

Corrosion Assessment & Control Techniques in RCC Structures Using Piezo Sensor

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ABSTRACT

The durability of reinforced concrete (RC) is a significant subject in contemporary discussions. The corrosion of RC structures has emerged as a primary factor contributing to structural failures. The corrosion process in steel-reinforced concrete is governed by a time-dependent equation, making real-time monitoring of corrosion a challenging endeavour. This study employs a piezoelectric sensor to facilitate real-time corrosion monitoring. Corrosion monitoring can help identify the extent and specific locations requiring repairs or replacements, thereby minimising rehabilitation expenses. In this research, the M40 and M50 concrete grades were evaluated using the non-destructive testing (NDT) method. The findings indicate that NDT techniques are effective in assessing the impact of steel corrosion on RC structures, as well as in evaluating the overall structural integrity. An oscilloscope was utilized to capture the individual ultrasonic waves corresponding to concrete grades M40 and M50. Additionally, a comparison of the ultrasonic waves from both grades was conducted, leading to the recommendation of the most suitable concrete grade for practical applications. The experimental outcomes successfully identified and quantified rebar corrosion with precision. This research will offer diagnostic engineers and researchers in the field of rebar corrosion a refined experimental methodology for comparing various concrete grades. The durability of reinforced concrete (RC) is a significant subject in contemporary discussions. The corrosion of RC structures has emerged as a primary factor contributing to structural failures. The corrosion process in steel-reinforced concrete is governed by a time-dependent equation, making real-time monitoring of corrosion a challenging endeavor. This study employs a piezoelectric sensor to facilitate real-time corrosion monitoring. Corrosion monitoring can help identify the extent and specific locations requiring repairs or replacements, thereby minimizing rehabilitation expenses. In this research, the M40 and M50 concrete grades were evaluated using the non-destructive testing (NDT) method. The findings indicate that NDT techniques are effective in assessing the impact of steel corrosion on RC structures, as well as in evaluating the overall structural integrity. An oscilloscope was utilized to capture the individual ultrasonic waves corresponding to concrete grades M40 and M50. Additionally, a comparison of the ultrasonic waves from both grades was conducted, leading to the recommendation of the most suitable concrete grade for practical applications. The experimental outcomes successfully identified and quantified rebar corrosion with precision. This research will offer diagnostic engineers and researchers in the field of rebar corrosion a refined experimental methodology for comparing various concrete grades.

Keywords- SHM, Oscilloscope, Piezoelectric, Amplitude, Accelerated corrosion.

I. INTRODUCTION

The longevity of concrete structures constructed globally is closely tied to the conditions they encounter and are subjected to, including factors such as corrosion, impact loads, climatic conditions, and pollution. These factors, along with the inherent quality of the structure's construction, can result in variations in the timeline for initial deterioration. A safety system is in place to safeguard concrete from both environmental influences and the operational demands it must fulfill. These protective measures extend the duration before initial deterioration commences. The strength of concrete can be attributed to hydration products, primarily formed through C-S-H gel. The characteristic that contributes to concrete's widespread use as a building material is its remarkable capacity to endure compressive stresses [1]. Most structures are typically designed for longevity; however, the reinforcing steel can corrode over time due to the adverse effects of the external environment, potentially compromising the stability of the structure. Reinforcement steel is crucial in construction

as it prevents the bending of structural elements under stress and other forces. It also resists compression but is unable to withstand tensile stresses. Consequently, reinforced concrete (RCC) is a composite of steel and concrete that can endure two types of stresses: compressive and ductile. Given that RCC structures are exposed to various environmental conditions, their maintenance is affected, leading to damage that results in both commercial and initial losses. One significant form of damage to RCC structures occurs when the steel embedded within the concrete begins to corrode [2-3]. Over time, corrosion diminishes the strength of the steel components, rendering them ineffective. Externally, the corrosion of steel bars may not be apparent, giving the impression of stability; however, a corroded structure becomes highly vulnerable to extreme loads (design loads). Additionally, there may be reductions in strength within reinforced and steel structures. It has been frequently noted that reinforced concrete (RC) structures exhibit strong and durable performance. Nevertheless, in certain instances, the corrosion of steel reinforcement bars can lead to structural failure, resulting in loss of life and financial resources. Corrosion is recognized as one of the primary factors contributing to the degradation of RC structures [4]. Corrosion is an electrochemical reaction that occurs in iron-based metals when they are subjected to environmental exposure, leading to material deterioration. The presence of concrete cracks is often attributed to the corrosion of steel rebar [5]. Consequently, various types of oxidation products are generated as a result of corrosion. The extent of corrosion in steel bars can vary based on the materials involved and the specific corrosion products formed. During this process, ultrasonic waves are transmitted through the steel bars. Subsequently, the wave energy is conveyed to the concrete section that contains the sensor [6]. In areas where corrosion is present, the wave energy will be diminished, resulting in a corresponding decrease in intensity. This reduction in wave amplitude will be recorded by an oscilloscope, allowing for the detection of corrosion through changes in wave amplitude [7].

