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Assessment of Global Behavior in Reinforced and Prestressed Concrete Buildings Using Geometrically and Physically Non-Linear Analysis

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Abstract. This work aims to present a comparative study of the global behavior of reinforced and prestressed concrete buildings, with an emphasis on evaluating the global instability of the structural frame. The analyses are conducted using three-dimensional models that incorporate physical and geometric nonlinearities. The methodology includes extracting the effective stiffnesses of the structural elements from the equivalent three-dimensional frame, with these values being compared against the stiffness coefficients for global analysis prescribed by NBR 6118. The study also addresses the increase in global stiffness provided by the introduction of prestressing and its impacts on structural stability. The obtained results aim to contribute to the improvement of structural modeling and the prediction of global instability in buildings, offering technical support for a more precise and safe design approach.

Keywords: Reinforced concrete, Prestressed concrete, Global instability, Structural stiffness, Non-linearity.

1 Introduction

The nonlinear behavior of reinforced concrete structures is intrinsically linked to the cracking of concrete under tensile stresses, as addressed by Leonhardt and Mönnig [1]. This cracking compromises the stiffness of the elements, influencing the global stability of the structure. NBR 6118 [2] recognizes this nonlinearity through stiffness reduction coefficients applied to beams, columns, and slabs in Ultimate Limit State (ULS) global analyses.

In contrast, prestressing in concrete structures promotes a state of initial compression, which can reduce or eliminate cracking in service. This characteristic suggests a mitigation of the loss of element stiffness and bring up of the direct applicability of the NBR 6118 stiffness reduction coefficients to prestressed elements [3].

Despite the relevance of prestressing in the Brazilian civil construction landscape, there is a perceived lack of specific normative guidelines in NBR 6118 that address the influence of prestressing on the global stiffness of structures and, consequently, on their stability. Furthermore, an in-depth literature review revealed a scarcity of scientific studies dedicated to quantifying the contribution of prestressing in beams to the mitigation of global instability in tall buildings, especially from the perspective of nonlinear physical analysis.

In this context, this study aims to analyze the influence of prestressing in beams on the global instability of tall buildings by evaluating how prestressing helps maintain the structural integrity of these elements. That is, the goal is to quantify the contribution of prestressing to mitigating stiffness loss due to cracking, using a geometrically and physically non-linear analysis in the commercial software TQS. Preliminary studies, comparing results from models processed with and without the slab incorporated into the spatial frame, indicated that the influence of the slabs on global instability was not very significant, with the γ_z coefficient remaining practically unchanged.

Therefore, the present research focuses on the impact of prestressing on the beams of the structural system.

2 Literature Review

2.1 Global Instability in Tall Buildings

Global instability in building structures refers to the propensity of a structural frame to undergo significant increases in displacements and integral forces due to the interaction between vertical loads and the horizontal displacements of the structure. This phenomenon is often called the second-order effect and is critical in the design of slender and tall buildings, as eccentricities generated by displacements induce additional internal forces that, if not controlled, can lead to a progressive collapse or a loss of the structure's global stiffness [2].

The consideration of these effects is imperative and advocated by NBR 6118 when global instability is not negligible, providing specific criteria, such as the γ_z coefficient, for a consistent analysis. The γ_z parameter is a dimensionless quantity for the evaluation of global instability in concrete structures, as established in item 15.5.3 of NBR 6118 [2]. This parameter quantifies the intensity of global second-order effects, resulting from the interaction between vertical loads and the horizontal displacements of the structure.

$$\gamma_z = \frac{1}{1-\frac{\Delta M_{tot,d}}{M_{1,tot,d}}}. \tag{1}$$

where, $M_{1,tot,d}$ is the overturning bending moment and $\Delta M_{tot,d}$ is the sum of the products of all vertical loads by the horizontal displacements at their respective points of application in the structure.

Essentially, the γ_z acts as an indicator of the amplification of integral forces due to the structure's displacements. Values close to 1.0 indicate that second-order effects are negligible. However, NBR 6118 establishes that if γ_z is greater than 1.10, second-order effects must be considered, and if it exceeds 1.30, a rigorous nonlinear geometric analysis is mandatory [2].

2.2 Physical Nonlinear Behavior of Concrete

Reinforced concrete is a composite material whose mechanical behavior is intrinsically nonlinear, especially under the action of tensile stresses. NBR 6118 recognizes this nonlinearity, which manifests primarily through the cracking of concrete. In loading regimes where tensile stresses exceed the concrete's tensile strength, cracking occurs [2].

