

# Evaluation and Repair of a Reinforced Concrete Structure: A Case Study

Fábio Giovanni Xavier de Oliveira<sup>1</sup> and Flávio Roberto Xavier de Oliveira<sup>2</sup>

1. Department of Engineering, Rehabilitar Engenharia Ltda., João Pessoa, Paraíba 58051-127, Brasil

2. Design Department, FR Projetos e Consultoria Ltda., João Pessoa, Paraíba 58051-840, Brasil

**Abstract:** Reinforced concrete structure durability has been getting a lot of attention in academic research related to building security and stability. Thus, knowledge about the condition of the structures, particularly those affected by issue symptoms, is a powerful tool to minimize costs and improve structural reinforcement and repair service efficiency. Steel corrosion in reinforced concrete frames is the most frequent pathological manifestation in buildings around the world, and it is closely linked to the concept of structural integrity and safety. This paper describes, explains and remarks on the services performed by a company specialized in structure pathology in determining the causes, origins and mechanisms involved in steel corrosion in reinforced concrete frames in the ground and mezzanine floors of a building located in the coastal city of Cabedelo/PB. Mechanical, physical, chemical and electrochemical tests were conducted in the structure, and the conclusion was that concrete carbonation was the mechanism behind the pathological manifestation, and the source of the issue was linked to the execution of the work. The therapy process adopted was divided into levels related to the degree and progress in the observed degradation, and a few structural repair techniques were adopted, such as traditional structure repair, chemical realkalinization, corrosion inhibition and surface protection.

**Key words:** Durability, carbonation, reinforcement corrosion, structural evaluation, structural repair.

## 1. Introduction

Reinforced concrete structure durability has been getting a lot of attention in academic research related to building security and stability. Knowledge about the condition of the structures, particularly those affected by pathological manifestation symptoms, is a powerful tool to minimize costs and improve structural security and repair service efficiency.

Steel corrosion in reinforced concrete frames is the most frequent pathological manifestation in buildings around the world, according to Fedrizzi, et al. [1], and it is closely linked to the concept of structural integrity and safety. The *Transportation Research Board Report* published in 1991 estimated that expenses with the degradation of the reinforced concrete structures of the bridges located on interstate highways due only to the action of de-icing salts

surpassed \$150 billion. The annual expenditure with repair reached \$300 billion.

The losses from rehabilitating works deteriorated only by the reinforcement corrosion phenomenon add up to 1.25 to 3.5 percent of the GDP (Gross Domestic Product) in developing countries [2].

Given these figures, the proper determination of the causes, origins and mechanisms involved in the corrosive process are very important to determine an adequate therapy to treat the pathological manifestations.

### 1.1 Reinforcement Corrosion

The steel corrosion in reinforced concrete frames is an electrochemical deterioration process that returns the metallic alloy to the initial state in which it was when extracted from deposits, in the form of oxides and hydroxides, mainly of iron [3].

When inserted in concrete, the carbon steel reinforcement goes into a condition of passivity [4].

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**Corresponding author:** Fábio Giovanni Xavier de Oliveira, civil engineer, research field: reinforcement concrete corrosion.

This passivity is obtained through a thin semiconductive layer of oxides that surround the reinforcement, protecting it physically and chemically [5]. This protection is popularly known as a passivation film.

### 1.2 Causing Agents

A few aggressive agents present in the environment penetrate through the porosity of the concrete cover and break down this passive barrier, sometimes by changing the pH of the concrete or by means of chemical reactions with the compounds of this passivating layer [6]. CO<sub>2</sub> and chloride ions are the main examples of these agents.

Carbonation, which consists of chemical reactions occurring between carbon dioxide (CO<sub>2</sub>) and calcium hydroxide [Ca(OH)<sub>2</sub>], has calcium carbonate (CaCO<sub>3</sub>) as its product, which reduces the concrete pH to levels that, according to Pourbaix [4], do not guarantee the reinforcement's state of passivation, leading to the end of the structure's useful life, as defined by Tutti [7], giving rise to the corrosive process.

