Corrosion Assessment in Reinforced Concrete Structures using Structural Integrity Monitoring and the Finite Element Method

Victória Góis[1], Lucas Gomes[1], Raquel Silva[1]
[1]Federal University of Uberlandia, Faculty of Civil Engineering,
Uberlandia, Minas Gerais, Brazil.
vcr.victoria@hotmail.com, lucas.g@ufu.br, raquelfernandes@ufu.br

Abstract

This study investigates the effective application of Structural Health Monitoring (SHM) to detect the onset of corrosion in reinforced concrete structures, using the electromechanical impedance (EMI) technique. Considering that corrosion develops slowly and often imperceptibly, an accelerated method, known as the impressed current technique, was used to simulate deterioration. In this context, an electrochemical potential was applied to steel bars immersed in concrete specimens submerged in saline solution, reproducing aggressive environments. Piezoelectric sensors made of lead zirconate titanate (PZT) were used to monitor the progression of damage. These sensors are able to record minimal mechanical changes in the structure, converting them into variations in electrical impedance. By monitoring these impedance signatures, it was possible to assess the progression of corrosion, as well as to quantify its effects on the structural integrity of the concrete. In parallel with the experiment, numerical simulations were performed using the Finite Element Method (FEM) to simulate the behavior of the materials and the progression of damage. This dual approach enabled the evaluation and deeper interpretation of the practical results. The results demonstrate the high sensitivity of the EMI technique in the early identification of damage. Together, the practical and computational analyses provide valuable data on corrosion processes, enabling the creation of more intelligent and preventive maintenance strategies, increasing the durability, safety and performance of concrete structures exposed to aggressive environments.

Keywords: *Monitoring, Structural Integrity, Corrosion, Reinforced Concrete, Finite Element Method.*

I. Introduction

Concrete structures must be designed and built to ensure safety, stability, and serviceability under expected environmental conditions and intended usage throughout their lifespan (ABNT NBR 6118:2014). In addition, compliance with usage and maintenance requirements prescribed by the structural engineer and builder is crucial, including timely repairs for any accidental damage that may occur over time.

Therefore, monitoring methods for concrete structures have become increasingly prevalent in the construction industry. These methods enable early detection of structural damage, avoiding high restoration costs, preventing harm to users, and mitigating performance failures at an early stage. Accurately assessing the current state of a structure also reduces costs, optimizes maintenance and repair planning, and improves the quality and safety of the structure.

Reinforced concrete structures are known for their versatility, cost-effectiveness, and reliable performance, primarily owing to their durability and resistance over time. However, failure can occur under specific conditions owing to design errors, construction execution, inadequate material selection, exposure to highly aggressive environments, or a combination of these factors [5]. In this context, reinforced concrete structures are subject to pathological problems that may compromise their structural performance. Various monitoring methodologies have been developed to detect these problems, with each method having unique strengths and limitations in terms of the data they provide.

This study adopted a structural health monitoring (SHM) technique based on electromechanical impedance to detect steel corrosion in reinforced concrete structures. The monitoring process began by incorporating a lead zirconate titanate (PZT) transducer in the study object. Owing to the piezoelectric effect, this method enables establishing the relationship between the mechanical properties and electrical impedance of the structure, facilitating effective structural monitoring [14].

However, steel corrosion in reinforced concrete structures is a gradual process owing to the protection provided by the concrete [1]. Thus, corrosion takes considerable time to manifest even under extreme exposure conditions. In this study, to enable analysis within a limited timeframe, the impressed current technique was applied to accelerate corrosion. Corrosion is induced by applying an electrochemical potential (impressed current) between the steel (anode) and a cathode, such as stainless steel, using chlorides [10].

In addition, the COMSOL Multiphysics® software was used to validate these techniques. The analysis also accounted for the effects of parameter variations that may influence the monitoring outcomes, incorporating computational routines to ensure reliable data analysis. The performance of the transducer was evaluated based on wave propagation responses, comparing impedance signals obtained by the transducer from undamaged and damaged concrete elements. To ensure data reliability, various statistical metrics were used to assess the accuracy of the monitoring system.

This study explored the efficiency and comprehensiveness that computer simulations, particularly those using the finite element method (FEM), can provide in experiments related to monitoring methods in reinforced concrete structures, focusing on steel corrosion induction. The analysis provides valuable insights into material interactions and the effects of corrosion, enabling the development of more effective maintenance strategies. In addition, integrating simulations and experimental monitoring offers a robust approach to structural integrity assessments, enhancing the safety and durability of concrete structures.

