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Study of global stability of tall buildings with prestressed slabs

Estudo da estabilidade global de edifícios altos com lajes protendidas

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Abstract

The use of prestressed concrete flat slabs in buildings has been increasing in recent years in the Brazilian market. Since the implementation of tall and slender buildings a trend in civil engineering and architecture fields, arises from the use of prestressed slabs a difficulty in ensuring the overall stability of a building without beams. In order to evaluate the efficiency of the main bracing systems used in this type of building, namely pillars in formed "U" in elevator shafts and stairs, and pillars in which the lengths are significantly larger than their widths, was elaborated a computational models of fictional buildings, which were processed and analyzed using the software CAD/TQS. From the variation of parameters such as: geometry of the pillars, thick slabs, characteristic strength of the concrete, reduceofthe coefficient of inertia for consideration of non-linearities of the physical elements, stiffness of the connections between slabs and pillars, among others, to analyze the influence of these variables on the overall stability of the building from the facing of instability parameter Gama Z, under Brazilian standard NBR 6118, in addition to performing the processing of building using the P-Delta iterative calculation method for the same purpose.

Keywords: global stability, analysis of 2nd order, Gama Z, P-Delta, prestressed slabs.

Resumo

A utilização de lajes planas de concreto protendido em edificações vem crescendo muito nos últimos anos no mercado brasileiro. Sendo a execução de edificações cada vez mais altas e esbeltas uma tendência na engenharia civil e arquitetura, surge a partir do uso das lajes protendidas uma dificuldade em se garantir a estabilidade global de uma edificação sem vigas. A fim de se avaliar a eficiência dos principais sistemas de contraventamento utilizados neste tipo de edificação, a saber, pilares em formado de "U" e pilares-paredes, elaborou-se modelos computacionais de edifíciosfictícios, que foram processados e analisados no programa comercial CAD/TQS. A partir da variação de parâmetros de modelagem tais como: geometria dos pilares, espessura das lajes, coeficiente redutor de inércia para consideração das não-linearidades físicas dos elementos, rigidez das ligações entre lajes e pilares, entre outros, buscou-se analisar a influência de tais variáveis na estabilidade global da edificação a partir do parâmetro de instabilidade gama Z, previsto na norma brasileira ABNT NBR 6118 [1].

Palavras-chave: estabilidade global, análise de 2° ordem, Gama Z, P-Delta, lajes protendidas.

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1. Introduction

The great market acceptance of the use of prestressed slabs in the construction of buildings, combined with the need to construct higher and slim buildings, due to the lack of space in big cities, justifies the study of buildings with these characteristics. These buildings have advantages such as the facility of application formwork, enabling extensive use of processed formwork, props and shoring industrial systems, the architectural flexibility that the absence of beams allows us, the better use of steel and concrete materials, productivity gains and runtime, which is a major issue from the market point of view, among others.
However, one of the most advantageous features of these structures, that is, the absence of beams, takes it to present a major drawback: the reduction of stiffness as the horizontal displacement and questions in what concerns to the overall stability of the structure. In this type of building, the main bracing system used are columns-walls shaped like "U" or "L" placed in the region of the stairs and lift shafts (see Figure 1). Such elements have high rigidity, and when combined with the other columns, ensure the overall stability of the building. The prestressed slabs, on the other hand, ensures that all the columns work together (diaphragm rigid effect), stabilizing the structure. By having active armor, the slabs have a low level of cracking for current active requests in the structure; this way, it would not be absolutely wrong to accept that the reduction of coefficients that take into account the nonlinearity of the slabs, according to the standard ABNT NBR 6118 [1], could have different values from those indicated in this one (less conservative values). Additionally, the typical distribution of reinforcement in prestressed slabs, ensures a high rate of armor in the region of the columns, increasing the rigidity of the connections between these elements, contributing to the overall stability of the structure.

2. Brief literature review

2.1 2rd Order effects

Because of horizontal loads, whether resulting from wind loads, or from equivalent charges relating to construction protrusions and asymmetry of vertical loads, the reinforced concrete buildings are always requested by composite flexion. Nevertheless, in practice, applications require no immediate time intervals (during the building process) and portions of the total values.
Named as 1st order analysis, one in which the structure of the calculation is performed in a non-deformed geometric configuration. The stress values and deflection of the system are obtained from formulations of conventional strength of materials.
When considering a deformed geometrical configuration, it appears in the system additional requests named 2nd order effects, and the analysis is said to be of the 2nd order. In summary, we can say that the effects of 2nd order are additional effects to the structure generated from its deformation. They are responsible for causing a non-linear behavior in the structure (geometric nonlinearity).

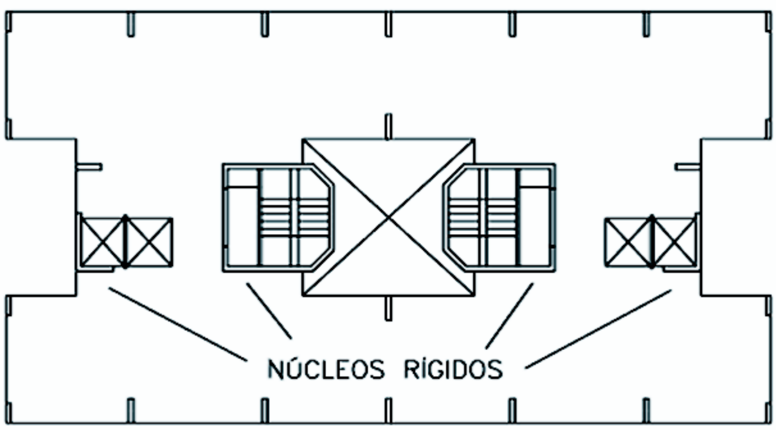
2.2 Nonlinear analysis

According to Kimura [6], in a simplified form, a nonlinear analysis is a calculation where the response of the structure, displacement, strain or stress, has a non- linear behavior, i.e., not linearly proportionally applied to a loading in it. Such behavior is a characteristic of reinforced concrete structures, and these effects should always be considered in the structural analysis.
The most relevant nonlinear behaviors in the case of concrete buildings are from physical (material) and geometric origin, both intrinsic to all actual structures of reinforced concrete.