Chloride ions from salts present in sea water migration driven by the action of the winds, as explained by O'Dowd, et al. [8], accumulate on the surface of the structural elements and, through absorption, penetrate the concrete. As soon as the concentration of these ions reaches the threshold around the reinforcement, a rate that depends on several factors, the passivation film is broken, and the corrosive process begins [9].

Other sources of chlorides, very common during the 1990s in Brazil, were the calcium chloride-based accelerator additives, which were inadvertently added to the concrete mass.

### 1.3 Structural Repair

The onset of the corrosive process coincides with that of the residual life of the structure, i.e. the moment at which the structure loses its bearing capacity until its collapse, or until repair services restore the structure's capability to withstand the efforts it was originally

designed to face [7].

There are several reinforced concrete structure repair types and processes. The structural repair processes can be called traditional and non-traditional. Traditional ones involve demolition techniques for the affected concrete, the mechanical removal of the reinforcement corrosion products and repositioning of the demolished concrete [10]. Non-traditional processes, meanwhile, involve chemical and electrochemical techniques aimed at attenuating or even interrupting the corrosive process, as well as at restoring the pH conditions of the concrete, re-establishing the reinforcement's passivity condition.

Chemical realkalinization is a technique that aims to restore the pH of the concrete using chemical compounds that reverse the carbonation process through the absorption of products impregnated on the surface of the structural elements that migrate through the porosity of the concrete [11].

Corrosion inhibitors are an effective, low-cost alternative to delay the onset of corrosion or even reduce the rate of steel corrosion in reinforced concrete frames [1, 12, 13]. These chemical substances are impregnated on the surface of the concrete and migrate towards the reinforcement, acting by forming a physical barrier, re-passivizing the oxidized surface, and by changing the characteristics of the medium in contact with the metal [14].

Corrosion inhibitors can also be divided into three types: anodic, cathodic and mixed, depending on where they interfere, whether at the anode, at the cathode or both [13, 14].

In this context, a structural assessment is both a technical and an economic necessity. Structure treatment and maintenance efficacy and efficiency tend to minimize the enormous costs of this issue. The present work addresses the activities carried out by a structural pathology company during the evaluation and repair services done for the reinforced concrete structure of a building affected by reinforcement corrosion.

## 2. Presentation

### 2.1 Location

The building is in the neighborhood of Intermares, in the coastal city of Cabedelo-PB, at longitude  $34^{\circ}50'29.12''$  W and latitude  $07^{\circ}02'25.070''$  S and about 450 m from the sea, as shown in Fig. 1.

### 2.2 Structure

The Porto Príncipe Residence building frame was made of reinforced concrete moulded at the site. It is composed of pillars, beams, and solid slabs, and the shallow foundations are in footing on the ground. The structural projection area covers approximately 5,000 m<sup>2</sup>.

During the anamnesis period, in an interview with the older residents, it was found out that in the mid-1990s, when the building's structure had already been completed, the construction company went bankrupt and the work was stopped, exposing the unprotected reinforced concrete structure for a few years until the owners of the apartments took the

construction over and finished the work in late 1997.

### 2.3 Microenvironment

The environment which part of Porto Príncipe Residence's frame was built in, has characteristics that are quite common to an urban and coastal microenvironment. Temperature and relative humidity measurements were made through continuous and daily readings during the months of February and March 2014 by means of two data loggers positioned in internal points of the structure.

The mean ambient temperature during the measurement period was 28.77 °C, while the relative humidity of the environment was 75.2%.

## 3. Methodology

A few assays and tests were carried out on the reinforced concrete structure at Porto Príncipe Residence to characterize the materials, the construction process, and the mechanism of the corrosive process that had set in.



Fig. 1 Building location. Source: Google Earth.

The assays and tests done on the depth of the carbonation front, on the presence of chlorides, thickness of the covering concrete, rebound hammer test, and on the electrochemical potential were done to obtain data on concrete resistance to aggressive agent penetration, on the type of the aggressive agent, on extent of the anodic areas, and on the aggressive agent penetration speed.

The tests were performed through sampling, and these representative and random samples were defined according to the microenvironmental characteristics in which the various parts of the structure were inserted. For example, pillars that were exposed to rain and to a given wind direction would be part of the same group, which would be represented by a sample size proportional to the number of elements in the group.

