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Structural Project: Diagnosis of Project Failures in the Execution of Reinforced Concrete Structures

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Abstract-The growing number of failures in reinforced concrete structure projects is becoming increasingly worrisome, as they generate numerous accidents that can be fatal. This study aims to identify the main failures in the execution of reinforced concrete structures resulting from the lack of correct use of descriptive rules. For this purpose, an analysis of the errors that occurred in the construction of the Guararapes Viaduct in Belo Horizonte that collapsed will be performed. Problems such as these show the need to analyze the reason for so many errors that have been happening in the execution of reinforced concrete structures. These failures may be due to negligence in the use of the current rules that regulate the procedures for calculating and executing structural projects. It will also explore the minimum requirements necessary for the implementation of reinforced concrete structures in accordance with the standards, and thus show what should have been done to prevent the accident from the fall of the viaduct. Therefore, an explanatory research was resorted to since it is necessary to explore the reason for such events

Keywords- *Standards, Failures, Structural Design, Reinforced Concrete.*

I. INTRODUCTION

This work is based on the study of flaws in reinforced concrete structure projects that arise during their execution. This study will be based on ABNT's (ABNT's (Associação Brasileira de Normas Técnicas)) standards that regulate the executive procedures of the structures and also which structural projects design should be made. Thus, we will analyze some cases in which there were fatal errors that led to the fall of structures and also pointing out what should have been done to prevent such an accident.

Given such analysis the following questions arise: is the negligence in the use of standardization of reinforced concrete structures design one of the main factors for the emergence of so many failures in the constructions after they are ready? What factors regulated by standards should always be considered in a structural design?

For each question, two hypotheses were created as to what may be the reason for the problems, since it is believed that the emergence of failures in reinforced concrete structure projects is due to not considering the factors exposed by descriptive rules for the execution of structural elements and also that it is important to consider all the requirements demanded by the standards for the design of a structural project.

This article aims to identify the main failures that occur in reinforced concrete structures due to the non-use of technical standards in the execution of structural elements. Thus, the article will take place through an analysis of the necessary requirements for the execution of structures in accordance with ABNT-NBR 6118 and complementary standards, as well as an investigation of the design failures that occurred in Guararapes viaduct in Belo Horizonte, which fell in 2014 and diagnosing what should have been done according to the standardization.

This study is justified by the need to highlight that the non-use of standardization for the execution of reinforced concrete structures can cause numerous failures in construction, since accidents that occur in structures can be fatal.

Lopes et al. [1] exposes that descriptive norms are created in order to standardize the execution processes of projects and works, so that there is safety and stability in constructions. Therefore, it is very important to follow the discretion regulated by the standards in the execution of reinforced concrete structure projects.

The first section of the article is a bibliographical review deepening in structural design and all its stages: conception, analysis, sizing and detailing. After this, the requirements for attesting the quality of the project will be shown, addressing the ability to withstand efforts, service performance and durability, as well as exploring some difficulties that arise during the execution of the structure. Within this literature review will also be dealt with actions on structures, showing what the limit states of the structure are and how they are important for the design of a project.

In the second section can be observed the methodology of the article, how the whole study was made and an analysis of the projects in which there were failures. And finally, in the third section, we will show the observed execution failures, making a diagnosis of what should have been done to avoid the accident.

II. STRUCTURAL PROJECT

Structural design as an important stage of construction, because this is the moment that all system of the work is defined, whether it will be in metal or wood structures, concrete walls, structural masonry, or most currently used, reinforced concrete structures [2].

A. *Design of Structural Project*

For Pinheiro, Muzardo and Santos [3], structural design, or also called structuring, is the process of choosing what system of structures that will make up the sturdy part of any building. Step that consists in determining the structural elements and their position in the system to obtain efficiency. The system must be able to absorb all esforces arising from incident actions, this way transmitting to the ground through the foundations.

The authors also affirm how important is the structural solution to meet all requirements established by technical standards, being these requirements the ability to endure, performance during use and durability.

This phase of structural design is defined where the beams will be, the position of the columns, the number of slabs and the preliminary design of the structural elements will be defined [4].

B. *Sctructural Analysis*

Structural analysis is considered as the most important stage of structural design, because in this phase are calculated the effects of actions and loads on the structure. About this, the author highlights “Structural analysis is a very important step. There is no point in dimensioning the reinforcement in a refined manner if the calculated efforts do not reflect the reality that the structure will be subject to” [5].