The working principle is shown in Figure 1.

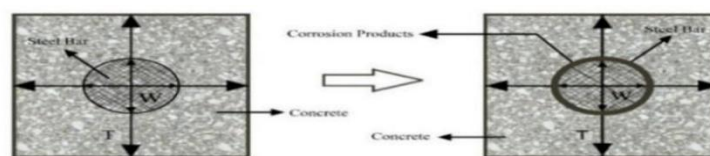


Figure 1: Propagation of ultrasonic waves in steel bar and concrete (W: wave propagating in steel bar) (T: wave transmitted into concrete) [7]

As the bonding between steel and solids weakens over time, the structure becomes less strong, leading to repair failures. Corrosion of metal structures may occur in various industries like oil and gas, aerospace, civil infrastructures, mining and processing. During operation, corrosion can be a serious threat to security and maintenance, causing huge economic losses as well as life-threatening situations. Globally, corrosion is estimated to cost almost \$ 2.5 trillion according to the World Corrosion Organization [8-9]. Economic losses and the injuries caused due to utilization of the faulty steel bars in RC structures are the biggest foundation problems faced by industrialized nations [10]. Due to this reason, repair cost is a very significant part of current infrastructure spending. Thus, many scholars have conducted vast amounts of research using the electrochemical method to investigate the corrosion of steel-rebar. For example, Weijie Li et al [11] investigated the Modeling and validation of electromechanically impedance instrumented circular piezoelectric-metal transducers for corrosion monitoring. Peng Liu et al [12] carried out the Integrating a piezoelectric transducer in the reinforced concrete to monitor corrosion. Visalakshi Talakokula and Suresh Bhalla [13] assessing the corrosion potential of reinforced concrete structures with surface-bonded and embedded piezo sensors. Dongsheng Li et al [14] studied the utilizing Ultrasonic Guided Waves to assess corrosion within reinforced concrete structures. Weihua Shi et al [15] studied the using piezoelectric smart materials to investigate the corrosion of reinforced concrete. Rajeshwara Chary Sriramadasu et al [16]

The detection of pitting corrosion in reinforced concrete rebars was conducted using longitudinal guided wave modes. In the last ten years, the use of piezoelectric sensors for corrosion monitoring has garnered significant interest due to their rapid detection capabilities, high sensitivity, and ability to provide continuous real-time tracking. To ensure the safety of structures, it is essential to maintain their integrity through effective monitoring techniques that can identify corrosion in the reinforcement. This necessity has led to the advancement of more sophisticated nondestructive methods, including acoustic emission and electrochemical techniques [17-20]. In contemporary practice, sensor-based corrosion monitoring is a recognized approach to enhance the stability and durability of facilities, which ultimately results in reduced operating costs. Among the various types of smart materials, piezoelectric materials are extensively utilized. They can function as both sensors and actuators. In this study, an innovative sensor was developed to monitor corrosion in steel bars. The sensor employs piezoelectric materials to generate and receive ultrasonic waves. The waves, guided by the steel bar, enable the detection of corrosion within the steel. The piezo-sensor embedded in the steel rebars was monitored, and the amplitude values were recorded using an oscilloscope. Additionally, a comparison was conducted between two higher grades of concrete (M40 and M50). The authors concentrated on the amplitude and frequency of these waves, as variations in these parameters can signify the presence and severity of corrosion in the embedded steel bars. The study evaluated both concrete grades at different corrosion rates (1%, 4%, 6%, 8%, and 12%). By analyzing how the characteristics of the ultrasonic waves

changed with increasing corrosion, the authors were able to evaluate the performance of each concrete grade under comparable conditions.

