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STRUCTURAL COLLAPSE OF REINFORCED CONCRETE BUILDINGS: AN ASSOCIATION BETWEEN OVERLOADS AND PATHOLOGIES

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ABSTRACT

Considering that the collapse of a building is a catastrophic episode, where lives and material goods can be lost, it becomes of extreme importance to investigate the causes and their dissemination by technical and scientific means, bearing in mind that this information is valuable for the progress of Civil Engineering and future constructions. In this sense, this work discusses one of the main processes that lead a structure to ruin, the depletion of the resistant capacity of the support elements, with a literature review that addresses the main topics associated with the subject, such as the ultimate and service limit states, the actions acting in a building, as well as their combinations of design recommended by the Brazilian standard NBR 6118. The pathological manifestations most common to reinforced concrete buildings were also studied, as well as the ways that these pathologies can lead to the compromise of the structural integrity of the building. Besides, a case study was conducted on the Andrea Building, which collapsed in October 2018, in the city of Fortaleza, reporting its causes and emphasizing the importance of both a strict control of the construction methodology and attention to pathological manifestations.

Keywords: Andrea Building. Pathologies. Reinforced concrete structures. Structural collapse. Structural safety.

1. INTRODUCTION

Reinforced concrete buildings are the most widespread in Brazil and are commonly used as a resource in the occupation of urban centers. The popularity of this construction methodology is due to the ease of execution and low cost of materials, however, these advantages do not exclude the need for constant evaluation of the building's condition and proper performance of the necessary maintenance, to ensure the safety of its residents.

According to Araújo (2010), a reinforced concrete structure, besides economic and aesthetic aspects, must meet some quality requirements, such as safety and good performance in service. When any of these requirements are not met, a limit state is considered to have been reached, at which point the structure ceases to fulfill the function for which it was designed.

In this scenario, the limit state method is the methodology adopted by the Brazilian standard NBR 6118 (ABNT, 2014a), specific for reinforced concrete structures, which defines that the resistances cannot be less than the requests and must be verified concerning all limit states and all loads specified for the type of construction considered. In general, the limit state method determines that, for each collapse mode or situation in which the structure ceases to meet its requirements, the condition that the design resisting efforts are equal to or greater than the efforts referring to the requesting actions must be respected. According to Sáles et al. (2004), a limit state method is a tool that helps evaluate design situations and simplifies the design process. Details of the ultimate limit state and the service limit state can be easily accessed in the referred standard.

Besides, considering the current scenario in which the occurrence of several accidents involving reinforced concrete buildings is verified, studying their causes and possible prevention measures becomes extremely important. Thus, this work is justified by the need to study the most common pathologies in these types of buildings, as well as by the importance of meeting the requirements of technical standards, so that the project is executed safely in order not to endanger people's lives.

In this paper, therefore, the various types of pathologies that occur in reinforced concrete buildings due to construction errors and lack of maintenance during their service life are presented. Some of these errors can be corrected through a structural analysis performed by specialized and competent companies to give an opinion about the current situation of the building. Thus, the structure can be reused without requiring major interventions, making the execution time shorter and the costs of the work cheaper, but always following the competent norms.

The general objective of this work is to make a diagnosis that explains the collapse mechanism of the Andrea Building. Specifically, it intends to analyze the errors and possible causes that led to the structural instability and the consequent collapse, considering the need to know the reasons for this episode to avoid future disasters. To achieve these objectives, information was collected to verify the panorama of collapses in Brazil, a literature review was performed about the main and most recurrent pathologies in reinforced concrete buildings, and a case study was conducted about the collapse of the Andrea Building.

2. REINFORCED CONCRETE PATHOLOGIES

Reinforced concrete pathology is the area of Civil Engineering that studies the causes, mechanisms, and consequences of failures common to reinforced concrete structures. To ensure the safety and good performance of reinforced concrete buildings, it is necessary that several precautions are taken, such as the correct definition and execution of the concrete mix, proper handling, and curing, periodic maintenance, and prevention against aggressive agents.

