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PARAMETRIC ANALYSIS OF THE MAIN DESIGN VARIABLES IN THE STEEL AREA AND THE RESISTANT CAPACITY OF REINFORCED CONCRETE COLUMNS, BEAMS AND SLABS

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ABSTRACT

Reinforced concrete elements are present in practically all constructions. Considering this and the high costs of construction materials, the sensitivity of the engineer in the project in reinforced concrete regarding the project choices, which are fundamental to guarantee an efficient project, is important. In this context, the present work aimed to investigate, through parametric analysis, the influence of the main design variables in the steel area and the resistant capacity of columns, beams, and slabs in reinforced concrete. 28 cases of columns, 32 beams, and 30 solid slabs were analyzed. In elements predominantly subjected to bending (slabs and beams), height was the parameter that exerted the greatest influence on the resistant moment and steel area. On the other hand, the concrete class had little effect on the resistant moment and the required steel area. In addition, the beam width showed intermediate sensitivity. Specifically, in the slabs, the embedding of the edges provided a reduction of the positive moment and the positive steel area, in addition to reducing the slab deflections. However, it causes greater consumption of steel, since negative longitudinal reinforcement is required. As for columns, if the objective is to decrease the longitudinal reinforcement steel area, there is a limit up to which increasing the strength of the concrete has results. On the other hand, if the intention is to increase the strength of the column, it is necessary to work with concretes with higher strength classes. Furthermore, it was found that the buckling length of the column causes significant variations in the reinforcement ratio.

Keywords: reinforced concrete; parametric analysis; sensitivity analysis.

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1 INTRODUCTION

The constructive system in reinforced concrete is widely spread and used in Brazil. However, despite its intense use, this fact does not mean that it is the most economical. Currently, with the great competition in the market, the high cost of construction materials, and the demand for qualified professionals, the sensitivity of the professional in the reinforced concrete project regarding the variables on which he depends, to obtain an efficient project, which considers cost and economy.

Nationally, the design of reinforced and prestressed concrete structures is guided by NBR 6118 (ABNT, 2014). In this context, several works have performed parametric analyzes on structural elements in reinforced concrete in the last 20 years (Brisotto, 2021; Carvalho Neto, 2019; Costa, 2021; Felix et al., 2017; Kunzier, 2013; Miranda, 2018; Paula, 2020; Real, 2000; Schmaltz, 2015; Silva et al., 2008; R. C. Soares, 2001; S. L. Soares, 2009). Among the works cited, is the research by Felix et al. (2017), Schmaltz (2015), and Paula (2020).

Felix et al. (2017) performed a parametric analysis of carbonation in reinforced concrete structures. To do so, he used Artificial Neural Networks via the object-oriented language C++. Among the main results, the authors observed that: carbonation decreases as the compressive strength of the concrete increases; and that the content of additions influences the carbonation in an inversely proportional way to the concrete strength.

In turn, Schmaltz (2015) investigated, through parameterizations, the effect of reinforcement in reinforced concrete frames using the theory of damage mechanics. The methodology described by the researcher demonstrated efficiency in predicting micro defects and also proved to be useful to aid in the compression of cracking effects.

Finally, Paula (2020) performed a parametric analysis on mixed steel and concrete-filled columns. In this work, it was observed that the diameter of the tubular column was the parameter that had the greatest influence on the strength of the structural element. Then, on the sensitivity scale, the area of steel reinforcement present in the cross-section was represented. Finally, the column length was the parameter that caused the least changes in the column's compressive strength.

Among the national works, which are based on the Brazilian technical standard NBR 6118 (ABNT, 2014), none were identified that simultaneously analyzed the effect of the main design variables on the design of beams, columns, and slabs.

Given this, the present paper aims to investigate, through parametric analysis, the influence of design variables on the bearing capacity of beams, columns, and slabs in reinforced concrete.

2 METHODOLOGY

The present work carried out parametric analyzes varying the characteristic compressive strength of concrete (fck), the transverse geometry and the longitudinal reinforcement steel ratio. Specifically, in the parametric analysis, the objective was to study the following parameters:

- Influence of fck, cross-section height and buckling length on the compressive strength and on the steel area of longitudinal reinforcement of columns;
- Influence of fck and the height and width of the section on the bending moment resistance and the steel area of longitudinal reinforcement of beams;
- Influence of fck, slab thickness and type of edge restraint on the bending moment resistance and the longitudinal reinforcement steel area of solid slabs.