II. EXPERIMENTAL PROCESS

Fabrication process of piezoelectric ceramic sensor

A variety of piezoelectric materials exist, with piezoelectric transducers (PZT) ceramics being the most commonly utilized in civil engineering applications. Consequently, PZT ceramics were employed as the sensing element for this research. The piezoelectric sensors consist of two ceramic components; one is responsible for generating and receiving ultrasonic waves, while the other serves as a wave guide. An ultrasonic sensor utilizing PZT-5 (Lead-Zirconate-Titanate modified with La, Nb, etc.) was implemented in this investigation [4]. The performance parameters are detailed in Table 1. In the piezoelectric ceramic element, coaxial cables were attached to the electrodes located at opposite ends. After encapsulating the sensor with epoxy, it was subsequently connected to the steel bars at varying lengths. The area was machined to achieve a smooth surface for bonding all bars to the sensor (patch).

Table 1: Parameters of the piezoelectric sensor used in this study [14]

PZT constant d_{33}		10^{-12} C/N
Density		7500 kg/m ³
Dielectric loss		0.02
Relative Permittivity ϵ_{r3}		1700
Electromechanical coefficient K_{33}	coupling	0.75
Curie temperature °C		320

Subsequently, the connection was covered with silver paste to shield it from corrosion exposure. The manufacturing procedure of the piezoelectric sensor is illustrated in Figure 2. A lightweight object is employed to exert gentle pressure across the entire smooth surface. To ensure the bonded material fully hardens, the entire assembly was allowed to remain undisturbed at room temperature for one day.

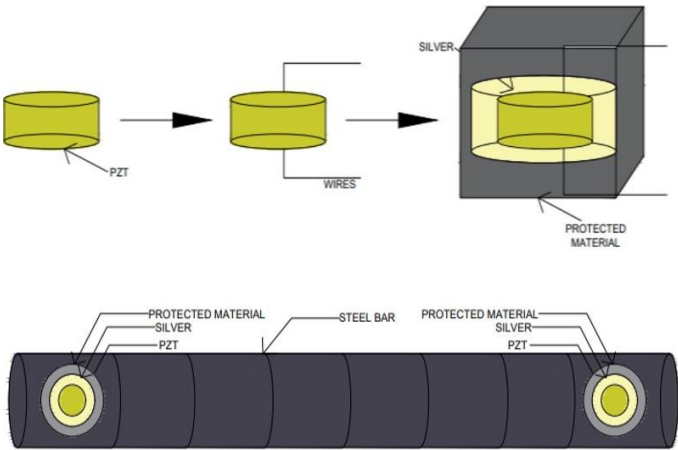


Figure 2: Fabrication process of piezoelectric sensor

Corrosion detection test

HYSD (high yield steel deformed) bars of grade Fe 415 (IS:1786, 2008) [21], measuring 450 mm in length and 16 mm in diameter, were utilized in this experiment. To conduct the corrosion test on the concrete specimen, rectangular moulds with dimensions of 100mm x 100mm x 500mm were prepared, as illustrated in Figure 3(a). Furthermore, to assess the compressive strength of the concrete, cube moulds measuring 150mm x 150mm x 150mm were also prepared, as depicted in Figure 3(b). All samples were created in accordance with the specifications outlined in the Indian standard IS 516-1959 [22], as shown in Figure 4. A total of 6 beams and 18 cubes were produced, each with a clear cover of 45mm. Grade 43 ordinary Portland cement from a single source was employed in this process. After mixing the concrete with cement, sand, and aggregates, two mix designs, M40 and M50, were utilized for the casting of the reinforced beam. The concrete mix

design entails a preparation process in which a combination of ingredients is formulated to achieve the necessary strength and durability for the concrete structure. The mix design proportions used in this experiment were calculated according to the codal provision 10262:2009 [23], as presented in Table 2. An admixture was incorporated to reduce the W/C ratio in the M50 design [24]. During the initial 24 hours, all samples were retained in the steel mould under controlled environmental conditions. After this period, all moulds were demoulded and immersed in a curing tank for 28 days to develop compressive strength.



Figure 3: Test specimen (a) Rectangular Mould



Figure 4: Reinforced concrete Samples Cast for experiment. (b) Cube Mould

Table 2: Mix design proportion

Description	M40	M50
Water to Cement ratio	0.4	0.30
Water	185 Kg/m ³	140Kg/m ³
Cement	400 Kg/m ³	410.85Kg/m ³
Fine aggregate	620 Kg/m ³	750.27Kg/m ³
Coarse aggregate	1120 Kg/m ³	1229.38Kg/m ³
Final mix design	1:1.5:2.7	1:1.8:2.8

Throughout the corrosion process of reinforcing bars, the properties of reinforced concrete will alter based on the degree of corrosion; thus, as the transmission medium changes, the acoustic characteristics of the ultrasonic wave will also be affected. By examining the fluctuations in acoustic parameters, one can ascertain the level of corrosion present in the reinforcing bars within the concrete.

