Structural Analysis Regarding to the Influence of Increases in the Compressive Strength of Reinforced Concrete Structures in Standard Buildings of Different Number of Floors

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Abstract—**High Performance Concretes (HPC) are still unusual in Brazilian structures. However, they can bring several benefits such as: reduction of structural elements sections, optimizing the floor area and height; reduction of maintenance; and durability increases. This study aimed analyzing the influence of concrete strength and building's height, in structural parameters, utilizing the Eberick V8 software. The performance improvement is more significant the higher the building gets. Related to the global stability coefficient (γz) in the x direction, this parameter reduced when the compressive strength of the concrete increased (25, 50 and 80 MPa), being this reduction greater when the building had more floors. Regarding to the horizontal displacements, in both directions, this parameter reduced with the increase of the compressive strength and increased with the increase of the quantity of floors. Therefore, the use of HPC demonstrates to improve the conditions of global stability and to reduce horizontal displacements with better results in larger buildings.**

Keywords— **Displacements, Global Stability, High Performance Concrete and Structural Design**

I. INTRODUCTION

Civil construction is in constant evolution, mainly when it refers to the use of new materials and construction techniques. This evolution made it possible to manufacture concretes with High-performance concretes (HPC) using chemical admixtures in the production of this cementitious composite or simply adjusting the mix proportion and the water/cement ratio which influences the porosity of the mixture, where the higher the ratio, the greater the porosity of the concrete, and the lower the compressive strength (Souza et al., 2012). However, in most of the works carried out in Brazil, it is adopted reinforced concrete with characteristic compressive strength (f_{ck}) of 25 MPa, which is the minimum required for reinforced concrete structures built in environments with environmental aggressiveness class II (urban environment, with small risk of deterioration of the structure), according to NBR 6118 (ABNT, 2014) equivalent to exposure class F0 from ACI 318-14 (ACI, 2014).

The HPC must have, at the same time, high workability, high strength and high durability (Tutikian et al., 2011) which are regarded as favorable factors of being a construction material.

High-performance concretes also have a sustainable character, since with the capacity of high resistance the volume of materials consumed in the structures is reduced (Valin Jr et al., 2013). Also, developments in this material have even led to it being a more ecological material in the sense that the components—admixtures, aggregates, and water—are used to their full potential to produce a material with a longer life cycle (Aïtcin, 2003). Thus, the use of high strength concretes must be seen as an investment, and not as an unnecessary expense.

In addition to these aspects, the strength of concretes also influences other characteristics, such as their modulus of elasticity, which interferes in their deformations. Therefore, this article reunites not only data and concepts about reinforced concretes, but also an analysis of the structures in terms of deformability and stability of the building.

Although it is common to use concretes with lower strengths, much research has been performed in Brazil utilizing concretes with better properties. Many construction companies and technical professionals are unfamiliar, or just do not have more accessible information related to this type of material. Therefore, a continuous study related to the improvement of input materials and demonstrations in daily situations of how these concretes can be applied, has a great importance. Changing, thus, the culture of comfort that exists in the civil construction industry, of always opting for the simplest and usual, which is not always the most economical and feasible. This work aims to analyze the behavior of reinforced concrete structures with varied compressive

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strength values and what this influence on horizontal displacements and on the global stability of the building.

II. THEORETICAL REFERENCE

For the present work, the main characteristics of the concrete to be considered are the compressive strength of the material and the modulus of elasticity, both characteristics of concrete in the hardened state

A. *Compressive strength*

The strength of a concrete is the most valued property in relation to quality control and there are several factors of great importance that will directly influence the final strength of the concrete, such as the water/cement ratio, density and curing process (Metha and Monteiro, 2014). Compressive strength is the main property of concrete in its hardened state, once it commonly has an excellent behavior when subjected to compressive efforts (Petrucci and Paulon, 2005).