2.3 Non Linearity Physics (NLF)

The variation of the physical properties of the material for a given load is a phenomenon usually incorporated in the analysis of concrete structures. The discrepancy between the ability to withstand compressive forces and traction in the concrete, leads engineers to necessarily work with this material outside the boundaries of elastic proportionality.
What really happens in the civil engineering practice is that the concrete is in most cases subjected to traction loads higher than

Figure 1 – Hard core plan. Source: Silveira (2012)



it can resist. Thus, the concrete fail by tension stress and the element in this configuration is so call cracked.
In reinforced concrete buildings, material properties are altered as the increase of charges (additional floors and walls) occurs, giving the elements a non-linear behavior, due to the effects of the its cracking, besides fluency, the presence of armor, among other factors.
In order to simplify the analysis and design, the ABNT NBR 6118 [1], proposes a way to directly change the value of the stiffness of the component elements of the structure, adopting reduction coefficients for each type of element according to the relevance of this to the overall stability and load type to which the element is subjected. To the rigidity adopted for calculating the structure, considering the reduction coefficients, is named effective stiffness or drying rigidity.
ABNT NBR 6118 [1] in item 15.3, mandates the analysis of reinforced concrete structures taking into account the NLF, and in item 15.7.2 indicates the values to be adopted to reduce the stiffness of the structural elements, when taking into account the 2nd order global effects in buildings with four or more floors:

- Slabs: $(EI)_{sec} = 0,3\ E_{ci}I_c$
- Beams:
  $(EI)_{sec} = 0,4\ E_{ci}I_c$ para As` ≠ As
  $(EI)_{sec} = 0,5\ E_{ci}I_c$ para As` = As
- Columns: $(EI)_{sec} = 0,8\ E_{ci}I_c$

I_c is the moment of inertia of the cross section of the concrete and E_{ci} is the initial tangential modulus of elasticity of concrete.
It is believed that even when the bracing structure is composed exclusively of beams and columns and the overall instability factor gamma z (γ_z) is less than 1.3, the secant stiffness beams and columns must be taken as;

- Columns and Beams: $(EI)_{sec} = 0,7\ E_{ci}I_c$

In the case of prestressed beams and slabs, the level of cracking of these elements is normally considerably smaller than that of a reinforced concrete element without active armor. Thus, we can consider the possibility of working with higher values for the stiffness reduction coefficients than those indicated by the standard as shown above.

2.4 Non Geometric Linearity (NLG)

In the analysis of a structural system considering its deformed state, there is the occurrence of larger effects than those predicted for a linear analysis starting from an undeformed condition, even for a linear elastic material behavior. Therefore, the effect is not linearly proportional to the action, which characterizes and names the phenomenon as geometric nonlinearity.
When carrying out an analysis taking into account the NLG, a safe formulation for the combination of actions is admitted to the ABNT NBR 6118 [1]. The increase of loads is given by the factor γ_f/γ_{f3}, and later, the effects are increased by the factor γ_{f3} equal to 1.1. Thus, for the design in the Ultimate Limit State (ELU – in Portuguese) of the structural element, the factor γ_f is fully considered, although the effects found was lower than the one that would be obtained if the γ_{f3} factor had been applied to the characteristic requesting loading at first analysis, because as it was said before, in the NLG there is no linear ratio between actions and effects.

2.5 Global stability

The overall stability of a structure is inversely proportional to its sensitivity to 2nd order effects, Kimura [6]. Thus, it is possible to distinguish a stable building from an unstable one through a calculation, or even an estimate of the overall effects of 2nd order that will be present in the structure.
The Brazilian ABNT NBR 6118 [1] dispenses the design of the structure considering the requests of 2nd order, since these ones are lower in intensity than 10% of 1st order requests. It happens that, to verify this condition, it would be necessary to conduct an analysis of 2nd order, regardless of if its effects are used or not for the design of the structure. Being the analysis of 2nd order a more complex order than the 1st order, there is a convenience in analyzing the structure from practical parameters that aid in the decision to consider whether or not the effects of 2nd order, being the parameter α (alpha) and the γ_z coefficient (gamma z) the estimated ones in the Brazilian standard.

2.6 The parameter is instability gamma Z

The parameter instability Gamma z (γ_z) was introduced by Franco and Vasconcelos [5], which is largely used for the analysis of structural projects in the country today. The parameter measures the sensitivity of a building in relation to second order effects, and it can be also used to increase the effects of the first order due to horizontal loads, then obtaining approximate second order effects. The formula of the parameter, considering the safety formulation, is as follows:

$$\gamma_z = \frac{1}{1 - \dfrac{\Delta M_d}{M_{1d}} \cdot \dfrac{1}{1,1}} \qquad (1)$$

Where ΔM_d is the sum of the products of all vertical forces acting on the structure, through the horizontal displacements of the respective points of application, obtained in the 1st order analysis; M_{1d} is the moment of tipping, i.e., the sum of the moments of all horizontal forces to the base of structure.

