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Design of a composite steel-concrete multi-storey building with high-strength steels and built-up sections

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Abstract. One of the main advantages of the composite steel-concrete structures is the feasibility to explore the combined potential of the materials, i.e., steel in tension and concrete in compression. The construction system allows two materials to be used together in beams, columns, and slabs to obtain a building with excellent structural performance. Therefore, this project aimed to evaluate the reduction of the self-weight of the structure of a multi-story (G+7 story) building using steel-concrete composite structures together the use of high strength steels, such as the ASTM A572 grade 65 (yield strength of 450 MPa). A complete building project of real building available in the literature was used to be the comparison parameter for this study. Originally, the design present in the literature adopted European rolled profiles with European S355 steel, which has yield strength similar to the ASTM A572 grade 50 (yield strength of 345 MPa). A complete finite element model of the building was developed using the finite element program Autodesk Robot Structural to carry out static and quasi-static structural analyses. Design verifications were implemented and conducted in Visual Basic for Applications (VBA) and MS Excel® macros using Brazilian design standards (NBR 8800 and NBR 6118) for ultimate-limit and serviceability states. This paper is included in the context of an undergraduate final project work and present the state of the ongoing research. At this first phase, the use of high-strength steel allowed the reduction of some built-up sections and hence the total weight of the structure.

Keywords: Composite steel-concrete structures, high-strength steels, multi-storey building.

1 Introduction

The composite steel-concrete systems have been present in the construction since the 1950s, and the design of composite beams has been provided for in Brazilian standards since 1986, but after the publication of the review of ABNT NBR 8800:2008, and the scope of the systems covered, the use of composite structures in Brazil has expanded. In general, this type of system is used in the construction of bridges and tall buildings (QUEIROZ *et al.*, 2012), as is the case presented in this article.

Among the advantages of composite structures, in relation to conventional concrete or metallic structures, there is the reduction of building self-weight and direct costs, reduction or dispensation of sanding and forms, and reduction of the execution time of the work (QUEIROZ *et al.*, 2012).

Besides the use adoption of composite steel-concrete structures, the use of high strength steels allows a reduction of building self-weight that can reach 30% (FAVARATO *et al*, 2021), being considered a promising solution engineering according to the Australian Steel Institute (2021).

Therefore, this article aims to evaluate the overall performance of a building by the adaptation of the design of a composite steel-concrete building proposed in the book "*Design of steel structures*" (Silva *et al.*, 2016). Specifically, the originally proposed European rolled profiles adopted for beams and columns with European S355 steel (yield strength of 355 MPa) will be replaced by high strength steels (ASTM A572 grade 65, yield strength of 450 MPa) and built-up welded section profiles, besides the steel deck slab commercialized nationally by ArcelorMittal Brazil (Polydeck 59S), with height of 59 mm. The design of the composite structures is based on "ABNT NBR 8800:2008: Design of steel structures and mixed structures of steel and concrete of buildings". The structural analysis is being carried out taking advantage of Autodesk Robot Structural Analysis with undergraduate student license. The present conference paper is within the context of an undergraduate final project thesis and present the state of the ongoing research.

2 Proposed investigated multi-storey building

2.1 Description

The building has an area of 21 m by 45 m, height of 33 m and 8 floors (G+7storys), being the height of the first storey 4.335 m from the ground floor to the top-of-steel profile flange and all the other storeys have a height of 4.135 m from top-of-steel profile flange to top-of-steel profile flange. The structure is designed as a braced frame with lateral restraint provided by cross bracing, around the three vertical access shafts.

Originally, the building design consists of the series of European profiles (IPE, HEA, etc.) in S355 steel (nominal yield strength of 355 MPa) replaced in this analysis by welded profiles of type I section in ASTM A572 Grade 65 steel (nominal yield strength of 450 MPa) of the series commercialized by ArcelorMittal-Tubarão. For composite slabs, it will be adopted the Polydeck 59S slab of ArcelorMittal Perfilor in ZAR280 galvanized steel (with yield strength of 280 MPa), thickness of 0.95 mm. The height of the slab for all storeys is 130 mm, as in the original design.

The structure of the building was designed for commercial multi-store use and represents a real case study where the building was used for well-known fire tests in Cardington (UK) in 1993, see Fig. 1, in order to assess the structural behaviour of composite steel-concrete buildings to fire. The complete information regarding the structural drawings can be found in Silva *et al.* (2016) and Silva (2022).