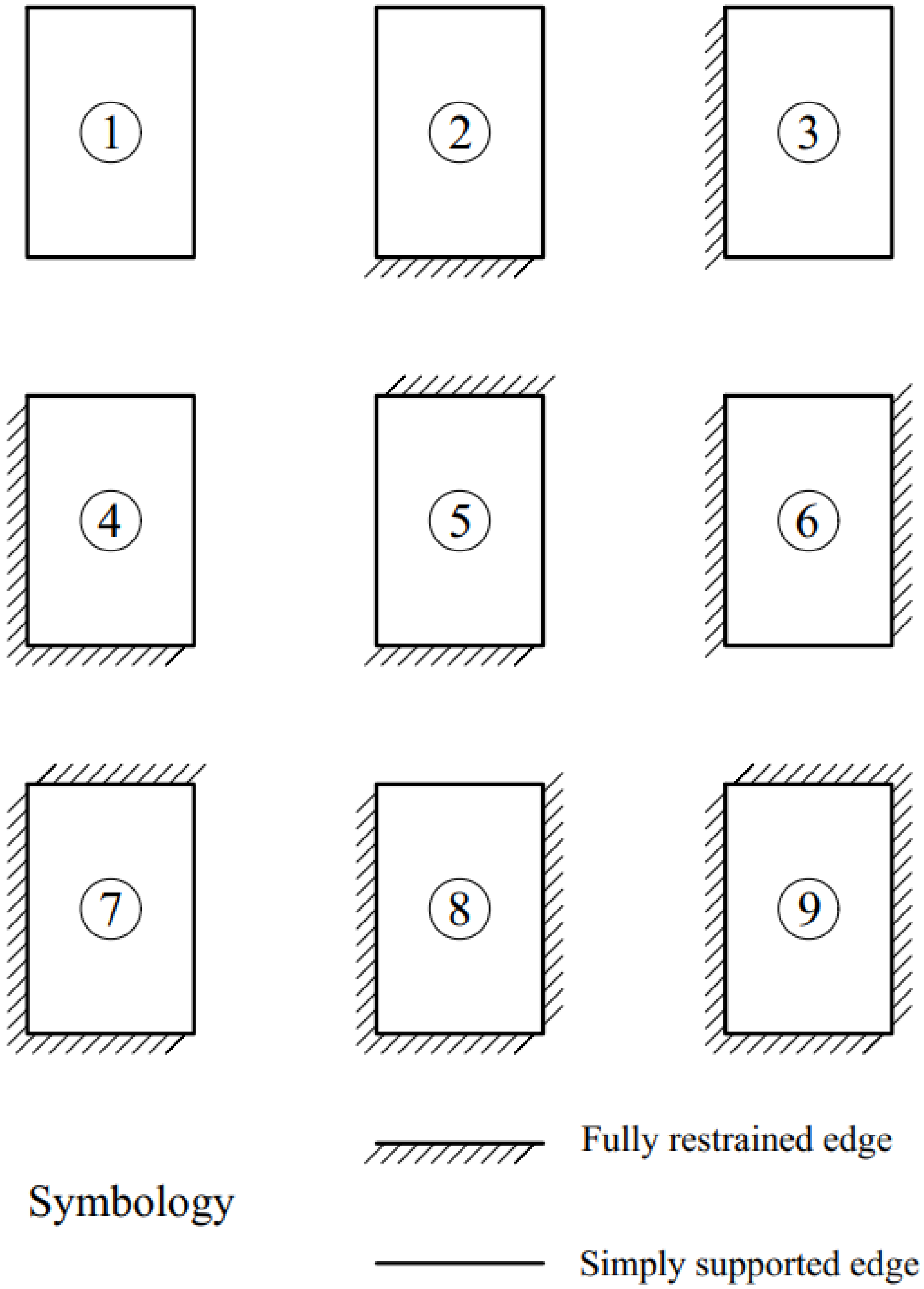
For this purpose, 28 cases of columns, 32 beams, and 30 solid slabs were analyzed. In the parameterizations, it was admitted:

- A rectangular cross-section in beams and columns;
- The width of the cross-section (b_w) of columns and beams is equal to 19 cm;
- Concrete cover of reinforcing steels equal to 3.0 cm for beams and columns and 2.5 cm for slabs;
- Armor with CA-50 steel;
- Transverse reinforcement with a diameter of 5 mm;
- Longitudinal reinforcement with a diameter of 10 mm;
- Square slabs with a fixed span of 3.50 m;
- Beam span equal to 10 times the height of the cross-section;
- The analysis of the column only concerning the axis of greatest inertia;
- Central pillars, that is, with initial eccentricity equal to zero. In addition, zero form eccentricity was considered;
- Design compression axial load (N_d) requesting the columns with an intensity of 1,120 kN, equivalent to a five-story building with a distributed load of 10 kN/m², acting in an area of influence of 16 m² (4x4 m), considering an augmenting coefficient of 1.4;
- Distributed vertical design load (p_d) on the slabs equal to 14 kN/m², equivalent to a characteristic distributed vertical load of 10 kN/m², weighted by a factor of 1.4;
- Linear vertical load on the beams (q_d) is equal to 2.5·L, in kN/m, where L is the longitudinal span of the beam. Such load is obtained by considering that, in a fully supported square slab with span L, 25% of the total load on the slab goes to each of the beams that surround it; and that the vertical distributed design load on the slabs is 14 kN/m².

To assist in the determination of the longitudinal reinforcement steel area of the columns, the abacuses developed by Venturini and Rodrigues (1987) were used for the design of rectangular pieces of reinforced concrete, requested to pure bending.

In the parameterization of the type of connection of the slabs, the 9 situations presented in Figure 1 were analyzed. In the parameterization of the type of connection of the slabs, the 9 situations presented in. Such typologies are defined in the book by Carvalho and Figueiredo Filho (2014). They present a methodology to determine the internal moments that require the slab and this was used in the present work.

Figure 1: Slabs types as a function of edge restrictions.



Source: Adapted from Carvalho and Figueiredo Filho (2014).

Tables 1, 2 and 3, respectively, present the properties of the cases studied for columns, beams and solid slabs, respectively.

Table 1: Description of the analyzed columns.

Case	Parameterization	b [m]	h [m]	L [m]	n_{floors}	N_d [kN]	f_{ck} [kN/m²]
1	Study of the influence of the concrete characteristic compressive strength (f_{ck})	0.19	0.40	4.00	5	1,120	15,000
2		0.19	0.40	4.00	5	1,120	20,000
3		0.19	0.40	4.00	5	1,120	25,000
4		0.19	0.40	4.00	5	1,120	30,000
5		0.19	0.40	4.00	5	1,120	35,000
6		0.19	0.40	4.00	5	1,120	40,000
7		0.19	0.40	4.00	5	1,120	45,000
8		0.19	0.40	4.00	5	1,120	50,000
9	Study of the influence of the cross-section height	0.19	0.20	4.00	5	1,120	30,000
10		0.19	0.25	4.00	5	1,120	30,000
11		0.19	0.30	4.00	5	1,120	30,000
12		0.19	0.35	4.00	5	1,120	30,000
13		0.19	0.40	4.00	5	1,120	30,000
14		0.19	0.45	4.00	5	1,120	30,000
15		0.19	0.50	4.00	5	1,120	30,000
16		0.19	0.55	4.00	5	1,120	30,000
17		0.19	0.60	4.00	5	1,120	30,000
18		0.19	0.65	4.00	5	1,120	30,000
19		0.19	0.70	4.00	5	1,120	30,000
20		0.19	0.75	4.00	5	1,120	30,000
21		0.19	0.80	4.00	5	1,120	30,000
22	Study of the buckling length influence	0.19	0.40	3.00	5	1,120	30,000
23		0.19	0.40	3.50	5	1,120	30,000
24		0.19	0.40	4.00	5	1,120	30,000
25		0.19	0.40	4.50	5	1,120	30,000
26		0.19	0.40	5.00	5	1,120	30,000
27		0.19	0.40	5.50	5	1,120	30,000
28		0.19	0.40	6.00	5	1,120	30,000

Source: Authors (2022).