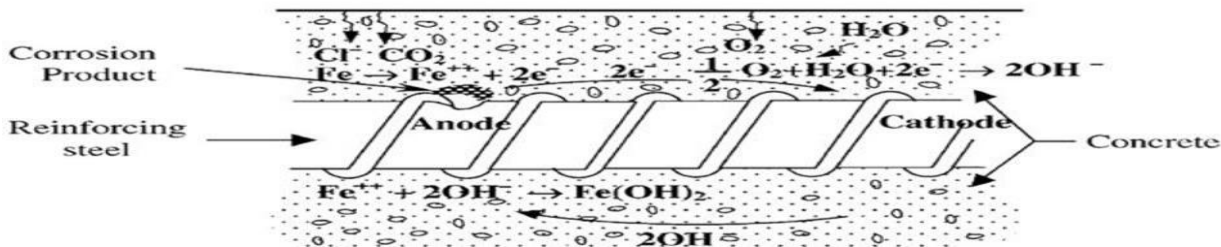
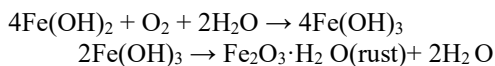


Figure 5: Chemical reaction of corrosion process

At anode: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$ At cathode: $2\text{e}^- + \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \rightarrow 2\text{OH}^-$
In order to develop ferric oxide or rust, the following equations need to be met:
 $\text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe}(\text{OH})_2$



As shown in Figure 5, corrosion of steel occurs as a result of chemical reactions. Anode and cathode reactions happen when an electric current passes through them. During the reaction at the anode, $\text{Fe}(\text{OH})_3$ is formed, which is commonly known as rust. Natural corrosion takes a very long time, and it is usually slow at first. In the laboratory, corrosion occurs faster when a chloride environment is created around the concrete beam. Figure 6 illustrates the corrosion monitoring setup of reinforcing bars within concrete. In a 10% NaCl solution, the piezoelectric sensor was bonded to the concrete sample. The terminals were powered by a DC power supply with a constant voltage of 25 volts. Because the corrosion of reinforced concrete occurs so slowly in the natural environment, the method of electrochemistry is used to accelerate the process in order to progress more rapidly. The Main Steel bar in concrete was used as the working electrode and stainless steel as the auxiliary electrode. It was necessary to examine the sensor's properties before embedding it into the concrete. A signal generator (SFG 1030) and oscilloscope were connected using two ends of the metal rods (as shown in Figure 7). PC Labview was used to control an oscilloscope, and an amplifier was used to amplify input signals. An actuation PWT at a distance of 5cm will be used on one end and a sensing PWT at 35cm will be used on the other end of the same rebar. An electrical pulse from a signal generator (SFG 1030) was stimulated with one piezoelectric component (at a distance of 5 cm from the end of the rod) together with another piezoelectric element (at 35 cm from the end of the rod). Data were acquired using an oscilloscope (GDS-1102-U). It can see that the detector could react to changes in its environment. In the acceleration test, 10 volts of potential was used. At a particular interval of time, the ultrasonic wave signals were measured. The wave amplitude detects the initiation of corrosion in the OPC concrete beam. By calculating Faraday's law, we calculated how much the steel reinforcement corrodes electrochemically:

$$QM \int I(t)dt (1)$$

$$\Delta m = n \times M = \frac{Q}{F|Z|} \times M = \frac{Q}{F|Z|} \times M$$

In this equation, mass of corroded steel is Δm , quantity of electrical charge is Q , and faraday constant is F . The current intensity is I and t is the time. Valence of ferric iron is determined by, $|Z|$, and corrosive steel contains certain quantities of n , and the Fe molar mass is M [12, 24]. Eq 2 calculates the corrosion rate of steel based on mass loss rates before and after corrosion.

$$\Delta m (2)$$

$$\Delta \vartheta = \frac{100m}{\Delta m}$$

Where,

$\Delta \vartheta$ stands for the rate of corrosion,

,and m represents the weight of steel before corrosion.