According to Souza and Ripper (1998), even correctly designed and built structures may develop pathological symptoms, and in many cases the structures need to have their bearing capacity increased, either by decreasing the resistant capacity of the structure or by increasing the load, thus justifying the adoption of recovery or structural strengthening works.

In building collapse cases, Cánovas (1988) states that the ruin does not obey only one origin, but several causes that together lead the structure to collapse. A series of minor errors and failures can superimpose their effects and bring serious consequences.

Souza and Ripper (1998) categorize pathologies according to their stages of occurrence into the pathologies generated in the conception stage (project), those generated in the execution stage (construction), and those generated in the use stage (maintenance).

Several failures can occur during the design stage of a structure, which can refer to poor assessment of acting loads, disregard of possible accidental loads, from wind, snow, or waves, due to not conducting a correct meteorological or hydrological study, among other factors during the preliminary studies, preliminary design or final engineering design phase. According to Souza and Ripper (1998), failures originating from an incorrect preliminary study, or a deficient preliminary design, are mainly responsible for the cost of the construction and inconveniences related to the use of the building. Faults generated during the final design are generally responsible for the appearance of serious pathological problems.

In the execution stage, the construction defects are quite frequent, and their origins, in most cases, are in the technical unpreparedness of the professionals working on the construction site, causing problems such as deficient concrete pouring, inadequate formwork, poorly executed shoring, or shoring removed in an improper manner or time, and deficiencies in the reinforcement, among others. Botelho and Marchetti (1996) states that the occurrence of pathological problems whose origin is in the execution stage is due, basically, to the production process that is greatly impaired by immediately reflecting the socioeconomic problems, which cause the low technical quality of the less qualified workers, such as servants and half-officials, and even of the personnel with some professional qualification. According to a study conducted by Piancastelli (2014), the execution stage of construction work is the one that presents the most pathological occurrences in reinforced concrete structures, concentrating 51% of the cases.

Besides, for the structure to perform well and be durable, it is necessary to observe the correct use for which the building was designed, especially concerning the loads applied and the possibility of the presence of elements that are harmful to reinforced concrete. Periodic maintenance is also necessary to ensure the integrity of the structure since pathological problems can be recognized and properly solved during maintenance before they become more serious problems. However, maintenance is often neglected for economic reasons or due to technical ignorance and incompetence.

At this point, it is important to itemize the responsibilities of the builders, designers, and users of the building, regarding both the use and the compliance with some technical standards, such as those that are briefly presented below: NBR 14037, which establishes the minimum requirements for the preparation and presentation of the contents to be included in the manual of use, operation, and maintenance of buildings prepared and delivered by the builder and/or developer, according to current legislation (ABNT, 2014b); NBR 5674, which prescribes the requirements for the management of the building maintenance system (ABNT, 2012); and NBR 15575, which emphasizes the requirements of durability and maintainability, specifying components and systems in strict observation of the criteria of the performance standard (ABNT, 2021).

The management of the maintenance system includes means to preserve the original characteristics of the building and prevent the loss of performance resulting from the degradation of its systems, elements, or components. According to Souza and Ripper (1998), the user, who has the greatest interest in the integrity and safety of the structure, can, paradoxically, be the agent that generates structural deterioration, due to carelessness or ignorance. Therefore, it is also important that the user is aware and follows the recommendations regarding changes in the structure, either by unduly removing some structural component of the building or by increasing loads with the installation of elements not foreseen by the original design of the structure.

2.1. CRACKS

Helene and Andrade (2010) define cracks as a discontinuity of small openings in concrete elements, induced by the action of loads that generate tensile stresses that exceed the resistant capacity of the material.

Commonly confused with cracks, which are fissures, cracks are usually found in sealing elements, such as masonry walls. In turn, cracks may indicate other pathological mechanisms, such as the differential settlement of foundation elements.

According to Trindade (2015), cracks, besides causing visual discomfort, also behave as an entrance door for aggressive agents to concrete and reinforcement and should be closed immediately.