The characteristic concrete strength, shorted by f_{ck}, is the strength value that has a 5% probability of not being reached, in tests of specimens of a specific batch of concrete after 28 days of its molding (Pinheiro et al., 2004). NBR 8953 (ABNT, 2015) defines the strength classes of the concretes according to their f_{ck}, being designated by the letter C followed by the value of the characteristic compressive strength. For example, C30 class concretes correspond to a concrete with f_{ck} of 30MPa. These classes are divided into group I, which covers concretes from class C20 to C50, and group II, including concretes from C55 to C80.

B. *Modulus of elasticity*

According to the Brazilian standard NBR 6118 (ABNT, 2014) equivalent to ACI 318-14 (ACI, 2014), the secant modulus of elasticity to be used in the elastic analysis of the design project, especially for the determination of requesting efforts and checking service limit states, must be calculated by Equation 1.

$$E_{cs} = 0.85 \cdot E_{ci} \tag{1}$$

Where:
E_{cs}: secant modulus of elasticity (MPa).
E_{ci}: initial modulus of elasticity, determined by Equation 2.

$$E_{ci} = 5600 \cdot (f_{ck})^{1/2} \tag{2}$$

Where:
f_{ck} : characteristic compressive strength at 28 days (MPa).

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C. *Figures*

Format and save your graphic images using a suitable graphics processing program that will allow you to create the images as PostScript (PS), Encapsulated PostScript (EPS), or Tagged Image File Format (TIFF), sizes them, and adjusts the resolution settings. If you created your source files in one of the following you will be able to submit the graphics without converting to a PS, EPS, or TIFF file: Microsoft Word, Microsoft PowerPoint, Microsoft Excel, or Portable Document Format (PDF).

D. *Reinforced concretes*

It is defined as reinforced concrete, according to NBR 6118 (ABNT, 2014) equivalent to ACI 318-14 (ACI, 2014), those whose structural behavior depends on the adhesion between concrete and reinforcement, and in which the initial reinforcement stretches are not applied before this adhesion materializes.

E. *High performance concretes*

A High- performance concrete is a material that presents a behavior at a higher level than a conventional concrete. The term high performance concrete is not just related to strength; durability is also one of the key attributes of HPC as a construction material (Salas et al., 2013). In this type of concrete some type of addition is always used, such as supplementary cementitious material (e.g. fillers) or chemical admixtures (e.g. superplasticizers). As HPC are dosed using a low water/cement ratio, it is necessary to apply substances that provide a better fluidity of the mixture. Thus, superplasticizers appear, which are highly efficient water-reducing admixture, because they are capable of reducing the water content from 3 to 4 times in a given concrete mixture, when compared to conventional water-reducing admixture (Metha and Monteiro, 2014). These substances are able to reorganize the particles that make up the concrete providing an arrangement capable of flowing with a smaller amount of water. Since the strength of the concrete is inversely proportional to the w/c ratio, superplasticizers provide greater resistance to the concrete.

F. *Global Stability (γ_z)*

To study the global stability of the structure, and the effects caused by the increase in the concrete strength applied in this study, a stability parameter known as Gamma Z (γ_Z) will be used. The Brazilian standard NBR 6118 (ABNT, 2014) defines that this coefficient takes into account the importance of global second-order efforts and is valid for reticulated structures composed of at least four floors.

Global second-order effects are related to the building as a whole, which includes all its structural elements. These can be defined as additional effects generated in a structure when its equilibrium is taken from an already deformed position (Pilz et al., 2019).

The structure analyzed through this coefficient is considered to be formed by fixed nodes if the condition $\gamma_z \leq 1.1$ is obeyed.

The value of γ_z is given by the Equation 3:

$$\gamma_z = \frac{1}{1 - \frac{\Delta M_{tot,\,d}}{M_{1,\,tot,\,d}}} \tag{3}$$

Where:

$M_{1,\,tot,\,d}$: is the sum of the moments of all horizontal forces in relation to the base of the structure (kN·m);

$\Delta M_{tot,\,d}$: is the sum of the products of the vertical forces acting on the structure by the horizontal displacements of their respective points of application, obtained from the first-order analysis (kN·m).

