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Main Factors that Compromise Resilience in Concrete Structures

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Although concrete structures are traditionally regarded as having great durability, it has been possible to notice, more and more, a higher vulnerability of such structures through new pathologies that compromise their durability. It elevates expenses with maintenance; a condition that may, not unusually, be seen on structures at a very young age. Because of that, the present article intends to discuss the main causes that compromise the resilience of such structures when facing the aggressions to which they are submitted. Starting with project related problems, going through the issue of the executive quality and finally, discussing the environmental attacks generated either by more aggressive environments or because of the lack of protection of these structures. Conditions that compromise their capacity to resist to small aggressions considered normal in the environment to which these structures are exposed. After the due discussions, this paper will try to provide some of the paths that should be followed by engineers, designers, builders, and other professionals who are responsible for these structures in a way that they will effectively present capacity for resilience that is more compatible with their functional importance and the financial cost spent for their effectiveness.

Keywords: Resilience, pathologies, concrete structures, aggressive environments.

1. Introduction

The resilience of concrete structures is characterized by the ability of such elements to absorb the variability of efforts and tensions, caused by frequent use and requests from nature, which should be foreseen in the project, without the normative limits of use being reached and/or exceeded; especially when it comes to cracking, deformations, and vibrations.

Observing the behavior of constructions, most precisely their structures, has allowed over time to verify that problems concerning these elements have arisen in an increasingly intense way and at younger ages (GAIOFATTO; FACHETTI, 2023). In particular, the appearance of cracks, excessive deformations and dynamic responses that cause a feeling of discomfort in users, and the detachment and breakage of coating elements, surprise residents and users, sometimes only a few months after the delivery of the constructions. This does not consider cases, which are not rare, of rupture of elements or even parts of structures with a few months or years of use.

This finding causes the need to understand the reasons that justify this inadequate behavior of the structures, which leads us to observe three lines of analysis: 1. the structural project, including its design, modeling, dimensioning, and detailing; 2. the execution of the structures, in terms of the quality of the concrete used in relation to the design specifications and care taken when placing, compacting and curing, the geometric quality of the execution (forms and positioning of reinforcement), the proper positioning and amount of reinforcement inside the forms, in addition to the protection of the structural elements used; 3. the proper use and effective maintenance of these structures over time.

The Guide to good practice of a reliability assessment of structural concrete – Safety and performance concepts, Bulletin 86 of the Fédération Internationale du Beton (FIB, 2018) demonstrates a strong concern with these three items, in addition to others that are no longer considered in this text as a matter of focus, not being, however, less important.

These will be the guidelines used in the search for the motivation that leads structures to present inappropriate behavior at an early stage, showing compromise of their integrity in most cases and of their safety in a significant number of cases.

This behavior must be considered unacceptable in the world of civil construction, especially when current performance standards recommend a minimum of 50 years to meet the useful life of the project, (NBR 15575-1, 2021). Early deterioration entails high repair costs, incompatible with the costs of construction, whether for housing or commercial use.

2. Structural Projects

In view of the structuring indicated in the present paper, each of the proposed topics will be evaluated below, aiming at understanding the inadequate behavior of the structure, where in very few cases the useful life of the project, recommended by the performance standards (NBR 15575-1, 2021), comes close to being met.

Before discussing each topic, one must remember that the accordance with the design service life presupposes that the basic conditions for the existence of reinforced concrete are effectively met. It means that the passivity of the reinforcement inside the concrete and its adhesion to the concrete is effective, thus ensuring that a reinforced concrete element effectively behaves in accordance with the design models used. Having said that, we will evaluate design, modeling, dimensioning, and detailing criteria used in the vast majority of structural projects and that end up becoming the motivation for reducing the resilient capacity of the structure in general.

Initially, we can consider the relationship between structures and foundations. Recently, many structural designers have stopped designing foundations, considering that this is another specialty to be carried out by geotechnical engineers. Usually, when the structure modeling is elaborated, the designer fits the bases, develops the model and the reactions in the bases are generated, composed of forces in the three main directions and moments, around the same three axes (XYZ) (GAIOFATTO, 2018). These efforts are sent to the foundation designer who, in theory, should design foundations that prevent any movement in the six degrees of freedom. However, this is naturally impossible, since the soil, like any other material, suffers deformations when subjected to a state of tensions.

These deformations in the foundations, which are different in each point, do not return to the structural design, thus resulting in a structure that works differently than predicted in the computational model. This fact, in many cases, inverts moments significantly, alters their values, as well as the shear values and the distribution of normal efforts (GAIOFATTO, 2018). These differences, in many cases, are partially absorbed by the hyperstatic structure; however, differences always remain. Most of the time still significant, such differences are enough to break structural elements, making cracks appear - often unexpected in beams and pillars, especially in the node zones, not always adequately detailed and verified as recommended by project regulations. These efforts still result in excessive deformation of beams or pillars, which cause the appearance of unforeseen efforts, fractures in masonry, rupture of pipes and numerous other damages to structural and construction elements.