Pursuant to test results, each group was characterized as to the type of aggressive agent, aggressive agent penetration speed, degree of the corrosive process, and extent of anodic areas. The type

of therapy to be adopted for each group was then defined and determined.

#### 4. Tests Done

During the activities carried out in the Porto Príncipe Residence structure evaluation work, a few tests were carried out to characterize the materials and the corrosive process.

##### 4.1 Carbonation

The carbonation thickness measurement test was done by sprinkling a solution of ethanol ( $C_2H_5OH$  or  $C_2H_6O$ ) with 1% pure phenolphthalein ( $C_{20}H_{14}O_4$ ) [15]. When meeting some medium or substance with a pH above approximately 9.5, this solution turns red, while at a lower pH it remains colorless, as can be seen in Fig. 2.

During the carbonation tests, the thicknesses of the structural parts' cover concrete were also checked, as can be seen in Table 1.



Fig. 2 Concrete carbonation/cover thickness test.

Table 1 Sample of results of the beam reinforcement carbonation thickness and cover tests.

Structural element	Pavement	Carbonation depth (mm)					Cover thickness (mm)					Finishing
		Lower face	South face	North face	East face	West face	Lower face	South face	North face	East face	West face	
V2-F1	Ground floor	47.4				5.2	39.5				1.6	Polyvinyl Acetate
V16-F2	Ground floor	48.8		45.3			33.9		30.9			Polyvinyl Acetate
V25-F2	Ground floor	48.6		25.9			63.0		44.8			Polyvinyl Acetate



Fig. 3 Sclerometry test detail.

#### 4.2 Rebound Hammer Test

The procedures used to perform this test comply with what is prescribed in NBR 7584 [16], using a James Instruments type N WM 250 model Rebound Hammer.

The surfaces chosen to perform the Rebound Hammer tests were all vertical. Surfaces with good surface conditions for the test, such as flatness, densification homogeneity, regions that showed no segregation, exudation, excessive reinforcement concentration, concrete joints, corners and edges were looked for, and abrasive cleaning done at the test site using a pumice stone.

To guarantee the absence of reinforcement in the concrete, a James Instruments model HR-7500 analog rebar locator was used, and this verification was carried out at all points where the Rebound Hammer tests were done. Some results are seen in Fig. 3.

#### 4.3 Corrosion Electrochemical Potential

The procedures adopted to perform this test comply with the requirements of ASTM C 876 [17]. The test was done through the half-cell of the reference copper/copper sulfate electrode.

#### 4.4 Presence of Chlorides

To determine the presence of chlorides in the building's structure, the beams and columns were fractured with an appropriate hammer, and a 0.1 N solution of silver nitrate ( $\text{AgNO}_3$ ) was sprayed

according to the colorimetric method recommended by Meck and Sirivivatnanon [18] based on ASTM [19]; the staining obtained was checked, presenting a white coloration for the presence of chlorides and a brown one for the absence of chlorides above a concentration of 0.4% in relation to the cement mass.

#### 4.5 Cover Concrete Thickness

Further verification of thicknesses of the concrete cover was done with a James Instruments model HR-7500 analog rebar locator on all tested elements (structural parts).

### 5. Diagnosis, Prognosis and Mechanisms

Test result evaluation shows that the reinforced concrete structure of the ground and mezzanine floors of Porto Príncipe Residence is affected by reinforcement corrosion. Although it was not possible to evaluate the building's structural designs, the great variety of thicknesses of the building's structural part covering concrete are indications that the source of this pathological manifestation is the execution.

The qualitative test for the presence of chlorides indicated that the free chloride content in the region around the reinforcement was not sufficient to allow for steel depassivation, a fact confirmed by the concrete carbonation test, which showed that in all corroded regions, the carbonation front was deeper than the concrete cover's thickness.

Section 10 of ASTM 876 C [17] indicates that regions with electronegative potential above -350 mV are those with high reinforcement corrosion likelihood, while in regions with potentials between -200 mV and -350 mV there is an uncertainty as to the state of the corrosive process. However, the mapping of the electrochemical potential in the structure showed that in the corroded regions this potential was more electronegative than -230 mV. This was then adopted as the minimum value for cataloging the anode regions of the pieces that were not part of those chosen for the other tests.

