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Structural Recovery of the *Ponte da Torre*: Identification and Analysis of Pathological Manifestations, Testing, and Adopted Solutions.

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ABSTRACT
This article presents the main pathological manifestations identified in the *Ponte da Torre* (Tower Bridge), the destructive and non-destructive tests conducted for accurate diagnoses that confirm the structural compromise, as well as the methods adopted for the recovery of this Special Engineering Structure (OAE). Tests performed include core extraction, corrosion potential, surface electrical resistivity, carbonation, rebar scanning, chloride profile, and compressive strength testing. The Tower Bridge is a structure of high architectural and infrastructural importance for the city of Recife, serving the traffic demands of the northern zone of the capital of Pernambuco. Recognizing its significance, it is evident that preserving this OAE for future generations is necessary, incorporating principles of conservation, recovery, restoration, and more recently, sustainability. This study is part of the practice and execution of projects, interventions, and requalification efforts in the contemporary city, where the influence of the environmental aggressiveness class due to the surrounding environment is a fundamental factor for understanding the damage found in the bridge. Despite this, it was observed that one side of the structure shows more damage than the other, necessitating greater reinforcement on that side. The severe deterioration of the structure, especially of the concrete, in the Tower Bridge is directly related to the lack of regular inspections and corrective maintenance. Through this study, knowledge was gained regarding the procedures and methods that support and inform sustainable solutions adopted to ensure the safety and durability of the bridge.

KEYWORDS: Pathological Manifestations. Diagnosis. Structural Recovery.

1 INTRODUCTION

This article falls within the field of reinforced concrete structure recovery, with the *Ponte da Torre*, a Special Engineering Structure (OAE), as its object of study. The bridge is one of the main access routes to the neighborhood that shares its name, Torre, located in the northern zone of Recife. It was part of the urban intervention projects that were integrated into the development plan of the state of Pernambuco during the period between 1922 and 1926. Classified as a beam bridge, which, according to Pinheiro (2019), is the cheapest and simplest type of structure for bridges, its structure comprises a platform, beams, and pillars, representing the superstructure, mesostructure, and infrastructure.

In 2018, the local media documented the alarming degree of deterioration in the structure of this and other bridges in the city. The study presented in this article aims to elaborate on the visual survey of pathological manifestations, as well as the results of tests such as core extraction, corrosion potential, surface electrical resistivity, carbonation, rebar scanning, chloride profile, and compressive strength testing, and to define the main damages caused by these pathological manifestations. Additionally, it seeks to showcase the services carried out for the restoration of the structure.

Thus, it becomes imperative not only to preserve the appearance of the Tower Bridge but also to ensure the integrity of all its elements, recognizing it as a unique structure. This implies adopting solutions that meet the criteria of sustainable development, adhering to the fundamental pillars of the environmental, economic, and social tripod (Barbosa *et al.*, 2018).

In the environmental context, preservation is recognized as a crucial tool to mitigate the impacts of future operations on the bridge, preventing the need for extensive interventions such as renovation, restoration, and rehabilitation. To achieve this, it is essential to adopt maintenance and conservation processes that effectively extend the structure's lifespan and ensure its integrity over time.

From an economic perspective, it is understood that the scarcity of resources and lack of investment in maintenance represent significant obstacles to preservation. Therefore, a preventive maintenance program proves to be more economically advantageous compared to corrective maintenance operations, preventing high costs and ensuring long-term financial sustainability (Castro, 2012).

From a social standpoint, the preservation of the Tower Bridge's infrastructure directly contributes to societal development, promoting well-being, quality of life, heritage appreciation, and a sense of belonging within the local community. By respecting the memory and identity of the region, the preservation of the bridge strengthens community ties and enriches the social fabric of the city, establishing it as a space that values its history and cultural legacy.

