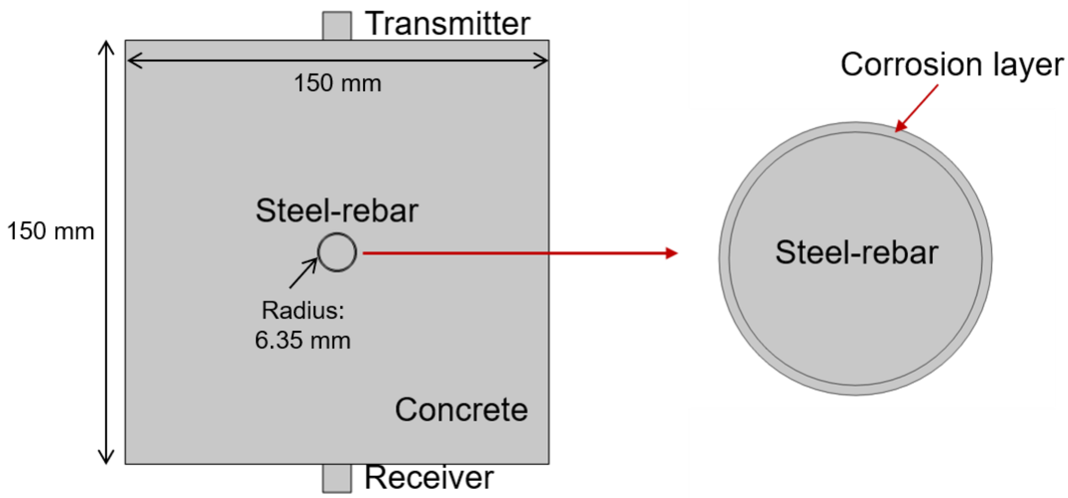


Figure 1. Simplified corroded RC model.

Three cases, as illustrated in Figure 2, were simulated:

i) Case 1: Intact steel reinforcement (no corrosion),
ii) Case 2: Steel surrounded by a 1 mm-thick corrosion layer
iii) Case 3: Steel surrounded by a 2 mm-thick corrosion layer

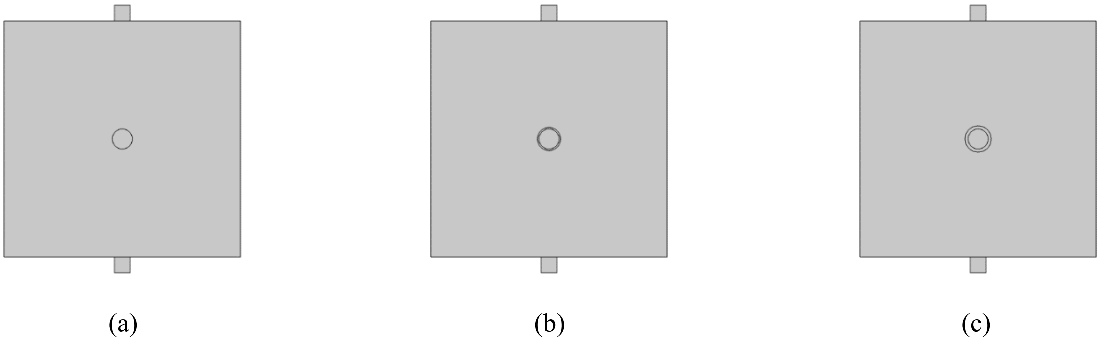


Figure 2. The generated RC model for (a) Case 1, (b) Case 2, and (c) Case 3.

The corroded layer was modelled as an annular region with reduced density and stiffness compared to steel to represent the degraded mechanical properties of rust. Concrete and steel were modelled as linear elastic isotropic materials.

To represent common structural concrete, the concrete properties were based on a nominal mix proportion of 1:2:4 (cement: sand: coarse aggregate volume) with a water–cement ratio (w/c) = 0.5, corresponding to a compressive strength of approximately 25–30 MPa. This composition reflects standard reinforced concrete commonly used in structural applications [17]. Concrete was assumed homogeneous and isotropic for simplicity. Table 1 summarizes the properties of steel and concrete.