III. CHOOSING AN INPUT SIGNAL

When the input signal is narrowband, the output signal can be distinctly interpreted; however, a broadband signal guarantees precise excitation at the desired frequency. The efficiency of the PWT is influenced by the distance between actuator and sensor pairs when a structural system is excited at a specific frequency. In this case, a five-cycle sine pulse, selected from the Hanning window, serves as the input signal to achieve a balance between the two. Parametric studies of PWT responses at different excitation frequencies are performed to identify the optimal frequency of excitation. The optimal frequency response was determined to be between 95 and 110 kHz. Consequently, 95 kHz was selected for the study.

IV. RESULTS AND DISCUSSION

As a reference point, ultrasonic waves detected from reinforced concrete after a curing period of 28 days can be taken into account. The ultrasonic waves travel through the steel reinforcement bars, and any existing corrosion diminishes the energy of the waves transmitted to the concrete, which is subsequently recorded by an oscilloscope. This technique facilitates the real-time assessment of corrosion levels. The waves were captured at various corrosion rates and documented for comparative analysis.

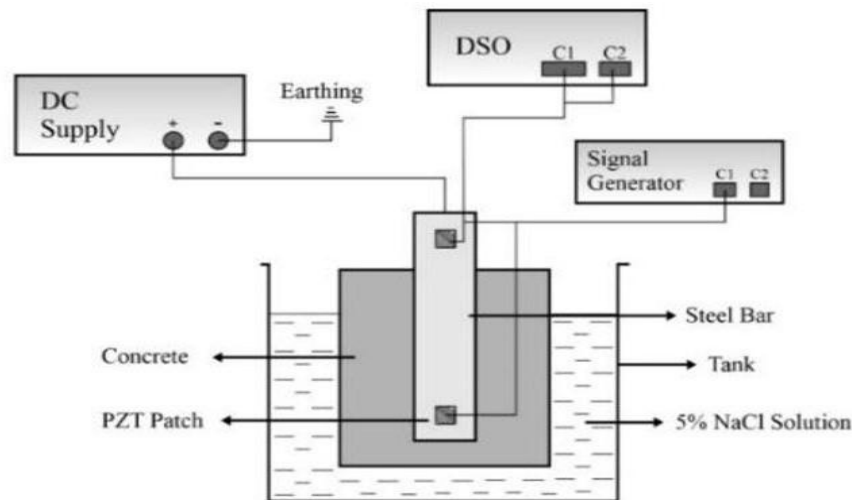


Figure 6: Schematic diagram showing the Corrosion monitoring in the lab

Utilising the accelerated corrosion setup described in the preceding section, six reinforced concrete samples underwent testing. It was essential to assess the properties of the sensor prior to its incorporation into the concrete. By activating one piezoelectric element with an electric pulse generated by a signal generator, and capturing the ultrasonic wave with the other piezoelectric element, an oscilloscope served as the recording device. This apparatus documents the amplitude and frequency of the waves, which are vital for assessing the condition of the embedded steel rebar. The ultrasonic waves facilitate the detection of corrosion initiation within the concrete beams. The input electric pulse was a step function of 30V. Testing was performed on four samples of M40 and M50 for a duration of 16 days, while the remaining two samples of M40 and M50 were tested for 2 days to monitor the onset of corrosion. The selection of 16 days for the extended tests likely indicates a timeframe adequate for observing significant corrosion effects, whereas the 2-day tests aimed to capture the initial stages of corrosion initiation. This dual methodology provides a thorough understanding of both the onset and development of corrosion across various concrete grades. Following the tests, the rebars were extracted for analysis, and the extent, intensity, and pattern of corrosion were evaluated. An excitation pulse with a frequency of 95 kHz and a peak-to-peak voltage of 30 V was employed. Because 95 kHz falls in a range



Figure 7: Test instruments equipment utilized in corrosion monitoring that transmits ultrasonic waves through concrete and steel, the frequency was likely selected.