In other words, reinforced concrete exhibits nonlinear behavior, mainly due to cracking when subjected to tensile stresses that exceed its strength. This phenomenon transfers the tension from the cracked concrete to the steel reinforcement, resulting in a loss of flexural stiffness in the structural elements [4].

It is therefore concluded that the occurrence of cracking implies a loss of stiffness resulting from the degradation of the element's cross-section. Consequently, the flexural stiffness is reduced after cracking, as the contribution of concrete in the tensile zone is compromised, which directly affects the structure's ability to resist deformations and, consequently, its global stability [4].

To account for this effect, NBR 6118 prescribes, in a simplified manner, the use of reduced stiffnesses for structural elements in Ultimate Limit State (ULS) global analyses, ensuring that second-order effects are evaluated more realistically. The aforementioned standard establishes reduction coefficients aimed at approximating the stiffness of the cracked section. These coefficients correspond to a percentage of the flexural stiffness: 40% for beams, 80% for columns, and 30% for slabs [2].

2.3 Behavior of Prestressed Concrete

Prestressed concrete (PC) is distinguished from reinforced concrete (RC) by the introduction of prior compressive stresses in the concrete. This process, known as prestressing, mitigates or eliminates cracking in service, resulting in greater durability and stiffness of the elements, which can lead to smaller deformations and displacements of the structure.

Prestressing directly impacts the structural response in both the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS). In the SLS, the prior compression in the concrete allows the element to remain uncracked or with controlled cracks under service loads, resulting in a more elastic behavior and, consequently, smaller deflections compared to reinforced concrete. In the ULS, prestressing optimizes the use of high-strength steels, which operate at high stress levels [5]. For tall buildings and complex structures, cracking control and stiffness maintenance are crucial, enabling the design of more slender and efficient elements that better resist second-order effects and global instability.

Unbonded prestressing, which uses greased strands, is a relevant method in the context of slender structures. Although in this technique the active reinforcement does not have a direct bond with the concrete along its length, this method offers construction advantages. Its impact on structural response is significant, affecting bending moment redistribution and post-cracking behavior, which requires specific design considerations.

3 Methodology

3.1 Preliminary Considerations and Reference Model

In this step, it should be noted that all results presented here were obtained from a computational model configured with the standard settings of the TQS software, version V25.9. No changes were made to the calculation and detailing criteria for any structural element. Additionally, the model's geometry, which was self-authored, was iteratively adjusted until, after processing and detailing, the structural elements did not show critical design errors or an excessive reinforcement ratio in the columns. However, for the purposes of this study, Serviceability Limit State (SLS) analyses were not considered here, given the building's typology which, due to its large spans, would be appropriately designed with prestressing to mitigate excessive displacements. The main objective of this work was to develop a model that met the ultimate verifications in compliance with NBR 6118.

Due to a software limitation that incorporates prestressing forces exclusively into a model where slabs are obligatorily included in the three-dimensional frame considering their rigid diaphragm effect (denoted "Model VI"), it becomes impractical to use the exact prestressing results in the processing of the physically and geometrically non-linear (PGNL) frame. This is because the computational philosophy of the PGNL analysis is currently present exclusively in the model that does not incorporate slabs into the three-dimensional frame (denoted "Model IV"). Consequently, for the purposes of this study, the axial prestressing forces were considered as centered, and the hyperstatic effects of prestressing were neglected. It is recognized that the redistribution of forces influences the bending moment-normal-curvature relationship and, consequently, the stiffness of the elements under an PGNL analysis. However, assuming the normal prestressing force as centered is a reasonable simplification, consistent with previous prestressing studies, allowing for the investigation of the compression state and the consequent reduction of cracks in beams for the extraction of stiffness values applicable to the three-dimensional frame.

For this study, a model was developed, consisting of a 20-story building with a total height of approximately 60 meters. The building has a formwork plan, as illustrated in figure 1, with a floor-to-floor height of 3.0 meters. The structural system was designed with 12 cm thick solid slabs supported by beams. The columns have a rectangular cross-section, each with its own dimensions. The foundation was not modeled, given that the study's objective was focused on the superstructure.