França Jr. [6] also points out that structural analysis can be done through different types, but those provided by NBR 6118:2014 are: linear analysis, linear analysis with redistribution, plastic analysis, nonlinear analysis and analysis through physical models.

The author also argues that structural analysis of structures can be done by any of these types highlighted above, which will determine what form will be used in the problem to be addressed. That is, the structures will be differentiated by the use of each type of analysis and the idealized behavior of the constituent materials.

The standard that regulates procedures for structural analysis is ABNT NBR 6118:2014. According to it, the objective of this phase of the project is to determine the effects of the efforts submitted to a structure in order to verify the ultimate and service limit states. Through this analysis it is possible to determine the internal esforces, stresses, deformations and displacements of the structure part or it as a whole.

There are five ways to do structural analysis in a project regulated by the standard, namely: linear, linear with redistribution, plastic, nonlinear analysis and analysis through physical models.

In the linear analysis, the elastic-linear behavior of the materials is allowed, in which geometric characteristics are defined by the gross section of concrete in structural elements. This method generates results to verify service limit states. In a linear analysis with redistribution, the effects of actions are redistributed by the structure and considered in all aspects of the project to meet ultimate limit state loading combinations. Plastic analysis, on the other hand, is used in cases where nonlinearities can be considered which materials have perfect rigid-plastic or perfect elastoplastic behavior, and used to verify ultimate limit states. To consider the nonlinearity behavior of materials, nonlinear analysis is adopted, in which case all structure geometry must be known. Finally, the analysis through physical models is done by determining the structural behavior from the tests performed with physical concrete models, taking into account the mechanical equality criteria [7].

C. *Sctructure Design, Verification and Detailing*

It is necessary to pre-dimension all structural elements (beams, pillars, ties, slabs, etc.) in order to obtain the structure's own weight, which is the first effort to be considered for stock calculation. It is by the dimensions that the spans of the structure and the stiffnesses are determined to calculate the connection between the elements [3].

When the requirements of the equation are met, it demonstrates that the minimum safety of the structure has been respected. In the sizing, verification and detailing phase, a structural arrangement is made to ensure the safety of the assembly, as well as minimum dimensions to determine the size of the formwork and reinforcement arrangement [7].

D. *Quality of Structures*

The ABNT NBR 6118: 2014 is constantly concerned about the quality and durability of reinforced concrete buildings, highlighting that it is very important that the structure reach the minimum quality requirements, both during construction as well as in the use and operation phase [8].

The minimum requirements to achieve quality are divided by the standard into the following groups:

> Group 1: requirements relating to the strength of the structure or its components;
>
> Group 2: requirements relating to performance in service, which consists of the ability of the structure to remain in full use, and must not present damages that compromise, in part or totally, the use for which it was designed; and
>
> Group 3: requirements relating to its durability, consisting of the ability of the structure to withstand the anticipated environmental influences defined in assemblies by the designer of the structural design and the contractor [8].

Finally, Kimura [5] says that a quality structural design should result in a safe, functional and durable structure.

As a way of assessing exposure conditions of the structure that may affect its durability, service performance and lifespan, which affect its quality. The Standard classifies environmental aggressiveness according to the environment in which the structure will be inserted. And from this, the project manager will be able to access the data relating to this site and make the structural design appropriately. This classification can be seen in Figure 1, which was taken from the above standard [7].

Classe de agressividade ambiental	Agressividade	Classificação geral do tipo de ambiente para efeito de projeto	Risco de deterioração da estrutura
I	Fraca	Rural	Insignificante
		Submersa	
II	Moderada	Urbana [a, b]	Pequeno
III	Forte	Marinha [a]	Grande
		Industrial [a, b]	
IV	Muito forte	Industrial [a, c]	Elevado
		Respingos de maré	

[a] Pode-se admitir um microclima com uma classe de agressividade mais branda (uma classe acima) para ambientes internos secos (salas, dormitórios, banheiros, cozinhas e áreas de serviço de apartamentos residenciais e conjuntos comerciais ou ambientes com concreto revestido com argamassa e pintura).

[b] Pode-se admitir uma classe de agressividade mais branda (uma classe acima) em obras em regiões de clima seco, com umidade média relativa do ar menor ou igual a 65 %, partes da estrutura protegidas de chuva em ambientes predominantemente secos ou regiões onde raramente chove.