Table 2: Description of the analyzed beams.

Case	Parameterization	b_w [m]	h [m]	L [m]	p_d [kN/m]	f_{ck} [kN/m²]
1	Study of the influence of the concrete characteristic compressive strength (f_{ck})	0.19	0.50	5.00	12.50	15,000
2		0.19	0.50	5.00	12.50	20,000
3		0.19	0.50	5.00	12.50	25,000
4		0.19	0.50	5.00	12.50	30,000
5		0.19	0.50	5.00	12.50	35,000
6		0.19	0.50	5.00	12.50	40,000
7		0.19	0.50	5.00	12.50	45,000
8		0.19	0.50	5.00	12.50	50,000
9	Study of the influence of the cross-section height	0.19	0.20	2.00	5.00	30,000
10		0.19	0.25	2.50	6.25	30,000
11		0.19	0.30	3.00	7.50	30,000
12		0.19	0.35	3.50	8.75	30,000
13		0.19	0.40	4.00	10.00	30,000
14		0.19	0.45	4.50	11.25	30,000
15		0.19	0.50	5.00	12.50	30,000
16		0.19	0.55	5.50	13.75	30,000
17		0.19	0.60	6.00	15.00	30,000
18		0.19	0.65	6.50	16.25	30,000
19		0.19	0.70	7.00	17.50	30,000
20		0.19	0.75	7.50	18.75	30,000
21		0.19	0.80	8.00	20.00	30,000
22	Study of the influence of the cross-section width	0.10	0.50	5.00	12.50	30,000
23		0.12	0.50	5.00	12.50	30,000
24		0.14	0.50	5.00	12.50	30,000
25		0.16	0.50	5.00	12.50	30,000
26		0.18	0.50	5.00	12.50	30,000
27		0.20	0.50	5.00	12.50	30,000
28		0.22	0.50	5.00	12.50	30,000
29		0.24	0.50	5.00	12.50	30,000
30		0.26	0.50	5.00	12.50	30,000
31		0.28	0.50	5.00	12.50	30,000
32		0.30	0.50	5.00	12.50	30,000

Source: Authors (2022).

Table 3: Description of the analyzed solid slabs.

Case	Parameterization	$l_x = l_y$ [m]	h [m]	f_{ck} [kN/m²]	Edge restriction type
1	Study of the influence of the concrete characteristic compressive strength (f_{ck})	3.50	0.12	15,000	1
2		3.50	0.12	20,000	1
3		3.50	0.12	25,000	1
4		3.50	0.12	30,000	1
5		3.50	0.12	35,000	1
6		3.50	0.12	40,000	1
7		3.50	0.12	45,000	1
8		3.50	0.12	50,000	1
9	Study of the influence of the cross-section height	3.50	0.08	30,000	1
10		3.50	0.09	30,000	1
11		3.50	0.10	30,000	1
12		3.50	0.11	30,000	1
13		3.50	0.12	30,000	1
14		3.50	0.13	30,000	1
15		3.50	0.14	30,000	1
16		3.50	0.15	30,000	1
17		3.50	0.16	30,000	1
18		3.50	0.17	30,000	1
19		3.50	0.18	30,000	1
20		3.50	0.19	30,000	1
21		3.50	0.20	30,000	1
22	Study of the influence of constraints on the slab edges	3.50	0.12	30,000	1
23		3.50	0.12	30,000	2
24		3.50	0.12	30,000	3
25		3.50	0.12	30,000	4
26		3.50	0.12	30,000	5
27		3.50	0.12	30,000	6
28		3.50	0.12	30,000	7
29		3.50	0.12	30,000	8
30		3.50	0.12	30,000	9

Source: Authors (2022).

All the design procedures for beams, columns, and solid slabs were carried out based on the recommendations of NBR 6118 (ABNT, 2014).