2.7 Factors influencing the global stability

Among the factors that most influence the overall stability of buildings there are loads and the stiffness. When analyzing the formulation of the parameter γ_z, it is observed that an increase in the value of horizontal load does not lead to an increase in the value of the parameter, therefore, effects of the 1st order increase in proportion to the 2nd order and the relationship $\Delta M_d/M_{1d}$ remains constant. However, increasing the value of the vertical load there is an increase in the value of the 2nd order effects, for the same horizontal loading. In summary, the horizontal load would have no direct influence on the stability of the structure, since this shows a rectangular and symmetric geometry, without unbalanced parts, features that do not represent the most general cases, indeed.
Intuitively, it is known that the more rigid structure is, more stable it gets. This fact is confirmed in the formulations of instability parameters. In the case of the γ_z coefficient and the increase of stiffness leads to lower values of lateral displacements and hence lower values of second-order moments, consequently for the same loading, it results in a decrease in the value of the coefficient.

2.8 Iterative method P Delta (Δ-P)

The P-Δ method is an iterative procedure used for analysis of the second order structures where the effect of the successive lateral displacement is transformed into the equivalent horizontal forces. The method consists of performing a first-order analysis in a given structure (undeformed initial configuration) considering the horizontal and vertical loads, and from the displacement (Δ) obtained in this analysis, we define fictitious horizontal loads equivalent to the loading of a second order, to consider a new stage of the analysis. In each stage, we obtain new fictitious lateral forces which tend to decrease as the structure converges to an equilibrium position. The iteration is stopped when the effect of n- umpteenth fictitious load is small when compared to the effect of the previous fictitious one.

3. Bracing systems

Due to the absence of beams in buildings of prestressed slabs, one bracing system formed by porticos able to withstand the wind side requests, would not be possible. On the other hand, as the Brazilian standard prescribes in item 13.2.4, the minimum thickness for a "smooth flat" slab, i.e. without beams, is sixteen cm, being common for prestressed slab the thicknesses of eighteen centimeters or more. This thickness is sufficient to ensure the effect of the rigid diaphragm and thus the locking of the columns.
The main bracing system for multi-story buildings made of prestressed flat slabs, is most commonly used with a hard core. Such a system can be complemented with pillar-walls and columns conveniently positioned with its greater stiffness mutually perpendicular directions to each other in order to stabilize the building in all directions.
The hard core in buildings with prestressed slabs is commonly formed by columns-walls of reinforced concrete in a "U" shape or "L" in the regions of boxes of elevators and stairs (Figure 1). In recent works Ching [3] recommends a centralized position for the hard core in order to avoid eccentricities between the center of mass and the stiffness of the building center. Nevertheless, he claims that regardless of the position, the ideal is to use a closed element in a tube format, formed even by bracing metal bars.

4. Criteria and models

For the analysis and evaluation of the main factors that influence the overall stability of multi-story buildings with prestressed concrete slabs, it was modeled on the commercial program CAD/TQS, developed by TQS Informática LTDA, a series of buildings with slenderness order of one to four, i.e., taking a width of approximately 16 meters between the end columns, we adopted a height of about 64 meters to the building. The building was modeled after an idealized blueprint, geometrically asymmetric in all directions, in which varied the most relevant parameters and criteria available in the program for the evaluation of their influence on lateral displacements and value of the instability parameter Gamma z (γ_z).

4.1 Constructive effects and Interactive P-Delta Method in CAD/TQS

As a building is constructed, the axial deformation suffered by the columns, due only to the weight of the structure, are compensated in the construction process by leveling the floors. This compensation (constructive effect) is incorporated to the modeling, simply from the increase of the axial stiffness of the columns during the assembly of the space frame stiffness matrix. This adaptation ensures outcomes compatible with the reality, particularly in the case of diagrams of bending moments in beams and slabs of the upper floors.
This adaptation, however, is worth only for the analysis of the behavior of buildings when the vertical loads are acting. For horizontal actions, such as the wind, the increase in the area of the columns is not considered. Therefore, the TQS Informática LTDA, using the works of Medeiros and França [9], developed the so-called P-Delta in two steps.
The method is to calculate the linear structure, at first considering only the vertical load. In this step, the axial stiffness of the columns is increased for the purpose to contemplate the construction and the distribution of normal forces and efforts on the elements (columns and beams) are considered. Secondly, the calculation becomes non-linear and iterative, with the application of horizontal loads only. Now, the axial stiffness of the columns are not increased, as it was before, and the displacement obtained in step 1 (stored stiffness matrix of the first linear analysis) are considered. In the following iterations, it corrects successively this matrix with the additions of normal strain caused by horizontal actions (geometric nonlinearity). The process repeats until the convergence of the structure is obtained. The final results, that is, the nodal displacements, efforts in bars and reactions of support of 1ª and 2ª order, are the sum of the amounts obtained in two steps, Manuals CAD/TQS [7].
Additionally, in order to facilitate the interpretation of the data generated by processing the frame by the P-delta method, TQS Informática created a so-called RM2M1 coefficient calculated by the same calculation principle Gamma Z.

$$RM2M1 = 1 + \frac{M_2}{M_1} \quad (2)$$

Where,
M_1: is the moment of the horizontal forces in relation to the building's base;
M_2: is the sum of the vertical forces multiplied by the displacement of the nodes of the structure under the action of horizontal forces resulting from P-Delta calculation on a non–linear combination.

4.2 Analysis model VI CAD program/TQS and the consideration of the cross stiffness of the slabs

In VI analysis model CAD/TQS program, the building is modeled as a single portico, composed of elements that simulate the beams, columns and slabs of the structure. Thus, besides the beams and columns, slabs start to resist to the loads generated by the wind. In this model, it is also considered the relaxation of beams and columns links. In summary in model VI, the slab stiffness is incorporated into the space frame, so the element starts to absorb some of the strain and to contribute to the stability of the building.
Martins [8] modeled in finite elements, buildings formed by slabs, beams and columns, including a "U" shaped-column in the region of the elevators, and concluded that the consideration of the

transverse stiffness of the slabs significantly influences the structural behavior of buildings, reducing the shifts of the sides of the building, favoring the overall stability and reducing instability of Alpha and Gamma z (γ_z) parameters.