2.2. SEGREGATION OF CONCRETE COMPONENTS

Segregation of concrete materials indicates that the material is not behaving in solidarity among its elements, influencing the analysis of the element as a rigid body. Lotterman (2014) classifies the segregation states of concrete, according to the level of damage, as follows:

i. Superficial: only the outer layer of the paste is damaged;
ii. Medium: the coarse aggregates of the concrete are exposed;
iii. Deep: the existence of reinforcement exposure.

Similar to the case of cracks, some segregation states can be an opening to harmful agents, in addition to compromising the structural integrity of the element in question.

According to NBR 14931 (ABNT, 2004), which prescribes the way to execute reinforced concrete elements, the causes of segregation of concrete materials can be incorrect concrete casting, grout leaking through the form due to bad positioning of the same, or the improper use of the vibration instrument.

2.3. LEACHING

Leaching is a process of dissolution of calcium hydroxide present in concrete in contact with pure water, understood as water with low or no concentration of calcium ions from fog condensation and rain. The leaching process produces calcium ions that react with atmospheric carbon dioxide, resulting in the appearance of white crusts on the concrete surface called efflorescence. According to Mehta and Monteiro (1994), the leaching process causes, besides undesirable aesthetics, the compromising of concrete mechanical strength.

According to Freire (2005), when it is not treated, the leaching process can make the concrete porous, thus accentuating the possibility of reinforcement corrosion. To avoid the effects of leaching, it is necessary to interrupt the contact of the water with the concrete element.

2.4. CORROSION OF STEEL REBARS

Corrosion is the name commonly given to the oxidation of metallic materials in contact with atmospheric elements. In the case of reinforced concrete elements, it is expected that the concrete itself fulfills the function of protecting the reinforcement from these aggressive agents, however, this protection can be affected by factors such as the pathological manifestations listed above, cracking, segregation of concrete materials, and leaching.

The corrosion process tends to reduce the cross-sectional area of the bars that compose the reinforcement of the reinforced concrete element, which affects the concrete-steel solidarity and decreases the element's resistance, especially to tensile stresses.

The reinforcement corrosion process must be stopped as soon as possible, covering the area where the reinforcement is exposed. However, according to Souza and Ripper (1998), in high corrosion cases, in which the reduction of the cross-section of the bar exceeds 15%, it is necessary to replace the reinforcement or install reinforcement.

2.5. INFILTRATION

A recurrent pathological manifestation in civil construction, it can cause problems such as dripping, staining, mold, rotting, reinforcement oxidation, leaching, and reduced service life of coatings. According to Ernica (2017), infiltration can be configured in three ways:

i. Infiltration by pressure;
ii. Coming from soil moisture and the atmosphere;
iii. By percolation or capillarity.

To be avoided, infiltration must be treated by investigating the path where the water comes from and interrupting it, through specific waterproofing for the site, and the replacement of faulty piping, among others, to prevent the effects of infiltration from creating other pathological manifestations.

3. CASE STUDY

3.1. THE ANDREA BUILDING

The Andrea Building, located at 2405 Tibúrcio Cavalcante Street, Central zone of Fortaleza (Brazil) was a residential building that had eight floors, the last being the penthouse, which came to collapse completely on October 15, 2019. Its collapse left nine fatalities and seven survivors, who were inside the building at the time it collapsed.

The building was built in 1982, but only in 1995 had its registration regularized by the competent bodies. During its life, according to Tavares (2019), the building rarely underwent inspections to ensure the maintenance of its structure, with inspections always being postponed. The first one, for example, was scheduled for 2015, more than thirty years after its construction, but was postponed to 2016 and later to 2017.

According to residents and authorities, before the collapse, the building had major structural and preventive maintenance failures. During its collapse, some stores close to the building were hit by the magnitude of the accident.

The building was under renovation on the day of the collapse, and the lack of support for the compromised pillars and the lack of structural stability caused all the weight exerted by the building to overload the pillars, which had exposed reinforcement and a high level of corrosion.

In addition, the responsible for the maintenance of the building issued a Technical Responsibility Document charging a much lower amount than necessary for such reforms and structural recoveries. The company and the service provider did not present any report containing everything that would be executed and spent.