G. Moment of inertia

The moment of inertia of a building is something that must be analyzed, since assuming that one of the dimensions of a building is much larger than the other dimension, the moment of inertia and consequently the rigidity of that first direction will be much greater than the other. Thus, the most critical efforts and dislocations will be in that direction with less moment of inertia. Taking into account this data, it is possible to perform changes and optimization of structural element sections, so that the building behaves in a more stable way.

III. MATERIALS AND METHODS

In order to perform this research, a bibliographical review about the characteristics of the concretes was assumed as a premise. The continuity of the study used a standard architectural floor plan for all simulations, which were carried out in the structural design Eberick V8 software by AltoQi - Information Technology Company, one of the most used software in structural design project of reinforced concrete in Brazil. The analysis was performed considering structural concretes of compressive strength of 25, 50 and 80 MPa.

Initially, a hypothetical architectural floor plan was defined, followed by the definition of the structural model was defined. Once the structural elements were insert in the Eberick V8 software, simulations were performed varying the number of floors (4, 8, 12 and 16 floors) and the compressive strength of the concrete (25, 50 and 80 MPa) in the beams and columns of the building. Thus, the interference of these variations in the horizontal deformation on the global stability of the building was analyzed.

IV. RESULTS AND DISCUSSION

Initially, a hypothetical architectural floor plan, measuring 25.00 x 14.70 m, with a projection area of 367.50 m², was defined, in which the columns were located, which would have the same section in all simulations. The floor plan of the standard pavement shapes is shown in Fig. 1.

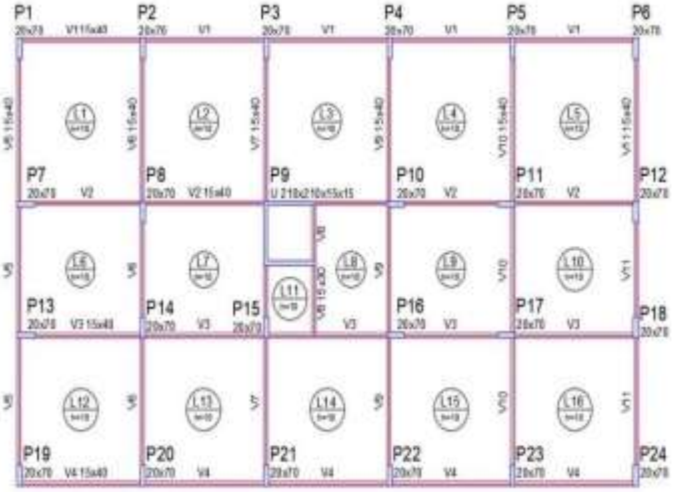

Fig. 1: Structural drawing of the standard floor.
Source: Adaptation from Eberick V8 software

When modeling such structure in the Eberick V8 software, in this first situation with 4 floors, the load acting on all beams was defined as 450 kgf/m, in order to simulate the masonry load. For slabs, the load of 150 kgf/m² represents the accidental load for residential buildings in bedrooms, living rooms, pantries, kitchens and bathrooms, according to the Brazilian standard NBR 6120 (ABNT, 2019) equivalent to ASCE/SEI 7-16 (ASCE, 2016). The load of coatings on the slabs was estimated at 80 kgf/m². The wind speed of 45 m/s was considered, being an estimation for the region of Cascavel (Paraná, Brazil), according to the wind speed isopleth of the Brazilian standard NBR 6123 (ABNT, 2013). The class of environmental aggressiveness was considered moderate (class of environmental aggressiveness II), which is found in urban environments. The height of each floor (difference in level between the floor of two consecutive floors) was considered 290 cm. In Fig. 2, the modeling of the structure is presented.