"[...]This is because the slabs, with the structural model adopted, have a more effective participation in the interaction of forces and displacements with the other elements (beams, columns and core), compared to other models that consider only as fully flexible diaphragms out of your plan. [...] In some cases the influence of the transverse stiffness of the slab became so significant that in a 2nd order theory considering the transverse stiffness of the slab, the shifts were smaller than in the model theory of 1rst order without consideration the bending stiffness of the slabs [...] ". (Martins, 2001, p 234).

4.3 Easing the connections between beams and columns

Although the target building has a limited number of beams (a basic feature of this type of building), it is common to use beams in the region of the stairs and elevators. In the case of beams that "close" the core of the elevators, there is the formation of a kind of lintel that contributes to the stiffness of the core, it partially restricting the warpage. Martins [8] shows that the presence of the beam (lintel) helps to reduce the lateral displacement of the floor.

It is important then to properly consider the restriction and locking level that the beam provides to the lift column, not to mention the other beams of the stairs area. For this purpose, the program considers the presence of fictitious springs defined in the ends of the beams, making the semi-rigid connection. The rigidity of the "springs" of flexibility is given approximately, as the term 4EI / L defined by the column next to the bars of the beams, where: E is the longitudinal modulus of elasticity of the column, L is the ceiling height of the column and I is the moment of inertia calculated from an equivalent section of the column to be effectively considered in connection stiffness.

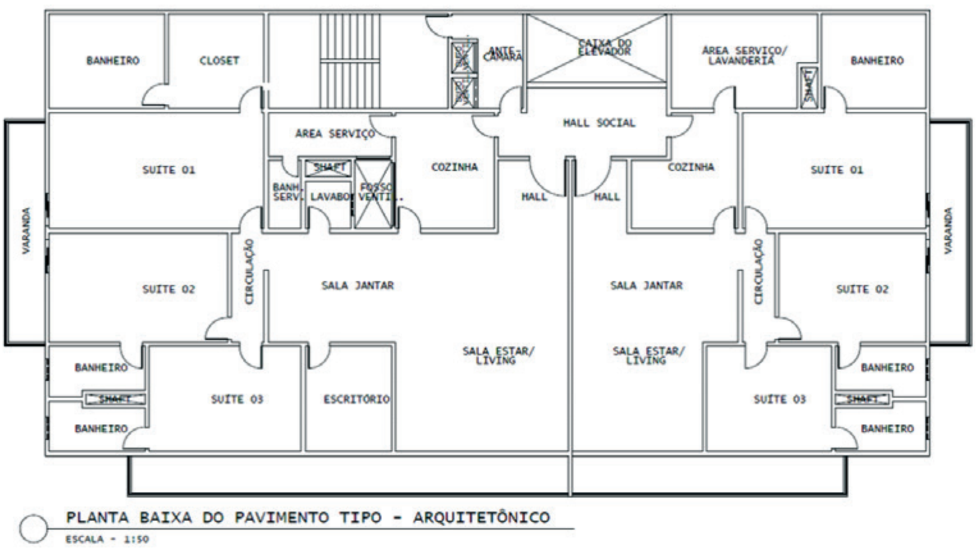
Two parameters defined in the general criteria of the program, called LEPMOL and REDMOL, allow the user to make weights in calculating the stiffness of these springs. The REDMOL directly reduces the stiffness value of "spring", while the LEPMOL multiplies the equivalent beam width of the support column, taking into account that the adopted width is not smaller than the beam width neither bigger than the width of the column.

The flexibility of these links makes the structure displaceable; however, to more realistically simulate what happens in practice. It is noteworthy that the effects of this flexibility are more significant and measurable in the case of conventional buildings, that is, slabs, beams and columns, and in the case of buildings analyzed in this work, flexibility, or even reducing stiffness to region of the slab connection with the columns, has greater influence on the results of the displacements.

4.4 Analysis model IV of CAD/TQS program

The analysis model IV, was the main model implemented by the CAD/TQS until the version 16. In this model, a space frame of the floor is assembled only contemplating the beams and columns. The effect of the rigid diaphragm is incorporated into the model from the increase of the lateral stiffness of the beams. The impacts of vertical and horizontal actions in beams and columns are calculated in the space frame. The slabs are modeled as separate bar grills of the portico, being the effects generated by the calculated vertical loads and the resulting strain transferred as loads for the space frame. It is also considered as easing of beam-column connections.

Figure 2 – Floor plan of Pav. Type - Proj. Architectural



4.5 Model 1

Below the main criteria adopted in Model 1 are listed:

- Analysis Model VI
- Easing of Beams-Columns Connections:
  – REDMOL:4
  – LEPMOL:1,5
- Without chapiter
- Crimped Base
- P-Delta
- A 25-centimetre-thick core
- f_{ck} of concrete:
  – Columns: 40 Mpa
  – Beams and Slabs: 30 Mpa
- Wind:
  – Speed Feature: 32 m/s
  – High Wind Turbulence
- Coefficient of Non Linearity Physics:
  – Slabs: 0,8
  – Coluns:0,8
  – Beams:0,8

The Figure 2 presents the architectural project used for the analisys. The Figure 2 presents the geometry of wall-colum and the Figure 3 presents the build's space model.

For the analysis of the developed model, a criterion of the program entitled "Vertical loads to calculate moments of 2nd Order" was modified where live loads charges can be considered in its entirety or with reduction in the calculation of moments of 2nd Order. This reduction (only for live loads) should improve the building results in relation to the horizontal displacement and instability parameter values Gamma z (γ_z).