[c] Ambientes quimicamente agressivos, tanques industriais, galvanoplastia, branqueamento em indústrias de celulose e papel, armazéns de fertilizantes, indústrias químicas.

Figure 1. Classes of Environmental Aggressiveness [7]

III. Actions and States Limits of Structures

Brazilian reinforced concrete standards are based on limit states to ensure the safety, quality and reliability of reinforced concrete structures. The actions that affect a structure can be: permanent, variable or exceptional, when they arise from the effects of time variation; direct or indirect according to their origin; fixed or mobile due to variations in space; and finally, static or dynamic, considering the nature and structural response [9].

A. *Limit States*

The limit states of a structure occur when it becomes unusable, either conventionally or effectively, because it no longer satisfies the predicted conditions that allow the use of the building. If the structure fails to meet the expected minimum requirements, which are: safety, functionality and durability, it means that it has reached a Limit State. Limit states can be of structural or functional order, divided into ultimate limit states (ruin) and utilization limit states (servisse) [10].

According to Almeida [11] limit states are linked to the reliability of structures, thus being defined as the limit between acceptable performance and non-acceptable performance of structural elements.

The ultimate limit states are seen as being those that are related to collapse or structural ruin and result in a break in the use of the structure. In other words, a structure when in service can in no way reach its ultimate limit state [12].

The standard lists all limit states that must be checked to ensure the safety of reinforced concrete structures:

a) ultimate limit state of the loss of balance of the structure, admitted as rigid body;

b) ultimate limit state of exhaustion of the resistant capacity of the structure, in whole or in part, due to normal and tangential stresses, admitting the redistribution of internal forces, provided that the plastic adaptation capacity is respected, and admitting, in general, the separate checks of normal and tangential stresses; considering, however, the interaction between them when it is important;

c) ultimate limit state of exhaustion of the resistant capacity of the structure, in whole or in part, considering the second order effects;

d) ultimate limit state caused by dynamic requests;

e) ultimate limit state of progressive collapse;

f) Other ultimate limit states which may occur in special cases [12].

The service limit states are those that are linked to the durability of the structure, as well as the appearance of structural elements and also with user's comfort during the use of the construction. It is this state that measures structural functionality [8].

The analysis of reinforced concrete structures safety, it is necessary to verify some service limit states already determined by NBR 6118:2014. These states can be defined as:

a) Crack formation (ELS-F): The state at which crack formation begins [...];
b) Crack width (ELS-W): Limit state in which the cracks appear with apertures equal to the maximum values [...];
c) Excessive deformation (ELS-DEF); state in which the deformations reach the limits established by the normal use of the structure [...]
d) Excessive vibration (ELS-VE): condition in which the vibrations reach the limits established for normal construction use [8].

Chong [13] defines service limit states, which can also be called utilization limit states, as those states that satisfy the specified utilization requirements for which a structure is conditioned. To check the safety it is necessary to carry out a control of deformation and damage to the structure.

Every structure project must have a sizing that meets the quality requirements. They are: safety, which must be verified from the construction phase to the entire lifetime, withstanding all anticipated loads without breaking or losing the static balance; good service performance, which is based on the functionality of the structure during use, allowing slight deformations under normal use, as well as the degree of cracking, however, the reinforcement and the use of structural elements cannot be impaired; and lastly, the durability, which is a condition of the structure that must be kept in a good state of repair throughout its useful life, even under the environmental conditions already defined in the project. These prescriptions will only be met when the limit states of a structure are defined, which is why they are so important in a project [14].

B. *Incidents Actions in the Structure*

Actions in a reinforced concrete structure are defined as causes or effects that provoke efforts or deformations in the structures, being considered, in a practical point of view, as imposed deformations (indirect actions) and forces (direct actions) [15].

The aforementioned standard also defines that these actions can be divided into permanent, variable, or exceptional. Permanent actions are "actions that occur with constant values or with a small variation around their average, during practically the entire life of the construction. The variability of permanent actions is measured in a set of similar constructions" [15].

Variable actions, on the other hand, are those that over the useful life of the structure have very significant variations. Variable actions cover both the accidental loads of the building and its effects, braking, impact and centrifugal forces, as well as, the effects of the climate, hydrostatic and hydrodynamic pressures, and friction of supporting appliances. Variable actions are classified as normal or special, depending on the probability of occurrence during the life of the construction. [15].

The loads of maritime actions will only be considered in regions close to the sea, and thus being applied for each situation [15]. There are also exceptional actions, which, according to the standard, are those resulting from explosions, vehicle crashes, fires, floods, among others.