The design premises included the use of concrete with a characteristic compressive strength (f_{ck}) of 40 MPa, falling within environmental aggressiveness class II. The vertical loads were defined according to NBR 6120 [6], with dead and live loads. On all slabs, a dead load of 1.0 kN/m², in addition to self-weight, and live loads of 1.5 kN/m² were considered. Furthermore, linearly distributed dead loads, referring to the masonry, were adopted on all beams with a value of 4.0 kN/m. Wind actions were considered according to NBR 6123 [7], with a basic wind speed of 30 m/s (Belo Horizonte/MG), a topographic factor of 1.00, roughness category IV, building class C, and a statistical factor of 1.0. The drag coefficients were estimated by TQS from the modeled geometry.

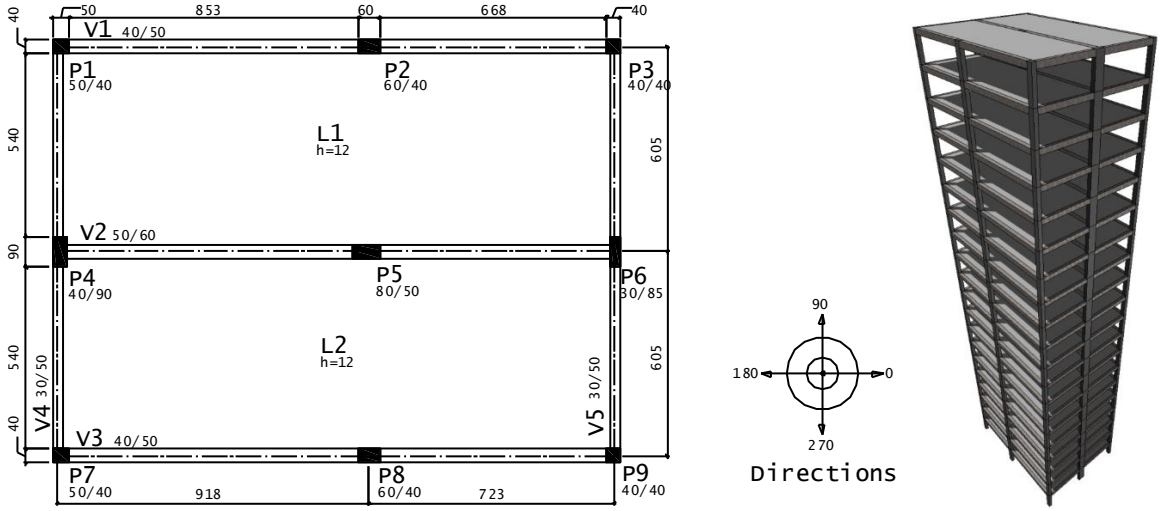


Figure 1. Typical floor formwork plan and 3D Model.

3.2 Prestressing of Beams

For the design stage of the prestressed beams, the VPRO module of the TQS software was used, aiming to determine the number of strands required for each element. The cable layout was designed in a straight line and coincident with the geometric center (GC) of the cross-section, in order to simulate a centered compression condition. Additionally, the safety verifications were performed in compliance with NBR 6118, covering the serviceability limit states (SLS-D, for decompression; and SLS-F, for cracking) and the ultimate limit state during prestressing (ULS-ATO).

3.3 Artificial Prestressing and PGNL Analysis

After processing with the VPRO tool, the required number of cables was obtained from an initial prestressing force of 139 kN, as well as the prestressing forces after all immediate and long-term losses.

In a second phase, the structural analysis was adapted to a global analysis model (Model IV), in which the prestressing elements were replaced by equivalent artificial loads, applied in the structural modeler. The magnitude of these axial loads was determined in proportion to the number of cables obtained in the prior analysis with VPRO. In determining these loads, immediate and long-term prestressing losses were considered, and the appropriate weighting factors for the actions were applied, classifying prestressing as a permanent action.

This methodological approach aimed to simulate, in an analogous manner, the application of prestressing forces on the beams, allowing for the simulation of a geometrically and physically non-linear analysis through the TQS PGNL module. The final objective was to obtain stiffness values of the beams under loading conditions that reflect the prestressed state, making the geometrically na physically non-linear analysis in TQS feasible for a prestressed structure.

3.4 Influence of Models on γ_z and Steel Consumption

As a consolidation of this study, the values of the γ_z coefficient and, consequently, the steel consumption in the structural elements were compared. This was done in a linear analysis using stiffnesses that consider the three different scenarios studied, namely: normative values; values obtained from the PGNL frame without artificial prestressing; and values obtained from the PGNL frame with artificial prestressing.