Table 1. Material properties used in the FE model

Parameter	Concrete	Steel
Density (kg/m³)	2000	7850
Young's Modulus (GPa)	30	200
Poisson's ratio	0.2	0.3
Speed of sound (m/s)	3400	5900

Figure 3 shows a finer mesh that was applied around the steel–concrete interface and within the corrosion layer to ensure accurate capture of wave interactions. In addition, low-reflection boundary conditions were applied at the outer boundaries of the concrete block to minimize reflections. Ultrasonic waves were generated using a single-cycle sinusoidal pulse with a central frequency of 200 kHz. The excitation was applied as a displacement boundary load at a point on the concrete surface directly above the steel bar.

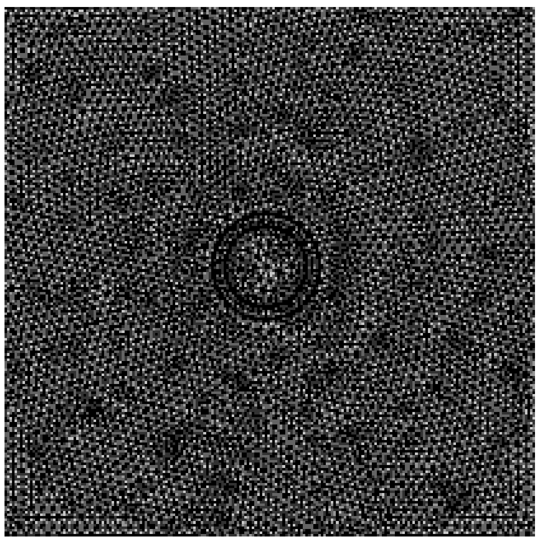


Figure 3. Detailed view of the finite element mesh in the vicinity of the steel–concrete interface.

The time-dependent solver in COMSOL was then used to simulate elastic wave propagation. It allows for direct comparisons between the intact, 1 mm-corroded, and 2 mm-corroded models. Changes in wave amplitude and the time delay of the first arrival were analyzed as potential indicators of early-stage corrosion around the steel reinforcement.

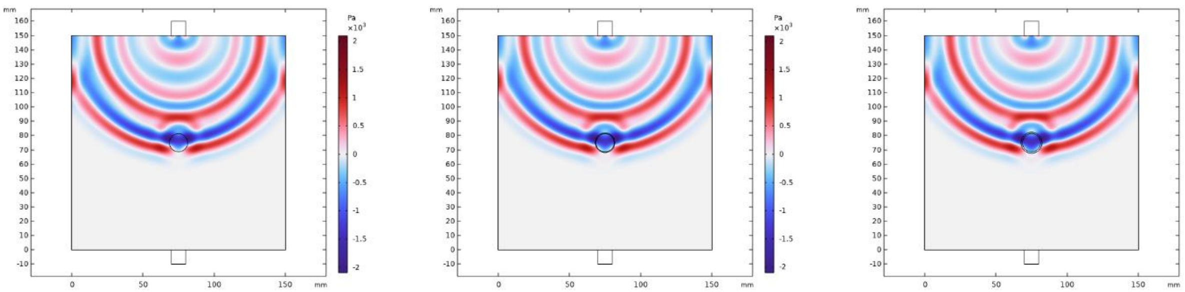
The main COMSOL parameters and solver configurations are summarized in Table 2.

Table 2. Simulation parameters and solver settings

Parameter	Description/Setting
Software version	COMSOL Multiphysics 6.0
Physics interfaces	Pressure Acoustics, Solid Mechanics, Electrostatics, Electrical Circuit
Study type	Time-dependent (transient)
Time range	0 – 100 µs
Excitation signal	Sinusoidal pulse, 200 kHz
Element type	Quadratic triangular elements
Mesh refinement	Fine near the steel-concrete interface and corrosion layer
Boundary condition	Low-reflecting boundary
Model type	2D plane, 150 mm x 150 mm
Outputs	Pressure wavefields, time-domain responses

3. Results and Discussion

Figure 4 illustrates the representative snapshots of the simulated wavefield for the three corrosion conditions at time 30 µs.



(a) (b) (c)

Figure 4. Simulated pressure wavefield snapshots for (a) intact, (b) 1 mm corrosion, and (c) 2 mm corrosion conditions.

For the intact model, the ultrasonic wavefront propagated across the steel–concrete interface with minimal distortion. In contrast, the presence of a corrosion layer produced noticeable scattering, and slight reflections were observed around the corrosion layer. These effects became more significant in the 2 mm corrosion case, where the wavefront was visibly delayed and distorted after crossing the degraded interface. These observations suggest that even a thin degraded layer significantly disrupts the transmission of high-frequency ultrasonic waves. Figure 5 presents the signals recorded at the receiver point for the three models.