IV. FAILURES IN REINFORCED CONCRETE STRUCTURES

It is currently seen that Brazil is experiencing great growth in civil construction. Thus, the construction process demands more and more effectiveness, efficiency and dynamism in all interactions of the project and the work. Therefore, as it is more difficult to execute this dynamism, they end up resulting in failures in the project process. All the engineering projects must be adequate to the client's needs, even being inserted in an increasingly society. This ends up generating changes in the executive process of the project, since they have to be more innovative, in order to meet the expectations of builders and the client, in relation to quality, efficiency and productivity. The high incidence of faults in works has its main origin in the conception of projects and in their execution. Often, the failures that occur during the construction phase are derived from lack of importance given to the quality of edification in previous stages of execution [2].

Failures that occur in a structural project can be classified according to their cause. The first one is congenital failure, which occurs due to the errors in the design of the project, inadequate study of the conditions of the place where the construction will be inserted and mainly by the nonobservance of the current technical standards for the execution of the stages of the project. There are also the failures acquired during the work, they have their cause due to the use of wrong materials or with different aspects of those that were specified, use of equipment and inadequate executive methods, lack of integration between the various components of the team, and the use of unskilled labor. There are also flaws caused by accidental causes, which originate from excessive loading in the structural elements, inadequate use of the structure, or floods and erosions. And finally, failures that arise from conditions of exposure to very aggressive environments [16].

Contextualizing all that was said by the aforementioned authors, the engineering projects as a whole that are improperly designed and executed may come to generate failures in the construction, which ends up causing very serious accidents during the use of that structure. In other words, those flaws could turn out to be fatal. Especially in the case of a structural project, these errors must be avoided as much as possible, since the structure is the whole body that supports the construction. Even one mistake in any structural element can cause major disasters, as in the case of the work that will be analyzed in this article: The Batalha dos Guararapes Viaduct.

A. *Fall of Batalha dos Guararapes Viaduct*

The Gerenal Olympio Mourão Filho Viaduct, popularly known as the Batalha dos Guararapes Viaduct, is one of the constructions that were part of the great project of widening Dom Pedro I Avenue in Belo Horizonte. According to prefecture of Belo Horizonte, the construction stages of the project began in 2011 and is expected to end in March 2013, but the conclusion came to happen only in the first half of 2014, to meet the demands of the government for the FIFA World Cup, which occurred that same year in Brazil.

According to Correia, Neuenschwander and Santos [17] the total investment announced for all the works was 173 million reais, since BRT (Bus Rapid Transit) tracks would also be installed in the Presidente Antônio Carlos Avenue and Dom Pedro I Avenue.

The purpose of this entire intervention was to facilitate the displacement of the population between various administrative regions of the city by means of a high-capacity transport system [18].

Also according to the aforementioned authors, the projected viaduct would have two loops and spans of almost 80 meters in length between the supports. The cost would be around R$ 15 million for a project concluded in 14 months. On July 3, 2014, after the construction was finished, the shoring used in the southern elevation of the viaduct was removed, that resulted in a very serious accident. The column P3, which was located on the edge of Dom Pedro I Avenue and which was 7 meters high, sank into the foundation, causing the overpass to fall. What happened was that the pillar punctured the crowning block on which it was supported.

The column sank about 6 meters into the ground, causing the shear of the block that was interconnected in the 10 piles positioned in two parallel lines. Many supervisory agencies still study this failure of the column and other errors in the execution of the reinforced concrete structure of the viaduct that came to appear later.

As a whole, the aforementioned authors pointed out that the viaduct presented several failures as causes of the collapse of the structure. However, the main errors found in the injected sheath, in the gaps of the deck and in the support devices.

It is necessary to fill in sheaths with a cement mass to ensure corrosion protection for the cables and ropes that are part of the prestressed reinforcements, as well as enable a mechanical connection between the prestressed concrete and theses reinforcements [19].

Thus, during a survey of the viaduct, it was noted that not all sheaths were properly filled before the shoring was removed. This error interfered in the resistant capacity of the section, since there was no bond between the concrete and the steel, which would be essential for the structure to resist the forces.

In the case of the gaps in the deck, several holes were noticed in the upper face of the deck of the two handles of the viaduct. There was no justification for the existence of these holes, but it is believed that they were made for the purpose of allowing the removal of internal formwork, as well as the application of prestressing to the cables anchored inside the closed box [20].

