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Corrosion in structural elements of the satellite unit of a reference hospital in Ceará, Brazil

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Abstract: The study of pathological manifestations that occur in buildings is based on the analysis of failures to diagnose their causes and offer rehabilitation methods. In summary, this paper's main objective is to diagnose the possible causes of corrosion manifestations in the structural elements, steel and reinforced concrete, of the satellite unit of a reference hospital in Ceará (Brazil) and to propose an adequate rehabilitation and prevention plan. The methodology adopted in the paper is divided into three stages: field visits for data collection; analysis of the results; and the proposition of therapies that offer the best recovery of construction systems, considering the cost. Considering that civil engineering has a social role, this article intends to show that the ensuring of safety and comfort is essential for maintaining the well-being of the population, especially in healthcare facilities. In conclusion, the proposed rehabilitation aims to offer a safe environment so that the establishment can regularly perform its activities without constraints to patients with a deteriorated physical condition.

Keywords: Corrosion; Steel structures; Reinforced concrete structures.

1. Introduction

Pathological manifestations are deleterious phenomena that can compromise the performance and lifetime of building materials and buildings in general. The pathology of buildings is the area dedicated to the study of these incident defects, seeking to understand their causes and mechanisms of deflagration, in addition to their forms of manifestation (Bolina *et al*., 2019).

Thomaz (2020) emphasizes that, in addition to impairing the performance of building systems, pathological manifestations can lead to the psychological embarrassment of its users. Healthcare facilities have a social and economic interest, are technically complex, and require constant attention to their constructive state to ensure the preservation of their operation and their useful life.

The appearance of deterioration in this type of building can directly or indirectly affect the reduction in the quality of services offered by these facilities. To certify the integrity of these facilities, the establishment must be submitted to regular preventive maintenance. Carlino (2012) states that in public institutions, the existence of maintenance programs certifies the quality of services provided, preserving the public patrimony and reducing unnecessary costs. The lack of maintenance can result in the appearance of pathological manifestations, accentuated degradation of the building, as well as physical and psychological damage to its users.

Therefore, Viana (2004) emphasizes that hospital environments at all levels of care need to include maintenance programs that allow the performance of building systems to be monitored throughout their useful life and to benefit positively from the influence of the environment on the therapeutic process.

Corrosion highlights among the most diversified pathological manifestations, as it can affect reinforced concrete and metallic structures. This deterioration can become a major issue if not properly treated. Bertolini (2010) stresses that corrosion phenomena can influence structural safety by reducing the steel and concrete section. The expansive reaction of corrosion products can induce deformations and cracks, in addition to modifying the external appearance of the damaged element. In summary, corrosion is a deterioration mechanism that, beyond compromising the state of the element, can cause other manifestations, such as cracks, which can lead to dangerous unforeseen ruptures, putting at risk the structural safety of the building.

Considering the specific nature of the building under study in this paper, the safety and comfort of its users are the main concerns at stake. The opportunity to review the constructive conditions of the structural elements of the building affected by corrosion, offer a diagnosis of its possible causes, and propose a rehabilitation plan and prevention strategies.

2. Literature review

2.1 Corrosion in steel structures

The steel structures provide space optimization, with slender pillars and beams, foundation relief, and architectural liberty. However, the corrosion of metal elements in structural systems consisting of steel sections is the most common deterioration phenomenon and is favored by the very nature of the material. Bolina *et al*. (2019) highlight that corrosion is also a spontaneous effect when steel is not adequately protected and will be faster the longer it is exposed. The incidence of corrosion comes with two main visual manifestations: the appearance of a rough surface texture and the colors of its by-products are located in a specific color spectrum (Khayatazad *et al*., 2020).

Corrosion can manifest in many different forms. The classification by the appearance of the corroded material is the most commonly used and will be adopted in this paper. In principle, it is required to separate macroscopic localized corrosion from microscopic localized attacks. In cases of microscopic localized attack, the corrosion rarely spreads beyond the point where it causes localized structural weakening, besides the possibility of considerable damage occurring before the manifestation becomes visible to the eyes (Pannoni, 2015).