This article is organized as follows: Section II presents the processes and elements that cause steel corrosion in reinforced concrete constructions. Section III presents the theoretical basis of the electromechanical impedance technique used in the assessment of structural health. Section IV details the experimental program, from sample preparation and corrosion induction to data collection methods and their implications. Finally, Section V summarizes the main results obtained and provides future recommendations for improving the technique and data evaluation.

II. STEEL CORROSION

Deterioration in reinforced concrete structures is primarily caused by steel corrosion [9]. This can significantly reduce load-bearing capacity and compromise structural integrity [18], as well as lead to economic losses resulting from frequent maintenance and repairs.

Various mechanical, physical, biological, and chemical factors cause steel reinforcement corrosion. Physical and mechanical factors, such as temperature variations between concrete components and vibrations, can cause cracks in reinforced concrete, allowing aggressive agents to penetrate. Biological factors, such as sulfate-reducing bacteria, produce hydrogen sulfide. Chemical factors, such as acids and salts present in water, soil, or the atmosphere, can impact concrete and steel reinforcement [6].

Among these causes, chemical processes are the most common owing to the ease of reaction with atmospheric compounds, such as carbon dioxide (CO2), and the penetration of chloride ions (Cl^-) into concrete through exposure to salts in the environment [3]. Corrosion processes can be classified into chemical or electrochemical. Chemical corrosion results from the interaction of gases that form oxide films on the material surface. Electrochemical corrosion results from the interaction among an electrolyte, potential difference (PD), oxidizing agents, and aggressive agents [4], resulting in material mass loss.

Reinforcement corrosion occurs through electrons and ion flow between the cathodic and anodic regions, driven by electrochemical reactions [12]. These reactions generally involve iron oxidation (anodic reaction) and oxygen reduction (cathodic reaction) in an alkaline medium. In addition, concrete covers are insufficient barriers against the penetration of oxygen and water to the steel reinforcement. Figure 1 illustrates the corrosion process [12].

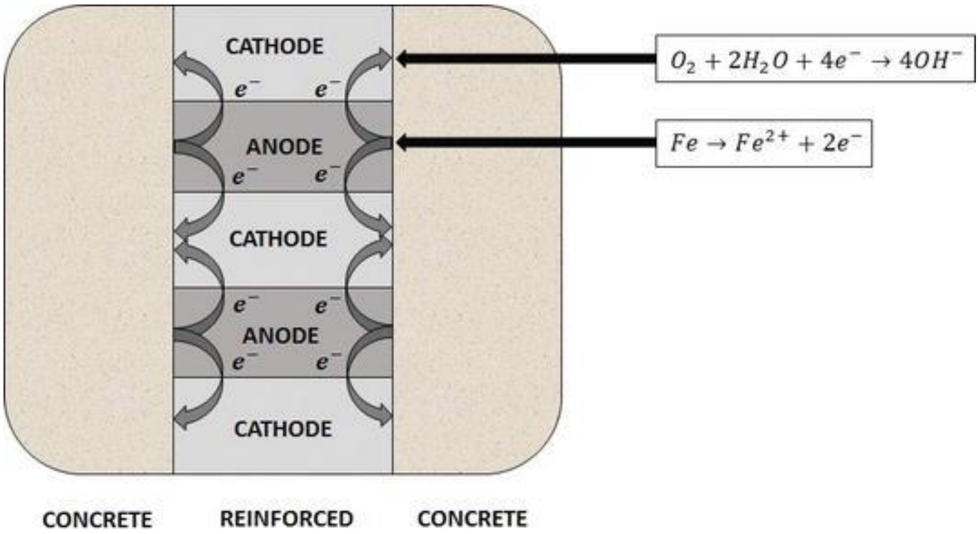

Figure 1. Schematic representation of electrochemical corrosion in the steel reinforcement of a reinforced concrete structure involving oxidation and reduction reactions [14].

III. STRUCTURAL HEALTH MONITORING

Steel degradation resulting from corrosion leads to factors that compromise the safety, aesthetics, and service life of reinforced concrete structures. These include surface stains, loss of bond between the reinforcement and concrete, reduced stress resistance and effective cross-section of the steel, and concrete cover spalling [8]. If not detected early, these effects can lead to serious structural failures, thus highlighting the need for efficient monitoring.

In this context, impedance-based SHM aims to detect changes in structural properties, characterized by variations in the electromechanical impedance of the structure. A transducer is excited at a predefined frequency, generating a small deformation in the monitored structure. This deformation is transferred to the transducer, which responds with a corresponding electrical signal. These electrical variations are indicative of damage, enabling early diagnosis and the implementation of corrective measures before corrosion further compromises the structure.

