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Performance and Safety Assessment of Prestressed Concrete Structures

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Abstract: This study investigates the structural performance of a post-tensioned concrete slab with a unbonded prestressing system, subjected to progressive tendon rupture. A numerical model was developed in TQS software to simulate three failure stages, involving the deactivation of up to 24 tendons. The case study results revealed an efficient redistribution of internal forces, with a maximum long-term deflection increase of 14% compared to the original model—remaining within the L/250 serviceability limit prescribed by NBR 6118:2023. Changes in the reinforcement ratio were also observed, with increases of up to 22% in specific slab strips. These results underscore the robustness of the system against localized failures and confirm the reliability of the adopted modeling approach, providing a close representation of the actual structural behavior. The findings emphasize the importance of precise detailing, thorough inspection, and systematic maintenance in prestressed concrete structures.

Keywords: Prestressed concrete; tendon rupture; structural performance; numerical simulation; structural safety; TQS software.

1 Introduction

Prestressed concrete has emerged as an effective structural solution due to its ability to control cracking, reduce deflections, and enhance overall structural efficiency. As highlighted by Hanai [1], conventional reinforced concrete exhibits significant tensile strength limitations, which are often mitigated by prestressing techniques that introduce compressive stresses to counterbalance the tensile forces generated by applied loads.

Prestressing—particularly post-tensioning systems—has enabled the design of slender and durable structures. According to Pfeil [2], the application of an initial tensile force to concrete elements enhances the performance of both the concrete and the steel, resulting in structures with lower maintenance requirements throughout their service life. A historical example of this advancement is the Plougastel Bridge in France, built in the early 1930s, which, as noted by Midant [5], represents one of the earliest and most successful large-scale applications of prestressed concrete.

Among the various prestressing systems, the unbonded post-tensioning method stands out for its practicality and performance, especially in slabs and precast elements. In this system, high-strength steel tendons are placed within polyethylene sheaths filled with grease, allowing low friction and preventing chemical bonding with the surrounding concrete [4]. Prestressing is carried out after the concrete reaches adequate compressive strength, with anchorage devices at the slab ends transferring the force to the structure. While this method allows easy inspection and even tendon replacement, it limits the redistribution of internal forces in the event of tendon rupture, which can significantly affect structural behavior under abnormal or accidental conditions [5].

Despite the efficiency of prestressing systems, numerous pathologies arise from construction deficiencies. Studies indicate that common issues—such as improper tendon positioning, sheath damage during concreting, premature or delayed stressing, and anchorage misalignment—can severely compromise structural safety [6].

Lima [6] highlights that field surveys conducted in northeastern Brazil indicate that more than 70% of the pathological manifestations in prestressed buildings are associated with execution-related deficiencies. The integrity of polyethylene sheaths is particularly critical; if damaged, aggressive agents such as chlorides can penetrate and initiate localized tendon corrosion, which is difficult to detect due to the unbonded configuration [7].

Over the long term, prestressed concrete structures become susceptible to various deterioration mechanisms. Factors such as concrete cracking, exposure to marine environments, alkali-silica reaction (ASR), and delayed ettringite formation (DEF) can significantly reduce service life [8,9]. Lima [9] reported the occurrence of cracking and DEF-related damage in prestressed railway sleepers, while Carvalho [10] and Sousa et al. [11] documented cases of excessive deflections, tendon corrosion, and cracking in precast and coastal structures.

Given these challenges, it is essential to investigate the structural behavior of prestressed systems under failure scenarios, such as partial tendon rupture. This research combines a literature review with numerical simulation using TQS software [14] to assess the impact of tendon failure in a post-tensioned slab. The simulation focuses on stress redistribution, deformation patterns, and potential implications for both serviceability and ultimate limit states. By analyzing these effects, the study aims to support safer structural designs, improve maintenance strategies, and contribute to extending the service life of prestressed concrete structures.