2 OBJECTIVES

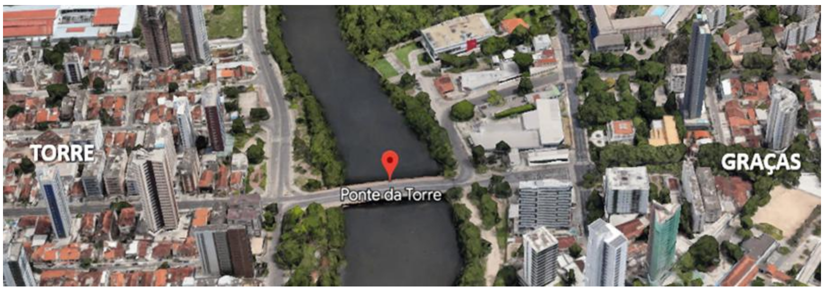
Identify the pathological manifestations and describe the structural recovery process of the *Ponte da Torre* in Recife, PE.

3 METHODOLOGY

3.1 Method

The Ponte da Torre (Tower Bridge), located over the Capibaribe River, connects the neighborhoods of Graças and Torre, which are part of the northern zone of Recife, the capital of the state of Pernambuco, as illustrated by the location map in Figure 1. The Capibaribe River flows through densely populated areas and receives a portion of the city's sewage, a significant factor contributing to the environmental aggressiveness affecting the reinforced concrete structure. Designed for road traffic, according to the National Department of Transport Infrastructure (DNIT), the bridge is approximately 120 meters long, with a 14-meter-wide roadway and a 3-meter-wide sidewalk.

Figure 1 – Location of the Ponte da Torre, Recife/PE

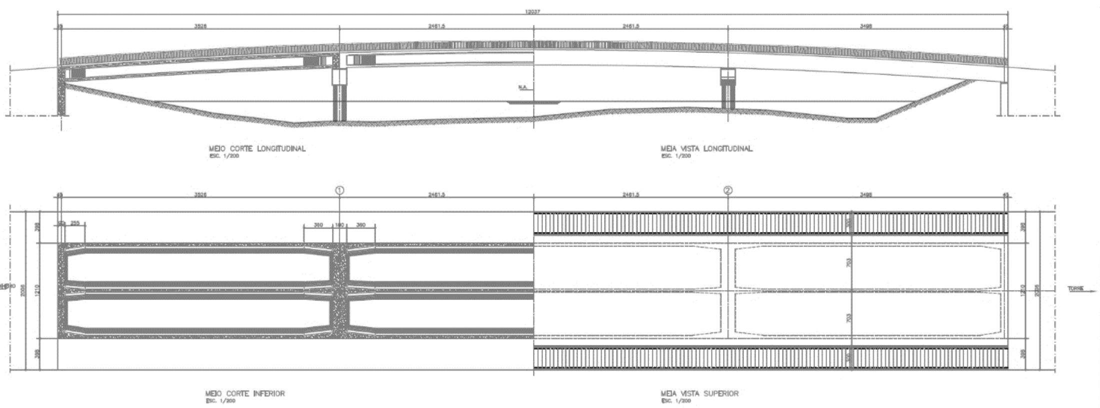


Source: Google Earth (2024).

Data collection initially took place in 2018 with images documenting the deteriorated state of the structure. Information regarding the types of tests conducted and the results obtained was produced in 2020. Site visits were conducted, and photographic records of the structural recovery work were made. The technical data were obtained from the engineering team and the project management, providing procedures and test results, as well as detailed construction drawings.

Figure 2 represents the longitudinal section and shows, in addition to its curved axis in relation to the horizontal, the deck, the two crossbeams (east and west), and their caissons (three in each crossbeam).

Figure 2 – Longitudinal Section of the Ponte da Torre



Source: EMLURB (2019).

The following tests were conducted: core extraction, compressive strength, measurement of reinforcement corrosion potential, electrical resistivity measurement, carbonation depth, chloride ion content, and rebar scanning, all analyzed using the recommended software for each evaluation equipment. To assist in interpreting the results, tools from the Office Suite were used.