The classic electromechanical impedance model is represented as a single-degree-of-freedom system, in which the transducer acts as an actuator and a receiver (Figure 2). In this context, ZM (ω) represents the impedance, F (ω) is the alternating force, v (ω) is the resultant velocity, and "ω" is the angular frequency. Mechanical impedance is expressed in Ohms (Ω).

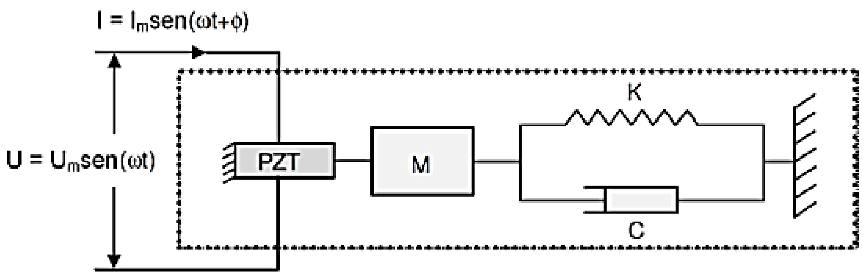

Figure 2. One-dimensional model of electromechanical coupling.

For the sensor, we denote C as the damping coefficient, K as the elastic constant of the spring, and M as the mass. The transducer is excited by a sinusoidal voltage source U, where Um represents the amplitude, and (ω) is the angular frequency, generating a current I with amplitude and phase φ. The premise is that if the mechanical properties of the piezoelectric material (PZT) remain constant over time, fluctuations in its electrical impedance will be directly correlated with changes in the mechanical impedance of the monitored structure. Combining analytical methods and computer simulations offers a robust approach for enhancing the effectiveness of this monitoring system.

Establishing indices that facilitate comparisons of measurements over time and using a scale based on statistical parameters are essential for detecting variations in structural behavior, such as damage, stiffness changes, wear, and performance. Several damage detection techniques use modal parameters and spectral comparisons of response curves [16].

Commonly used statistical quantifiers include the root mean squared deviation (RMSD), correlation coefficient deviation (CCD), mean square difference (ASD), and mean absolute percentage deviation (MAPD) [2]. The RMSD index is derived from the root mean squared (RMS) deviation, which measures impedance variations at each frequency point and then sums the results. Variants of this metric, such as RMSD1, RMSD2, RMSD3, and RMSD4, and their definitions, can be found in an earlier study [11].

Notably, reference points, known as baselines, have to be defined to establish a comparison parameter and identify the evolution of the indices. In addition, damage is identified by comparing the electrical impedance measured in the intact state and that after damage occurs across different frequency ranges [7].

IV. METHODOLOGY

The experimental technique involved developing a structural integrity monitoring system that could measure the corrosion process of steel in a reinforced concrete element using piezoelectric sensors. The sample was submerged in a 3.0% NaCl solution and subjected to an impressed current to induce corrosion in the reinforcement. Two reinforced concrete specimens were developed in a laboratory to evaluate the electromechanical impedance technique during the corrosion process and its influence on reinforced concrete structures. The samples were monitored from assembly to signal reading using a structural sensor monitoring system.

4.1. Concrete test specimens

The structural elements developed were two cubic concrete blocks measuring 100 mm × 100 mm × 100 mm with 12.5 mm diameter CA-50 steel bars inserted in the center of the sample (Figure 3). After molding, densification, and finishing, the specimens were maintained in a humid chamber for 48 h. Subsequently, the sample was uncovered (removed from the formwork) and left to cure underwater for 28 days. The entire molding and curing procedure followed the ABNT NBR 5738:2015 standards.

Subsequently, a piezoelectric sensor (PZT) of diameter (25 ± 0.25) mm and thickness (7 ± 0.05) mm was incorporated into each sample for structural monitoring. Table 1 lists the electrical specifications. Figure 4 shows a schematic of the PZT with the poling direction. A professional epoxy resin was used to insulate and fix the PZT (Figure 5).

Figure 3. CP molding.