This frequency allows for optimal interaction with the material properties of the concrete and the embedded steel rebar, facilitating the detection of changes in wave amplitude due to corrosion. To generate detectable ultrasonic waves, the peak-to-peak voltage was chosen at 30 V. This voltage level is high enough to produce clear signals while avoiding damage to the piezoelectric sensors or the surrounding concrete. By measuring the difference between the baseline and actual ultrasonic wave, the variation in corrosion of reinforcing bars of concrete was evaluated. As For M40 and M50 grades, we tested the received ultrasonic wave for corrosion rates of 1%, 4%, 6%, 8%, and 12%. Figure 9 (a) & (b) show the time and frequency- domain spectra of the emitted ultrasonic wave for M40 Grade. The ultrasonic wave received in the oscilloscope on 1% showed a large amplitude, and the amplitude began to decrease minimally when the corrosion rate was 4% in concrete of M40 grade. Due to the decreasing amplitude of the ultrasonic wave in the initial corrosion period, there is little corrosion product present. With increased corrosion rate, the amplitude of the receiving ultrasonic wave starts to decrease noticeably,

especially at 6%. A significant increase in corrosion level causes an increase in corrosion products, which results in a reduction of the transmitted ultrasonic wave. As a result, the wave's amplitude gradually decreases. Since the concrete to steel wave propagation efficiency was approximately 8%, the results were weak. It indicates that the reinforcing bars in concrete were heavily corroded. As corrosion proceeds, corrosion products are produced in increasing amounts, thus cracking of the concrete surface and a large loss in ultrasonic waves. The ultrasonic wave's amplitude therefore decreases, causing corrosion rate to further increase. Fig. 9(b) shows that when the corrosion rate is 1%, a peak is also visible around 100 kHz, and multiple peaks appear in the low-frequency region as well. As corrosion time increases, the dominant frequency peak's amplitude decreases gradually, and a new peak emerges in its place. Approximately 85 kHz becomes the dominant frequency peak when the corrosion rate reaches 12%. When the corrosion rate exceeds 12%, there are no obvious peaks in frequency. It is possible to determine the corrosion level over time by the frequency peak of the received ultrasonic wave as a function of corrosion rate.



Figure 8: Image shows a reinforced concrete beam after corrosion.

Increasing the strength of our concrete grade serves as an effective safeguard against the harsh external environment. Additionally, the spectral characteristics of M50 grade concrete exhibit a wave pattern that closely resembles that of M40 grade concrete. In the initial phase, the amplitude of the first wave peak shows minimal variation when the corrosion rate surpasses 1%. For M50 grade concrete, the ultrasonic wave detected at a 12% corrosion rate demonstrated a significantly higher amplitude compared to M40 grade, indicating that we can also assess the corrosion rate for an additional percentage. As illustrated in Figure 10 (a) & (b), the time and frequency domain spectra of reinforced concrete at varying corrosion rates were recorded for M50 grade. The frequency-domain spectrum of M50 reinforced concrete is akin to that of M40 reinforced concrete. During the corrosion process, weak resonance peaks emerge around the dominant frequency peak, while the value of the dominant frequency peak gradually diminishes. At a corrosion rate of 1%, the domain frequency peak is noted near 120 kHz; however, as the corrosion rate escalates, this peak begins to decline. In comparison to M40 grade, at a corrosion rate of 12%, the dominant frequency peak for M50 grade is observed around 95 kHz.

V. CONCLUSION

In this research, a novel and straightforward approach for detecting reinforcement corrosion in reinforced concrete (RC) structures has been introduced, utilizing the admittance signatures of embedded PZT patches. The admittance values across three distinct intervals were analyzed. The proposed method is non-destructive and entirely autonomous. The use of a PZT patch for corrosion monitoring can effectively assess the level of corrosion in rebars within actual reinforced concrete structures, where direct visual inspection is not feasible. By employing the PZT detection technique, representative samples of each grade were evaluated against corrosion monitoring outcomes to confirm the nature of the changes indicated by the amplitude signature.

Amplitude values for each concrete beam of varying grades (M40 and M50) were examined to identify the most suitable working samples for practical applications.

- a) In the case of concrete, amplitude attenuation is significant for M40 when the corrosion rate is below 1%, and it diminishes as the corrosion rate surpasses 8%. Both time-domain and frequency-domain spectra exhibit a similar trend. At a corrosion rate of 12%, the observed frequency peak was around 85 kN.
- b) Test results indicate that the M55 grade is more suitable for applications susceptible to corrosion. The dominant frequency peak shifts to approximately 95 kHz when the corrosion rate reaches 12%.