In the case of macroscopic phenomena, metallic corrosion can be uniform or localized. Pannoni (2015) states that uniform corrosion causes uniform mass loss throughout the metal surface, occurring continuously, with an approximately equal rate at each point of the element. This phenomenon is easy to detect and monitor; regular inspections can prevent the element's collapse. Atmospheric corrosion is the most effective form of uniform corrosion: the extensive use of metals in outdoor structures allows direct contact with the atmosphere; the metals are affected by being subjected to an attacking front that is equally uniform.

Corrosive attack rarely occurs uniformly over the entire surface of the metal. Several circumstances can favor the localization of the attacks. Localized corrosion manifests in corrosion spots with varying geometries, distinct depths, and random distribution on the material's surface. Bolina *et al*. (2019) point out that this mechanism can develop in four ways: pitting, alveoli, plaques, or crevices.

Sales *et al*. (2018) describe pitting corrosion as developing pits with a high ratio between length and diameter. This manifestation causes mass loss in specific regions and highly damaging effects on the metallic material. The pitting presents a high growth rate throughout the corrosive process; when it occurs in piping, it can result in the perforation of the component, causing leaks. Pitting also has deleterious effects on the mechanical properties of the material by acting as an amplifier site for tensile stresses.

This action can also cause a significant reduction in the fatigue strength of the metallic material with the formation of stress corrosion cracks. Alveoli corrosion develops cavities smaller than pitting corrosion.

Furthermore, plaques corrosion is defined as an intermediate between uniform and localized corrosion, as it manifests itself irregularly and does not ignite punctually and constantly (Bolina *et al*., 2019).

And finally, crevice corrosion results from the deposit of water and dirt in regions of connections between elements. The interface between two elements in an external environment is propitious for water retention and renders its condition ideal for corrosion on bolts, welds, and localized spots. Designs with a high level of detail that focuses on preserving the element's performance adopt geometric configurations that obstacle the accumulation of water or dirt. Pannoni (2009) emphasizes that the detailed design and the suitable choice of a protection system are crucial in corrosion control and should be part of any successful project.

The more humid and contaminated the element's surface, the faster the corrosion reaction occurs. Pannoni (2009) explains that the oxygen in the air has an acceptable solubility in the liquid film of water deposited on the material, which promotes the settlement of aggressive agents and the activation of the mechanism.

2.2 Corrosion in reinforced concrete structures

The Brazilian civil construction industry often uses reinforced concrete elements as a structural solution. The low cost of production and easy access to materials partly justifies this. However, there have been several incidences when such structures necessitate maintenance far before the end of the design lifetime. Shevtsov *et al.* (2022) highlights that reinforced structures are susceptible to collapse when deprived to timely and proper maintenance. Most cases of premature deterioration of reinforced concrete structures are due to corrosion of reinforcements. Just like in steel structures, reinforced concrete is susceptible to deterioration that, in addition to damaging the concrete, can result in reinforcement corrosion, with severe damage to structural performance and the physical integrity of users, since this pathological manifestation can lead to the collapse of the affected buildings.

Corrosion in reinforced concrete structures is a concern affecting civil construction worldwide. In Brazil, Meira (2017) highlights that this problem occurs throughout the country, especially in the structures located in the coastal marine areas. At first, the reinforcement embedded in concrete structural components must be protected and passivated against the risk of corrosion. The concrete cover offers protection, which forms a physical barrier to the ingress of external agents, especially by chemical protection attributed to the high alkalinity of the aqueous solution found in the concrete pores. Sales *et al*. (2018) explain that the loss of this protection can occur due to carbonation and chloride contamination and unchain a progressive deterioration process. Cracks and incorrect execution contribute to the risk of losing this protection, besides favoring the acceleration of a corrosive process already started.

Bolina *et al*. (2019) explain the insufficient cover of reinforcement: a mechanism that makes the concrete structure more susceptible to corrosion deterioration of the rebars due to environmental aggressiveness. This type of manifestation is a phenomenon that involves conditions such as oxygen and water, and its consequences can be perceived throughout the lifetime of the structure, depending on the magnitude of these conditions. Thus, it is understood the fundamental role that the cover layer of the reinforcement has in its protection. Meira (2017) explains that the cover ensures chemical and physical safety as the concrete thickness prevents aggressive agents from reaching the rebars.

