STEEL AND CONCRETE COMPOSITE BUILDING STRUCTURES AN ECONOMICAL APPROACH

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Abstract. *Steel and concrete composite structures are becoming a more and more common solution for buildings, since its structural efficiency and fast erection methods make its use economically competitive. A parametric study dealing with steel and concrete composite structures for typical office buildings braced horizontally and with regularly spaced columns is presented. The varying parameters are the type of column layout, the spans and the structural steel class. The general modeling principles of these building structures are briefly described, and for each structure within the parametric study the structural layout and geometry, the design criteria meeting ultimate and serviceability limit states, and the most representative internal forces are presented and discussed. Furthermore, the steel weight of the main and secondary girders, of the columns, and of the whole structure is analyzed and presented in the form of illustrative graphics, relating the amount of steel to the span and to the structural steel class.*

1 INTRODUCTION

In composite structures the proper association of steel and concrete enables the creation of very effective composite members, where the concrete absorbs the majority of compression stresses and the steel the tension stresses. It is however a starting condition that both materials work together, with shear transfer between them being assured by specific devices – the connectors. These elements are used in girders and columns, but in composite slabs shear transfer is usually assured by some proper steel sheet geometry.

The most commonly used connectors are the studs, but some alternative connectors, like the Perfobond [12], where proposed in the past and are also of spread using, with some possible structural and economical advantages [11].

The use of composite solutions clearly brings to the building market a new set of possibilities, in new buildings and in reconstruction projects [10], where some weight may be saved comparing to the traditional single material solution. Also, looking at the erection process, formwork and propping may be strongly reduced or even eliminated.

These advantages, adding to the fact that an effective cost saving is achieved when implementing larger free areas and larger spans with composite structures justifies the increase in the use of composite structures for industrial, residential, and other buildings.

Also, hybrid structures result from the association of steel or composite structures (with composite members) and reinforced concrete elements, such as vertical stairways and lift cores that absorb most of the horizontal loads. This structural system is particularly attractive since the steel or composite structure is braced, resulting in a much more economical and simpler to calculate structure.

Figure 1 shows some examples of composite and hybrid structures of some office buildings in São Paulo, Brazil.

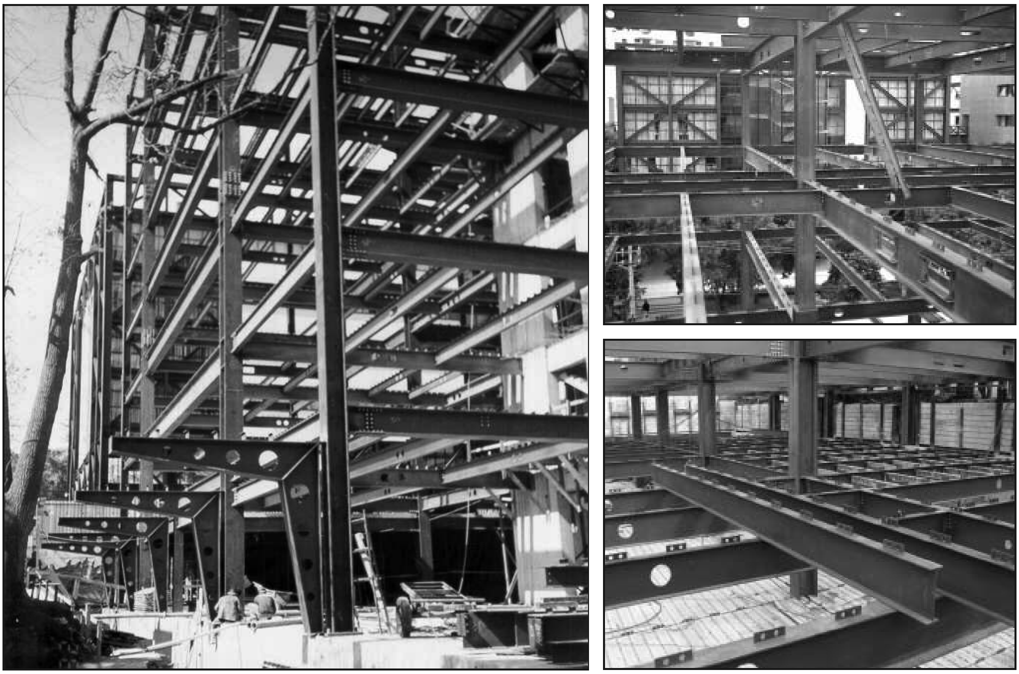

Figure 1: Current steel and composite building structures (courtesy of Prof. Sebastião Andrade).