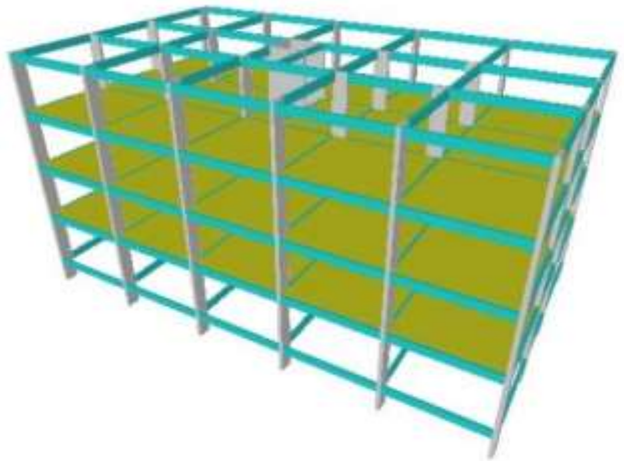

Fig. 2: 3D view of the initial structure.
Source: Eberick V8 Software

After the modeling of this structure was completed, the material of the columns, beams and slabs was defined as being the concrete of class C25 (concrete with f_{ck} of 25 MPa). As the aim of the study is to analyze the deformations and the global stability, the important data are the horizontal displacement and γ_z.

The continuation of the study deals with the same building, but with columns and beams being made of concrete of class C50 and, in another simulation, concrete of class C80, keeping the sections and loads of structural elements constant, thus obtaining the data presented in Table I.

TABLE I
MODELING WITH 4 FLOORS.

F_{ck} (MPa)	γ_z limit	γ_z of x	γ_z of y	Limit displacement (cm)	Displacement in x (cm)	Displacement in y (cm)
25	1.10	1.02	1.01	0.77	0.05	0.08
50	1.10	1.01	1.01	0.77	0.04	0.06
80	1.10	1.01	1.01	0.77	0.03	0.05

The limit γ_z and limit displacement values are constant. The γ_z limit coefficient of 1.10 means that the structure will be considered in its structural analysis as consisting of fixed nodes. From this value, the structure is considered to be formed by mobile nodes, up to the limit of $\gamma_z = 1.30$. The limit displacement is calculated according to the height of the structure, according to the Brazilian standard NBR 6118 (ABNT, 2014), determined by the Equation 4.

$$\text{Displacement limit} = H/1700 \qquad (4)$$

Where H is the height of the building.

The analysis that the Eberick V8 software makes of the effective displacement is related to the efforts of the wind for frequent combination (Silva, 2013).

Then, 4 more floors were included in the initial structure, totaling 8 floors, maintaining the characteristics of sections, loads and location of columns, beams and slabs, which were once again made up of C25 concrete. After collecting the relevant data, the f_{ck} of the columns and beams was changed to 50 MPa and also to 80 MPa, the data being shown in Table II.

TABLE II
MODELING WITH 8 FLOORS.

F_{ck} (MPa)	γ_z limit	γ_z of x	γ_z of y	Limit displacement (cm)	Displacement in x (cm)	Displacement in y (cm)
25	1.10	1.07	1.05	1.45	0.45	0.71
50	1.10	1.05	1.03	1.45	0.32	0.50
80	1.10	1.04	1.03	1.45	0.25	0.40

In these simulations, the limit displacement changes from 0.77 cm to 1.45 cm. In relation to the γ_z coefficient, the structure had not crossed the limit value of 1.10 yet, so it was still considered to be made up of fixed nodes.

Continuing the study, 4 floors were inserted, reaching a total of 12 floors, making the simulations with beams and pillars consisting of concrete of classes C25, C50 and C80, respectively. Table III presents the data obtained for these simulations.

TABLE III
MODELING WITH 12 FLOORS.

F_{ck} (MPa)	γ_z limit	γ_z of x	γ_z of y	Limit displacement (cm)	Displacement in x (cm)	Displacement in y (cm)
25	1.10	1.15	1.10	2.14	1.40	2.36
50	1.10	1.10	1.07	2.14	0.99	1.67
80	1.10	1.08	1.05	2.14	0.78	1.32

To complete the analysis, 4 more floors were added to the previous structure, totaling 16 floors, again with the same configuration as the previous structures and varying the f_{ck} of columns and beams, again being of 25 MPa, 50 MPa and 80 MPa. The results obtained are shown in Table IV.