3 RESULTS

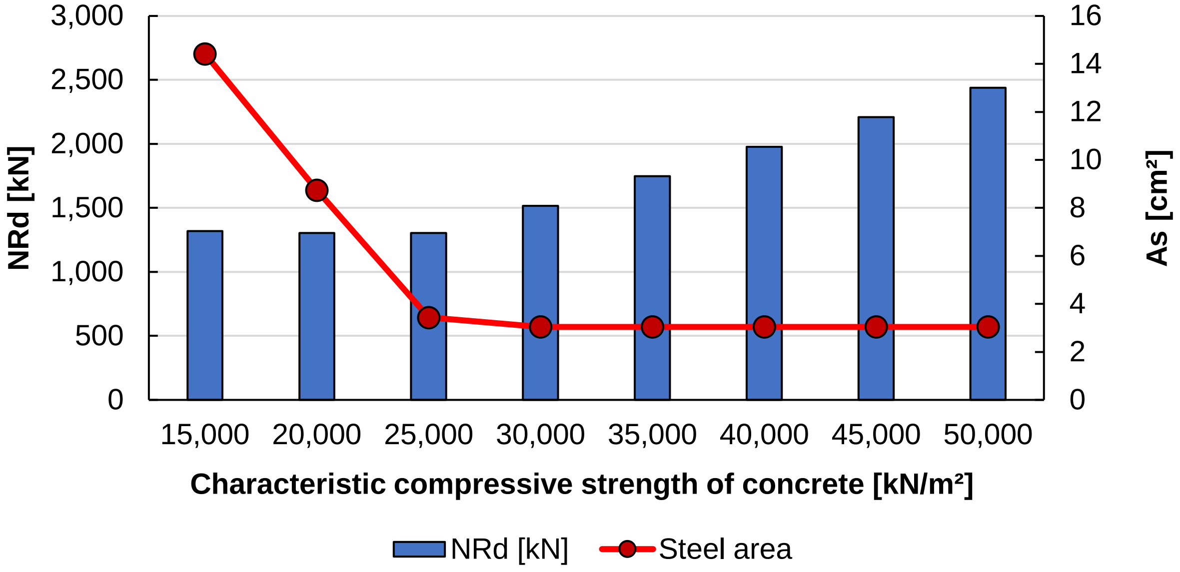
3.1. Columns

In the dimensioning of columns, when relevant, the methodology used to calculate the second-order eccentricity was the approximate method of the standard column with maximum curvature.

3.1.1. Influence of fck on compressive strength and longitudinal steel area of columns

Figure 2 shows the influence of the characteristic compressive strength of concrete (f_{ck}) on the compressive strength of the column (N_{Rd}) and on the area of longitudinal reinforcement steel (A_s).

Figure 2: Influence of f_{ck} on compressive strength and area of reinforcing steel.



Source: Authors (2022).

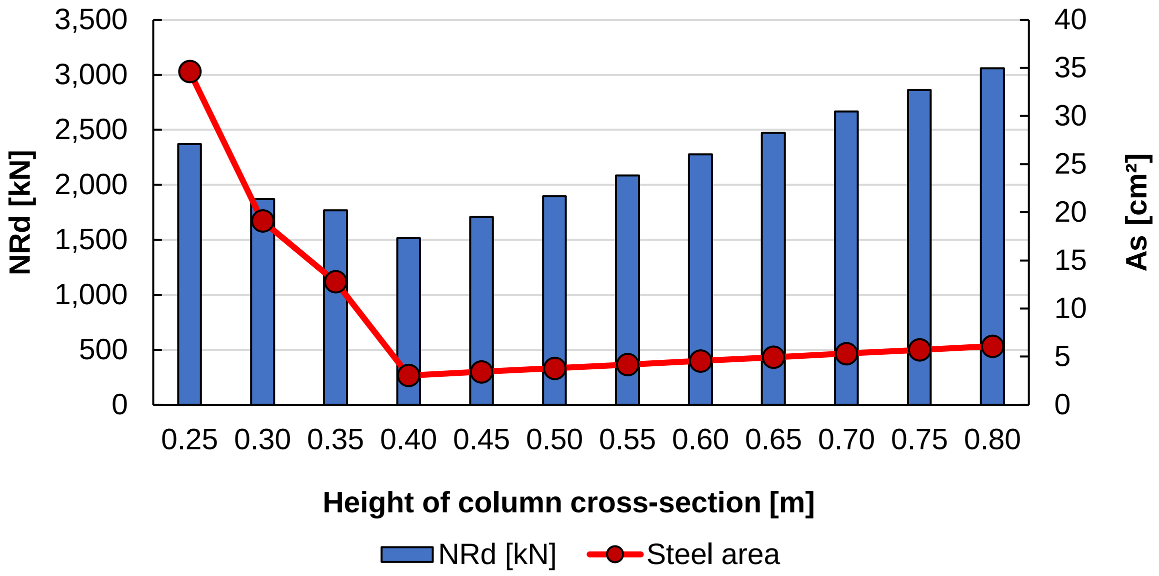
From Figure 2, when increasing the f_{ck} from 15,000 to 25,000 kN/m², the resistance capacity practically does not change. On the other hand, there is a significant reduction in the steel area of 76%. In turn, when increasing the f_{ck} from 25,000 to 50,000 kN/m², the opposite occurs, that is, the steel area practically does not change (change of less than 1%), and the resistance capacity increases by 47 %.

Thus, it can be concluded that, if the objective is to decrease the longitudinal steel area of reinforcement, there is a limit up to which it is feasible to increase the f_{ck}. If the objective is to increase the resistant capacity, it is necessary to use concrete with a resistance class above this limit. In this case, it was necessary to consider concretes with classes higher than C25.

3.1.2. Influence of column cross-section height on compressive strength and longitudinal steel area

Figure 3 shows the influence of column cross-section height on compressive strength (N_{Rd}) and longitudinal reinforcement steel area (A_s).

Figure 3: Influence of column cross-section height on strength and area of reinforcing steel.



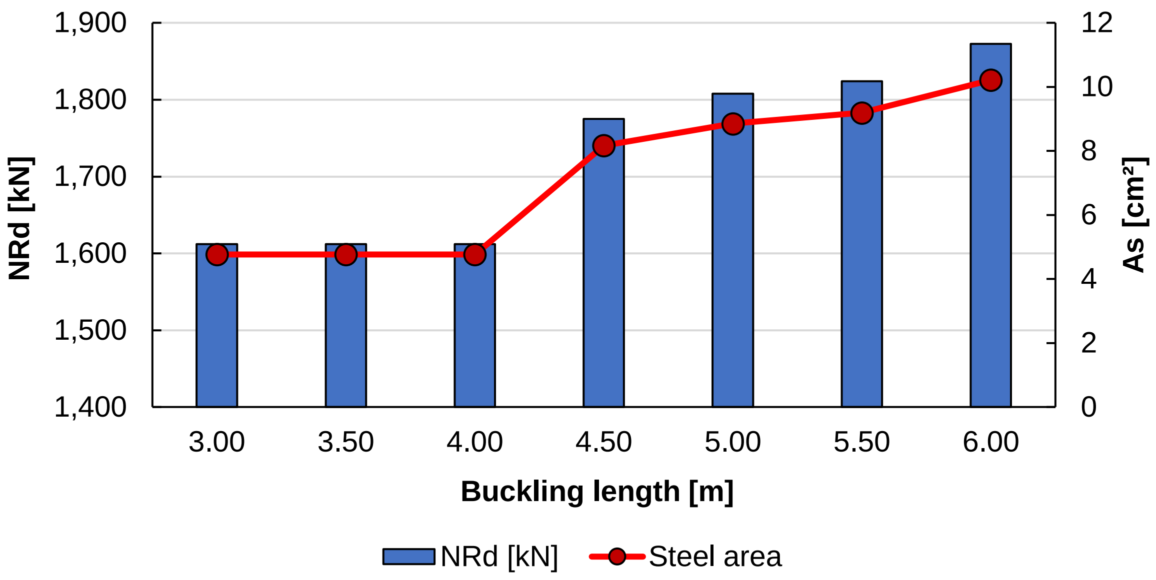
Source: Authors (2022).