Diagnosing pathological manifestations cannot always be made directly; some equipment and materials help diagnose. Traditionally, phenolphthalein-based indicators or equivalents indicate the pH change between 8 and 11. The phenolphthalein aspersion test contributes to the definition of the carbonation depth of concrete, which is a determinant of reinforcement corrosion in concrete structures.

3. Methodology

The paper has an exploratory approach. The methodology adopted is a descriptive evaluation of the building, based on visual inspection and photographic survey. The main objective was to identify the existing corrosion manifestations in the structural elements and its possible causative agents. Then, propose a rehabilitation plan with the assistance of bibliographic research and technical guidelines.

During the inspections, phenolphthalein aspersion was used on the affected structural elements to verify if the concrete was under carbonation and to assist in the diagnosis. The analyses and data records of the building resulting from the field visits and photographic records took into account the geographic location and the season in which the inspections were made to identify any influence on the current condition of the building.

3.1 The building

The building under study is a clinic that operates as a satellite unit for dialysis and kidney transplantation of the reference hospital in Sobral, in Ceará, Brazil. According to information provided by the administrative sector, the facility can assist up to 130 patients. The unit has competencies in emergency and inpatient care and operates in preventing kidney disease, early diagnosis, and hemodialysis treatments. The clinic is located in the city center, an area with a high flow of cars (Figure 1).

Figure 1 – Building's façade

Highlighted constructive features of the building: Constructed area: 507,69 m²; Only ground level pavement; Reinforced concrete structure; Sealing masonry consists of ceramic blocks and mortar; The roofing system consists of metallic tiles in the water storage tank area and ceramic tile in the other areas of the building; Masonry water storage tank with 12 m³ volume; Interior floors consists of ceramic tiles and weternal floors consists of "pedra cariri" (a limestone intensively explored in the state of Ceará).

Through interviews with the employees of the establishment and older residents of the city, it was possible to obtain information about the history of the building. It was built between the 1980s and 1990s for residential use until 2002. Between 2002 and 2005, the facility operated as a fitness center. Between 2005 and 2011, the building remained closed and nonoperational. Since 2011, the building began to operate as a renal replacement therapy unit of the reference hospital in Ceará (Brazil).

According to the employees, the establishment undergoes maintenance only when an issue arises, such as the occurrence of infiltrations. The administration does not conduct inspections and preventive maintenance, which allows failures not identified by the employees to escalate.

The field visits occurred in September, in the morning and afternoon shifts; this is the winter period in the southern hemisphere, characterized by drought for the state of Ceará, with strong winds, low precipitation, and low air humidity, besides the increased incidence of solar radiation. Conditions such as geographic location and the season can influence the intensity of the pathological manifestations.

Through the development of the building's floor plan, it was possible to map the corrosion manifestations detected. Thus, it is feasible to structure a diagnosis and, consequently, to define a rehabilitation plan, considering the potential agents causing the damage. Figure 2 illustrates the plan of the roof's structure in the region of the building's water storage tank composed of a metal structure. It is possible to identify a corrosion process that extends throughout the structure.