3.2 Analysis of Pathological Manifestations

According to Brisola (2019), the mesostructure consists of the bridge or viaduct pillars that support the entire superstructure and transfer the loads to the infrastructure. This area is directly exposed to tidal variations, which is associated with a high risk of structural deterioration. Therefore, according to NBR 6118:2023, the bridge under study is classified as Environmental Aggressiveness Class III, indicating the need for greater concrete cover to provide more effective protection.

According to Ribeiro (2014), the reinforcement is protected by the concrete cover, which acts as a physical barrier against the entry of external agents and is also protected by a chemical layer provided by the high alkalinity of the aqueous solution in the concrete pores. However, over time, this protection diminishes, a process known as depassivation of the reinforcement, as explained by Verly (2015). This phenomenon can occur in two ways: through the carbonation of the concrete, a process intensified in urban areas due to high

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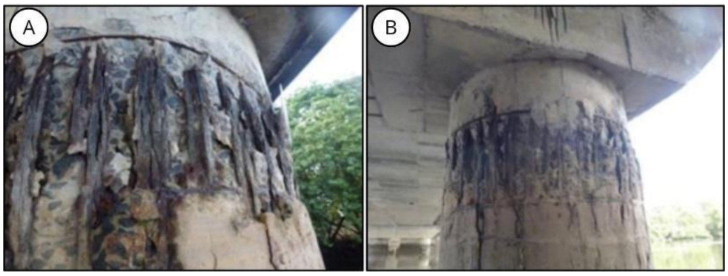
concentrations of carbon dioxide, and through chloride attacks. With the loss of this protection, the steel becomes susceptible to corrosion.

According to Zucareli et al. (2021), steel corrosion in concrete is classified into internal and external factors. The external factors pertain to concrete quality parameters such as cement content, additives, the quality and quantity of water used, aggregates, and chloride salts, as well as the composition and structure of the steel. The internal factors are related to the environment at the level of the steel within the concrete, such as oxygen, relative humidity, temperature, carbonation, gaseous pollutants, acids, and ions. Corrosion in steel occurs due to a reduction in pH, which can result from these factors.

According to Bertolini (2010), the most common type of corrosion is triggered by contact with water, known as wet corrosion, which is prevalent in environments exposed to water due to the presence of chlorides. Wet corrosion is the primary pathological manifestation that contributes to the reduction in durability and load-bearing capacity of the concrete structure's reinforcements. Figure 3 shows the corrosion and spalling of concrete due to the loss of adhesion between the steel and concrete as the corrosion process progresses.

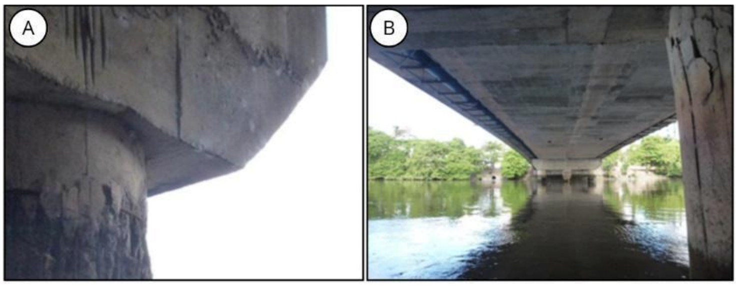
Figure 3 – Reinforcement Corrosion. (A) Caisson reinforcement exposed and section loss due to corrosion; (B) Area with exposed reinforcement and concrete cracking due to corrosion



Source: Authors (2018).

White stains, characteristic of a phenomenon known as efflorescence, were also observed on the crossbeams and the lower slab of the deck of the OAE, as shown in Figure 4. According to Ribeiro et al. (2018), efflorescence results from the formation of saline deposits on the concrete surface, caused by its exposure to water, whether from infiltration through cracks or from the hot and humid environmental conditions. In some cases, the salts that make up these deposits can be aggressive and cause deep degradation of the material.