From Figure 3, it can be seen that, by increasing the height of the column from 0.25 m to 0.40 m, the column's compressive strength was reduced by 34% and the steel area by 91%. When increasing the height of the column from 0.40 m to 0.80 m, both the bearing capacity and the steel area showed proportional increases in the order of 1:1, that is, 100%. In detail, the height of the column had a significant influence only up to a boundary enclosure, which, in this case, was 0.40 m. This limit was defined by the minimum steel area of longitudinal reinforcement established by NBR 6118 (ABNT, 2014). Thus, for heights greater than 0.40 m, the column started to be reinforced with the minimum steel rate prescribed by NBR 6118 (ABNT, 2014) and more significant increases in the resistant capacity were obtained.

Influence of buckling length on compressive strength and longitudinal steel area of columns

Figure 4 shows the influence of column buckling length on compressive strength (N_{Rd}) and longitudinal reinforcement steel area (A_s).

Figure 4: Influence of buckling length on compressive strength and area of reinforcing steel.



Source: Authors (2022).

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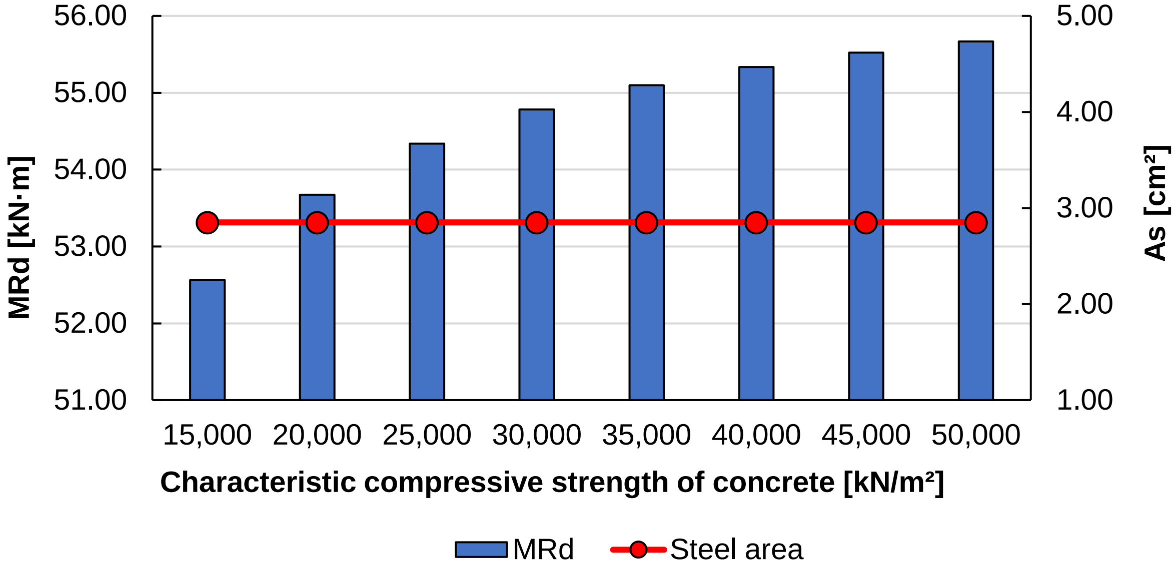
Figure 4, it can be seen that the variation in the buckling length from 3 m to 4 m did not influence the compressive strength or the steel area. In turn, when varying the buckling length from 4 m to 6 m, it was necessary to increase the longitudinal steel area by 114% and, consequently, there was an increase in the compressive strength of 16%. In other words, more steel was needed to meet the checks arising from a longer buckling length.

3.2. Beams

3.2.1. Influence of fck on the bending moment resistance of the beam

Figure 5 shows the relationship between the beam's characteristic compressive strength (f_{ck}) and its bending moment resistance (M_{Rd}).

Figure 5: Influence of the concrete f_{ck} on the bending moment resistance and area of reinforcing steel.



Source: Authors (2022).