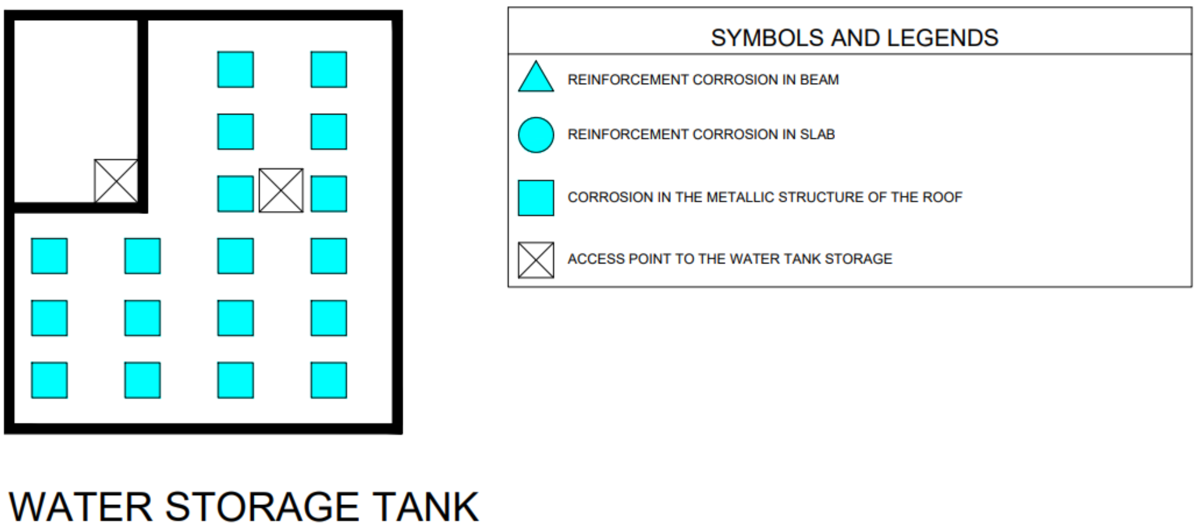

Figure 2 – Map of the corrosion manifestations on the metallic structure

Figure 3 shows all the environments of the ground floor and the respective corrosion manifestations identified in a reinforced concrete beam of the ventilation area and in a reinforced concrete slab of the water treatment room.

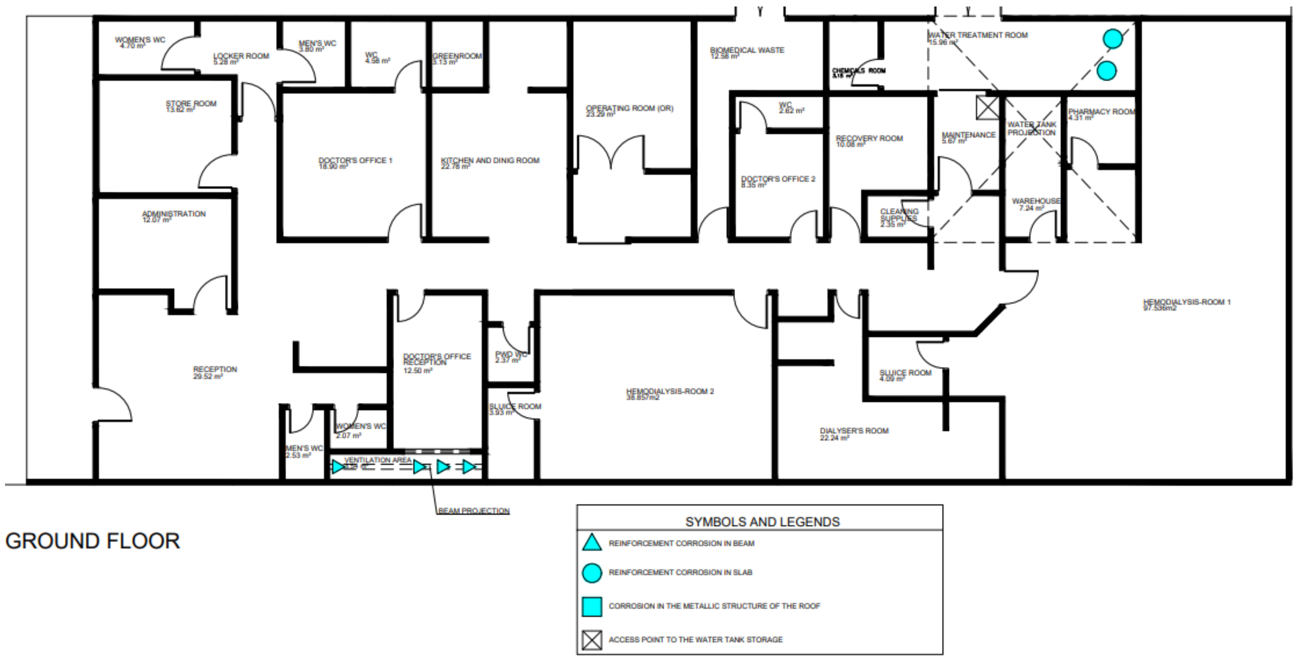

Figure 3 – Map of the corrosion manifestations on the ground floor

4. Case study

4.1 Corrosion in the metallic structure of the roof

The roof's structure in the region of the building's water storage tank consists of metallic sections and is affected by uniform and crevice corrosion. The uniform corrosion process is visible in Figure 4, where a uniform crust of corrosion product is apparent along the entire structural element length.