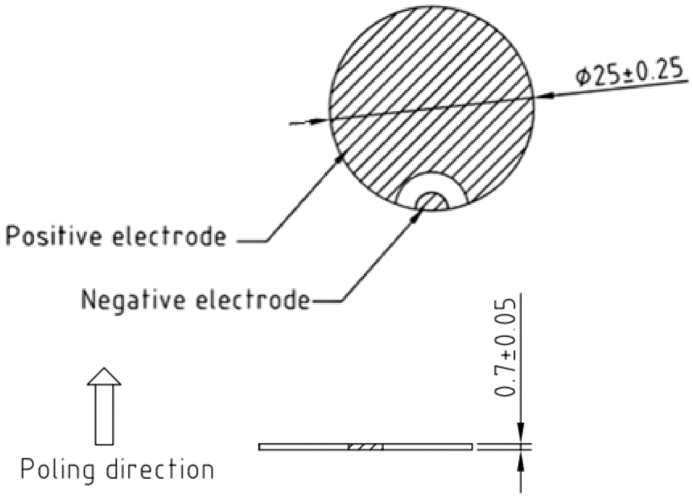

Figure 4. PZT schematic drawing.

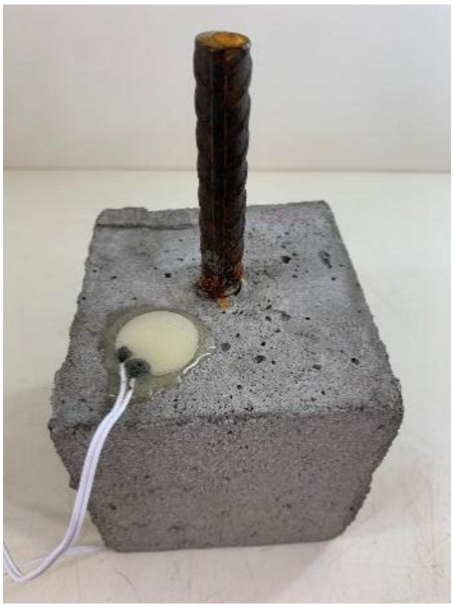

Figure 5. Sample with PZT and epoxy

Table 1: PZT specifications [15].

Properties	Data
Resonant frequency	3 MHz ± 5%
Resonant impedance	Zm ≤ 1 Ω
Electromechanical coupling coefficient Static capacitance Test condition	Kt ≥ 45% Cs = 8400 p F±15%@1 kHz LCR meter at 1 kHz 1 Vrms (23±3) °C 40–70% R.H.

Compressive strength tests were performed on the specimens according to ABNT NBR 5739 (2018), with an average compressive strength (fcm) of 25.72 MPa obtained from three specimen ruptures. The proportions of cement, medium sand, and gravel 0 were 1:2.7:3.3:0.5.

4.2. Impressed Current

The impressed current technique was implemented by applying a direct current from a power supply connected to the reinforcement embedded in the concrete. This process accelerates the induction of chloride corrosion, resulting in a significant corrosion rate in the steel bars over a short period [1]. For the schematic design of the test, the ASTM G109:2021 standard was used as a reference, which outlines the induction of steel corrosion in a saline solution. This standard recommends a concentration of approximately 3% NaCl to ensure a significant degree of corrosion in the steel rebars. Subsequently, the power supply was connected: one part to the reinforcement in series and the other part to the stainless steel (cathode). A constant current of 13 V was introduced into the system for 90 days (Figure 6).