According to the definition of Tutti [7], when the corrosive process starts, the building's operation useful life is extinguished, with only residual useful life remaining, which is of an indeterminate period for this structure due to lack of more precise information about the speed of the corrosive process and about the structural design. Thus, the structural pieces in this condition had to be repaired immediately.

Structural pieces from which the reinforcements had not yet been removed, i.e. the aggressive agents had not yet reached the reinforcements still had operating useful life in effect and based on the average penetration speed of the carbonation front and on the average cover concrete thickness, the operating useful life would be less than 5 years. Thus, chemical realkalization would be recommended for such cases.

The structural parts whose carbonate thickness did not exceed 50% of the thickness of the cover concrete have a useful life of more than 8 years, according to the carbonation front evolution rate, if the protective coating and micro-environmental conditions were to be maintained. The application of an open pore protection was recommended for these pieces to reduce the internal moisture of the concrete during a specific period of time—summer months—followed by the application of a closed pore protection.

## 6. Therapy

The repair process for the reinforced concrete

structure of Porto Príncipe Residence was based on the three types of situations generalized in the section above: situation 1, where corrosion is established; situation 2, where the operating useful life is reduced, and situation 3, where there is still plenty of operating useful life.

Situation 1 imposes a traditional structural recovery consisting of the replacement of all carbonated concrete, especially that surrounding the reinforcements, throughout the anodic extension of the pile, which is recommended in the recovery project. The reinforcements should be replaced if section loss exceeded 10%.

The carbonated concrete could be replaced by a self-compacting micro-concrete with a minimum characteristic compressive strength of 40 MPa and a minimum characteristic strength of adhesion to old concrete of no less than 2.5 MPa, the latter being obtainable through cement bonding bridge. A repair polymeric mortar could also be used if the thickness does not exceed 40 mm.

For the part of the structure that was in situation 2, the proposed therapy was the application of a chemical realkalization process using silicatization aiming to return the cover concrete pH to an acceptable level.

Situation 3 did not require structural repair, but the application of an open pore protection in the inner regions followed by a closed pore protection and hydrofugation in the outer regions was recommended. This protection consists of the application of an open pore protection (polymer mortar) during a minimum period of 3 months during the summer months, followed by a closed pore protection (acrylic, polyurethane, epoxy). Silane/siloxane-based water repellent should be applied on the outer regions.

## 7. Conclusion

The quality of the material—concrete—does not create an environment conducive to maintaining carbon steel reinforcement physical integrity. The thick coatings on the pillars and beams minimized

aggressive agent penetration, which was not detectable in some of the structural parts.

The microenvironment created favors a medium CO<sub>2</sub> gas diffusion rate; on the other hand, it creates conditions for a high rate of corrosion. The quality of the material favors a high CO<sub>2</sub> diffusion rate and a high reinforcement corrosion rate. Based on the assays, tests and observations of the structure, the general condition of the work is one of medium deterioration—REHABILITAR ENGENHARIA Rating. Reinforcement corrosion appears in continuous elements in part of the structure, accompanied by the advance of the carbonation front at depths greater than the thickness of the concrete cover. The high standard deviation of the concrete cover thickness was the main variable in the depassivation of the reinforcement, despite the poor quality of the concrete.

From the point of view of the structure being attacked by the chloride salts, the colorimetric test showed little presence of this salt. This quick chloride presence test is greatly influenced by the type of cement, with higher or lower aluminate content, which influences the content of free and combined chlorides (Friedel's Salt); by concrete resistivity; by concrete moisture, and by the pH of the concrete, thus, other sources of information must be considered to analyze the data of this result, as was the case with the carbonation test.

## 8. Concluding Remarks

The period between the completion of the structural evaluation and the structural repair activities was too long, and, in some places, it may have affected the condition of the structural parts in situation 2. This aspect raised doubts about the progress of the carbonation front and led the person responsible for the technical opinion to re-evaluate the solution adopted to treat the regions in the situation 2, replacing the chemical realkalinization by the application of a mixed corrosion inhibitor.