Figure 4 – Corrosion in the steel structure

Potentially, the unsealed screwing regions allow rainwater to enter and run down the metal profile. Eventually, this mechanism operates in conjunction with the oxygen in the environment, causing corrosion of the sections. Figure 5 shows the advanced state of the corrosion that consumes the element.

Figure 5 – State of corrosion of the steel section

In some regions of the metal roof, the identification of localized crevice corrosion was possible: regions of bolt connections that allow water retention, providing ideal conditions for the corrosion mechanism to develop. At the moment of the photographic record in Figure 6, it is possible to confirm that the corrosion is already in such an advanced state that the two upper bolts have been expelled, probably due to the shearing of the stem.

Figure 6 – Crevice corrosion

As uniform and localized corrosion (with the exception of galvanic corrosion) do not occur without moisture, the arrangement of the metal sections should not enable water retainment. Screwed or riveted joints and discontinuous welding points are some construction features that leave voids that allow the retention of water, dirt, and even the abrasives used in the surface preparation since points where a small distance separates two metallic surfaces are potential corrosion cells. Figure 7 shows the absence of bolts in the joint, probably also due to the advanced corrosion state of the joint.

Figure 7 – Crevice corrosion

It is fundamental to avoid some geometrical design that allow the accumulation of water and dirt since it enhances the deflagration of the corrosion mechanisms. As the structural geometry of the system at the joints of the metallic element is not appropriately suited, as Figure 8 illustrates, water and dirt are deposited at these points of "open section," which allows the corrosive process throughout the extension of the metallic element, because the water has access to drain through the entire profile. Figure 8 indicates one of the existing irregular designs that enable water to accumulate and flow through the section.

Figure 8 – Irregular geometrical design

Figure 9 represents some of the anomalous design identified in the metal profile. These conditions can impact the durability and lifetime of the structural system, as they offer sites for water and dirt accumulation.

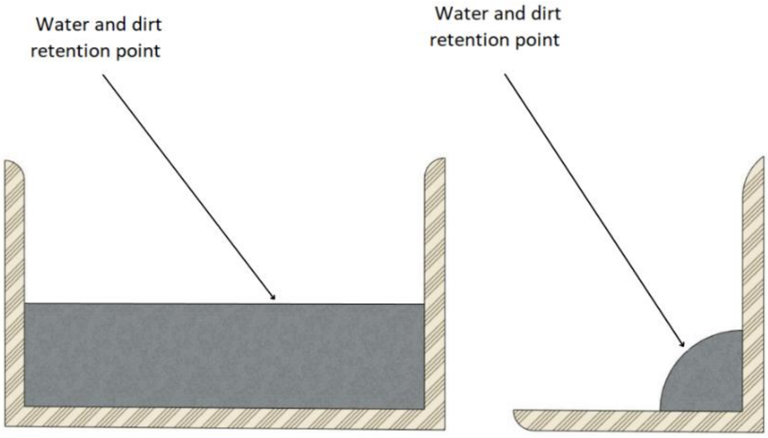

Figure 9 – Irregular geometrical design representation

Figure 10 indicates the absence of elements that prevent infiltration of water, which allows direct contact of the metallic element with rainwater drops and allows the accumulation of dirt. The corrosion prevention system (such as painting) used to block the exposure of the material to the corrosive environment is inappropriate since corrosion spreads throughout the entire length of the sections. The combined action of all these constructive flaws observed enables the manifestation of corrosive processes.

Figure 10 – No elements to prevent rain splashes

The employees reported that there had not been any inspection of the metal structure for two years, resulting in an advanced deterioration at the most damaged sections.

4.1.1 – Rehabilitation plan

Initially, supposing that the local administration chooses to replace the structure, it is essential to elaborate on a project based on an anticorrosive design to improve surface preparation, painting, inspection, and maintenance. Several scenarios must be considered, such as bolted connections, rivets, irregular welds, and sharp corners. One of the most crucial points in the project for corrosion control is to avoid cracks, where water-soluble compound deposits can accumulate and not have a visible or accessible location for maintenance.