3.2. THE BUILDING CONDITIONS

As previously mentioned, the building was in a precarious structural condition and was not maintained. It presented several pathologies, such as cracks, columns with exposed reinforcement, and high levels of corrosion, as shown in Figure 1. Besides, it did not have the inspection certificates attesting to its structural maintenance.

Figure 1 – Exposed column reinforcements

Source: Tavares (2019). Adapted by the authors.

According to Tavares (2019), it was possible to observe that a covering of the structural steel had been made in some pillars by applying a layer of plaster, which does not serve as a structural material. The author also states that such pillars had already suffered previous interventions, where the oxidized steel did not undergo an adequate treatment to fulfill its function in that structural system. Figure 1, shown above, presents the situation of one of the pillars before the collapse.

In this aspect, it can be seen that those responsible for the maintenance of the Andrea Building neglected essential standards for reinforced concrete buildings, such as NBR 6118, by maintaining the steel at a high level of corrosion and applying plaster coating where there should be concrete to resist compression efforts, and NBR 5674 (ABNT, 2012), which deals with housing maintenance, as well as other standards mentioned before. The company and the service provider hired for the maintenance that was occurring in the building on the day of the collapse, in turn, did not comply with the requirements of the NBR 16280 (ABNT, 2014c), whose recommendations indicate that the building already presented a situation of structural collapse and that the evacuation of the building should have been carried out.

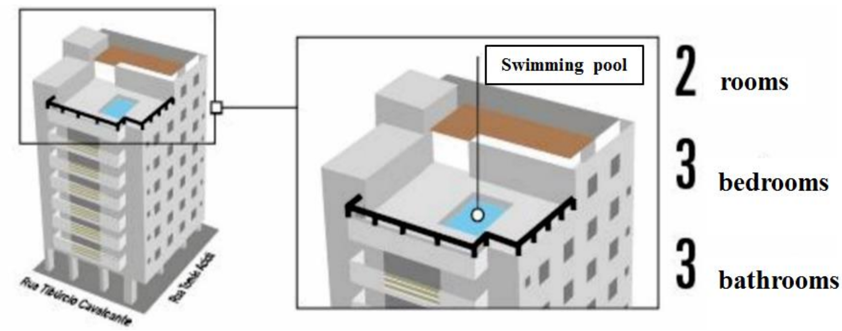
Within this context, it could be seen that the entire structure of the condominium was in its limited state of effort. According to Tavares (2019), there was already a lack of concrete covering that would act in compression, which led to a redistribution of compression stresses in the structural elements. According to the author, this was the failure responsible for the collapse.

In addition, several walls of the building showed signs of surface treatment or deformations. There were stretches without treatment, and the maintenance was done in an inadequate way, which pointed to the need to use more favorable and reliable techniques and materials, to avoid the detachment of the concrete.

3.3. INTERVENTIONS

After its construction was finished, the Andrea Building was overloaded on the roof floor, as shown in Figure 2. Two living rooms, three bedrooms, and three bathrooms were built where previously it was an open area, and the construction of these rooms occupied an area of approximately 60 m^2. This overload contributed to the reduction of the building's global safety factor. In this aspect, it is very important to highlight that, to make modifications in the structure of a building, in general, it is necessary to redo the structural project and check the structural stability of the building, which did not occur in the Andrea Building.

Figure 2 – Modifications to the building's roof



Source: Nordeste (2019). Adapted by the authors.

In this building, constructive errors were found, because, as pointed out by Tavares (2019), the steel of the columns had high levels of corrosion, which is due to the covering of the reinforcement done wrongly at the time of its construction. Besides, it was also found that the loss of the columns' section was one of the fundamental factors for the collapse since they had their compressive strength was compromised by the alteration of the distribution of structural loads. Furthermore, there were superficial deformation treatments, such as in the execution of the plastering, which presented flaws throughout the building and were deteriorating, as shown in Figure 3.

Figure 3 – Intervention made in the pillars

Source: Tavares (2019). Adapted by the authors.