In a first analysis, we performed the building process considering the overall live loads. In a second analysis, the reduction of live loads criterion was employed. Detailed results of this model are in Tables 1 and 2. The Gamma z (γ_z) instability parameters obtained are listed below:

- 1° Analysis:
  – Wind 90°-270°: 1,719
  – Wind 0°-180°: 1,374
- 2° Analysis:
  – Wind 90°-270°: 1,652
  – Wind 0°-180°: 1,344

As expected, reducing live loads to determine the 2nd order moments, leading to lower values for the parameter instability of the

Figure 3 – Perspective 3D

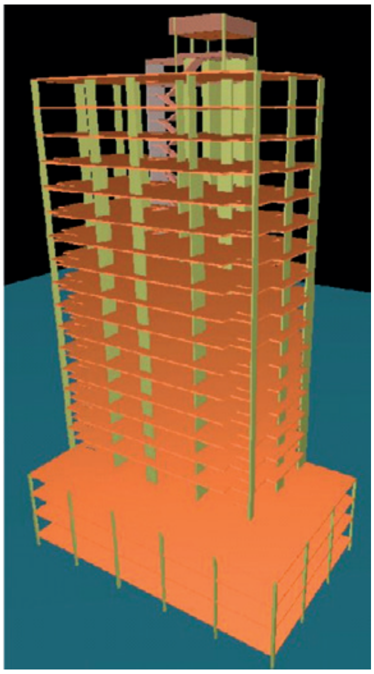


Table 1 – Model 1 - 1st analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,719	1,732
0°-180°	1,374	1,209

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	3,56(2008)	0,2(1645)
0°-180°	1,41(5096)	0,1(3282)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
5030,7	18757,7	26,82%
Concrete volume (m³)		
Colum	Total	Taxe
632	3025,6	20,89%

Process P-Delta	
RM2M1	
Combination 31	2,038
Combination 35	2,02
Combination 59	2,053
Combination 63	2,035
Combination 67	1,897

Table 2 – Model 1 - 2ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,652	1,662
0°-180°	1,344	1,159

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	3,56(2008)	0,2(1645)***
0°-180°	1,41(5096)	0,1(3282)

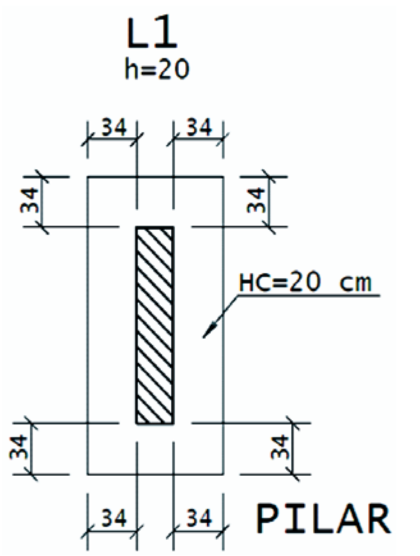
Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
5030,7	18757,7	26,82%
Concrete volume (m³)		
Colum	Total	Taxe
632	3025,6	20,89%

Process P-Delta	
RM2M1	
Combination 31	1,98
Combination 35	1,963
Combination 59	1,994
Combination 63	1,977
Combination 67	1,847

* Maximum lateral displacement of the building to the Wind Combination of State Service Limit.
** Maximum lateral displacement of a floor for Wind Combination of State Service Limit.
*** The values in parentheses indicate the ratio between the total height and the obtained displacement in each case.
List of Combinations:
Combination 31: Own weight + Permanent loads + Accidental loads(with reduction) + 0,51.Temperature loads + 0,6.Wind 270°
Combination 35: Own weight + Permanent loads + 0,8.Accidental loads(with reduction) + 0,86.Temperature loads + 0,6.Wind 270°
Combination 59: Own weight + Permanent loads + 0,8.Accidental loads(with reduction) + 0,86 Temperature loads + 0,6 Wind 180°
Combination 63: Own weight + Permanent loads + Accidental loads(whitout reduction) + 0,51 Temperature loads + Wind 180°
Combination 67: Own weight + Permanent loads + Accidental loads(with reduction) + 0,51 Temperature loads + 0,6 Wind 0°

building, but keeping the lateral displacement values (as shown in Tables 1 and 2).
During the structural and architectural design of multi-story buildings with prestressed slabs, it is relevant and advantageous to work with lightweight materials such as drywall, and laser leveling techniques, seeking thus thickness of minimum subfloor, which contribute to its structural stability. Such material and designed methodology are becoming increasingly accessible and acceptable in the national market.

Figure 4 – Chapiter dimensions



However, the model 001, the parameter value Gamma z (γ_z) is found above the acceptable limits, being the structure considered unstable by the parameters of ABNT NBR 6118 [1], although the lateral displacements meet the requirements for the State Service Limit (ELS – in Portuguese). Thus, we sought to stiffen the model by reviewing the size of the columns.

4.6 Model 2

After the stiffening of the structure by increasing the geometry of the columns (Figure 5), including the increased thickness of the rigid core 25 centimeters to 35 centimeters, a value of gamma Z was obtained at the limit of the acceptable range by the ABNT NBR 6118 [1] that is, 1,305. We sought then to assess the influence of a variation in the reduction of the coefficients to consider what the non-linearity would have on the values of the instability and lateral displacement parameters. In a first analysis, values indicated by the ABNT NBR 6118 [1] for the coefficient values were taken, which are:

- Slabs: 0,3
- Coluns:0,8
- Beams: 0,4

In a second analysis, even the Model 2, we adopted the following values for the coefficients of non-linearity:

- Slabs: 0,8
- Columns: 0,8
- Beams: 0,8

Comparing the results (see Tables 3 and 4 with results below for details), it is noted that the improvement in parameter values and displacement are negligible measurable only for certain combinations and the third decimal place, in particular the value of Gamma z (γ_z) obtained in the 2nd analysis was 1,303. This result was below expectations of improvement in the overall stability of the building. Analyzes and more refined models should be developed for verification of the results, besides the possible limitations of the program.