TABLE IV
MODELING WITH 16 FLOORS.

F_{ck} (MPa)	γ_z limit	γ_z of x	γ_z of y	Limit displacement (cm)	Displacement in x (cm)	Displacement in y (cm)
25	1.10	1.25	1.17	2.82	3.74	6.26
50	1.10	1.16	1.12	2.82	2.18	3.80
80	1.10	1.13	1.09	2.82	1.72	3.01

Through the γ_z coefficient results, it was noticed that the structure has a better performance on the y-axis, however analyzing the displacement results, the most favorable is the x-axis. This is due to the fact that most columns have their greatest moment of inertia favorable to stability on the y-axis (around the x-axis). For the displacements, the largest dimension of the structure is on the x-axis, as well as the displacements are also smaller at x-axis, since the greatest moment of inertia of the building in general is more favorable in this direction.

To equalize or make the coefficient γ_z more similar in the two axes, one option would be to rotate, for example, the columns P8 and P14, however this would cause the increase of the displacement in y direction, worsening the performance of the structure in this aspect. To solve the two situations, you can also increase the section of columns and beams and create more rigid cores (wall-pillars). As determined by the Brazilian standard NBR 6118 (ABNT, 2014), when the γ_z coefficient exceeds the limit of 1.10 the structure is considered to consist of mobile nodes. This means that the effects of geometric non-linearity and physical non-linearity must be considered and, when dimensioning such a structure, the global and local second-order effects, which the Eberick V8 software calculates through the P-Delta process, must be considered.

This calculation procedure is valid for the γ_z limit value of 1.30. The simulated structures with 12 floors in C25 concrete and all structures with 16 floors fit this situation. If the γ_z coefficient is below 1.10, this means that the structure is formed by fixed nodes and its calculation is performed considering singly each compressed element. The fact that the structure is classified as being made up of fixed nodes dispenses with the consideration of global second-order efforts. Another aspect analyzed was the change in coverings. The Brazilian standard NBR 6118 (ABNT, 2014) mentions that, for concrete with a strength class higher than the minimum required, the coverings of the reinforcement can be reduced by up to 5.0 mm, being increased from 3.0 cm to 2.5

cm. In this study, as the intention was to maintain the constant section of the elements, this information served to increase the lever arm of the longitudinal reinforcements, optimizing their structural function.

This change has no effect on these two parameters analyzed, but on the design of the reinforcement, which is not the focus of this study, but is an advantage obtained when using concrete with greater characteristic compressive strength than the minimum recommended by standardization. It was noticed that there was no significant increase in global stability in models with 8 and 4 floors, and it would not even be necessary, since acceptable results were obtained. In models with 12 and 16 floors, the use of concretes with higher f_{ck} had a significant improvement in the γ_z coefficient and in the displacements.

V. CONCLUSION

For the global stability in the simulation with 4 floors, the use of concretes from C25 to C80 in the x direction was reduced by only 0.98% and in the y direction it did not change. In the simulation with 16 floors, the reduction in the x-axis was 9.60% and, in y-axis, 6.84%. In relation to horizontal displacements, in the analysis with 4 floors on the x-axis there was a reduction of 40% and on the y-axis it reduced 37.50%. In the simulation with 16 floors, in x the reduction in horizontal displacement was 54.01% and, in y, 51.92%.

Considering the analyzes with 4 and 8 floors, the increase in concrete strength was not justified, since the structures simulated with C25 concrete already met the established limits. However, the projection area of the structure and the dimension of the columns influenced them to present such parameters so far from the limit, as established in the Brazilian standard. If the structure had a smaller projection area and smaller columns, certainly the parameters analyzed would be closer to the tolerated limits, as they are factors that influence the behavior of the structure for both stability and displacements.

However, for the situation in question, the use of high strength concretes to benefit global stability and reduce horizontal displacements due to wind effort is more relevant for large-scale constructions, presenting even other advantages, such as the optimization of spaces and greater durability of the material.