To support their design, engineers have a set of design documents – the eurocodes, namely the Eurocode 4 – Design of Steel and Concrete Composite Structures [7]. This document should be used in coordination with Eurocode 0 – Basis of structural design [2], Eurocode 1 - Actions on structures [3], Eurocode 2 – Design of concrete structures [4], Eurocode 3 – Design of steel structures [5], [6], and Eurocode 8 - Design of structures for earthquake resistance [8].

One of the first questions arising to the designer of a building structure is the choice of the most suitable span. This choice should of course meet the architectural demands and other non-structural aspects, but looking at the problem from the structural point of view, it is important to find the most efficient span, likely the most economical as well.

This paper presents a parametric study developed in [9], where the variables were the structural layout, the span and the structural steel class. In all cases the structure was designed and the amount of steel resulting from this design for each structural element type was assessed. The results are presented in curves linking the parameters, from which some relevant conclusions may be derived.

2 PARAMETRIC STUDY

The parametric study was performed considering a rectangular building with 40x40 m^2, with three floors and a total area of 4800 m^2, corresponding to an ordinary office building with composite beams and slabs and steel columns. The building was considered as braced, so that no horizontal forces were considered in the study - Figure 2.

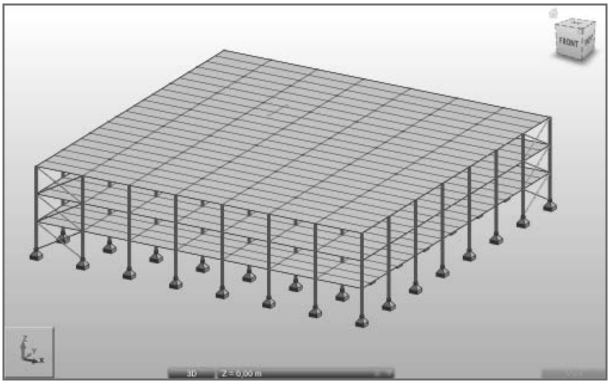

Figure 2: Building geometry.

The one way composite slabs were spanning between IPE composite secondary beams supported by IPE composite main or principal girders that transmit the vertical forces to the HEA columns. The main variables of the study were:

- the structural layout (rectangular or square);
- the span or distance between two columns (4 to 10 meters);
- the structural steel class (S275 and S355).

The composite slab and the concrete class were kept constant in the study. Six models with square layout and four models with rectangular layout were considered, and are shown in Table 1.

Table 1: Span and number of secondary beams for each model.

	Square layout						Rectangular layout			
Span Direction X (m)	4.0	5.0	5.7	6.7	8.0	10.0	4.0	4.0	5.7	5.7
Span Direction Y (m)	4.0	5.0	5.7	6.7	8.0	10.0	8.0	10.0	8.0	10.0
Secondary beams/span	1	2	3	4	4	5	4	5	4	5

Also shown in Table 1 are, for each case, the span and the number of secondary beams in each spam. The non-integer value of some spans results from the fact that the building was divided into an integer number of spans. Since all models were built with S275 and S355 steel, twenty models were analyzed, designed and had their weight assessed.

3 NUMERICAL MODEL

In a first step manual calculations considering all beams as simply supported were performed, having the advantage of giving internal forces distributions independent from the elements stiffness, shrinkage and creep, and columns flexural stiffness. These internal forces were the starting point for the pre design of the composite girders. Also, the results from this simpler model may be used to assess the reliability of the results from a more complex model.