4.7 Model 3

Although we have found that weight reduction positively influences the overall stability of the structure, we proposed to increase the thickness of the prestressed slab model in order to examine whether the increase in stiffness of the slab-column connection and the increased of flexural transversal stiffness, would

Figure 5 – Forms of pavement type

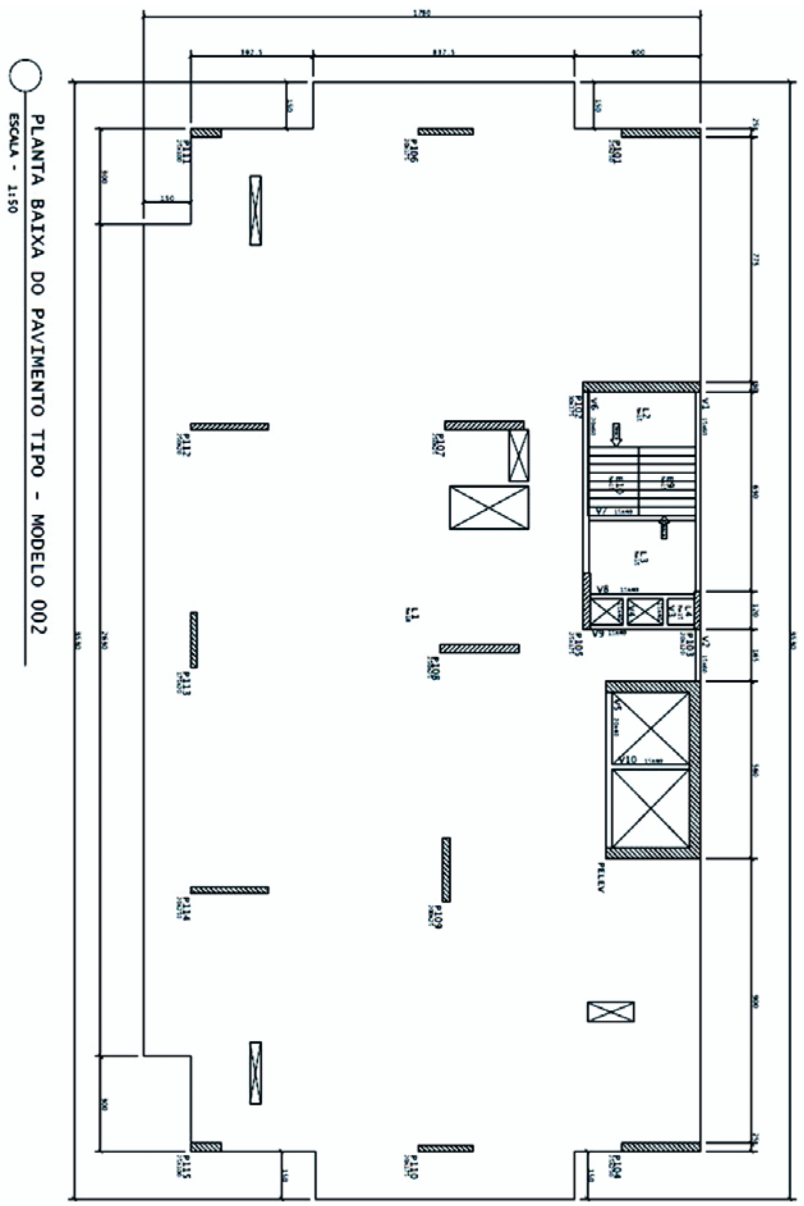


Table 3 – Model 2 - 1ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,305	1,298
0°-180°	1,248	1,030

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	3,77(1900)	0,27(1412)
0°-180°	2,08(3446)	0,18(2117)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19781,4	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3135	23,91%

Process P-Delta	
RM2M1	
Combination 31	1,536
Combination 35	1,528
Combination 59	1,564
Combination 63	1,556
Combination 67	1,456

compensate for the increased weight of the structure contributing to its overall stability.
Using model 2 based on the 2nd analysis, the thickness of the slabs increase from 18 cm to 20 cm. After processing, a direct comparison with the base model, we observed a significant improvement in the results of the parameter instability, being the value found of 1,27, and a reduction in horizontal displacements (see results detailed in Table 5 below). When keeping the initial span, it was clear that an increase in thickness of the slab would reduce active armor to 20 cm rates (prestressing tendons), quite close to the minimum consumption reasons listed by Emerick [4], ranging from 3,5 kg/m² to 5,5 kg/m², which would partially compensate the increase in the volume of concrete.
The increased of stiffness in the region connecting the slab-column along with the increase in bending of the transversal stiffness appear to justify improvement in the overall stability of the structure. In order to analyze the influence of plasticization of the region of support of the columns, a result of natural pull requests in the region, it is proposed to introduce chapiter with the same thickness of the slabs and adjust the stiffness of the bars (grid bars that simulate the slabs) this region.