The company that carried out the structural

evaluation and repair also provided a maintenance plan for the building's reinforced concrete structure, in which, among other activities, periodic surveys were foreseen.

## References

- [1] Fedrizzi, L., Azzolini, F., and Bonora, P. L. 2005. "The Use of Migrating Corrosion Inhibitors to Repair Motorways' Concrete." *Cement and Concrete Research* 35: 551-61.
- [2] Oliveira, Fábio G. X. D. F., Vinicius, J. B. F., Meira, G. R. C., and Arnaldo, M. P. 2007. *Custos de Recuperação Estrutural: Um Estudo de Caso*. Quito, Equador: IX Congresso Latino-Americano de Patologia das Construções—CONPAT 2007.
- [3] Nunes, L. D. P. 2007. *Fundamentos de Resistência à Corrosão*. ABRACO. Interciência: Rio de Janeiro. (in Portuguese)
- [4] Pourbaix, M. 1974. *Atlas of Electrochemical Equilibria in Aqueous Solutions*. Houston, TX: National Association of Corrosion Engineers (NACE), and Centre Beige d'Etude de la Corrosion (CEBELCOR), Bruxelles.
- [5] Zhang, Y.-L., and Li, Q.-L. 2006. "Electrochemical Study on Semiconductive Properties of the Passive Film on Rebar in Concrete." *Journal of Zhejiang University Science A* 51 (8): 1447-52.
- [6] Broomfield, J. P. 1997. *Corrosion Steel of Concrete*. E & FN SPON.
- [7] Tutti, K. 1982. *Corrosion of Steel in Concrete*. Stockholm: Cement and Concrete Institute.
- [8] O'Dowd, C. D., Smith, M. H., Consterdine, I. E., and Lowe, J. A. 1996. "Marine Aerosol, Sea-Salt, and the Marine Sulphur Cycle: A Short Review." *Atmospheric Environment* 31 (1): 73-80.
- [9] Xu, J., and Jiang, L. 2008. "Influence of surface conditions, Inhibitor of the Chloride Threshold Level for Corrosion of Steel in a Simulated Concrete Pore Solution." Presented at 1st International Conference on Microstructure Related Durability of Cementitious Composites. Nanjing, China.
- [10] Grantham, M. G. 2011. *Concrete Repair: A Practical Guide*. New York and London: Taylor & Francis Spon Press.
- [11] Araújo, F. W. C. D. 2009. "Estudo da Repassivação de Armaduras em Concretos Carbonatados Através da Técnica de Realcalinização Química." Tese de Doutorado, Escola Politécnica da Universidade de São Paulo. (in Portuguese)
- [12] Ormellese, M., Berra, M., Bolzoni, F., and Pastore, T. 2006. "Corrosion Inhibitors for Chlorides Induced Corrosion in Reinforced Concrete Structures." *Cement and Concrete Research* 36: 536-47.

- [13] Saraswathy, V., and Song, H.-W. 2007. "Improving the Durability of Concrete by Using Inhibitors." *Building and Environment* 42: 464-72.
- [14] Al-Amoudi, O. S. B., Maslehuddin, M., and Lashari, A. N. 2003. "Effectiveness of Corrosion Inhibitors in Contaminated Concrete." *Cement & Concrete Composites* 25: 439-49.
- [15] ÖNORM EN 14630. Products and Systems for the Protection and Repair of Concrete Structures—Test Methods—Determination of Carbonation Depth in Hardened Concrete by the Phenolphthalein Method.
- [16] NBR 7584. 2012. Concreto endurecido—Avaliação da dureza superficial pelo esclerômetro de reflexão, Método de ensaios. (in Portuguese)
- [17] ASTM C-876. Standard Test Method for Half-Cell Potentials of Uncoated Reinforced Steel in Concrete.
- [18] Meck, E., and Sirivivatnanon, V. 2003. "Field Indicator of Chloride Penetration Depth." *Cement and Concrete Research* 33: 1113-7.
- [19] ASTM C-1202. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.