These problems are aggravated, in general, by the effect of the wind, when behaving as a structure NOT FRAMED in its base. Unlike the computational model built, the structure loses rigidity and becomes more vulnerable to efforts caused by winds, or even earthquakes. This fact allows deformations well above normative limit values, or values expected by computational models. These excessive deformations lead to considerable fractures in the closing masonry and even in some structural elements.

FIB Bulletin 242 (1988), Ductility of Reinforced Concrete Structures, sustains numerous precautions that must be adopted in the elaboration of structural projects, due to the highly complex behavior of the reinforced concrete material. Its ductility allows the occurrence of rotations in all structural elements, especially in the regions of the nodes, which, in many cases, make conventional models result in a prediction of behavior very different from that which effectively occurs in real structures.

Of great importance in the construction of structural models, is the definition of the degree of stiffness of the nodes, where the rotation capacity of the concrete elements and their frames must be considered. When these factors are no longer considered individually at the nodes, since they depend on dimensions and loads applied, the behavior of the structure becomes quite different from that predicted in the computational models, causing pathologies that compromise the integrity and durability of the structures. It leads to an early compromise of safety if corrective measures are not taken, often demanding high costs and inconvenience to construction users.

As presented by Sanchez (2023), the kinematic mechanisms in discontinuities, very little known and consequently little applied in structural modeling, can be important reasons for inadequate structural behavior, especially when computational models are applied without adequate considerations. In the same publication, Gaiofatto (2023) warns of numerous analysis and detailing criteria that must be measured in computational models to obtain an adequate structural design.

As it can be seen, several failures are common in the construction of computational models, a fact that significantly reduces the resilient capacity of structures. The appearance of cracks, in general, becomes an open door to the penetration of aggressive agents, starting with the carbon contained in the air and eventually chlorides available in marine or industrial environments, but above all, it means a reduction in the rigidity of the structural elements, once again changing the responses predicted by the computational models. As a result of the loss of rigidity, new deformations occur, causing visual insecurity in users and allowing excessive movement of structures that cause an unpleasant sensation of fear in users.

3. Execution of Structures

The execution of concrete structures is one of the factors that weigh most in compromising their resilience, becoming one of the factors of greatest responsibility in the generation of pathologies that compromise the useful life of structures (GAIOFATTO, 2008). Starting with the lack of quality of the concrete, resulting from an inadequate quality control, insufficient in most cases, to the inadequate positioning of the reinforcements, aggravated by the change of position, especially of the negative reinforcements, during the concreting operations.

In a general way, issues such as economy and haste are factors that strongly compromise the quality of execution of concrete structures. Reduction in the quantity and quality of labor, associated with the reduced availability of technical supervision, often considered a superfluous factor by many builders, have led to loss of quality in the structures, which severely compromises their resilience.

Failures in casting, compaction and curing of concrete cause changes in its properties that escape the usual quality control once the concrete of the construction is no longer represented by the molded, cured and tested specimens according to the regulations. In many cases, due to inadequate consolidation and absence or insufficiency in the curing processes, we will have porous concrete as a result, consequently with lower mechanical resistance and much greater vulnerability to chemical attacks from the environment.

The lower mechanical resistance directly compromises the modulus of elasticity, allowing greater deformations and therefore, a higher state of cracking (GAIOFATTO, 2018), which compromises the rigidity of the structural elements and their durability as mentioned above.

The inadequate positioning of the reinforcements inside the structural elements, significantly alters the resistant capacity of the piece, once again resulting in the occurrence of cracking and its consequences. And in many cases, errors have such serious consequences that they can result in effective loss of structure stability. Especially when the negative reinforcement sinks in the structural element, reducing, or even eliminating, the ability to balance these moments, allowing excessive rotation of the kneecaps in the support zones (FIB, 1988), with consequent deflections and excessive cracking, with the possibility of ruining elements such as slabs and beams.

In the case of pillars, it is very common to see the lack of compaction of the concrete at their base, also due to the casting of concrete from great heights and in the middle of many layers of frames (stirrups and clamps). The formation of voids in the lower sections seriously compromises the support capacity of the pillars, with a possible crushing in this region and significant settlement on the upper floors (FIB, 2018). These occurrences, once again, may be responsible for the ruin of the structure, caused by an unforeseen movement on one of the floors of the structure (GAIOFATTO, 2018). Best case scenario, excessive deformations and high cracks are the consequences of these problems, unfortunately, these are common features in the execution of structures today.

In his chapter on Durability of Concrete Structures, Appleton (2013) warns of the diverse and serious pathologies that affect structural concrete, especially due to failures and inadequate execution conditions.

Finally, it is possible to consider the large number of cases in which projects are disregarded and the execution ends up being carried out without the details, or even, due to the lack of them, the execution becomes different from what was considered in the calculation models used in the development of the projects.