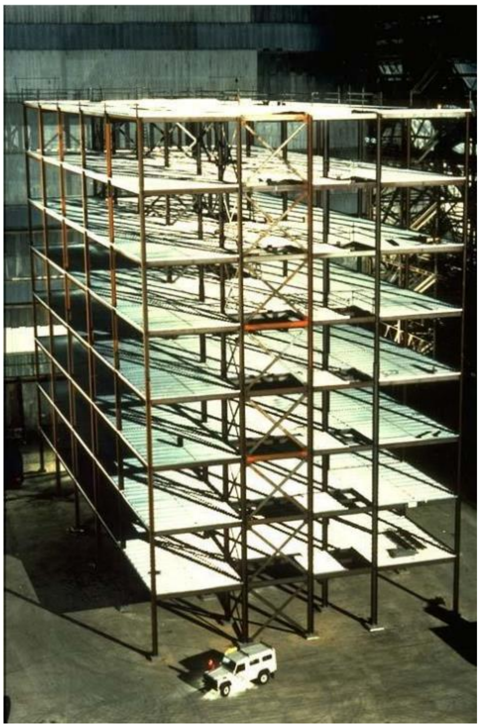


Figure 1. Test building in Cardington (UK). Source: Marc *et al.* (2011).

The loads proposed for the original building are shown in the following Tab. 1. The same loads will be used in the design and verification of the new version of the building with high strength steel and welded built-up profiles. The employed steel material had a Young modulus of 200 GPa and Poisson coefficient of 0.3, and a concrete with secant Young modulus of 23.8 GPa and Poisson coefficient of 0.2 (according to NBR 6118:2014).

Table 1. Loads cases

Type	Description	Value
Permanent action	Self-weight	varies
Permanent action	Partition walls	0.50 kN/m²
Variable action	Imposed load of use	3.00 kN/m²
Variable action	Wind direction θ=0°	Varying within +0.73 and -2.20 kN/m² – See Silva *et al.* (2016)
Variable action	Wind direction θ=90°	Varying within +0.64 and -2.23 kN/m² – See Silva *et al.* (2016)

2.2 Structural Model

The structural modelling of the building was performed in the software Autodesk Robot Structural Analysis (version 2022), with undergraduate license. Complete structural modelling of the building can be seen in Fig. 2. The design and verification of the structure was carried out with the help of the Results Connect extension tool to MS Excel®, which through the VBA language exports to worksheets all the data and results of the structure.

The columns of the building are metallic, modelled with bar elements (2 nodes and 6 degrees of freedom per node) and are continuous elements connected to the beams by simple shear connections. All beams in the building are composite, and it is admitted that the shear connectors are sufficient to ensure complete interaction between the beams and concrete slab. The connections in the end of the beams are pinned-pinned in the main direction of bending (major y inertia axis in Eurocode 3 convention and major x inertia axis in NBR 8800 convention).

All building slabs are composite, modelled as shell elements (four nodes and 6 degrees of freedom per node). The design of the slabs is carried out according to the design tables provided by ArcelorMittal-Brazil - Perfilor. The slab shape thickness of 0.95 mm was adopted in order to allow for complete construction without shoring, and total height of 130 mm to maintain the original slab height proposed (Silva *et al.*, 2016). The complete stiffness and inertia of the composite section of the slab elements were computed taking advantage of the tool available in Autodesk Robot (see Fig. 3). The slab elements distributed the loads in just one direction, by adopting shell elements with geometric properties in just one main direction (orthotropic slab).