2 Failures in Prestressed Slabs

Unbonded post-tensioning is widely used in flat slabs and beams of commercial and residential buildings, particularly where long spans are required, due to its ease of execution and flexibility in stress distribution. In this system, steel tendons are encased in lubricated plastic sheaths that prevent bonding to the concrete, enabling better control of prestress losses and allowing for future interventions, such as re-stressing or tendon replacement [1,4].

However, as noted by Soares [3] and Figueiredo [4], the performance of this system is highly dependent on construction quality. Common on-site issues include improper positioning of sheaths and tendons, excessive curvature causing undesirable friction, physical damage during concreting, insufficient use of spacers, and inadequate protection of anchorages. NBR 14931:2023 [12] emphasizes the importance of protecting the system from aggressive agents and ensuring proper installation procedures.

One of the most severe consequences of these deficiencies is the loss of sheath watertightness, which allows moisture and chlorides to penetrate, initiating tendon corrosion. As detailed by Figueiredo [4], corrosion can reduce the steel cross-section and lead to premature tendon rupture. Furthermore, recent studies indicate that even in seemingly well-executed structures, pathological manifestations may develop over time due to environmental exposure and the absence of maintenance. These include excessive cracking, prestress losses, differential settlements, and slow but progressive corrosion, which may remain undetected until more severe damage or failure occurs [4].

Such long-term pathologies directly affect structural performance over the service life and present challenges for both design and durability management. NBR 6118:2023 [13] explicitly addresses these delayed actions and cumulative effects, requiring greater robustness and redundancy in prestressed systems. Therefore, understanding how a structure behaves under progressive degradation is essential to ensuring long-term safety and functionality.

In this context, the numerical modeling was developed to represent realistic scenarios of construction defects and pathological manifestations over time, focusing on the redistribution of internal forces, resulting displacements, and resistance mechanisms activated after localized prestress loss. The objective is to assess the residual structural capacity and safety under unforeseen failures, contributing to safer design practices and the improvement of technical standards related to prestressed concrete.

3 Methodology

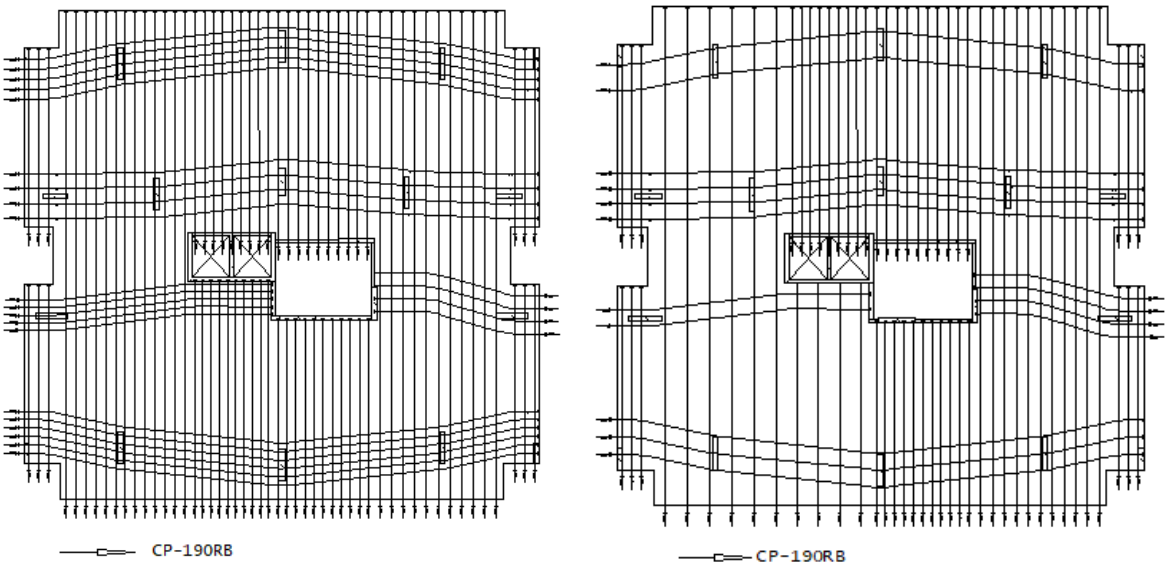
The present study was carried out through numerical modeling and structural analysis using commercial software, with the aim of evaluating the behavior of prestressed concrete structures under specific failure conditions—particularly the rupture of prestressing tendons in a critical region, defined as the area exhibiting the greatest deformation in the original structural model.