Although it is normal to expect structures to be built according to their projects, this is often not the reality, that is, the projects are used as a reference, but the detailing, when it exists, is usually left out in exchange for greater executive speed, causing serious impairments in structural behavior. In few opportunities, the effective control of the concrete is carried out, often allowing that the fundamental material does not meet the design specifications, especially the module of elasticity, essential to obtain adequate rigidity of the structural elements.

4. Use and Maintenance of Structures

The resilience of concrete structures depends not only on the quality of design and execution, but on their proper use and regular maintenance (GAIOFATTO; FACHETTI, 2023). Naturally, the use of a concrete structure must respect load limits, which in turn must be defined in a user manual, duly disclosed and informed to users.

In the same way, proper maintenance of a concrete structure is essential to ensure its durability and safety over time (CRUZ at AL, 2017). All structures, even those well designed and executed, can suffer natural deterioration and aging, affecting their resilience. Therefore, it is important to establish preventive maintenance plans that can detect and correct problems before they get worse and compromise the integrity of the structure.

It is essential that building users follow design recommendations regarding usage and the maximum load the structure can support. Overloads, concentrated loads, and excessive vibrations can lead to premature deformations and cracks, compromising the durability and safety of the structure.

Unfortunately, in many cases, the lack of proper care during the life of the structure can compromise its integrity and result in pathologies that reduce its resistance capacity and increase maintenance costs.

The first step towards good maintenance is knowing the characteristics of the structure, such as age, materials used, environmental conditions and loads supported. With this information, it is possible to establish a maintenance plan appropriate to the specific needs of the structure.

Corrective maintenance must be carried out based on an accurate diagnosis of the identified pathology, followed by an action plan that includes the choices of the most suitable materials and techniques for the repair, as mentioned by Cruz et al (2017). It is important to remember that the choice of inappropriate materials and techniques can exacerbate the problem and further compromise the durability of the structure.

Amongst the most common protective measures are the waterproofing of surfaces exposed to water contact, applying protective coatings and treating surfaces to prevent dirt and dust from accumulating. Besides, it is important that users are aware of the precautions that must be taken on daily use, by avoiding the overload of structural elements, the deposit of heavy objects in inappropriate places and the use of chemical products that could compromise the integrity of the concrete.

Another important aspect of maintenance is the cleanliness of the structure, especially in harsh environments such as coastal or industrial regions. Preventive maintenance should include regular inspections to detect fissures, cracks, deformations, displacements, reinforcement corrosion, among other problems that could compromise the integrity of the structure, as discussed by Cruz et al (2017). These inspections must be carried out by trained professionals specialized in concrete structures, who know how to identify problems and propose appropriate solutions.

In addition to inspections, it is important that maintenance includes repairs and reinforcements when necessary. These repairs can be simple, such as filling cracks with mortar, or more complex, as replacing compromised structural elements.

Preventive maintenance is essential to preserve the resilience of concrete structures, but it is also important to highlight predictive maintenance as an additional feature. Predictive maintenance consists of continuously monitoring the behavior of the structure and identifying signs of possible failures before they occur. Therefore, different methods are used, such as vibration analysis, displacement measurements and thermography, among others. With predictive maintenance, it is possible to anticipate problems and carry out corrective interventions more efficiently and economically, further increasing the resilience and durability of structures.

To ensure proper maintenance of concrete structures, it is important to follow, at least, the following recommendations (CRUZ at AL, 2017):

- Regular inspection – annual, carried out by a professional in the structural area.
- Immediate repair of cracks or damage - identification and elimination of their causes.
- Surface Protection - regularly maintained according to user manual.
- Treatment of pathologies - immediately upon finding them.

Finally, it is important that the maintenance plan is updated periodically, considering the new conditions of use and the new repair and reinforcement techniques that come with time. Thus, it is possible to guarantee the durability and resilience of the structure over time, avoiding problems and reducing maintenance costs in the long term.

To sum up, proper and regular maintenance of concrete structures are essential to ensure their resilience and durability. Also, it is highly important that those responsible for the maintenance are trained and have the technical knowledge to detect and correct problems before they get worse; last but not least, investment in predictive and/or preventive maintenance can reduce repair costs and extend the useful life of the structure, ensuring the safety and comfort of users.

5. Conclusion

In view of the facts discussed above, and the references presented, verified with greater regularity than one would consider acceptable in real world, reinforced concrete structures have shown low resilience to normal conditions of use, causing a lot of problems to users, especially regarding their safety and the high cost generated by regular and highly complex maintenance.

Having said that, once the main factors that compromise the resilience of structures are understood, it is essential that the professionals involved in the projects, execution and maintenance, be attentive to the application of appropriate techniques and recommendations of the various documents that regulate their activities; most particularly the technical norms, aiming to achieve adequate behavior of the structures for their expected use and for which they must be designed.

The proper resilience of concrete structures should be the objective of all professionals involved with them, so that this technique can return to its behavior considered long-lasting as it was usual during the entire time of its use. Since the end of the 19th century and the beginning of the 20th century, concrete constructions have been compared to rocks, with long-lasting durability, low maintenance and high reliability.

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