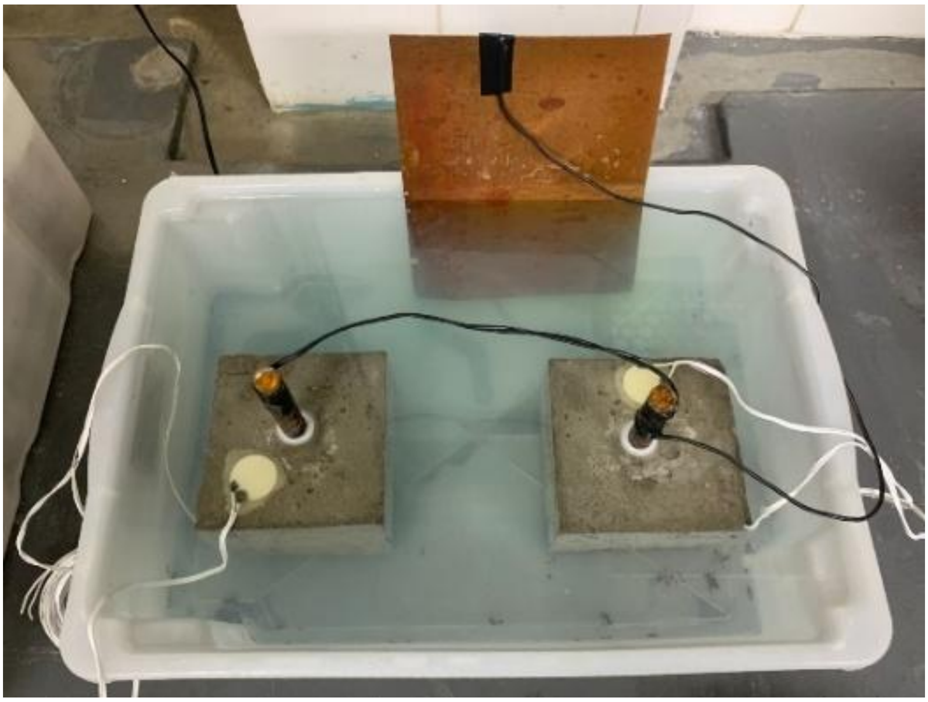

Figure 6. Representation of the printed current technique.

After 90 days of testing, significant corrosion was observed in the steel, as shown in Figure 7. Subsequently, the CPs were removed from the saline solution. After 7 days, once the samples were free of moisture, impedance signatures were collected.

Figure 7. Induced corrosion test after 90 days - a) Block 1 after corrosion; b) CP 1 and 2 in series.

4.3. Electromechanical impedance simulation

The impedance and corrosion responses were evaluated using the FEM, in which the signature characteristics and damage evolution were examined. The FEM software COMSOL was used for modeling and analysis. Initially, the properties of the materials involved in the simulation were defined (Table 2) following the nomenclature of the software; the other properties were the same as those described previously.

Table 2: Material properties.

Material	Parameters	Symbols	Values	Units
PZT	Density	ρ	7600	kg/m^3
	Dielectric loss factor	$tan\delta$	0.0169	
	Compliance	$s_{11} = s_{22}$ s_{33} $s_{44} = s_{55}$ s_{66} s_{12} $s_{13} = s_{23}$	1.538 1.282 2.380 2.770 9.845 9.310	Pa
	Relative electric permittivity	$\varepsilon_{11} = \varepsilon_{22}$ ε_{33}	796.5 762.9	
	Piezoelectric stress coefficients	$d_{31} = d_{32}$ d_{33} d_{15}	-4.730 15.258 13.095	C/m^2
Epoxy	Density	ρ	1250	kg/m^3
	Poisson's ratio	v	0.40	
	Young's modulus	E	2	GPa
Steel	Density	ρ	7850	kg/m^3
	Poisson's ratio	v	0.28	
	Young's modulus	E	200	GPa
Concrete	Density	ρ	2300	kg/m^3
	Poisson's ratio	v	0.20	
	Young's modulus	E	30.45	GPa

The impedance signatures were collected using the PZT glued to the top face of the CP. The PZT was polarized in the thickness direction. In the FEM study, the bonding interface was considered to be 1/3 of the thickness of the transducer, according to the study by Yang et al., to avoid the influence of damping losses caused by the epoxy [17]. The thicknesses of the electrodes were considered insignificant.

The PZT sensor was modeled using Multiphysics as a solid element, coupled to a concrete block using the Solid Mechanics and Electrostatics modules. Corrosion was modeled using Tertiary Current Distribution, with parameters defined according to the experiment in terms of the analysis interval and properties of the constituent materials. The mesh was generated with tetrahedral elements, suitable for three-dimensional geometries.

The proposed model uses oxidation with current distribution to simulate the corrosion process. The area around the reinforcement was modeled as a linear elastic material and subjected to deformations at different time intervals to assess the resulting damage.

A time-dependent analysis was performed, covering the interval from 0 to 1500 days. Subsequently, a frequency domain analysis was conducted to obtain response signatures with harmonic excitation in the 0–400 kHz range, distributed over 801 points according to the impedance meter limitation. The resonance peaks were evaluated by selecting the 50–90 kHz interval as the primary area of interest, enabling a more detailed analysis of the behavior of the system.

The PZT was modeled with its top and bottom surfaces connected to the same node, representing the electrodes. A voltage of 1 V was applied to the top surface, while 0 V was applied to the bottom surface to simulate the PZT polarization.

V. Results

5.1. Impedance signatures and the application of metrics

Figure 8 shows the signatures of the real part of the impedance as a function of frequency, measured both in the simulation and in the structure's healthy state. The figure also shows the signatures corresponding to the test and simulated damage, corresponding to the region of the first resonance peak.