Pannoni (2015) highlights that rounded corners ensure a more accessible application of a uniform and long-lasting protective coat of paint, as the coating film on sharp corners can become flawed and accelerate deterioration in these areas. Figure 11 shows straightforward examples of precautions and recommendations for geometric details to avoid water and dirt accumulation points on the steel. A structural geometry designing inclined or chamfered surfaces and eliminating open sections are some precautions that allow water to drain away from the structure.

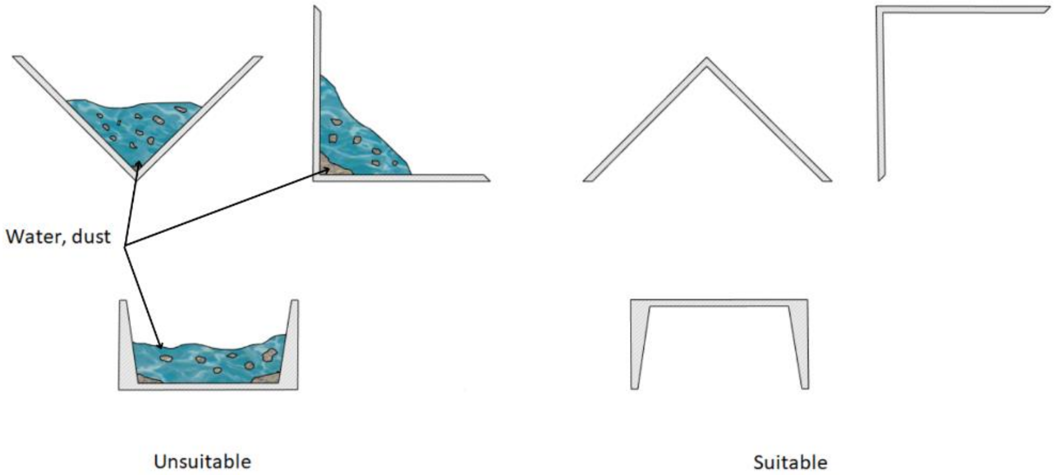

Figure 11 – Geometric details

As previously highlighted, the metallic element under analysis presents several points where the crevices manifest corrosive processes, causing the deterioration of the bolted connections. If the local administration prioritizes the restoration of the structure, it is required to repair the cracks and protect the structural steel by applying anti-corrosion paint. An additional recommendation is the execution of roof gutters to avoid the rainwater's direct contact with the metallic section.

Pannoni (2015) claims that this corrosive process can be inhibited by sealing the crevices with an epoxy sealer or polyester filler. The crevice filled with a steel shim project from the section and is welded all around it. In order to prevent the ingress and storage of water and dirt, sealing coupling regions with continuous welding is a viable alternative. Cardoso (2013) emphasizes that using a good coating prevents the direct exposure of the metallic element to the corrosive environment, offering a physical barrier.

A painting system stands out among the various forms of protection for metallic structures. To ensure the durability and efficiency of this system, it is necessary to previously prepare the steel surface through cleaning and subsequent mechanical anchoring. Fragata (2009) explains that a properly clean, dry surface, free of corrosion products or contaminants, is an ideal substrate for a good performance of a painting system. At first, it is essential to remove the mill scale that can prevent direct contact of the paint with the steel.

The presence of electrolytes favors the formation of a galvanic pile, where the steel is the anode, and the scale is the cathode. This scale is a natural coating that covers the metal and has a different expansion coefficient than steel. Due to temperature variations, it forms fissures that allow the penetration of water, oxygen, and contaminants to the surface of the steel. After some time of weathering action, the rust progresses under the scale, expelling it from the steel surface (Pannoni, 2015).

The surface preparation for scale removal can be achieved by cleaning with solvents, abrasive blasting, or even manual tools. Nunes *et al*. (2007) sustain that the preparation by abrasive blasting is the most recommended method since it has a high performance, offers adequate cleaning, and ensures that the surface has the ideal roughness for anchorage the paint film. Ensuring the increase in surface roughness is essential, as it increases the contact surface between steel and paint, increasing adherence.