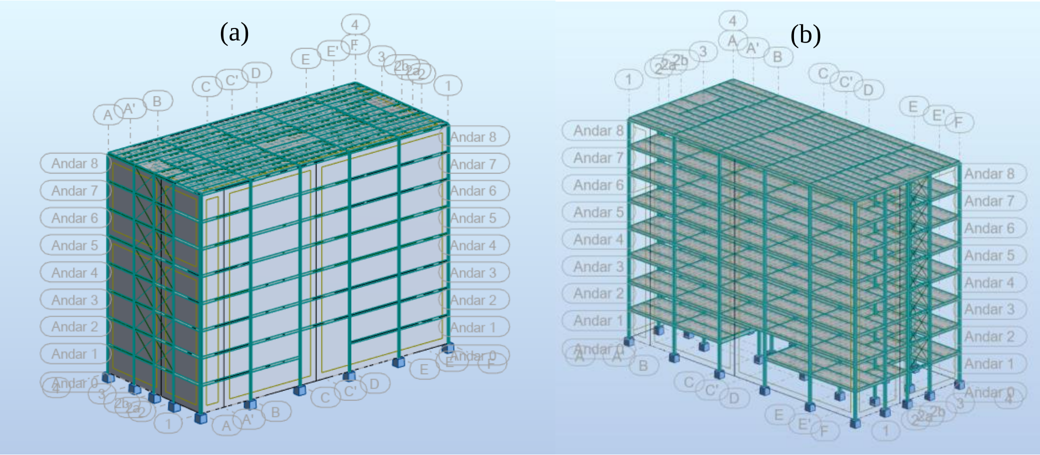
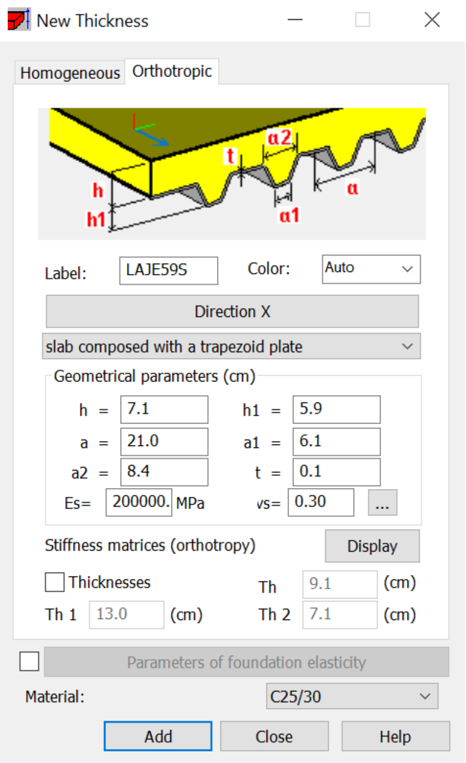


Figure 2. Complete building modelling: (a) Building with side panels in order to apply the wind design loads and (b) Building show the interior slab shell elements. Source: Authors.



Label: LAJE59S
Color: Auto
slab composed with a trapezoid plate
Geometrical parameters (cm)
h = 7.1
h1 = 5.9
a = 21.0
a1 = 6.1
a2 = 8.4
t = 0.1
Es= 200000. MPa
νs= 0.30
Stiffness matrices (orthotropy)
☐ Thicknesses
Th 9.1 (cm)
Th 1 13.0 (cm)
Th 2 7.1 (cm)
☐ Parameters of foundation elasticity
Material: C25/30

Figure 3. Composite trapezoidal slab settings. Source: Autodesk Robot Structural Analysis 2022.

The slab shapes were design for the 3 m typical bays, this system supports up to 793 daN/m² for the condition of 3 supports, without the need of shoring during erection, for the adopted thickness of 0.95 mm and total height of 130 mm, meeting the loads requests. Refer to Fig. 3 for the geometry of the slab shape used.

2.3 Structural Analysis

According to NBR 8800, the stability of the structure must be verified to determine the type of analysis. In this context, the main objectives of structural analysis is to determine the effects of loads on the structure and to verify the ultimate and service limit-states.

The type of structural analysis can be defined according to material considerations and the effects of structure displacements. Considering the effect of displacements, the method of amplification of effects (NBR 8800:2008, Annex D) can be considered an acceptable approximation for second-order analysis and the sensitivity to lateral displacements of the structure can be classified with coefficient B2, according to Eq. (1) and Tab. 2.

$$B_2 = \frac{1}{1 - \frac{1}{R_S} \frac{\Delta h \sum N_{Sd}}{h \sum H_{Sd}}} \tag{1}$$

Table 2. Classification with coefficient B2

Displacements	B2
Small	B2 ≤ 1,1
Medium	1,1 < B2 ≤ 1,4
Large	B2 > 1,4

Where $\sum N_{Sd}$ is the total gravitational load that acts on the floor considered, $\sum H_{Sd}$ is the relative horizontal displacement between the upper and lower levels of the floor considered and R_S is an adjustment coefficient, equal to 0.85 in structures where the horizontal action-resistant system consists only of brace substructures formed by gantries. The Tab. 3 below shows de results of B2 considering the critical case of loads and displacements resulting in an average value of 1,331, being classified as a “medium displacement” structure. Thus, according to NBR

8800:2008 the second-order effects can be approximated by the method of amplification of effects.