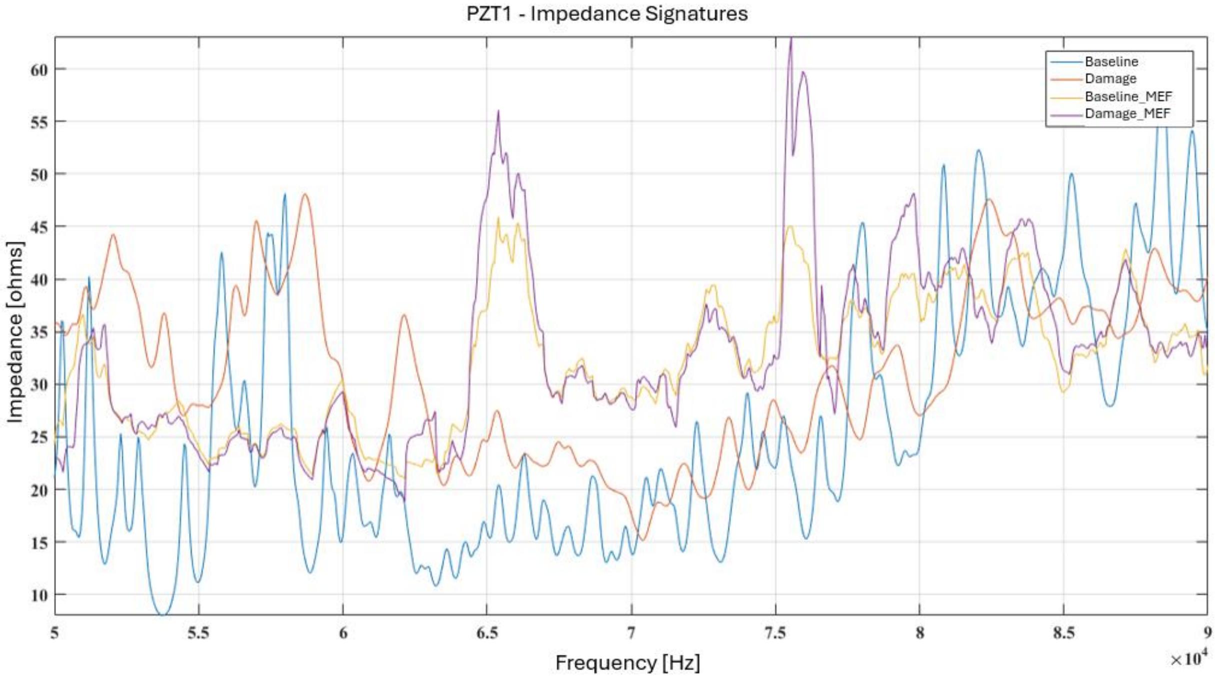

Figure 8. Impedance signature in the frequency range between 50 and 90 kHz

The FEM results are consistent with the trend of the experimental signatures, although some discrepancies are observed in high-frequency regions. The peak at 7.5 x 104 Hz is more pronounced in the simulation, while that in the experiment exhibits an attenuation in this region. This can be attributed to the simplifications adopted in the simulation model. Table 3 compares the results obtained from the FEM simulations and the experimental data.

Table 3: Comparative values between experiment and simulation (FEM).

Metrics	Experiment	MEF
RMSD	11.47	14.64
RMSD1	9.74	11.61
RMSD2	2.27	2.90
RMSD3	395.9	501.9
RMSD4	10.10	12.67
CCD (%)	47,91	77.13
ASD	1.761E+05	3.014E+05
MAPD	395.9	501.9
M	1.054E+05	1.717E+05

An impedance analysis was performed in the undamaged state and compared directly with the experimental and FEM-simulated signatures, considering the presence of damage. The ASD values differ, rendering direct comparison difficult. However, the MAPD and RMSD3 exhibit similar values, confirming their consistency.

5.2 FEM simulation

The simulation revealed damage after 600 days of testing (Figure 9), with the evaluation extending to 1500 days—a period during which crack formation was not observed. In Figure 9-b, the values shown on the side represent the growth of the oxide layer, which generated internal stresses in the concrete.