Initially, a representative structural model was developed based on the geometry, material properties, and loading conditions of an actual building. The prestressing system was modeled with unbonded tendons, and the concrete and steel properties were defined according to the parameters established by current Brazilian standards (NBR 6118:2023 and NBR 14931:2023) [13,12].

Subsequently, different rupture scenarios were simulated, considering simultaneous failure of the prestressing tendons. Four distinct cases were analyzed: the original model (no failure) and three progressive failure stages involving the successive removal of 8, 16, and 24 tendons, respectively, concentrated in the region of maximum deformation. These simulations aimed to evaluate the redistribution of internal forces, overall structural integrity, and the potential for progressive collapse. The analyses were performed using TQS software, which enabled detailed control of the prestressing stages and simulation of tendon losses.

The results were interpreted in terms of displacements, stress variations, and failure mechanisms. Comparisons were made between the intact structure and the models affected by tendon rupture, highlighting the importance of robustness and redundancy in prestressed systems.

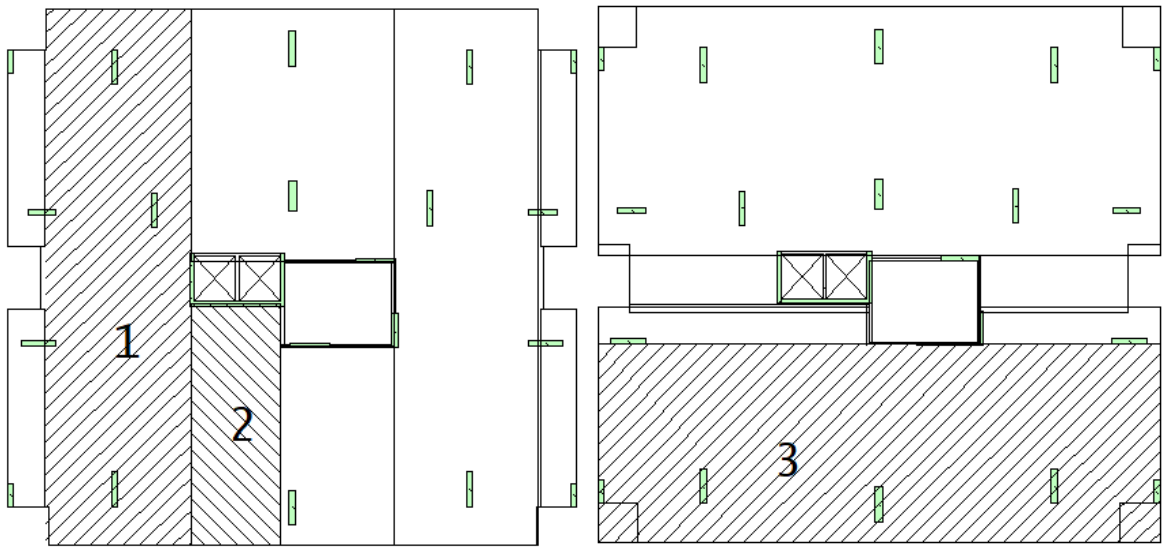
In addition to global effects such as displacements and stress redistribution, the simulations also allowed for an in-depth assessment of the reinforcement ratio in each scenario, considering both passive reinforcement and the contribution of the tendons prior to failure. The goal was to identify how tendon rupture influenced the internal force distribution and altered the demand on the remaining structural elements. Figures 1 (a) and (b) present the tendon layouts for the original model and the third simulation stage, respectively.