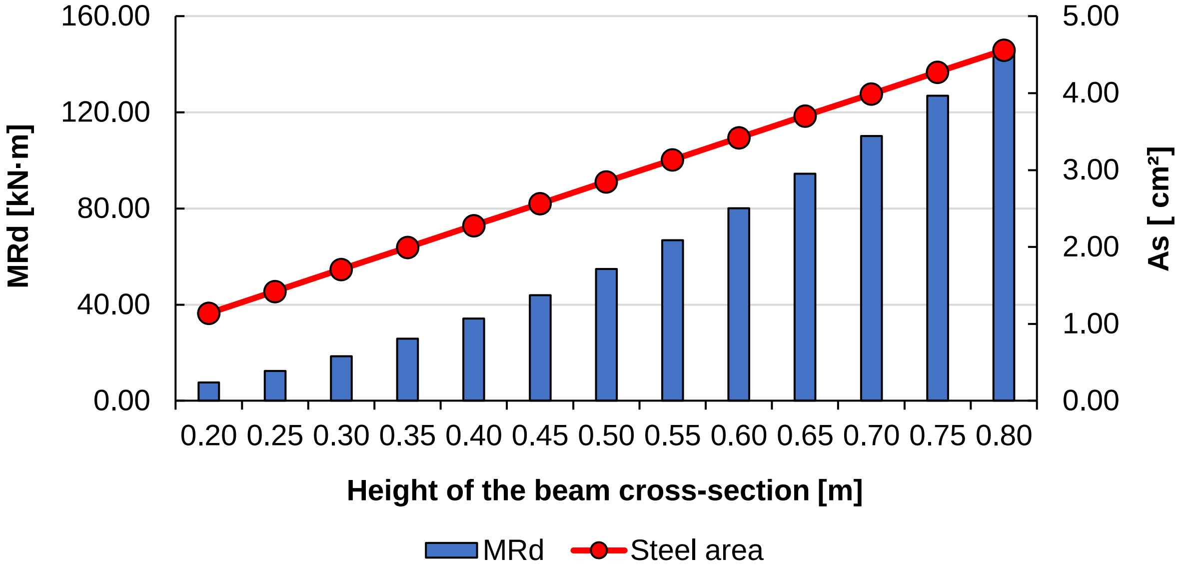
From Figure 5, it can be seen that, by increasing the f_{ck} from 15,000 to 25,000 kN/m², the increase in the flexural strength of the beam was 3.4%. In turn, with f_{ck} ranging from 25,000 to 50,000 kN/m², the increase in M_{Rd} was even less expressive - only 2.4%. In total, by raising f_{ck} by 233% (from C15 to C50 class), M_{Rd} increased by 6%.

This is an average ratio between the variables of approximately 1:0.025. Given this, it is concluded that the concrete's characteristic compressive strength contributes little to its flexural strength.

3.2.2. Influence of beam cross-section height on bending moment resistance

Figure 6 shows the relationship between the beam height and its capacity to resist bending moment (M_{Rd}).

Figure 6: Influence of cross-section height on bending moment resistance and longitudinal steel reinforcement area.



Source: Authors (2022).

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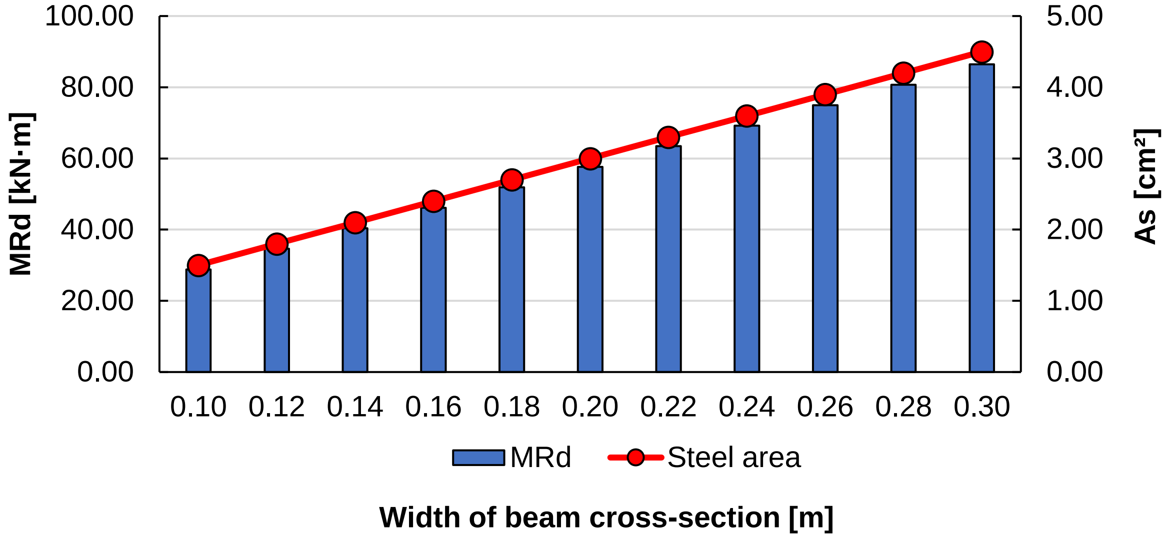
Figure 6, it can be seen that, as the height of the beam increases, the respective increase in the resisting moment is almost exponential. For beams 0.20 cm high, the bending capacity is 7.97 kN·m. For beams with a height of 0.80 m (400% increase), the resistance to bending moment is 152.63 kN·m, representing an increase of 1,815% concerning the beam with a height of 0.20 m. It is also worth mentioning that, as the reinforcement ratio equal to twice the minimum was used and this is proportional to the dimensions of the section, the steel area grew linearly with the increase in the beam's height.

Thus, the average ratio between beam height and M_{Rd} is approximately 1:4.54. Therefore, it appears that the height of the beam has a very expressive influence on flexural strength. This is justified by the fact that the greater the height of the beam, the greater the lever arm between the compressed region and the tensioned region of the concrete beam.

3.2.3. Influence of the width of the beam cross-section on the bending moment resistance

Figure 7 presents the relationship between the width of the beam's cross-section and its capacity to resist bending moment (M_{Rd}).

Figure 7: Influence of cross section width on bending moment resistance and longitudinal steel reinforcement area.



Source: Authors (2022).

From Figure 7, it can be seen that a 200% increase in beam width (from 0.10 m to 0.30 m) caused a 200% increase in flexural strength as well. This is a 1:1 order increase, with linear behavior. Again, it is worth mentioning that the longitudinal steel area grew linearly because the minimum reinforcement is directly and linearly proportional to the dimensions of the beam's cross-section.