Figure 4 – Pathological manifestations found along the bridge. (A) Presence of white stains on the crossbeam; (B) Efflorescence on the deck slab, cracking, and detachment of the caisson's concrete cover



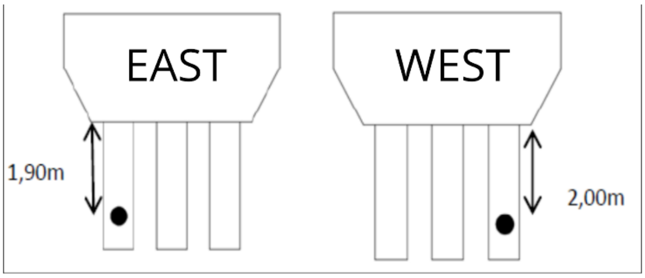
Source: Authors (2018).

4 RESULTS

To diagnose the causes and extent of the damage from the identified pathological manifestations, tests were conducted on the caissons of the OAE, including core extraction, compressive strength, chloride profile, rebar scanning, corrosion potential, surface electrical resistivity, and carbonation.

Core extraction is the initial testing method, which involved taking a sample from a caisson on each side, as shown in Figure 5. According to NBR 7680 (2015), the results obtained through this procedure can be used for the acceptance of concrete in case of non-conformities, for evaluating the structural safety of an ongoing project, or for verifying the structural safety of an existing structure. The analysis of the core samples revealed the existence of two internal layers that were possibly constructed at different times, as the concretes do not show any bond between them, despite having the same mix design.

Figure 5 – Figure 5 – Location of Core Extraction Points



Source: Adapted from the Technical Testing Report (2024).

The compressive strength tests of the core samples were conducted based on NBR 7680-1 (2015). On the east side, the minimum strength was 24.3 MPa, and on the west side, it was 33.2 MPa. Pieces 1 and 5 represent the west side, and pieces 2 and 3 represent the east side. To obtain the test results, correction factors stipulated in NBR 7680 were applied: K1 is the ratio of height to diameter of the core; K2 pertains to the effect of the extraction process using the drill, meaning that the greater the effect, the smaller the diameter of the core; K3 relates to the direction of the extraction model in relation to the placement of the concrete, orthogonal to the structural element; and K4 pertains to the effect of moisture in the core, where K4= -0.04 is considered for dry or air-dry testing, and K4= 0 for saturated testing. Table 1 displays the test results.

Table 1 - Compressive Strength Test Results of the Caisson Samples

Piece	Diameter	Length	Initial fci, ext	Correction Factors				fci, ext
	(mm)	(mm)	(Mpa)	K1	K2	K3	K4	(Mpa)
West Caisson - Piece 1	74.8	138.4	30.5	-0.01	0.09	0.05	-0.04	33.2
West Caisson - Piece 1	74.9	142.6	34.8	-0.01	0.09	0.05	-0.04	38
East Caisson - Piece 2	74.9	143.2	22.3	-0.01	0.09	0.05	-0.04	24.3
East Caisson - Piece 3	75.1	141.8	25.2	-0.01	0.09	0.05	-0.04	27.5

Source: Adapted from the Technical Testing Report (2024).

The test called Chloride Profile was conducted in the laboratory, following Romano (2009), and it determines the ionic concentration of water-soluble chlorides. The sample was collected from Caisson 1 on the east side and Caisson 3 on the west side, and it was necessarily taken at the height of the tidal variation level. Table 2 explains the depth of each piece.