(a) (b)

Figure 1. (a): Original Tendon Layout; (b): Third-stage Tendon Layout

The comparison of positive reinforcement ratios was conducted for three specific slab strips, shown in Figures 2 (a) and (b). The analysis of these strips enabled a localized observation of the effects of force redistribution after tendon rupture, contributing to the evaluation of reinforcement adequacy and safety under failure conditions.



(a) (b)

Figure 2. (a): Vertical Reinforcement Ratio Strips Analyzed; (b): Horizontal Reinforcement Ratio Strips Analyzed

These findings underscore the importance of assessing not only the global structural performance but also the adequacy of local reinforcement under accidental failure scenarios. The study highlights the fundamental role of redundancy and robustness in prestressed concrete structures, emphasizing that structural safety in the event of partial tendon loss directly depends on the system's capacity to redistribute and resist internal forces through the remaining elements.

4 Results

Throughout the analysis, the immediate, time-dependent, and long-term deflections of the post-tensioned slab were evaluated, comparing the effective area of prestressing steel at each stage with that of the original model simulated in the TQS software.

It is important to note that the tendon layout and quantity used in the simulations did not follow the parameters suggested by the software, but rather those defined in an actual executive design prepared by a local structural engineering office responsible for the design of the analyzed structure. This approach provided greater realism to the modeling and the results obtained.

The figures below illustrate the long-term deformation of the slab under the two conditions analyzed: the initial situation, without failures (Figure 3), and the most critical scenario, with the removal of 24 tendons (Figure 4). A 0.34 cm increase in long-term deflection between the two cases is observed, highlighting the impact of prestress loss on the deformation behavior of the structure.