4.8 Model 4

In a model of grids as the one used by CAD/TQS program, depending on their discretization, few bars intercept the column. Thus, introducing chapiter to increases the discretization grid in this region and applying a inertia flexural divider of the chapiter bars and a inertia flexural divider about the support column, it is obtain a reduction of uniform and smoothed moments, closer to

Table 4 – Model 2 - 2ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,303	1,297
0°-180°	1,248	1,030

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	3,76(1901)	0,27(1412)
0°-180°	2,08(3447)	0,18(2118)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19781,4	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3135	23,91%

Process P-Delta	
RM2M1	
Combination 31	1,536
Combination 35	1,528
Combination 59	1,564
Combination 63	1,555
Combination 67	1,455

Table 5 – Model 3 - 1ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,272	1,226
0°-180°	1,231	1,002

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	1,88(3805)	0,16(2466)
0°-180°	0,95(7500)	0,07(4348)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19776,5	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3306,6	22,67%

Process P-Delta	
RM2M1	
Combination 31	1,492
Combination 35	1,485
Combination 59	1,523
Combination 63	1,516
Combination 67	1,419

reality, without peaks of negative moments in overlapping grid bars with the columns. The total division of the stiffness of the bars in the region is the product of two values. Alternatively the use of inertia dividers bending in support of the column, you can define a coefficient of cantilever at the ends of the bars (slab) that "come" to the column, Manuals CAD/TQS [7].
By varying the value of dividers or cantilever coefficient, we attempted to reduce the negative moments in general on the columns to 85% of its original value, that is, in a direct comparison with Model 3 - 1st Analysis without chapiter and with full cantilever between slabs and columns (see detailed results in Table 6).
The chapiter were modeled in all columns of floors. The dimensions taken to the chapiter were 2d in each direction of the columns (see figure 4), where *d* is the effective depth of the slabs, equivalent to the critical perimeter punch slabs. We sought in a first analysis to reset the values of the negative moments by refining the mesh in the region of the support of the columns, therefore, to introduce the chapiter we can locally change the discretization grid. A grid was adopted twice bigger than the slab in general, that is, the distance between the bars in the region of the chapiter is half the standard distance. In the first analysis, the parameters adopted were:

- Inertia divider to the bending of the bars of chapiter:1
- Partial cantilever coefficient of the slabs on columns: 1

After the processing, it was observed that just the action to refine the mesh in support of the region, resulted in a significant reduction in the values of the bending moments (see detailed results in Table 8), and it affected the values of the instability parameter of Gamma Z , as well as lateral displacements in a negative way, but in absolute numbers, which is of little significance. The value found for Gamma Z was 1,274, which is equivalent to an increase of 0.115% (see detailed results in Table 7).

Table 6 – Moments in the region of the Coluns Model 3 - 1ª Analysis without Chapier

	Moments (tf.m)			Moments (tf.m)	
Colum	COMB17*	COMB25**	Pilar	COMB17	COMB25
P101	-4,1	-4,1	P109	-7	-6,6
P102	-3,5	-3,5	P110	-8,5	-8,7
P103	-10,7	-14,1	P111	-7,9	-8,7
P104	-5,6	-5,6	P112	-9	-8,3
P105	-18,9	-15,6	P113	-6,4	-5,6
P106	-8,9	-9,2	P114	-6,8	-6,2
P107	-8,6	-9,4	P115	-6,8	-6,6
P108	-7,9	-8,4	PELEV	-5	-5,5

Table 7 – Model 4 - 1ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,274	1,229
0°-180°	1,231	1,002

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	1,87(3832)	0,15(2506)
0°-180°	0,94(7626)	0,07(4383)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19776,5	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3306,6	22,67%

Process P-Delta	
RM2M1	
Combination 31	1,506
Combination 35	1,499
Combination 59	1,538
Combination 63	1,530
Combination 67	1,428

In the 2nd analysis, the parameters adopted were:

- Inertia divider of to the bending of the bars of chapiter: 1
- Partial cantilever coefficient of the slabs on columns: 0,85

After the processing, it was found that changing the parameter "partial cantilever coefficient of the slabs on columns" of 1 to 0.85 resulted in no significant change, either on the overall stability, is about the values of bending moments (see results detailed in Tables 9 and 10).

In a 3rd Analysis, the following values for the parameters are adopted:

- Inertia divider to the bending of the bars of chapiter: 3
- Inertia divider bending in support of intermediate pillar: 50

This time, the plasticization of the bars in the region of the chapiter, easing the structure to the point of making it be considered unstable by the premises of ABNT NBR 6118 [1]. The value of the parameter Gamma Z was found to be 1.354 (see detailed results in Table 11). In what concerns to the deviation of the bending moments, comparing it to the results of the 1st analysis with this, there were variations with up to 69% of the reduction and increasing moments up to 49%, among all the columns, being the average reduced by 15% in the value of the moments (see detailed results in Table 12).

Finally, in 4th analysis, the following values for the parameters are adopted:

- Inertia divider to the bending of the bars of chapiter : 2
- Inertia divider bending in support of intermediate column: 5

With this change, the building again showed values within the limits prescribed in the Standard Gamma Z instability parameter, being the value found 1.3 (see detailed results in Table 13). Considering the moments, comparing them with the results of the 1st analysis, there were variations up to 37% of reduction and increase of the moments up to 24%, among all the columns, being the average

Table 8 – Moments in the region of the Coluns Model 4 - 1ª Analysis

Moments (tf.m)			Moments (tf.m)		
Colum	COMB17	COMB25	Pilar	COMB17	COMB25
P101	-2,3	-2,3	P109	-4,6	-4,7
P102	-2,3	-2,1	P110	-4,2	-3,5
P103	-11	-5	P111	-5,7	-5,8
P104	-3,6	-3,3	P112	-4,1	-4,4
P105	19,7	17,9	P113	-3,5	-4
P106	-4,5	-4,3	P114	-4,1	-4,5
P107	-4,3	-3,7	P115	-4,3	-3,9
P108	-3,8	-3,3	PELEV	-4,9	-5,1

Table 9 – Model 4 - 2ª Analysis

Instability coefficients			State Service Limit (SSL)		
Wind	Gama Z	Alfa	Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	1,275	1,231	90°-270°	1,87(3832)	0,15(2506)
0°-180°	1,232	1,003	0°-180°	0,94(7626)	0,07(4383)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19776,5	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3306,6	22,67%

Process P-Delta	
RM2M1	
Combination 31	1,508
Combination 35	1,501
Combination 59	1,540
Combination 63	1,532
Combination 67	1,430

being a reduction of 9% in the amount of time (see results detailed in Table 14).
It was observed in this model the difficulty in adjusting the percentage reduction in negative moment keeping the building in the stability limit, but it is possible to see the great influence of this parameter on the overall stability. An efficient methodology for defining the level of plasticization of the support region of the slabs on the columns must require a considerably larger number of models, analyzed on different aspects, such as the rates of active and passive reinforcement region, the thickness of the slab, as well as analysis and field experiments.