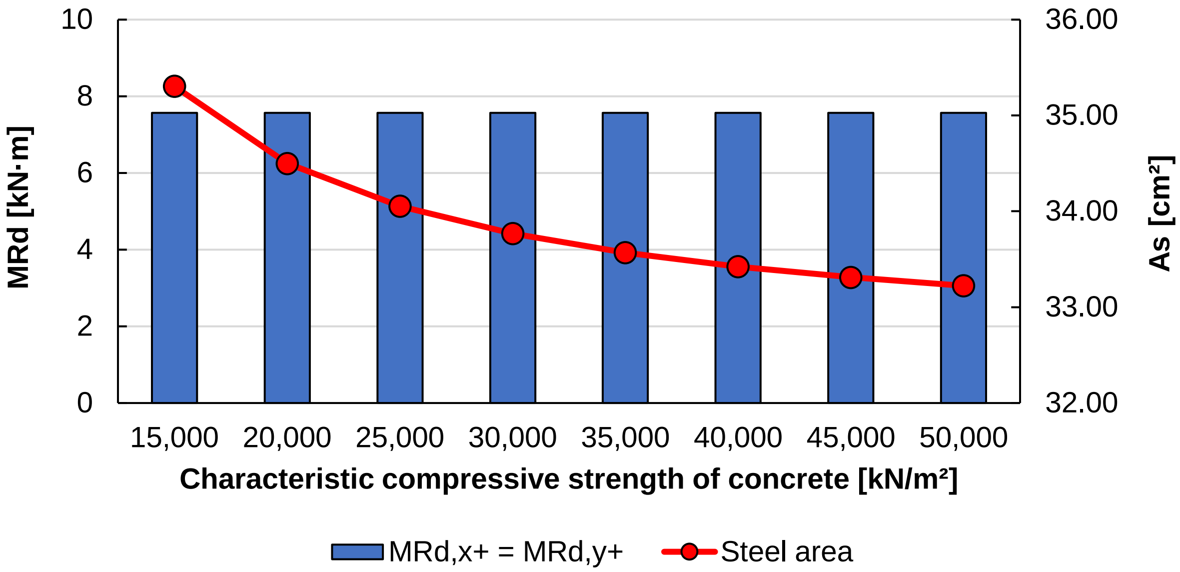
Therefore, the bending moment resistance is sensitive and directly proportional to the width of the beam's cross-section. This parameter influences more than the fck and less than the height of the beam.

3.3. Slabs

3.3.1. Influence of fck on bending moment resistance and longitudinal steel area

Figure 8 shows the influence of the characteristic compressive strength of concrete (f_{ck}) on the slab's bending moment resistance (M_{Rd}) and the longitudinal reinforcement steel area (A_s).

Figure 8: Influence of the concrete f_{ck} on the bending moment resistance and area of reinforcing steel.



Source: Authors (2022).

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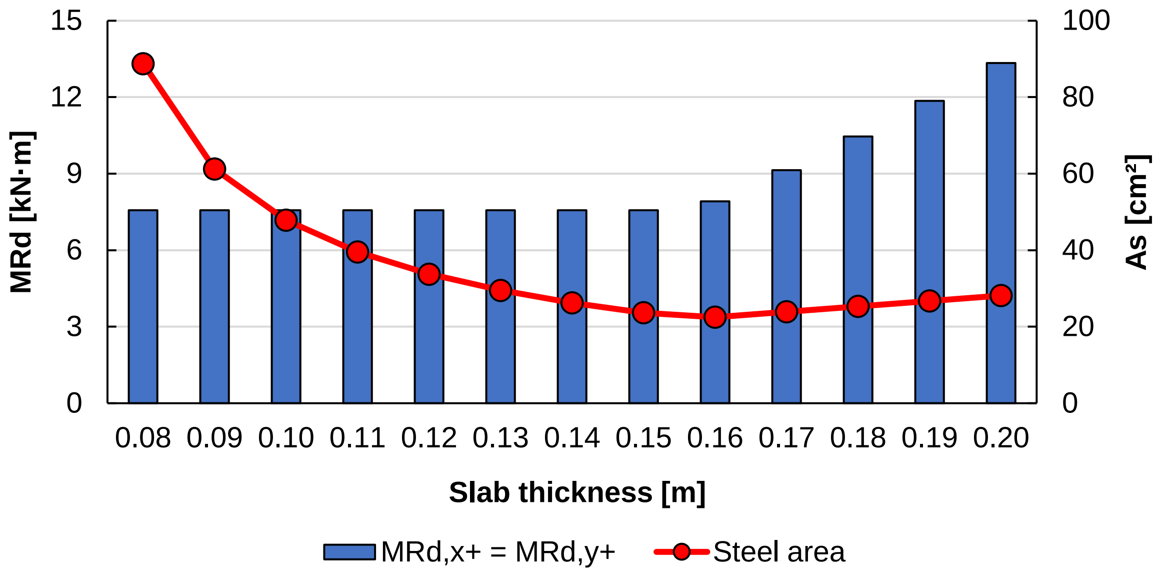
Figure 8, it can be seen that, for the admitted conditions, an increase in concrete f_{ck} by 233% (from 15,000 kN/m² to 50,000 kN/m²), and the total steel area required was reduced by 6.3% (from 35.3 cm² to 33.2 cm²). In general, it was not such an expressive reduction and that is economically justified by the increase in the f_{ck} of the concrete, which also has a significant cost.

3.3.2. Influence of slab thickness on bending moment resistance and longitudinal steel area

Figure 9 shows the influence of slab thickness on the slab's bending moment resistance (M_{Rd}) and on the longitudinal reinforcement steel area (A_s).

Figure 9: Influence of slab thickness on bending moment resistance and longitudinal steel reinforcement area.



Source: Authors (2022).