The second step was the construction of a more complete model (Figure 2) with the software Autodesk Robot Structural Analysis Professional 2009 [1]. In this model the joints to the columns minor axis were modeled as pinned, and to the major axis as fully continuous. The concrete slab was not directly modeled, but its stiffness was taken into account by the consideration of the properties of an equivalent section having the concrete slab with the EC4 effective width.

No horizontal actions were considered in the analysis, since it was assumed that all these forces were directly absorbed by the bracing system.

4 RESULTS

For each structure in Table 1 code loads for office buildings were applied and the results from the analysis were used to design the members, coping with the EC3 and EC4 requirements of section resistance, member stability and serviceability limit states. Also, bare steel beams were verified for the construction stage, and this was generally the governing design criterion for the secondary beams.

The design enables the weight of the global structure and the amount of steel used in each structural element type to be assessed. The following paragraphs show these results.

4.1 Columns

Figure 3 and Figure 4 show respectively for square and rectangular structural layouts the required weight of steel in the columns for each structure in Table 1. The results are shown for S275 and S355.

Columns			
Layout	Span	S275 kg/m^2	S355 kg/m^2
Square	4.0 x 4.0	8.1	6.9
	5.0 x 5.0	7.7	7.7
	5.7 x 5.7	7.2	6.1
	6.7 x 6.7	7.0	6.3
	8.0 x 8.0	6.6	6.6
	10.0 x 10.0	7.3	6.6

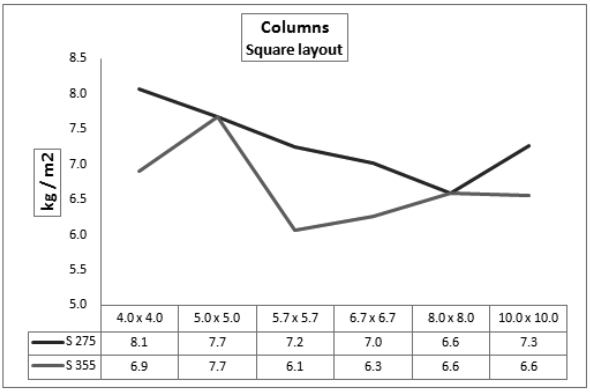

Figure 3: Weight of steel used in columns for square layout and its variation with the span.

The irregular shape of the curves is due to the variation in the governing design failure mode. For some spans the governing criterion is the section resistance, and for some others the member stability. In this case the required section for S275 and for S355 is the same, since the Young modulus is the same as well. It may be observed that for S275 the most economical span is of about 8 meters for the square layout (about 64 m^2 for each column), and of about 45 m^2 for the rectangular layout. For S355 the economical span is shorter, being of about 6 meters for S275, and corresponds to an influence area per span of about 40m^2 for the rectangular layout.

Columns			
Layout	Span	S275 kg/m²	S355 kg/m²
Rectangular	4.0 x 8.0	7.5	7.5
	5.0 x 10.0	7.0	6.2
	5.7 x 8.0	6.9	6.9
	5.7 x 10.0	7.3	7.3

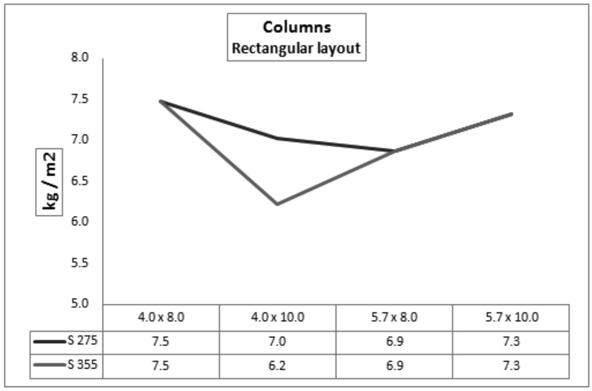

Figure 4: Weight of steel used in columns for rectangular layout and its variation with the span.

4.2 Secondary beams

Figure 5 and Figure 6 show respectively for square and rectangular structural layouts the required weight of steel in secondary beams for each structure in Table 1. The results are again shown for S275and S355 steel classes. It may be concluded that, since the governing criterion for the selected beams was always the mid span deflection (serviceability limit state), the required section is independent from the steel class.