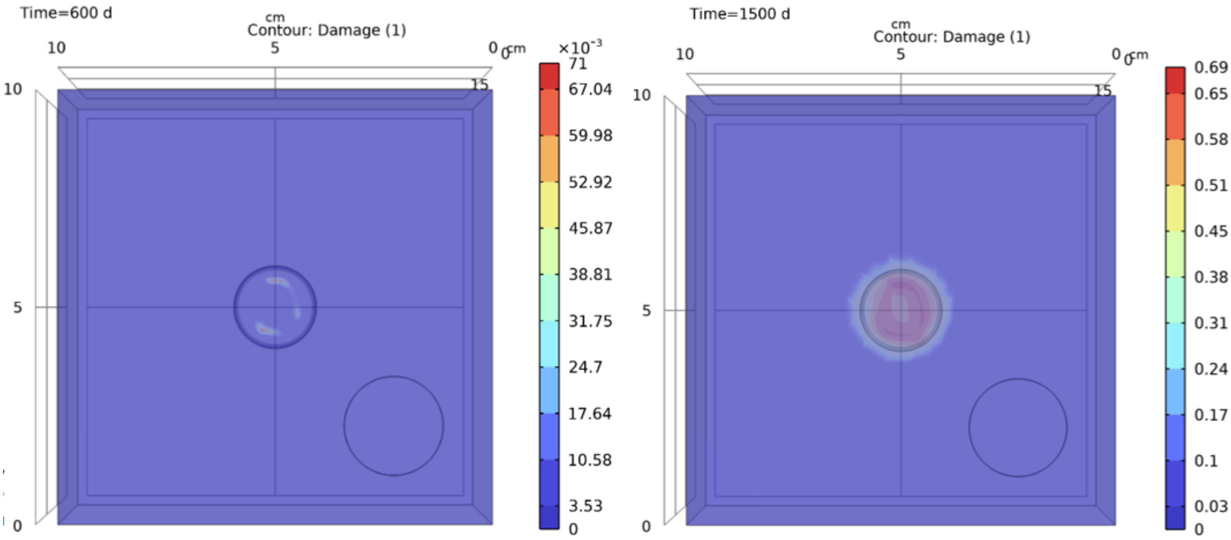

Figure 9. Representation of the FEM simulation: a) 600 days; b) 1500 days

The simulation also analyzed the current flow lines, determined based on the electrical conduction model, considering the dissociation of positively and negatively charged particles (Figure 10). A difference was observed only at the initial time (0 day), when the material was not immersed in water, resulting in a different conduction field. After this period, the conduction field readings remained constant.

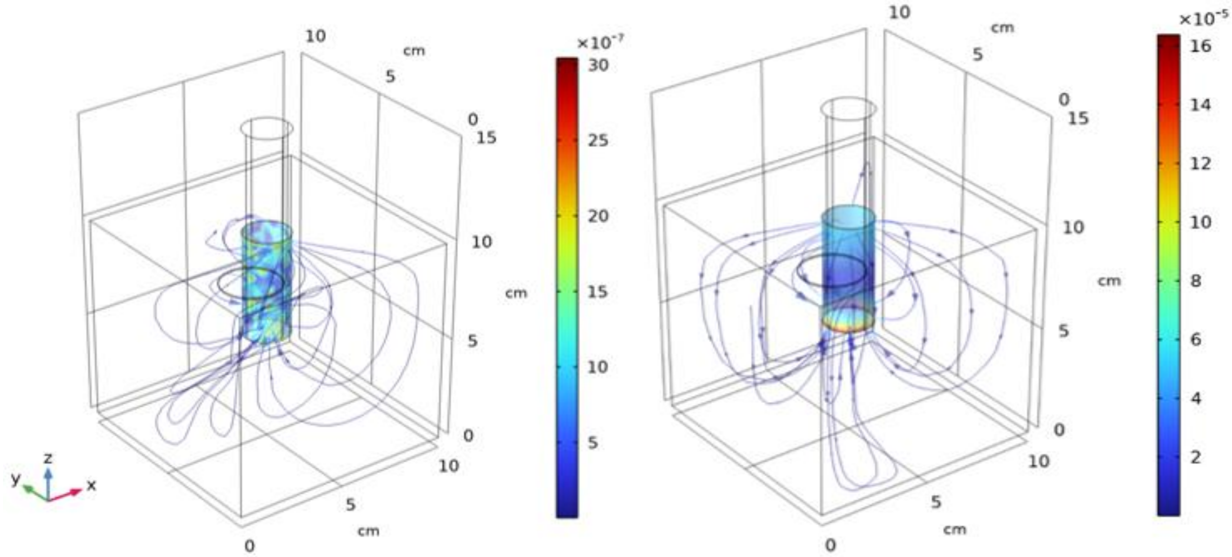

Figure 10. Representation of current flow lines (A/m²) - a) 0 days; b) 600 days

A water concentration model was also evaluated. At this stage, owing to the limitations of the simulation, only an upward capillarity flow was introduced. However, the simulated trend is consistent with the experiment results, as observed in the lines shown in Figure 11.