4 Results and Discussion

This section presents a comparative analysis of the global behavior of reinforced and prestressed concrete

buildings, in light of a geometrically and physically non-linear analysis. The results aim to demonstrate the contribution of prestressing in mitigating the loss of stiffness due to cracking. The methodological approach involved the extraction of effective stiffnesses from elements whose prestressing was previously calculated and then simulated as centered axial loads for their subsequent application in a linear analysis for the calculation and comparison of the global instability coefficients γ_z. The objective is to compare the obtained values with the stiffness coefficients prescribed by NBR 6118, offering technical support for a more precise and safer design approach.

4.1 Preliminary Analysis: Influence of the Slab on Global Stability

Based on the analyses performed here, it was concluded that the influence of slabs as rigid diaphragms on the contribution to the global instability of the building was small for the structure analyzed here. The influence of the slab showed an increase of 1.14% in γ_z for the 90º direction, and 0.62% for the orthogonal direction (0º). The values obtained in this preliminary analysis are presented in table 1.

Table 1. Contribution of the slabs to the γ_z.

Contribution of the Slabs	Direction	Value
No	90º	1.242
Yes	90º	1.228
No	0º	1.131
Yes	0º	1.124

This result justifies the subsequent exclusive focus of the investigation on the contribution of beam prestressing to the maintenance of the physical integrity of these elements and, consequently, to their collaboration for the global stability of the structure. It should be noted, however, that in certain structural systems, such as those without a significant set of beam and column frames, the contribution of the slabs flexural stiffness can be fundamental to global stability, as demonstrated in previous studies, such as Sgarbi [8], which obtained a significant reduction in horizontal displacements and stability parameters when considering the slab in the bracing system.

4.2 Prestressing of Beams

Considering the greater influence of the beams on the global instability of the structure, prestressing was applied to all beams using the VPRO TQS tool. For this study, a straight cable layout was adopted with the central cable positioned at the geometric center (GC) of each beam's cross-section. The results obtained for meeting the normative verifications are detailed in table 2.

Table 2. Results of Prestressing in Beams.

Beam	Number of strands	Total force after losses [kN]	Prestressing force per strand [kN]	Force per strand after losses [kN]	Total loss (%)
1	14	1,370	139	97.86	29.60
2	24	23,450	139	97.71	29.71
3	14	13,700	139	97.88	29.60
4	6	595	139	99.17	28.66
5	6	595	139	99.17	28.66

It is observed that the total prestressing loss in the beams, in percentage terms, varied between 28.66% and 29.71%, indicating a similar loss behavior among the prestressed elements. The observed variations in the number of strands and the total force after losses are due to the design requirements of each element, which are influenced by their respective loads.

It is important to highlight that the straight cable layout, although simplified, allows for a direct evaluation of the compression effect generated by prestressing. The use of parabolic layouts, with variable eccentricities along

the beam, could optimize the number of strands by counteracting the service bending moments, thus minimizing cracking. However, the objective of this study is to quantify the contribution of the prestressing force to the system's global stiffness, and the simplification of the layout is acceptable for the validation of the mathematical models and for the analysis of structural behavior on a global scale.

4.3 Geometrically and Physically Non-linear Analysis with Artificial Prestressing

The prestressing force, after considering all losses, was applied to the model as a concentrated load. This approach is consistent with the assumptions of a straight layout and centered prestressing. However, it is relevant to note that, in this method, the hyperstatic effects resulting from prestressing are neglected.

This simplification results in an analysis that favors safety from the perspective of the flexural-compression of the beams. Although the hyperstatic effects of prestressing tend to redistribute moments, smoothing peaks in the beams and transferring part of the loads to the columns, the non-consideration of this redistribution results in a more conservative evaluation of the beams. However, it becomes non-conservative in the geometrically and physically non-linear analysis, as the increase in force in the columns is not accounted for.

A relevant aspect in the geometrically and physically non-linear (GPNL) analysis of the frame that is the object of this study was the determination of the final stiffness of the elements. This was obtained from the combination of actions in which the wind at 90º was treated as the main live loads, while prestressing was considered a favorable dead load, with a reduced weighting factor, in accordance with NBR 6118 [1]. This approach aims to simulate the most critical conditions for this study, incorporating smaller axial compressive forces that combat cracking.