Furthermore, when the span increases, the amount of steel increases as well for all the span range. This conclusion is valid for both layouts.

Secondary beams			
Layout	Span	S275 kg/m²	S355 kg/m²
Square	4.0 x 4.0	8.3	8.3
	5.0 x 5.0	14.5	14.5
	5.7 x 5.7	14.4	14.4
	6.7 x 6.7	19.2	19.2
	8.0 x 8.0	22.2	22.2
	10.0 x 10.0	35.6	35.6

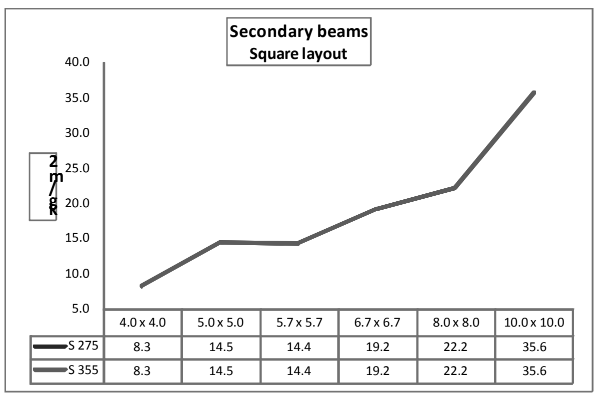

Figure 5: Weight of steel used in secondary beams for square layout and its variation with the span.

The growing rate of steel weight seems to be higher for larger spans, suggesting that spans over 8 meters in square layouts should be avoided to achieve an economical solution.

Secondary beams			
Layout	Span	S275 kg/m2	S355 kg/m2
Rectangular	4.0 x 8.0	8.3	8.3
	5.0 x 10.0	9.8	9.8
	5.7 x 8.0	13.5	13.5
	5.7 x 10.0	16.3	16.3

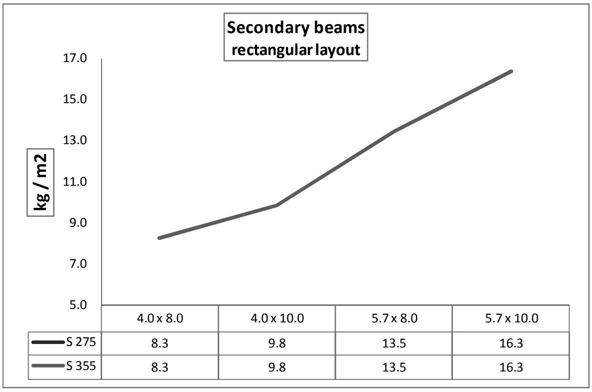

Figure 6: Weight of steel used in secondary beams for rectangular layout and its variation with the span.

4.3 Principal beams

For each structure in Table 1, Figure 7 and Figure 8 show respectively for square and rectangular structural layouts the required weight of steel in the main girders. The results are again shown for S275and S355 steel classes.

It may be concluded that since the governing design criterion was always the flexural resistance, S355 steel is always a more economical material than S275 steel (its use leads to a lighter structure, and their price is roughly the same).

The amount of steel is always a growing function to the adopted span.

Using an higher steel grade seems to lead to an higher advantage for larger spans, as depicted in Figure 7 for square layouts, where a difference of 4 kg/m^2 was found for 10 m spans comparing to a difference of only 0.9 kg/m^2 for 4 m spans.

It is interesting to observe that also for square layouts the growing rate of steel per square meter is roughly constant up to 6.7 meters spans, but starts to grow for larger spans, suggesting that for spans of 8 and 10 meters other solutions could be envisaged in order to achieve a more economical solution.