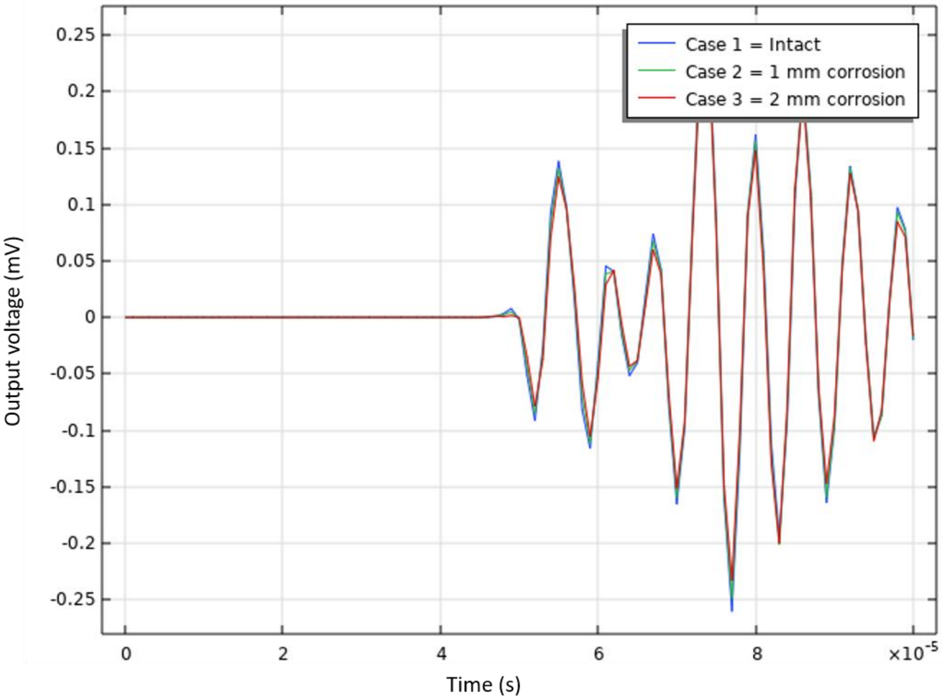


Figure 5. Simulated time-domain for intact, 1 mm, and 2 mm corrosion conditions.

The simulation results indicate that the presence of a corrosion layer at the steel–concrete interface introduces noticeable changes in the propagation of ultrasonic waves. In particular, the first arrival of the wave is delayed in corroded models compared to the intact condition, reflecting a reduction in the effective wave velocity. This slowing occurs because the corrosion layer exhibits lower stiffness and altered mechanical properties compared to the surrounding steel, which impedes the transmission of elastic energy.

In addition to the delay in arrival, the amplitude of the transmitted wave is attenuated as the corrosion layer becomes more pronounced. This reduction in amplitude arises from partial reflection and scattering at the degraded interface, which diverts a portion of the wave energy away from the main propagation path. As a result, less energy reaches the receiver, and the waveform exhibits a decrease in peak intensity.

The simulation results clearly demonstrate that early-stage corrosion around reinforcing steel significantly affects ultrasonic wave propagation. The corrosion layer causes delays in wave arrival, reductions in amplitude, and waveform distortion. This behavior highlights the potential of ultrasonic techniques to detect corrosion before it becomes visually observable or causes structural deterioration.

4. Conclusions

This study presented a finite element simulation approach to investigate the ultrasonic response of reinforced concrete (RC) structures subjected to early-stage corrosion at the steel–concrete interface. A simplified two-dimensional model was developed in COMSOL Multiphysics, which consists of a steel rebar embedded within a concrete block. The simulation results showed that the presence of a degraded interfacial layer caused measurable changes in the ultrasonic signals compared to the intact condition. In particular, increasing corrosion thickness resulted in a reduction in the peak amplitude, a slight increase in wave arrival time, and greater distortion of the waveform. These effects result from the reduced acoustic impedance and higher scattering at the corroded interface, which attenuate and delay the transmitted wave energy. The results demonstrate that ultrasonic techniques have the potential to detect significant interfacial changes associated with early corrosion before visible cracks or major damage occur. Future work will focus on refining the model to include more realistic conditions, including three-dimensional geometries, non-uniform localized corrosion patches, and surface ribs on the rebar. Experimental validation using physical RC specimens with controlled corrosion levels will also be conducted to verify the simulation predictions.

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