Table 2 - Depth of Chloride Content Found Above the Limit

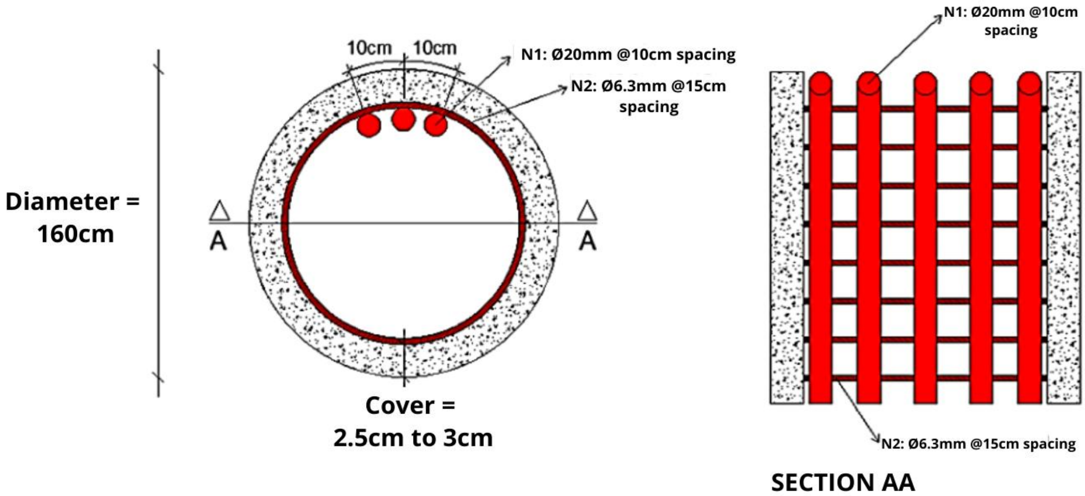
PIECE	DEPTH (cm)
Caisson 1 - Inner Face	4.5
Caisson 1 - Outer Face	3.5
Caisson 3 - Inner Face	4
Caisson 3 - Outer Face	4.5

Source: Adapted from the Technical Testing Report (2024).

The research results indicate that both samples showed chloride content above the limit. The minimum chloride content at a depth of 5 cm, measured during the test, was on the inner face of the eastern caisson, with 1.56% relative to the cement mass. However, the outer face of the western caisson showed a maximum chloride content of 2.88% under the same depth conditions.

To verify whether the concrete cover meets the requirements of NBR 6118 (2023) and to determine the position of the reinforcement in the caissons, a rebar scanning procedure was performed. According to Carvalho et al. (2017), this is a non-destructive and non-invasive method that identifies the location of reinforcement bars, as well as their diameter and concrete cover thickness. The equipment used was the Ferroscan PS35, and this method is based on the principles of electromagnetism. Figure 6 illustrates the result obtained using this tool.

Figure 6 – Detailing of the Reinforcement Bars Inside the Caissons



Source: Adapted from the Technical Testing Report (2024).

With the proper traceability of the reinforcement bars, the corrosion potential test can be conducted, with readings taken at the lowest height allowed by tidal variation, selecting areas with the least concrete loss in the regions affected by corrosion. This measurement is a

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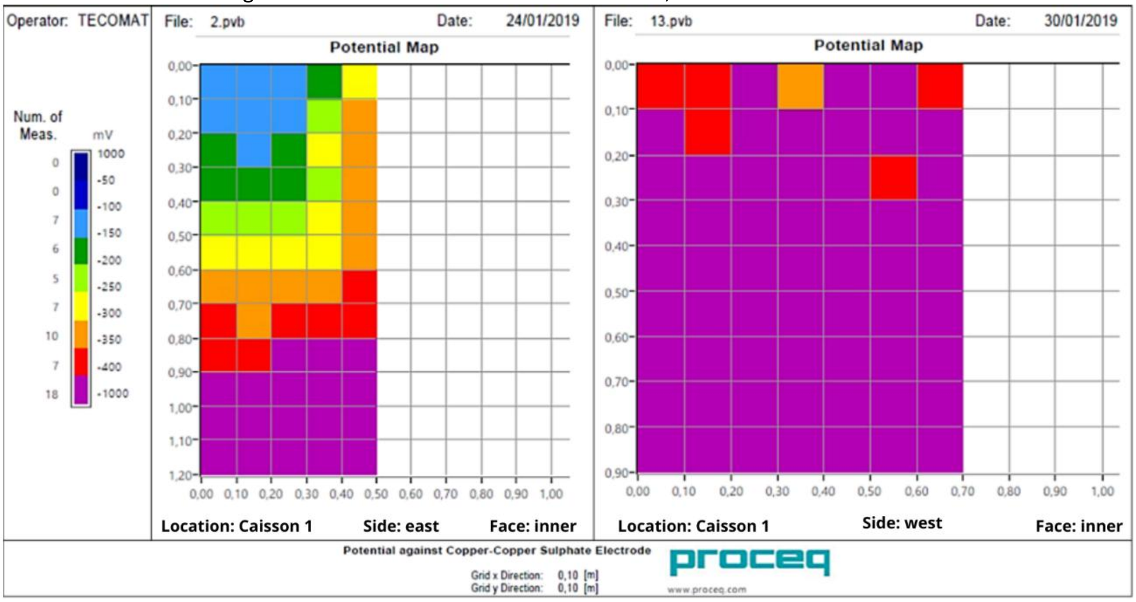
non-destructive, quick, and comprehensive test. The half-cell method was used, and the CANIN+ equipment was operated to determine, through the concrete surface, the corrosion characteristics of the steel present in the structure.