Principal beams			
Layout	Span	S275 kg/m^2	S355 kg/m^2
Square	4.0 x 4.0	5.2	4.3
	5.0 x 5.0	6.9	5.9
	5.7 x 5.7	8.4	7.2
	6.7 x 6.7	10.0	8.6
	8.0 x 8.0	13.6	11.6
	10.0 x 10.0	19.3	15.3

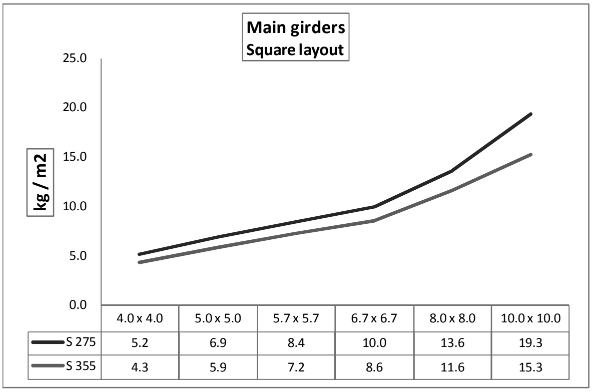

Figure 7: Weight of steel used in the main girders for square layout and its variation with the span.

The trend for rectangular layouts is similar concerning the growing amount of steel for larger spans and the relative advantage of higher grade steels, also increasing with the span.

Principal beams			
Layout	Span	S275 kg/m^2	S355 kg/m^2
Rectangular	4.0 x 8.0	13.5	11.7
	5.0 x 10.0	18.2	15.7
	5.7 x 8.0	15.5	13.7
	5.7 x 10.0	18.1	15.5

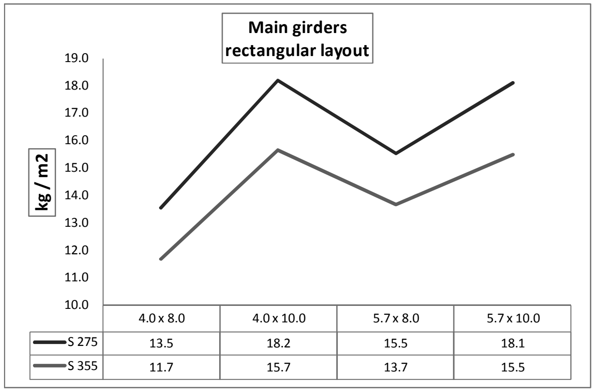

Figure 8: Weight of steel used in the main girders for rectangular layout and its variation with the span.

4.4 Whole structure

Figure 9 and Figure 10 show the required weight of steel in the whole structure (models in Table 1).

Whole structure			
Layout	Span	S275 kg/m^2	S355 kg/m^2
Square	4.0 x 4.0	21.5	19.5
	5.0 x 5.0	29.1	28.1
	5.7 x 5.7	30.0	27.6
	6.7 x 6.7	36.2	34.1
	8.0 x 8.0	42.4	40.4
	10.0 x 10.0	62.2	57.4

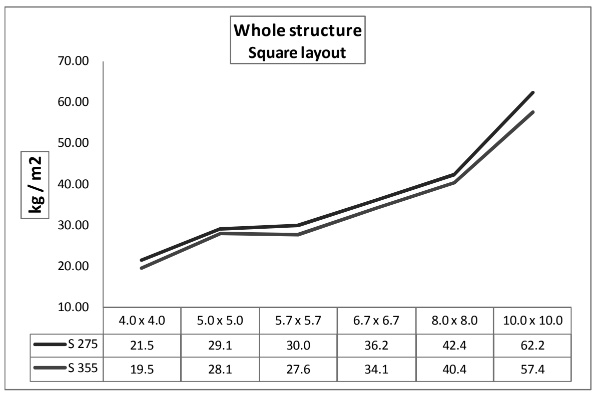

Figure 9: Weight of steel in the whole structure for square layout and its variation with the span.