After blasting, it is necessary to apply a paint that offers resistance to weathering. Bertolini (2010) states the benefit of effective and lasting protection through a painting cycle that starts with the surface preparation, continues with the application of a layer of paint with active pigments (primer), and completes with a thick layer that ensures a barrier effect to the penetration of water and oxygen. This procedure ensures that the metallic structure is impermeable and resistant to environmental aggression on the surface, whether by the effect of mechanical actions, weathering, etc.

4.2 Reinforcement corrosion in slab

In the ceiling lining of the water treatment room, a protuberance was identified in the coating, representing expansion reactions caused by corrosion of the structure's reinforcement (Figure 12).

Figure 12 – Concrete expansion

The room is located below the building's water storage tank, indicating that the tank has an ineffective waterproofing system that enables water infiltration into the slab and reinforcement corrosion.

Thomaz (2020) highlights that corrosion processes, regardless of their nature, produce iron oxide, whose volume may be higher than the volume of the original metal. This expansion caused by corrosion products causes cracking and spalling of concrete in the areas near the reinforcement. At the beginning of this process, the corrosion products form a crust on the rebars, generating its expansion and causing internal pressures in the concrete. Due to the small capacity of concrete to resist tension, it tends to crack as a form of relaxation. Figure 13 illustrates the structure and the reinforcement corrosion mechanism.

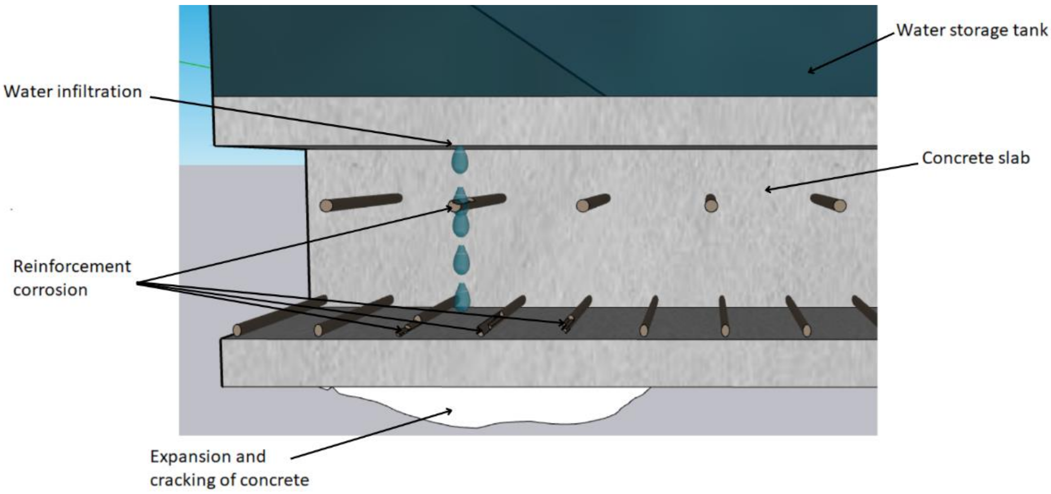

Figure 13 – Reinforcement corrosion

It was impossible to detect the cracks during the field visits, but there is an expectation that these pathological manifestations will appear in the short or medium future. Due to the development of cracks in this area, there is the risk for efflorescence manifestations resulting from the transportation of soluble salts present in the concrete, especially calcium carbonate ($CaCO_3$), to the external surface (concrete leaching).

4.2.1 – Rehabilitation plan

Initially, it is crucial to ensure an efficient waterproofing system for the bottom of the building's water storage tank, to inspect and treat all existing cracks, preventing water percolation through the slab. Subsequently, repair the structural element affected.

The indicated technique is the most common in cases of non-accelerated corrosion (without loss of steel section), based on the reconstitution of the deteriorated concrete and cleaning of the corroded rebars. Before any intervention, it is necessary to shore the structure to relieve the element's tensions and ensure the safety of all those working on this service. The repair contour must be delimited for subsequent scarifying of all the deteriorated material until an entire concrete surface. The reinforcement is then manually cleaned using a steel bristle brush and compressed air blasting to remove any remaining dirt. This procedure allows the repair materials to reach the whole reinforcement.