Table 3. Coefficient B2

Pavement	B2
1	1,839
2	1,619
3	1,445
4	1,283
5	1,187
6	1,195
7	1,053
8	1,027
Average	1,331

3 Design of composite steel-concrete beams according to NBR 8800:2008

According to NBR 8800 (2008), for the composite beams, in the design it is admitted that the beams work in plastic regime until the formation of the first plastic bearing, thus the following condition of not slenderness expressed in Eq. 2 must be verified.

$$\frac{h}{tw} \leq 3.76\sqrt{\frac{Ea}{fy}} \tag{2}$$

The plastic neutral axis can be either on the beam or on the concrete slab, according to Fig. 4. Considering the complete interaction (degree of interaction 1, that means compact composite beams), if the plastic neutral axis on the slab concrete, that is $0.85f_{cd}bt_c \geq A_af_y$, the bending resistance M_{Rd} is determined according to Eq. 3 and Eq. 4. Then, if the plastic neutral axis lays on steel profile, M_{Rd} is determined according to Eq. 5 to Eq 9.

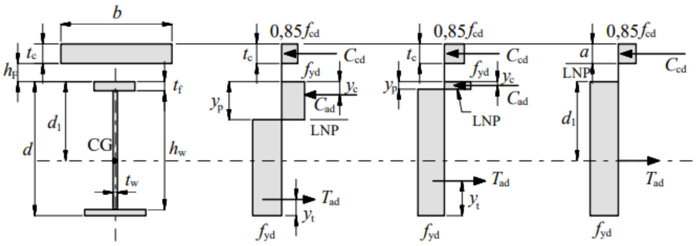


Figure 4. Stress distribution in compact composite beams under positive moment. Source: NBR 8800 (ABNT, 2008).

$$a = \frac{A_af_{yd}}{0.85f_{cd}b} \leq t_c \tag{3}$$

$$M_{Rd} = A_af_{yd}(d_1 + h_F + t_c - \frac{a}{2}) \tag{4}$$

$$C_{cd} = 0.85f_{cd}bt_c \tag{5}$$

$$C_{ad} = \frac{1}{2}(A_af_{yd} - C_{cd}) \tag{6}$$

$$T_{ad} = C_{cd} + C_{ad} \tag{7}$$

$$C_{ad} \leq A_{af}f_{yd} \therefore y_p = \frac{C_{ad}}{A_{af}f_{yd}}t_f \tag{8}$$

$$C_{ad} > A_{af}f_{yd} \therefore y_p = t_f + h_w(\frac{C_{ad} - A_{af}f_{yd}}{A_{aw}f_{yd}}) \tag{9}$$

4 Preliminary results analysis

Table 4 below shows the complete building modelling (beams and columns), for the first analysis performed using the profiles (nominal yield strength of 450 MPa). “CS” and “VS” stands for “Coluna Soldada” (welded column) and “Viga Soldada” (welded beam/girder), respectively. The first number refers to the height of the built-up section, and the second number refers to the linear mass of the section. The complete dimensions are normalized by Brazilian standard ABNT NBR 5884 (2013).

Table 4. Profiles adopted in the first design

Element	Profile
Columns	CS 350×89
	CS 350×112
Beams	VS 350×51
	VS 400×53
	VS 600×125

In this design the building is globally stable, and it was analyzed the reduction of columns self-weight using the ASTM A572 Grade 65 steel (nominal yield strength of 450 MPa). For all combinations cases (10 cases) the global extremes were verified and as expected the ground floor columns are subjected to the highest loads. The list of adopted ultimate normal limit-state were generated using the coefficients recommended by NBR 8800 (2008).