The survey established by the equipment readings, interpreted by its software, indicates that the reinforcement bars in the caissons on the west side have a higher corrosion potential in all three elements compared to the other three on the east side. Figure 7 presents the software's readings for Caisson 1 on both sides, generally representing the collected data. According to the criteria of ASTM C 876-09, the probability of corrosion is less than 10% for readings greater than -200mV, with an uncertain probability of 50% if the readings are between -200mV and -350mV. The probability of corrosion is greater than 90% if the readings are below -350mV.

Figure 7 – Corrosion Potential Test. Caisson 1, East Side and West Side



Source: Adapted from the Technical Testing Report (2024).

Table 3 presents the results of the surface electrical resistivity test and reinforces that the west side shows a high risk of corrosion based on the concrete resistivity. However, the east side showed values indicating a moderate risk. "Two measurements of the potential difference between the internal electrodes and two readings of the passing electrical current between the external electrodes of the specimen should be taken" (SILVA, 2016, p. 28).

The RESIPOD device was used, and the Wenner method was adopted, which involves applying an alternating electric current to the concrete surface using four electrodes. The procedure was carried out at two points on each caisson, referred to as upper (positioned 0.80 m from the bottom of the crossbeam) and lower (positioned 1.90 m from the bottom of the crossbeam), with five readings taken at each point.

Table 3 - Resistivity Test - Caisson 1, Inner Face, East Side and West Side

	Upper Position (UP) East Resistivity Values (KΩcm)	Lower Position (LP) East Resistivity Values (KΩcm)	Upper Position (UP) West Resistivity Values (KΩcm)	Lower Position (LP) West Resistivity Values (KΩcm)
	28.9	12.6	11.7	13.8
	29.4	13	10.2	13.3
	30.6	13.2	6	12.8
	32.4	13.5	7.7	12.5
	13	11	10.1	12.5
Mean	27	12.7	9.1	13
SD	7.9	1	2.3	0.6

Source: Adapted from the Technical Testing Report (2024).

To compare the results obtained on the surface of the caissons with the concrete resistivity, the criteria from RILEM TC 154 were used, as determined in Table 4.

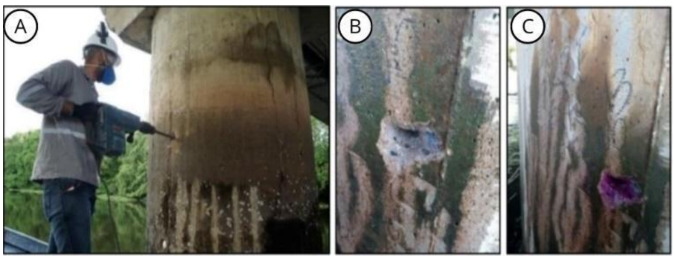
Table 4 – Concrete Resistivity (RILEM TC 154)

Concrete Resistivity (kΩcm)	Corrosion Risk
≤ 10 kΩcm	High Risk
10 to 50 kΩcm	Moderate Risk
50 to 100 kΩcm	Low Risk
≥ 100 kΩcm	Negligible Risk

Source: Adapted from the Technical Testing Report (2024).