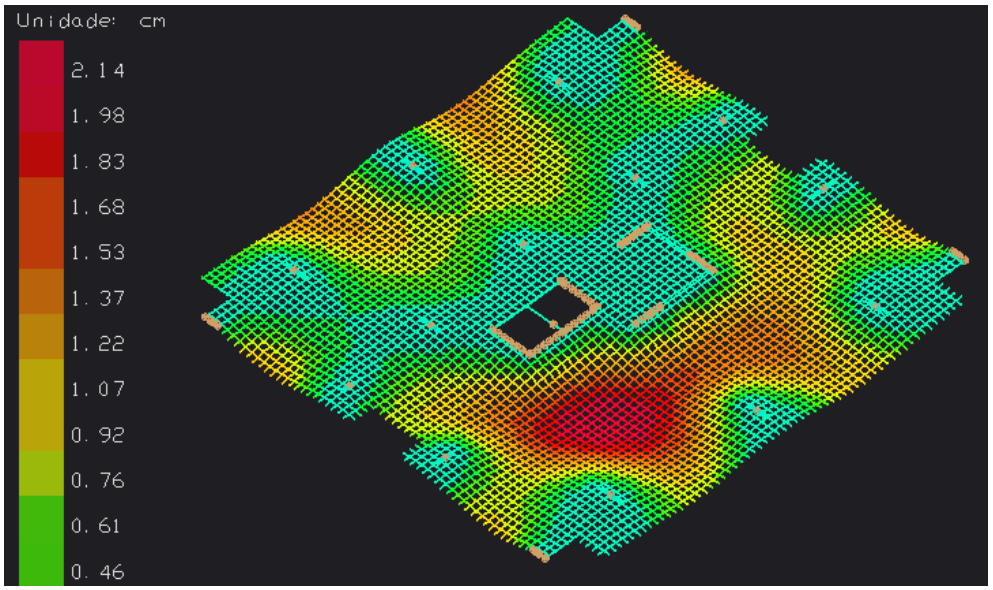


Figure 3: Original Max. Long-Term Deflection

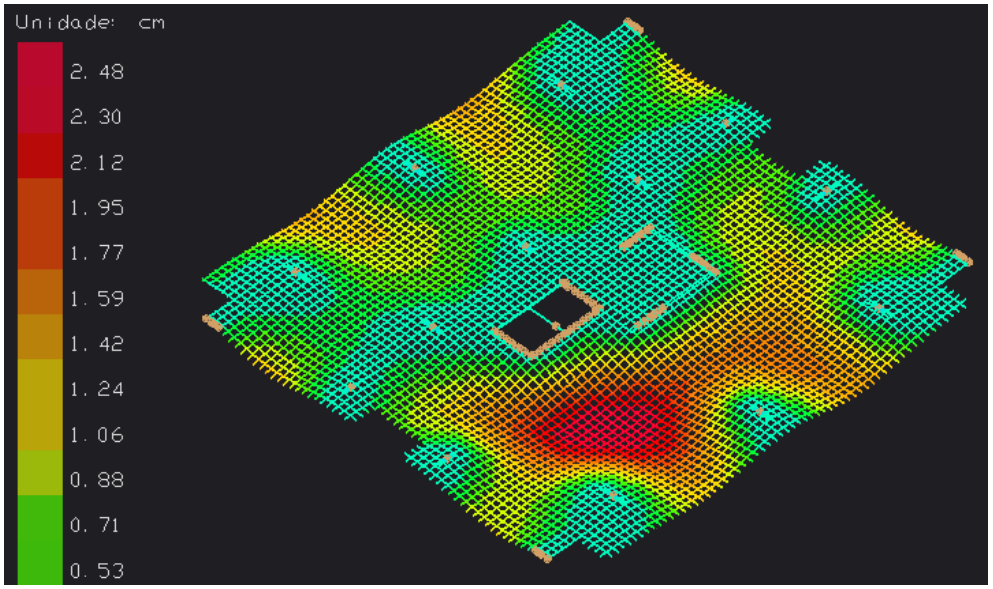


Figure 4: 3rd Stage Max. Long-Term Deflection

The following tables 1 and 2, present the slab deflection results for the original model and the three simulation stages carried out. It is noted that, despite the removal of a significant number of tendons in the final stage, the deflection increased by only 14% compared to the original model.

Regarding the positive reinforcement ratio, an increase of 19% was observed in strip 1, 22% in strip 2, while strip 3 showed a 3% reduction. These results emphasize the redistribution of internal forces and the distinct structural response of different slab regions to the simulated tendon ruptures.

Table 1. Structural Behavior - Deflection (cm)

Structural Behavior	Original	1st Stage	2nd Stage	3rd Stage
Max. Frequent Deflection	1,10	1,15	1,19	1,24
Max. Deferred Deflection	1,23	1,29	1,34	1,41
Max. Long-Term Deflection	2,14	2,25	2,37	2,48

Table 2. Reinforcement Ratio (cm²)

Strip	Original	1st Stage	2nd Stage	3rd Stage
1	32,99	34,86	36,73	39,22
2	24,64	27,34	29,65	30,15
3	192,011	190,05	188,10	185,41

5 Conclusions

The results of the numerical simulations demonstrated that the unbonded post-tensioning system exhibited satisfactory structural behavior even under the condition of progressive tendon rupture. The redistribution of internal forces proved effective in limiting the increase in deflections at each removal stage.

In the most critical condition, with 24 tendons deactivated, the slab deflection increased by only 14% compared to the original model and remained below the L/250 limit defined by NBR 6118:2023 for elements requiring deformation control. These results highlight the robustness of the system in the face of localized failures and reinforce the relevance of detailed analyses in the design of post-tensioned structures.

Furthermore, the comparison between the results provided by the TQS software and the values obtained from the executive design validated the adopted modeling approach, bringing the simulated behavior closer to the actual structural performance.

The findings of this study contribute to a better understanding of the effects of tendon loss and underscore the importance of inspection, maintenance, and precise detailing in the design and execution of prestressed concrete structures.

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