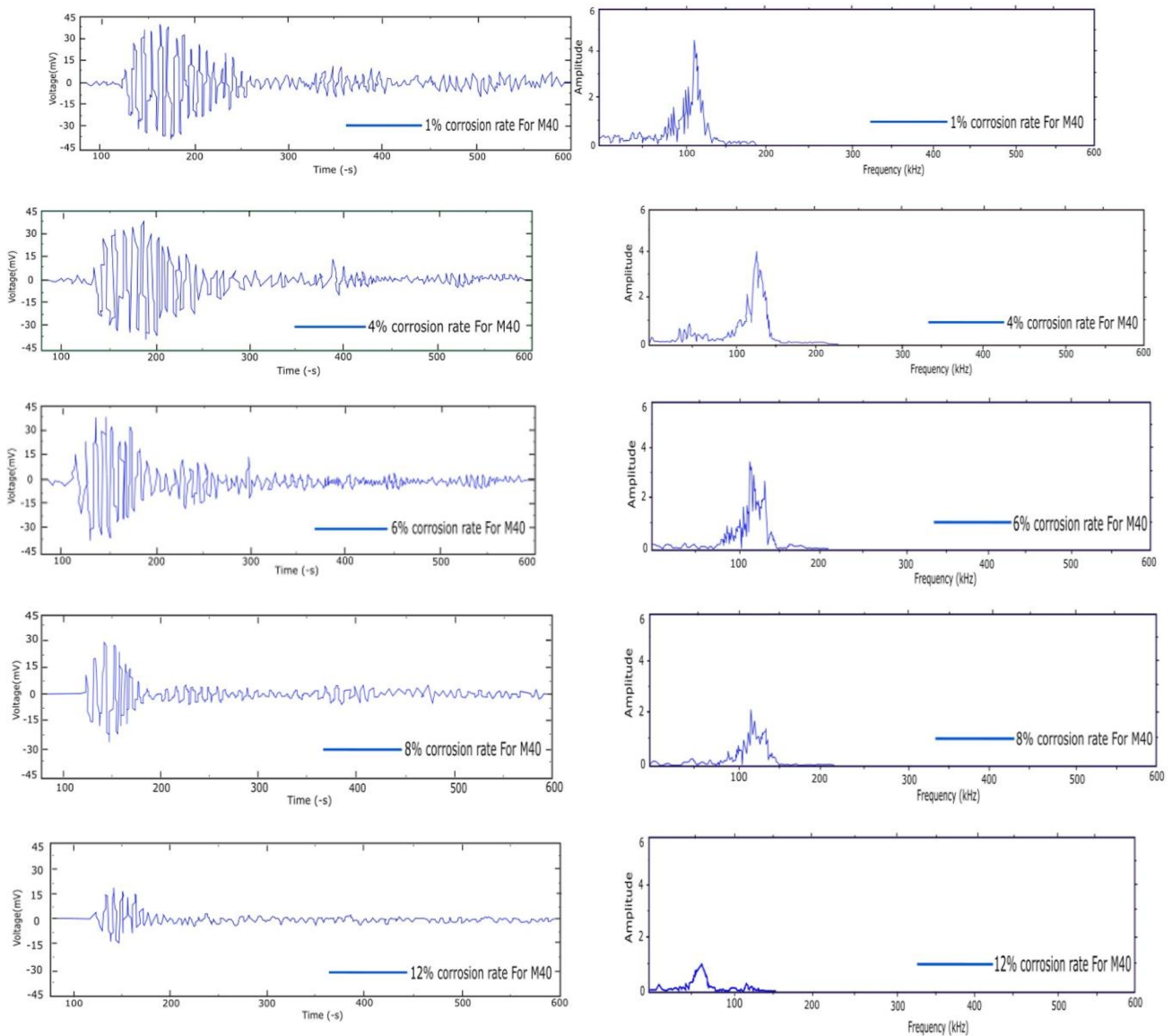
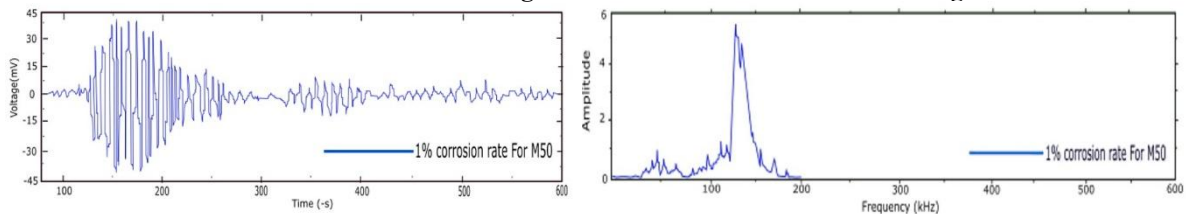