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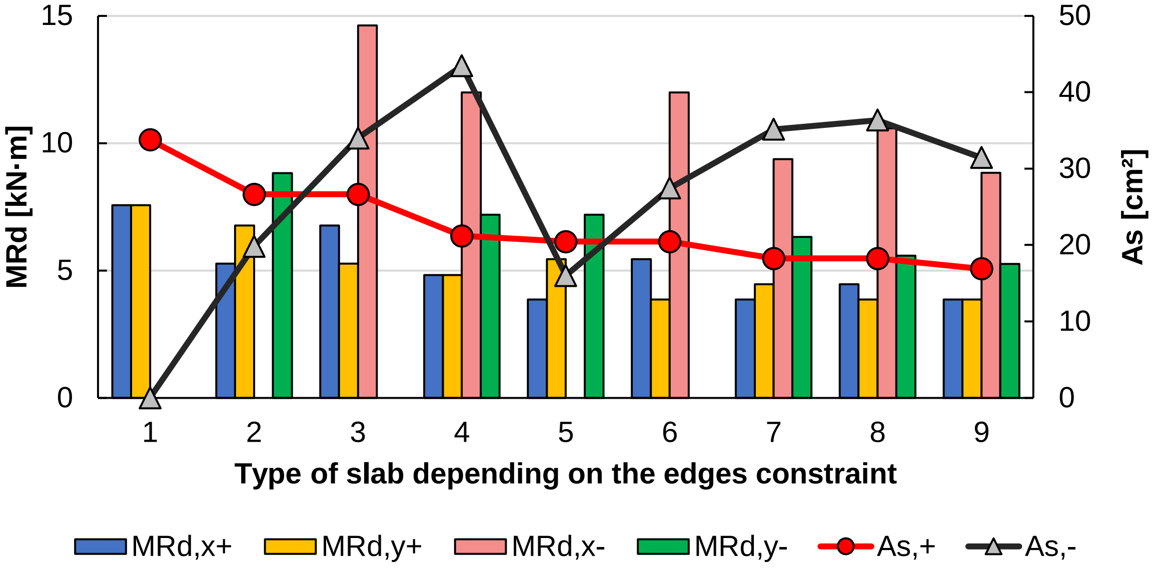
Figure 9 it is possible to observe that when the slab height is varied from 8 cm to 16 cm, the steel area decreases from 88.78 cm² to 23.65 cm², a percentage reduction of 74%. In turn, comparing a slab with a thickness of 17 cm and a slab of 20 cm thickness, there was a 25% increase in the total steel area required (from 22.51 cm² to 28.14 cm²). This occurred because, from the thickness of 17 cm, the minimum reinforcement became greater than the calculated reinforcement.

Therefore, it is concluded that there is a limit up to which the increase in thickness provides significant reductions in the steel rate and that these parameters are highly sensitive to each other.

3.3.3. Influence of the slab edge restriction on the bending moment resistance and the longitudinal steel area

Figure 10 shows the influence of the type of constraint on the slab's edges on the slab's bending moment resistance (M_{Rd}) and the longitudinal reinforcement steel area (A_s). In this parameterization, the positive (A_s^+) and negative (A_s^-) reinforcement, as well as the positive and negative bending capacity in the x and y directions ($M_{Rd,x}^+$, $M_{Rd,y}^+$, $M_{Rd,x}^-$ and $M_{Rd,y}^-$, respectively).

Figure 10: Influence of the restriction type of the slab edges on the bending moment resistance and the longitudinal steel reinforcement area.



Source: Authors (2022).

From Figure 10, it can be seen that the cantilever generates a negative moment at the edge of the beams, causing the need for negative reinforcement to resist such stresses. Despite this effort and additional reinforcement, there is a reduction in the positive moment and, consequently, in the area of positive longitudinal reinforcement steel.

Furthermore, it is not possible to delineate a clear behavior between the variables to make statements about the best design choice. Embedding the edges provides a reduction in the positive moment and positive steel area, in addition to reducing slab deflections. However, it causes a higher consumption of steel, since negative steel reinforcement is necessary. Thus, it can be said that the choice of the type of restriction of the slab edges depends, above all, on the peculiarities of the project.

4 CONCLUSION

The present paper aimed to investigate, through parametric analyses, the influence of the main design variables. In the columns, the influence of these variables on the compressive strength and the resulting longitudinal steel area was analyzed. In turn, in the beams and slabs, the influence on the flexural strength and the areas of longitudinal reinforcement steel was analyzed.

From the analysis of the columns, it was found that, if the objective is to reduce the longitudinal reinforcement steel area, there is a limit up to which increasing the fck is the solution. In turn, if the objective is to increase the bearing capacity of the column, it is necessary to work with concretes with higher strength classes. Furthermore, it was found that the buckling length of the column causes significant variations in the required longitudinal reinforcement steel area.

In the parametric analysis of the beams, the parameter that exerted the greatest influence on the bending moment resistance was the beam height, because this parameter is directly related to the lever arm existing between the tensioned and compressed regions of the concrete. The average relationship between height and M_{Rd} was 1:4.54. Subsequently, the most sensitive factor was the width of the beam, with an average ratio. Finally, there is the f_{ck} of the concrete, which had little influence on the M_{Rd}, with an average ratio of 1:0.025.

Finally, similarly to what was observed in the beams, the f_{ck} of the concrete had little influence on the longitudinal reinforcement steel area and the slab thickness was the parameter that most caused changes in the amount of steel. In the study of the influence of linkages, it was found that it is not possible to delineate a clear behavior between the variables to make statements about the best design choice. In this context, constraining the edges of the slab provides a reduction in positive moment and positive steel area, in addition to reducing slab deflections. However, this causes greater consumption of steel, since negative reinforcement is necessary. In turn, the external loading was directly and linearly proportional to the bending moment strength and longitudinal steel area.

For future research, it is suggested to carry out parametric analysis to study the influence of design variables on prefabricated slabs, ribbed slabs, hollow core slabs, side pillars, corner pillars, cantilever beams and prestressed concrete beams.

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