As already mentioned, for comparison and validation purposes, the final stiffnesses of columns and beams in the PGNL model were also determined without the action of prestressing forces. This comparative analysis allows for confronting the results of the PGNL model, even in a specific case study, with the stiffness reduction coefficients advocated by NBR 6118 for a linear global analysis in the Ultimate Limit State (ULS). The results obtained throughout this step are listed in table 3.

Table 3. PGNL Analysis.

Artificial Prestressing	Element	Stiffness (PGNL)	Stiffness (NBR 6118)	Variation (%)
No	Columns	0.796 EI_c	0.800 EI_c	- 0.50
No	Beams	0.253 EI_c	0.400 EI_c	- 36.75
Yes	Columns	0.725 EI_c	0.800 EI_c	- 9.37
Yes	Beams	0.629 EI_c	0.400 EI_c	+ 57.25

When prestressing was not considered, the stiffness of the beams showed a value 36.75% lower than the normative value. This lower value indicates that, with regard to the structure that is the object of this study, the normative prescription appears to be on the non-conservative side. As for the columns, the value obtained in the geometrically and physically non-linear analysis was consistent with the normative value (a variation of -0.50%).

The analysis with prestressing showed an increase in the flexural stiffness of the beams of 57.25% compared to the normative value and 148.61% compared to the PGNL analysis without prestressing. This result corroborates the hypothesis that the prestressing force, by counteracting tensile stresses, better preserves the integrity of the cross-section and, consequently, the stiffness of the elements. In contrast, the columns showed a stiffness value 9.79% lower than the value obtained in the PGNL analysis without prestressing, which suggests a redistribution of forces in the frame.

4.4 Global stability and Steel Consumption

In accordance with the main objective of this study, the aim here was to quantify the influence of prestressing on the global instability of the analyzed structure. Furthermore, at this stage, the total steel consumption of the building by element type was also investigated, in light of the three scenarios considered in this study. Table 4 presents the critical γ_z values for each case, as well as the total steel consumption in beams and columns.

Table 4. Results of the Critical γ_z and Steel Quantities for the Different Analyses

Analysis	Element	Stiffness	Steel Quantities [kg]	Critical γ_z (90º)
NBR 6118	Beams	0.400 EI_c	49,299	1.242
NBR 6118	Columns	0.800 EI_c	17,062	1.242
PGNL without prestressing	Beams	0.253 EI_c	50,336	1.358
PGNL without prestressing	Columns	0.796 EI_c	19,040	1.358
PGNL with prestressing	Beams	0.629 EI_c	48,645	1.180
PGNL with prestressing	Columns	0.725 EI_c	15,211	1.180

As discussed, in the scenario without prestressing, the stiffness of the beams was 36.75% lower than the normative value, resulting in an 8.54% increase in the γ_z coefficient, which indicates lower structural stability than that predicted by the standard. The introduction of prestressing optimized the stiffness of the beams, exceeding the normative value and, consequently, reducing γ_z by 15.08% when compared to the result extracted from the PGNL without prestressing. This improvement in stiffness and stability resulted in an optimization of steel consumption, with notable reductions in both beams and columns.

5 Conclusions

This comparative study evaluated the global behavior of a reinforced and prestressed concrete building from the perspective of geometrically and physically non-linear (PGNL) analysis. The methodology employed, which included the simulation of prestressing as centered axial loads, allowed for the quantification of the influence of prestressing on the stiffness of the elements and, consequently, on the global stability of the structure.

The results demonstrate that the inclusion of prestressing in the beams promoted a 57.25% increase in the flexural stiffness of these elements compared to the reference stiffness values of NBR 6118. This increase in stiffness corroborates the hypothesis that the prestressing force, by counteracting cracking, better preserves the integrity of the elements' cross-section. Consequently, the global instability coefficient, γ_z, was reduced from 1.358 to 1.180, indicating an improvement in the stability of the structural frame.

The analysis also revealed that the prestressing model resulted in a reduction of 8.64% in total steel consumption compared to the model without prestressing (PGNL). Specifically, steel consumption in the columns was reduced by 20.1% compared to the model without prestressing.

In summary, the application of prestressing to the beams, even with a simplified layout, proved to be an effective strategy to mitigate the loss of stiffness resulting from concrete cracking, contributing to the global stability of tall buildings and promoting an optimization in steel consumption.

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