Whole structure			
Layout	Span	S275 kg/m^2	S355 kg/m^2
Rectnagular	4.0 x 8.0	29.3	27.4
	5.0 x 10.0	35.1	31.7
	5.7 x 8.0	35.8	33.6
	5.7 x 10.0	41.8	39.1

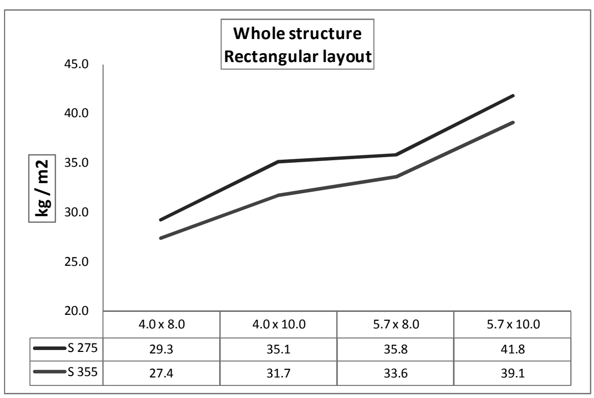

Figure 10: Weight of steel in the whole structure for rectangular layout and its variation with the span.

It may be concluded that, although the steel weight always increases with the span growth, there is an intermediate range of spans for the square layout where the rate of increase of the amount of steel is smaller. This suggests that a span between 6 and 8 meters is appropriate. For larger spans the amount of steel increases very quickly, suggesting that probably alternative structural solutions like lattice girders would be more appropriate.

Globally, it is more economical to use S355 steel rather than S275, supposing approximately the same price for both grades.

5 CONCLUSIONS

Estimation of the amount of steel needed to erect braced steel structures with composite slabs, computed for each structural element type was presented. It could be concluded that globally there is no intermediate optimal span, and the trend is a global increase in the amount of steel with the span increase.

The economical application range of steel laminated sections is known to be of up to 9 meters. In this study this conclusion seems to be confirmed, since the amount of steel needed grows very fast for such large spans.

The use of higher grade steel, S355, rather than S275, is an advantage, since it leads to savings in the amount of steel in columns, main girders and in the whole structure.

No significant differences were found in the amount of steel per square meter when using similar bay areas in square and rectangular structural layouts.

REFERENCES

[1] Autodesk, Robot Structural Analysis Professional, 2009.

[2] Eurocode Nº 0 – Basis of Structural Design - EN 1990, CEN, Brussels, 2001.

[3] Eurocode Nº 1 - Actions on structures - Part 1-1: General actions - EN 1991-1-1, CEN, 2001.

[4] Eurocode Nº 2 - Design of concrete structures - Part 1.1: General rules and rules for buildings - EN 1992-1-1, CEN, Brussels, 2003.

[5] Eurocode Nº 3 - Design of Steel Structures. Part 1-1: General Rules and Rules for Buildings - EN 1992-1-1, CEN, Brussels, 2004.

[6] Eurocode Nº 3 - Design of Steel Structures. Part 1-8: Design of Joints - EN 1993-1-8, CEN, Brussels, 2004.

[7] Eurocode Nº 4 - Design of Composite Steel and Concrete Structures. Part 1-1: General Rules and Rules for Buildings - EN 1994-1-1, CEN, Brussels, 2004.

[8] Eurocode Nº 8 - Design of structures for earthquake resistance. Part 1-1: General Rules and Rules for Buildings - EN 1998-1-1, CEN, Brussels, 2003.

[9] Costa, Catarina S.S., Estudo económico de estruturas mistas contraventadas aço-betão, Dissertação apresentada para a obtenção do grau de Mestre em Engenharia Civil na Especialidade de Mecânica Estrutural, FCTUC, Coimbra, 2009.

[10] Costa Neves, L. F., Lima, L. R. O., "Concepção e construção de uma estrutura metálica para reforço de um edifício de pequeno porte", in Lamas, A., Martins, C., Abecassis, T., Calado, L., editores, Actas do V Congresso de Construção Metálica e Mista, VCMM, Lisboa, 2005.

[11] Vianna, J.C., Costa Neves, L.F., Vellasco, P.C.G.S., Andrade, S.A.L., "Estudo Comparativo de Conectores de Corte para Estruturas Mistas de Aço e Betão", Construção Magazine, 2007.

[12] Vianna, J.C., Costa Neves, L.F., Vellasco, P.C.G.S., Andrade, S.A.L., "Experimental Assessment of "perfobond" and "T- Perfobond" Shear Connectors' Structural Response", Journal of Constructional Steel Research, doi:1016/j.jcsr.2008.02.011, 2008.