So, the autores concluded that these holes committed the geometry of the cross section of the stringer and deck, since there was a repositioning of the center of gravity because of these gaps, there was a significant increase in the compressive tension in the upper slab.

At last, regarding to the support devices, it was pointed out a difference in the parts that were used in the construction with those that were stipulated in the project. Therefore, there were exaggerated horizontal movements that caused excessive deformations in the structural elements. Ideally, they should be levelled through leveling wedges, as planned in the project. However, it is assumed that they were not used, because of the result obtained [17].

V. Methodology and Results

This article was carried out by means of an in-depth bibliographic research approaching the concepts of structural design in reinforced concrete structures, as well as their correct execution and the current rules that determine the procedures. It was also shown about the main characteristics of reinforced concrete and the materials that compose it.

The research is also a field study, where information was collected on two different works in order to understand the failures that occurred and point out what caused these errors. The study is classified in this way because it is broader and does not concern itself with the representativeness of the sample.

The research was based on scientific articles, theses and dissertations that were within the theme. We also studied books about reinforced concrete structures and all the norms that are related to structural designs.

A. *Methodology and data collection*

Initially, the study was based only on bibliographic research, where the focus was on the conceptualizing and better explaining the aspects of the structural project. It was explained openly about the stages of project, being them: conception of the structure, structural analysis, dimensioning, verification and detailing of the structure where it is said that the calculation requests must lower than the calculation resistances, to ensure quality and safety of the building. The factors that determine the structural quality were also addressed, which are resistant capacity, the service performance and the durability.

Then, the basis of the study was focused on the actions and deepening in the importance of knowing and calculating the limits states of a structure (ultimate limit-states and service limit-states) that are connected to the ruin and the use of the building. It was also mentioned the permanent, variable, exceptional actions. Finally, the rest of the research was based on the study of the failures found in the construction of the Batalha dos Guararapes viaduct in the city of Belo Horizonte.

B. *Results and discussions*

Regarding the fall of the Batalha dos Guararapes viaduct, the result of the analysis of the projects shows that the execution failures presented during the construction work potentiated a structural collapse that resulted to the fall of the viaduct. It was found that the openings in the upper slab of the deck should have been made in the lower slab for being a box section in prestressed structure. This fact compromised the stiffness of the structure. It was stated in the project that definitive openings would be made for inspection and maintenance of the viaduct, these openings would be positioned in zones of lower bending moment, but the shape, location and number of openings ended up hindering the stability of the structure, which helped in the concentration of loads in the P3 column block [17].

Another factor pointed out by the authors was the failure to fill the sheaths with concrete, which impaired the mechanical bonding of the chords not giving the proper adherence. Because of that, it was observed that the operation of the prestressing system did not contribute to resist the efforts imposed on the structure. If the filling was done correctly, the extent of the damage to the entire viaduct could have been avoided.

It was also found that the block was made as a rigid block, without using any reinforcement that would prevent the tangential stresses coming from the punching. Thus, the shear forces that occurred between the column and the pile cap ended up being absorbed. According to the standards, the ideal would be to adopt a higher height for the block or a more square geometry. However, this lack of armor was not the main aspect of the collapse, since the maximum loads that rigid or reinforced blocks support are equivalent. In the analysis of the compression struts there was no uniformity in the load distribution, because all the effort was concentrated in the central piles [17].

The block was supposed to withsand at 3,200-ton load, however, when the fall occurred, the only action was the structure's own weight, about 2200 tons. The authors concluded that the excess load for the collapse had its origin in the rupture of the deck between columns P2 and P3, causing an imbalance in the structure that redistributed the loads in the columns and foundation blocks. Therefore, this rearrangement of efforts, subjected the column P3 to a higher load than it was designed to support.

VI. Concluding Remarks

The study found that the main flaws that arise in structural designs are due to negligence in the use of descriptive standards and poor execution of projects, as was raised in one of the hypotheses. The standardization makes it very clear which are the correct procedures to take and the appropriate way to execute them.

It is necessary that professionals adhere to the size of the responsibility that is to conduct works such as these, since the main concern is the safety of the structure, as well as its durability, to ensure a good useful life and that the construction is suitable. for use and operation.

It is concluded that in all the structural project must be included and considered all the actions that will affect the structure and also the right procedures to be executed in a way that the construction can support all the loads requesting, along with safety factors to reach the maximum useful life, and avoiding the occurrence of so many failures.

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