4.9 Model 5

As a last model, we performed the processing of Model 3 using the IV analysis model CAD/TQS program. As previously mentioned, in this analysis model, the slabs are not part of the space frame, having their reactions transmitted to the portico that is subsequently resolved. The program identifies the lock column on each floor; however, in this model there is no contribution of the transversal bending stiffness to resist the horizontal internal forces.
After processing, there is a discrepancy between the results of Model 3 and Model 5 (see detailed results in Table 15), showing that the Model Analysis IV CAD/TQS program is not adapting to global stability analysis of building multi-stage compounds of prestressed slabs, and exemplifying the relevant difference in considering whether or not the slab as a resistant element to horizontal requests.

5. Conclusions

From the analyzes, it can be observed that despite the extra vertical loads generated by increasing the thickness of prestressed

Table 10 – Moments in the region of the Coluns Model 4 - 2ª Analysis

	Moments (tf.m)			Moments (tf.m)	
Colum	COMB17	COMB25	Pilar	COMB17	COMB25
P101	-2,3	-2,2	P109	-4,4	-4,3
P102	-2,3	-2,6	P110	-4	-4,3
P103	-11	-13,8	P111	-5,7	-5,5
P104	-3,6	-3,6	P112	-4,1	-3,8
P105	-19,7	-16,5	P113	-3,4	-3,2
P106	-4,4	-4,5	P114	-4,1	-3,6
P107	-4,2	-4,3	P115	-4,3	-4,2
P108	-3,8	-3,9	PELEV	-4,9	-5

Table 11 – Model 4 - 3ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,354	1,371
0°-180°	1,295	1,088

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	1,87(3832)	0,15(2506)
0°-180°	0,94(7626)	0,07(4383)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19776,5	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3306,6	22,67%

Process P-Delta	
RM2M1	
Combination 31	1,650
Combination 35	1,640
Combination 59	1,685
Combination 63	1,675
Combination 67	1,547

Table 12 – Moments in the region of the Coluns Model 4 - 3ª Analysis

Moments (tf.m)		
Colum	COMB17	COMB25
P101	-1,6	-1,5
P102	-1,8	-1,8
P103	-10,7	-14,1
P104	-2	-2
P105	-22	-18,4
P106	-1,4	-2,6
P107	-2,6	-4,7
P108	-4,9	-4,8

Moments (tf.m)		
Pilar	COMB17	COMB25
P109	-3,6	-3,4
P110	-2,6	-2,7
P111	-3,8	-3,6
P112	-5,1	-5,7
P113	-2,5	-3,1
P114	-6,1	-5,8
P115	-2,9	-2,8
PELEV	-5,2	-5

Table 13 – Model 4 - 4ª Analysis

Instability coefficients		
Wind	Gama Z	Alfa
90°-270°	1,304	1,293
0°-180°	1,255	1,037

State Service Limit (SSL)		
Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	2,07(3456)	0,16(2341)
0°-180°	1,07(6713)	0,08(4055)

Coluns quantitative		
Form area (m²)		
Colum	Total	Taxe
6099	19776,5	30,83%
Concrete volume (m³)		
Colum	Total	Taxe
749,6	3306,6	22,67%

Process P-Delta	
RM2M1	
Combination 31	1,567
Combination 35	1,559
Combination 59	1,600
Combination 63	1,591
Combination 67	1,478

Table 14 – Moments in the region of the Coluns Model 4 - 4ª Analysis

Moments (tf.m)			Moments (tf.m)		
Colum	COMB17	COMB25	Pilar	COMB17	COMB25
P101	-1,8	-1,8	P109	-2,9	-2,8
P102	-2,8	-3,1	P110	-2,8	-3
P103	-11	-14,1	P111	-4,4	-4,2
P104	-2,6	-2,5	P112	-5,1	-4,5
P105	-20,6	-17,2	P113	-2,3	-2,8
P106	-3	-3,1	P114	-5	-4,5
P107	-4,3	-4,4	P115	-3,1	-3,1
P108	-4,3	-4,5	PELEV	-5,2	-5,3

Table 15 – Model 5

Instability coefficients			State Service Limit (SSL)		
Wind	Gama Z	Alfa	Wind	Global Disp.(cm)	Local Disp.(cm)
90°-270°	4,913	2,481	90°-270°	12,81(559)	0,74(440)
0°-180°	2,616	1,782	0°-180°	8,09(884)	0,9(428)

slabs, the contribution to the stiffness of the links slab-columns and transverse flexural stiffness, compensate the increase in vertical load, helping significantly to the overall stability of the building. Similar conclusions were found by Martins [8], who analyzed multistory buildings compounds slabs, beams and columns, and a "U" shaped-column in the region of the elevator shaft, working as a hard core. The point is that, being the target building devoid of beams, slabs being considered as resistant elements to horizontal forces, become even more relevant, as well as a coherent account of the degree of plasticization of the bars that simulate the slabs in the binding region with columns. Being the fine-tuning of this last parameter something which must be carefully investigated in future research. Thus, the slab-column connection takes another role: of influencing the global stability of the structure, besides being a limiter for spans of prestressed slabs due to shear stress (puncture).
Observing Model 5, there is no doubt that an algorithm that does not take into account the full slab contribution to the overall stability of multistory buildings formed by prestressed slabs, it is not suitable for analysis of this type of building, leading to conflicting results and that would incorrectly subvert this type of structure.

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