Figure 9 (a): Voltage vs Time graph for different corrosion Figure 9 (b): Amplitude vs Frequency graph for different rates of M40 grade concrete corrosion rate of M40 grade concrete



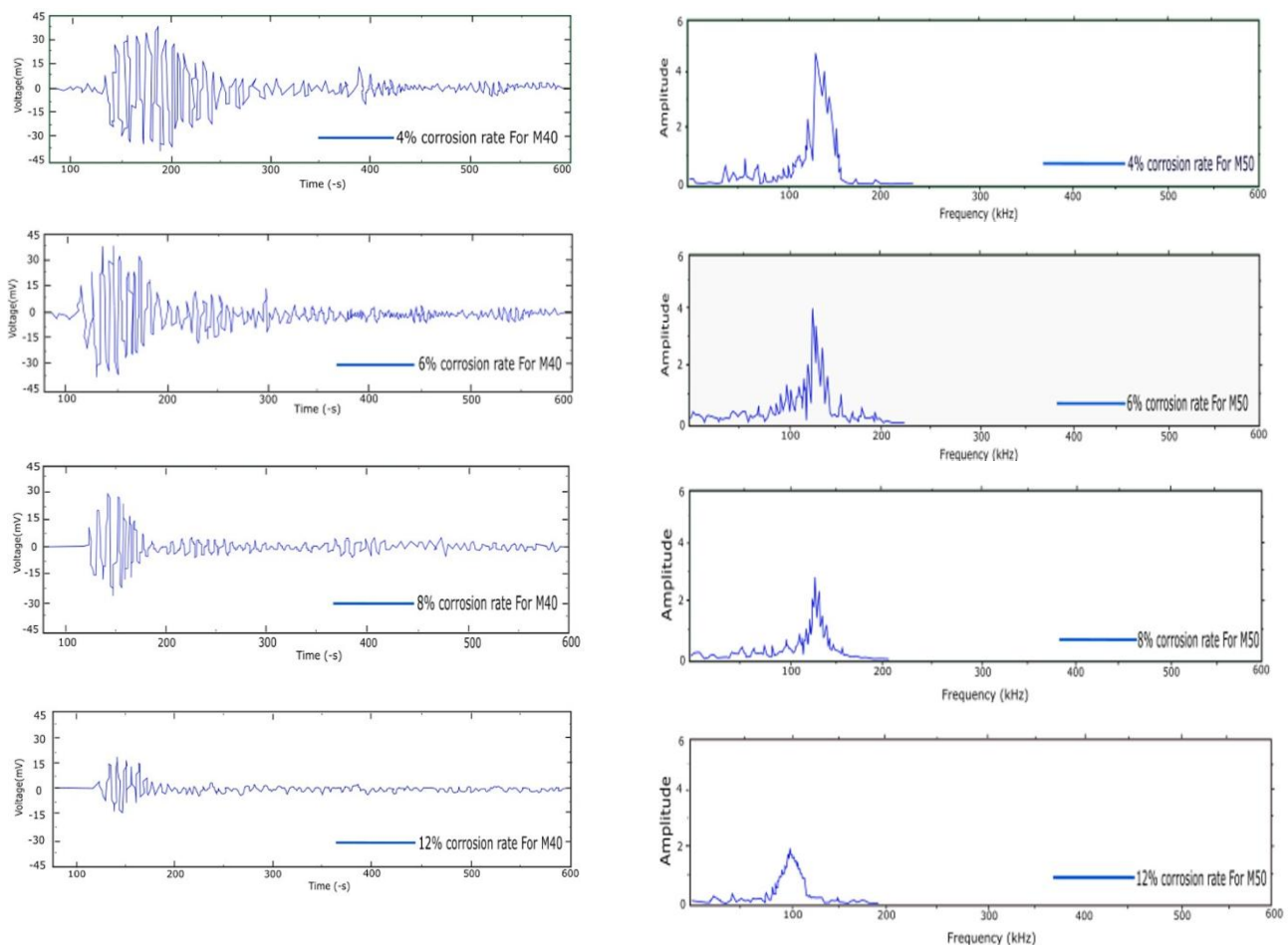


Figure 10 (a): Voltage vs Time graph for different corrosion rate of M50 grade concrete

Figure 10 (b): Amplitude vs Frequency graph for different corrosion rate of M50 grade concrete

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