4.1 Preliminary design and results analysis: steel welded columns

In order to exemplify the reduction of weight for a single element at a first glance, in this topic it is presented the design and verification of the bar submitted to maximum compression efforts. Figure 5 below shows the diagram for the bar with maximum normal effort (bar 99, ground floor, axis E2, refer to Fig. 2b), and minimum normal effort (bar 79, ground floor, axis F2b, refer to Fig. 2b). Eq. 10 shows the calculation of the efficiency of bar 99, and Eq. 11 shows the calculation of the efficiency of bar 79, according to the design method of NBR 8800 (2008) of elements subjected to combined bending and compression/tension, which will be described in detail in a later stage, but the reader can refer to Fakury *et al.* (2016).

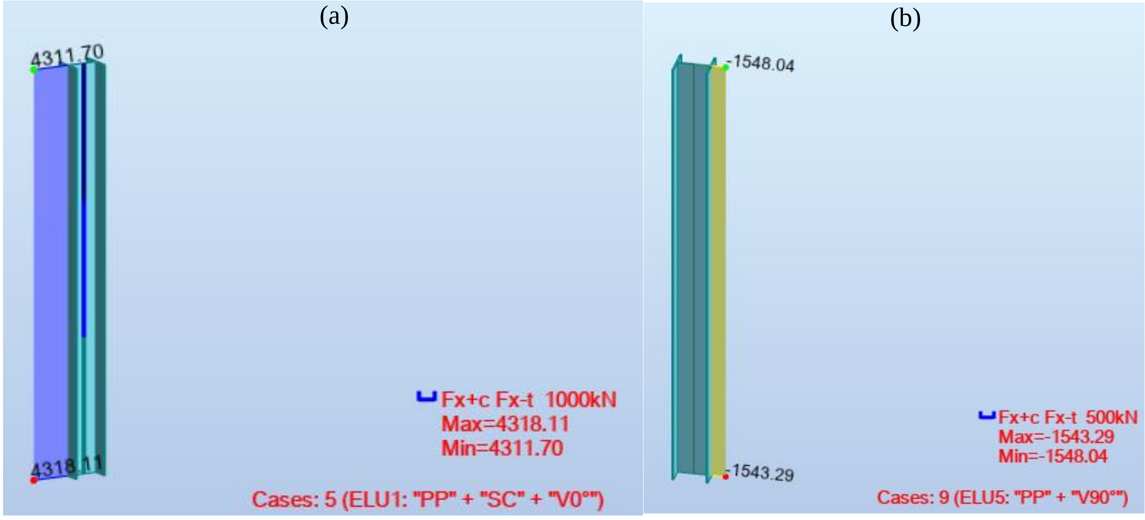


Figure 5. Diagram of maximum compression/tension efforts in columns: (a) Bar 99 (left) and (b) Bar 79 (right). Source: Authors.

$$\frac{Nsd}{Nrd} = \frac{4316.62}{5141} = 84\% \tag{10}$$

$$\frac{Nsd}{Nrd} = \frac{1554.61}{4592} = 33.9\% \tag{11}$$

For these columns, it was adopted the profile CS 350X112 (111.6 kg/m) with nominal yield strength of 450 MPa. In the original project it was adopted the profile HEB 340 (134.0 kg/m) with nominal yield strength of 345 MPa, that means a reduction of 16,71% of column self-weight.

This process was repeated for all columns of the building and resulted in an overall reduction of 15.98% of column self-weight in relation to the original structure. As can be seen, for the composite steel-concrete beams and girders subjected mainly to bending, the efficiency of the profiles can be increased by adopting lighter profiles, and the overall reduction of self-weight can be even greater, as will be demonstrated in a later stage.

5 Conclusions

This work will continue in assessing the present building with high strength steels and welded profiles, but at a first stage it is concluded from a first simplified analysis that the use of high strength profiles results in the reduction of the self-weight structures, according to the main objective. The ongoing research showed that in this analysis, the solution adopted resulted in a reduction of 15.98% of column self-weight but increasing the efficiency of the profiles the reduction for the complete building may reach 30%, for other arrangements profiles solutions. In addition, this solution does not require shoring slabs, except for the slabs adjacent simply supported to the shafts, which gives the work more speed and less direct costs.

The next steps of this work include assessing the global stability of the building, the service limit-state combinations (maximum deflections due to gravity and wind loads) and also the ultimate limit-state design of the composite beams/girders.

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Authorship statement.

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