The purpose of the carbonation test was to assess the potential for reinforcement corrosion and was conducted only on the 3 caissons on the east side, on both internal and external faces, following the recommendations of RILEM TC056 CPC 18. This is a partially destructive and low-cost method, requiring only a sprayer filled with a solution of phenolphthalein and ethanol. According to Silva (2012), phenolphthalein is an organic compound used as an indicator in a 2% ethanol solution. When in contact with the medium, it remains colorless at acidic pH <7.0 and turns pink at basic or alkaline pH >7.0, as shown in Figure 8.

Figure 8 – Carbonation Test. (A) Concrete fracture;; (B) Cleaning the area with water; (C) Result after spraying



Source: Adapted from the Technical Testing Report (2024).

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According to the depth of the test and observed cover, Table 5 estimates the deactivation and remaining time for the reinforcements. It can be observed that the external face of Tubulão 2 is the most critical regarding these aspects.

Table 5 – Depth of Carbonation

Element	Carbonation Depth (cm)	K (cm/ano$^{0.5}$)	Found Covering (cm)	Estimated Deactivation of Reinforcements (years)	Remaining Time (years)
T1 - East (Internal Face)	0.4	0.031235	5	6406	6365
T2 - East (Internal Face)	0.4	0.06247	2.2	1204	1199
T3 - East (Internal Face)	0.5	0.078087	3.8	2368	2327
T1 - East (External Face)	1.8	0.281113	3.5	155	114
T2 - East (External Face)	2.9	0.452904	3.7	66	25
T3 - East (External Face)	1.8	0.281113	4	202	161

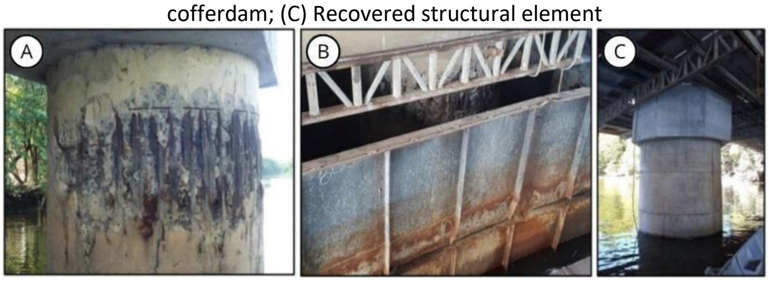
Source: Adapted from the Technical Testing Report (2024).

4.1 Solutions Adopted for Structural Recovery

After analyzing the results, structural recovery and reinforcement services for the caissons, crossbeams, and deck were carried out. The adopted solutions included cleaning and removal of existing stains, protective painting, replacement of support devices, and replacement of drains on the walkway slabs and the expansion joint between the structure and access.

The structural reinforcement of the caissons began with "apicoamento," which involves drilling or cutting away a layer of concrete to remove damaged material. This was followed by protective painting to shield the concrete structures from external damage, such as moisture and atmospheric pollutants, thereby extending their service life. Subsequently, new reinforcement was installed, hydro blasting was performed, grout was applied, and a 15 cm jacket was added. For work below the water level, temporary water diversion using cofferdams was essential, as shown in Figure 9.

Figure 9 – Caisson Recovery Process. (A) Caisson of the bridge in a deteriorated state; (B) Recovery process inside a cofferdam; (C) Recovered structural element



Source: Authors (2020).

For the crossbeam blocks, the recovery techniques were similar, as shown in Figure 10.

Figure 10 – Process of recovery of the crossbeam. (A) Crossbeam of the bridge without maintenance; (B) Execution of the recovery of the crossbeam block; (C) Repaired structural element

Source: Authors (2020).