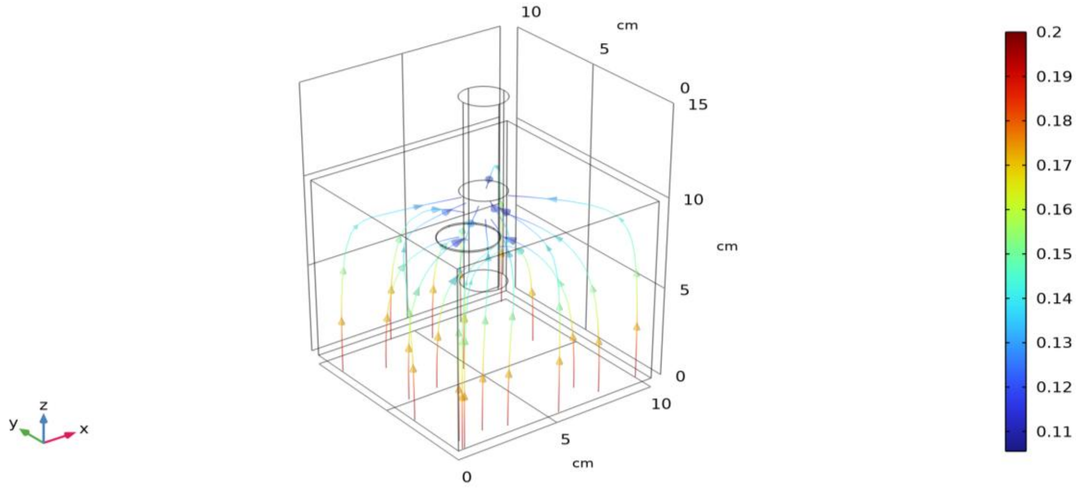

Figure 11. Representation of water concentration (mol/m³).

The analysis using the numerical solution showed the corrosion performance. This enabled the evaluation of damage behavior around the concrete reinforcement over time, aligning with the proposed model. Despite the computational limitations of the model, the results provide valuable insights into internal stresses, current, and water flows, crucial for evaluating corrosion in concrete structures.

VI. CONCLUSIONS

Combining analytical methods with computer simulations offers flexibility in modifying the physical properties and conditions of the system under analysis, enabling visualization of the problem and facilitating efficient optimization. In addition, the analytical approach combined with experimentation can reduce the costs and time required to perform physical tests. Simulations have produced models that yield results closely aligned with experimental data. This simplifies the process of analyzing different scenarios and conditions, thus saving time and resources. The approach significantly reduces the risk of unexpected events and failures during testing.

Within the frequency range of 50–90 kHz, the proposed technique could effectively detect damage in the PCs, as evidenced by the impedance signature. Thus, the structural integrity monitoring method based on electromechanical impedance for detecting damage in concrete structures was effectively evaluated within this frequency range. This method enables system analysis even with the sensor placed on the surface of the specimen. This will contribute to future studies on the safety of reinforced concrete structures in civil construction, particularly when reinforcement corrosion occurs.

For future research, we propose an FEM simulation and experiment with a steel bar placed near the edge of the concrete block to identify cracks or fissures in the specimen while monitoring using SHM.

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Authors

Victória Góis – Civil Engineer graduated from UFU, with experience in structural design and construction management. Conducts research in the field of Structures and Materials, with an emphasis on monitoring the integrity of reinforced concrete structures. Interested in the study of concrete corrosion, the use of structural health monitoring technologies, and the application of solutions to mitigate pathologies in reinforced concrete structures.

Lucas Gomes – Master's in Civil Engineering from UFU, with a concentration in Spatial Analysis, Urban Engineering, Water Resources, and Environmental Sanitation. Civil Engineering degree from UNIPAM. Currently pursuing a degree in Computer Engineering at UFU. Interests include computational methods, structural modeling, and the application of engineering technologies in urban and environmental systems.

Raquel Naiara Fernandes Silva – Ph.D. in Solid Mechanics and Vibrations from UFU, Master's in Geodetic Sciences from UFPR, and a degree from UFV. Associate Professor at UFU's Faculty of Civil Engineering. Research Structural Health Monitoring (SHM), focusing on Electromechanical Impedance in concrete structures. Experienced in Geodetic Monitoring of Concrete Dams and the application of Geotechnologies in Civil and Environmental Engineering.