The repair of the rebars is done by isolating the structure with physical barriers, and controlling the access of water and oxygen to the structure, to ensure higher efficacy in preventing the recurrence of the corrosive process. For the safety of this anticorrosive system, it is essential to paint the reinforcement with epoxy paint enriched in zinc since this element behaves as a sacrificial anode, meaning that in case of scratches in the paint, the zinc will suffer corrosion, protecting the steel.

The next stage refers to the reconstitution of the removed area of the structure using cement mortar with an epoxy or polyester base since these are notable for a faster process, incorporating the boost in resistance, adherence, and waterproofing. Finally, the objective is to protect the structural element to prevent the ingress of corrosive agents such as water. Among the materials on the market with this purpose, organic paints are indicated because they usually have a lower cost and offer a successful performance in protection.

4.3 Reinforcement corrosion in beam

A reinforcement corrosion process was identified in a concrete beam with concrete cover peeling, exposing the rebars to the atmosphere (Figure 14).

Figure 14 – Beam corrosion area

The absence of reinforcement covering is one of the main causes of corrosion in this context since the lack of this thickness of protection can favor the attack of chemical agents. Onofre et al. (2021) explain that these agents can attack the concrete, reducing its pH and accelerating the steel oxidation. Eventually, this process will expand the section of the steel, leading to cracks and loss of section. Figure 15 highlights the corrosion process of the exposed rebar.

Figure 15 – Exposed rebar

The absence of elements that allow the proper drainage of rainwater (such as roof gutters) favors corrosion in the area (Figure 16). The rainwater runs down the structural element and accumulates under it, in a shaded region, with slow evaporation and absorption through the pores of the concrete.

Figure 16 – Absence of drainage elements

The process of reinforcement corrosion progresses from the concrete surface to the interior of the structural element. The concrete cover is a physical protection that prevents aggressive agents from coming into contact with the steel. Removing part of the beam cover made it possible to identify that this cover was insufficient (Figure 17).

Figure 17 – Insufficient concrete cover

The decision to conduct a phenolphthalein solution test provided a clearer view of the state and depth of concrete carbonation by sprinkling the solution on the corroded area of the beam and a on fraction of the coating. Figure 18 illustrates the application steps: 1 - indicator's application in the beam's corroded area; 2 - result of the application, with no color change and 3 - result of the application in a fraction of the element's concrete cover. Both remained colorless, which indicates that the cement paste reacted with carbon dioxide, leading to the conclusion that the the carbonation process is occurring and the rebars are not adequately protected since they are not in an alkaline environment.

Figure 18 – Phenolphthalein solution test

Since the building's administration did not allow removal at greater depths of the concrete, it is impossible to accurately conjecture the state of progression of the carbonation process.

4.3.1 – Rehabilitation plan

Localized corrosion spots must have the rebars exposed and rigorously cleaned using steel bristle brushes to remove all corrosion products. Subsequently, it is necessary to apply a primer to the reinforcement and replace the concrete coating with a minimum thickness of cover for the reinforcement adequate to the environmental aggressiveness to which the structure is exposed. According to the Brazilian normative ABNT NBR 6118:2014, the minimum coverage must be 30 mm since it is an element in an aggressive environment II (urban environment).

5. Conclusions

This paper was mainly motivated by recognizing the value of preventive maintenance programs in public healthcare facilities, given their social and economic role and the need for continuous attention to their constructive condition. Therefore, those preventive maintenance programs aim to ensure performance and structural safety in order to preserve public patrimony.

Based on the study of the conditions of the corrosion manifestations in the structural elements and the diagnosis of their potential causes, these deteriorations could have been prevented through the implementation of a corrosion protection system and a waterproofing system for the water storage tank, as is the case of the corrosion in the metal structure of the roof and the corrosion on the slab, respectively.

These pathological manifestations could also have been treated sooner if a regular maintenance program was provided at the facility. In conclusion, the paper offers both techniques for rehabilitating the affected structures and a plan for preventing these degradations, which were proposed based on the ease of execution and the costs involved.

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