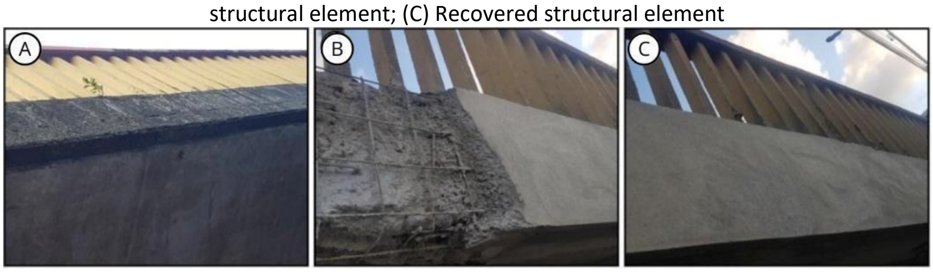
For the deck, the solution differed only in the thickness of the projected concrete for covering, which was seven centimeters, as shown in Figure 11.

Figure 11 – Deck recovery process of the bridge. (A) Scabbling on the deck; (B) Projected concrete; (C) Installation of reinforcements on the deck

Source: Authors (2020).

Figure 12 – Recovery of the walkway slab also considered a preventive measure.

Figure 12 – Walkway slab recovery process. (A) Condition of the walkway slab before recovery; (B) Covering of the structural element; (C) Recovered structural element



Source: Authors (2020).

5 CONCLUSION

The *Ponte da Torre* faced a series of structural problems due to a prolonged lack of maintenance. The images presented in this article revealed the critical state of its structural elements, and through visual inspection, it was possible to identify significant pathological manifestations, such as numerous cracks, efflorescence, corrosion, and spalling of the concrete. These damages compromised both the aesthetics and the durability and strength of the concrete.

Concrete testing is performed to evaluate the quality, integrity, and compliance of concrete structures. Given the findings, the importance of precise identification and diagnosis of pathological manifestations became evident. This approach was crucial for accurately guiding the necessary corrective measures during the process of restoring reinforced concrete structures. The use of specific scientific methods and techniques for evaluating structural conditions provided a basis for effective intervention, and the diagnoses obtained helped determine the actual condition of the bridge, ensuring the effectiveness and durability of the adopted solutions. Thus, identifying pathological manifestations and the results of the tests conducted were essential for directing actions aimed at preserving and conserving this important heritage

The tests revealed that the concrete's compressive strength ranged from 24.3 to 33.2 MPa, with some values falling below current standards. The chloride profile test indicated chloride levels above the limit, and while the carbonation depth did not reach the reinforcement, it suggests that in some areas, the remaining service life could be as short as 25 years. With proper tracing of the reinforcement in the caissons using the pachymetry method, it was also found that the west side had a higher corrosion potential, confirmed by the surface electrical resistivity test, indicating a high risk of corrosion.

For the implemented solutions, a multifaceted approach was adopted to address the identified issues. Initially, a cleaning process was performed to remove existing stains from the affected surfaces. This aimed to eliminate residues and debris that could compromise the effectiveness of subsequent interventions. Subsequently, a protective paint layer was applied to the treated areas to provide an additional barrier against external aggressive agents. As part of the structural reinforcement measures, damaged support devices were replaced to restore the load-bearing capacity and stability of the structure. Another action taken was the replacement of drains on the sidewalk slabs and the expansion joint between the main structure and the adjacent access. This measure aimed to improve surface water drainage and reduce moisture accumulation in vulnerable areas, thus preventing corrosion and other damage resulting from prolonged exposure to moisture.

In this context, considering future interventions to promote the structural integrity of the bridge, regular inspections are recommended, especially assessing waterproofing and the service life of support systems, along with cleaning and debris removal and environmental monitoring, which can be done using sensors. Considering sustainability in contemporary urban interventions, it becomes clear that prioritizing methods that have the least possible impact, whether environmental or social, and that result in lower recovery costs is crucial.

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