3.4. COLLAPSE DIAGNOSIS

According to Tavares (2019), the collapse of the Andrea Building was not caused by a single reason, but by a combination of causes that, when they overlapped, led the residential building to ruin.

It is understood that the structure entered into structural collapse mainly by the exhaustion of the resistant capacity of its columns, which characterizes the reaching of one of the ultimate limit states established by NBR 6118 (ABNT, 2014a) since the internal forces exceeded the structure's strength.

Since the construction of the building occurred in 1985, 33 years before its collapse, it can be admitted that, during the life of the building, the ultimate limit state design condition mentioned above was no longer satisfied. Moreover, there are two ways for this to happen, the increase of the internal forces or the decrease of the resistance capacity. Thus, in the building collapse, it is inferred that both occurred, as detailed in the following topics.

3.4.1. INCREASED LOAD EFFECTS

The increase in the load on the structural elements of the Andrea Building during its life was due to the overload due to the construction of elements not foreseen in the project: the reform carried out on the roof of the building, in which several rooms that were not foreseen in the original project were executed; and the construction actions: the reformulation of the roof caused loads that were not considered in the original project.

3.4.2. STRENGTH CAPACITY REDUCTION

Several pathological manifestations can be pointed out as compromising the resistant capacity of the building's columns: the reinforcement corrosion: the oxidation of the reinforcement of the columns observed and highlighted by Tavares (2019), a phenomenon that compromises the strength of the material; the segregation of concrete materials: the columns had deep segregation of materials, exposing the reinforcement, increasing its oxidation, and compromising the solidarity between concrete and steel of the structural element; and the covering of plaster instead of concrete: due to the segregation of the column concrete and its peeling, it was observed that the reinforcement of the columns was covered with plaster where there should be a concrete cover of at least two centimeters, according to NBR 6118, which shows that interventions were performed before the collapse incorrectly.

3.4.3. MAIN CAUSE OF THE COLLAPSE

Even with the decrease in resistant capacity and increase in the load due to the reasons described above, the columns of the building had not yet reached their ultimate limit state, which only came to occur through another event.

Aware of the deterioration state of the columns, the administration of the Andrea Building hired a service provider company to perform the maintenance of the deteriorated elements. However, according to Tavares (2019), the service provided did not follow the minimum procedures to avoid the collapse of the building.

An incorrect construction methodology was adopted by the service provider company, not being executed the proper shoring or structural reinforcement so that the covering of the pillars could be performed, further decreasing the resistant capacity and causing construction loads on the already compromised support elements. Thus, the columns reached their ultimate limit state, compromising the structural integrity of the building and culminating if is the focus of this work: the collapse of the Andrea Building.

4. CONCLUSIONS

In this paper, a literature review was conducted about relevant elements in the collapse process of a reinforced concrete building, such as the limit state method, actions, combinations of actions, and pathologies in reinforced concrete buildings. Then, a case study was elaborated on about the collapse of the Andrea Building.

It was found that there was great negligence during the life of the aforementioned building. According to the inspection made by Tavares (2019), the same presented the causes that led to the building's collapse. In this analysis, it was confirmed that the building was already doomed to collapse, because its supporting pillars had a high rate of corrosion, causing the entire stability of the building to be compromised.

In the same analysis, it was confirmed that the company that provided services in the building did not follow the minimum procedures for correct and safe maintenance. Those responsible for the building neglected the necessary maintenance such as shoring the pillars, reports presenting the materials and techniques used in the maintenance, lack of inspection from the city hall that is necessary to make corrections when needed.

Another important finding was the issue of a Technical Responsibility Document by the person responsible for maintenance, charging an amount far below those commonly practiced for this type of service, demonstrating a lack of quality service and disagreement with the technical standardization.

Thus, it ratifies the extreme importance of all the analyses being passed on to the qualified agencies, so that all the works nationwide present reports, ART of those responsible, inspections and compliance with technical standards, always aiming to ensure safety in the reform or construction, reassure and ensure the lives of residents.

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