REFERENCES

[1] American Concrete Institute. ACI 318-14 (2014) Building code requirements for structural concrete. Michigan: ACI.

[2] American Society of Civil Engineers. ASCE/SEI 7-16 (2016) Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Virginia: ASCE.

[3] Aïtcin PC (2003) The durability characteristics of high-performance concrete: a review. Cement and Concrete Composites 25(4): 409-420. DOI: 10.1016/S0958-9465(02)00081-1.

[4] Brazilian Association of Technical Standards. NBR 6118:2014 (2014) Design of concrete structures - Procedure. Rio de Janeiro: ABNT.

[5] Brazilian Association of Technical Standards. NBR 15575-1:2013 (2013) Residential buildings - Performance Part 1: General requirements. Rio de Janeiro: ABNT.

[6] Brazilian Association of Technical Standards. NBR 8953:2015 (2015) Concrete for structural use - Density, strength and consistency classification Rio de Janeiro: ABNT.

[7] Brazilian Association of Technical Standards. NBR 8681:2003 (2003) Actions and safety of structures - Procedure. Rio de Janeiro: ABNT.

[8] Brazilian Association of Technical Standards. NBR 6120:2019 (2019) Design loads for structures. Rio de Janeiro: ABNT.

[9] Brazilian Association of Technical Standards. NBR 6123:2013 (2013) Building construction - Bases for design structures - Wind loads - Procedure. Rio de Janeiro: ABNT.

[10] P.S.L. Souza, I. Carvalho, R. Preza, R. Togneri and A. Bueno (2012) Effects of partial replacement of cement by silica fume on the performance of concrete in terms of compressive strength and sulphate attack (in Portuguese). In: 54th Brazilian Congress of Concrete (ed IBRACON), Maceió, BR, 8-11 October 2012, pp. 1-16. São Paulo: IBRACON.

[11] L.M. Pinheiro, C.D. Muzardo and S.P. Santos (2004) Características do Concreto. In: Pinheiro LM (eds) Estruturas de Concreto. São Paulo: Engineering School of São Carlos (EESC), pp. 1-10. Available at: www.fec.unicamp.br/~almeida/ec702/EESC/Concreto.pdf (accessed 25 May 2020).

[12] P.K. Metha and P.J.M. Monteiro (2014) Concreto: estruturas, propriedades e materiais. São Paulo: IBRACON.

[13] S.E. Pilz, R. Ribeiro, D. Pilz, R.C. Pavan and M.F. Costella (2019). Global stability analysis in reinforced concrete buildings with transfer beams. Proceedings of the Institution of Civil Engineers - Structures and Buildings, 172(9), 685–699. DOI: 10.1680/jstbu.17.00120

[14] E.G.R. Petrucci and V.A. Paulon (2005) Portland cement concrete (in Portuguese). Porto Alegre: Globo.

[15] A. Salas, S. Delvasto and R. M. Gutiérrez (2013). Developing high-performance concrete incorporating highly reactive rice husk ash. Ingeniería e Investigación, 33(2), 49-55.

[16] F.M. Silva (2013) Horizontal Displacement (in Portuguese). Available at: http://faq.altoqi.com.br/content/255/626/pt-br/deslocamentos-horizontais.html (accessed in 20 February 2018).

[17] B.F. Tutikian, G.C. Isaia, P. Helene (2011) High and Ultra-High-Performance Concrete (in Portuguese). In: Isaia GC (eds) Concreto: Ciência e Tecnologia. São Paulo: IBRACON, v. 2, pp. 1283-1325.

[18] M.O. Valin Jr, P.H.A. Silva, M.D.C. Brito, L.G.B. Fleury and Silva DGS (2014) The viability of using the high-performance concrete (in Portuguese). In: 56th Brazilian Congress of Concrete (ed IBRACON), Natal, BR, 7-10 October 2014, pp. 1-16. São Paulo: IBRACON.