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One-way slabs. Modelling and comparison of structural solutions with lattice and pre-tensioned joists

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Abstract

The main objective of this work is the development of a methodology for decision-making on the structural typology of floors, combining steel consumption and environmental impact to obtain the optimal structural design. This methodology focuses on the development of a spreadsheet under the criteria established by current regulations. Based on the required dimensions of the building to be studied, a comparative study of the different cases that may occur can be carried out, obtaining the most appropriate one in each case. The work focuses on unidirectional slabs; more specifically those that incorporate prefabricated elements, such as the reinforced and prestressed joist. The characteristics of the joists are obtained from technical sheets supplied by the manufacturer. From the efforts that the beams support in each case, the amount of steel per square meter of slab is calculated, both in reinforced and prestressed joists. In addition, the CO2 emissions produced in the treatment of steel are analyzed. The calculations are made for a slab with a depth of 30 centimeters and a series of permanent and variable loads fixed from the beginning. The results obtained are expressed in the form of a table or graph in a way that simplifies and makes the choice as easy as possible. The results achieved show that a bad design can produce up to 191% more steel consumption and therefore a considerable increase in emissions.

Keywords: Modelling structures, Reinforced concrete, pre-tensioned joists, lattice joists, Economic analysis, Global warming potential.

1. Introduction

The construction sector is one of the sectors with the highest environmental emissions. Increasingly, society demands solutions in all areas that are cleaner and more conservative with the environment. The construction sector cannot be left behind in this matter and for this reason the concept of "Sustainable Construction" is gaining more and more strength. This concept tries to carry out designs and constructions of buildings that aim to integrate environmental, economic and social criteria that positively impact its inhabitants and reduce the consumption of natural resources. Much of the material resources used in construction are used in structures. To analyze the environmental issue, a very useful tool is the Life Cycle Analysis (LCV). Global warming is a category of environmental impact that has gained great importance in recent years. This paper combines modeling and simulation with such impact category to optimize the system from an environmental point of view.

2. State of the art

Residential building has multiple typologies and structural alternatives. Each type has advantages or disadvantages. There are numerous works showing that steel consumption is very representative of environmental emissions[1], [2]. Other studies focus on environmental emissions of very specific elements, such as the study on the carbon footprint of reinforced concrete columns[3]. Unidirectional slabs are the most used in construction and this sector is very traditional and they do not implement major changes. There are studies where an attempt is made to innovate in this type of slabs, such as the slabs of the precast slabs, incorporating corrugated cardboard[4]. The slabs have many criteria to cover, such as economic, social or environmental[5], [6].

This paper beyond the exposed state of the art, presenting a methodology that allows the search for optimal solutions, in the reduction of raw material, more specifically in the steel used in both reinforced and prestressed joists, as well as the search for lower CO_2 emissions for certain dimensions of edification.

3. Materials and Methods trough a case-study

The research focuses on the modeling of different buildings by varying the lengths of each of the two floors, to make different combinations (figure 1).

Figure 1. Modeling of the study building

Before carrying out the study, it is necessary to know a series of concepts that are fixed from the beginning. The building to be studied will be a structure formed by supports, flat beams and unidirectional slab, executed with prefabricated reinforced or prestressed concrete joists. It is necessary to consider the loads that are expected to act on the structure [7], these are established according to table 1.

Table 1. Loads used in the study

	Own weight	floor	partition	usage overload
Loads (kN/m2)	3.5	1.5	1	2

Therefore, the permanent load (QP) will be 6 kN/m2 and the variable load (QV) 2 kN/m2. The loads used in the calculation of the reinforcement will be weighted under the coefficients established in the current regulations [8], leaving for the last limit state as follows,

QTOTAL = 1.35 QP+1.5 QV = 11.1 kN/m2

The total depth that the slab must have is established, which is 30 cm for both reinforced and prestressed joist slabs (figure 2), this value is the sum of the depth of the lightening element (concrete vault) of 25 cm and the layer compression of 5 cm. In addition, a center distance of 70 cm is established between the joists.

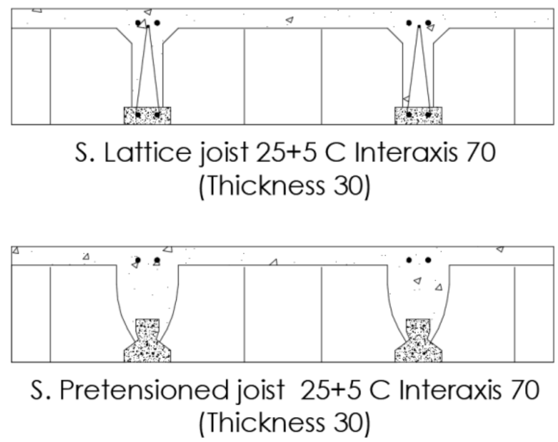

Figure 2. Types of joists edges and center distances.

Table 2 shows the materials used in the two types of joists.

Table 2. Materials used in the joists

lattice joists	HA-25/P/15/I	HA-25/P/20/I	B500S	B500S
pre-tensioned joists,	HP-50/P/12/IIa	HA-25/P/20/I	Y 1860 C	B500S

98 different configurations are established as case studies. These are obtained by varying the type of unidirectional slab (reinforced joists and prestressed joists) and the variation of the lengths of the slab spans, which will have a minimum length of 3 meters and a maximum length of 7 meters. Each of the two spans will increase by 0.25 meters establishing all possible combinations. Therefore, if we add the two slab spans studied, it will be possible to calculate buildings with a maximum total span of 14 meters (in the case of 2 spans of 7 meters each) and a minimum of 6 meters (in the case of 2 spans of 3 meters).

To model the different alternatives, a general model has been automated, made up of two spans, so that all their lengths can be varied, being able to analyze the different cases.

For each of the study cases, the ultimate limit state has been calculated, obtaining the calculation of the moment diagrams, as well as that of shears. Once the efforts have been obtained, the type of joist is analyzed. In the reinforcement of the reinforced joist, from the manufacturer's technical file, the dimensions of the main reinforcement and reinforcement necessary to cover the moment produced in each span, both for negative bending and for positive bending, are obtained. For the prestressed beam, the type of beam for positive bending and the reinforcement diameter for negative bending are also determined with the manufacturer's sheet. Finally, once the types of beams to be used have been defined, the CO_2 emissions from the steel treatment product stage have been analysed, that is, in obtaining raw materials, transport and manufacturing. The results obtained are expressed in kg of CO_2 equivalents per square meter of slab in proportion to the kg of steel obtained in the reinforcement.

4. Results and Discussion

In the first place, the results obtained in the calculation of the reinforcement for reinforced and prestressed joists are studied, in order to make a comparison between the two types of slab.

Figure 3 shows the graph for the type of reinforced joists and Figure 4 for prestressed joists. These show on the "Y axis" the kg of steel per square meter used in the joists and on the "X axis" the total lengths of the sum of the spans of the two slabs. Said graphs are interpreted in the form of dispersion points, specifically 49 points for each graph, where each one shows the combination of spans used (for example, the value (3+4.5) means that the span of the first span is 3 and that of the second is 4.5 meters, achieving a total length between the two slabs of 7.5 meters). The Y axis has different ranges in the two figures to show the data obtained more clearly.

Such results have been obtained using specialized software (SimaPro) and a database (Ecoinvent), such as indicated in [9] and [10]. In these papers a similar methodology is used applied to other different subjects.

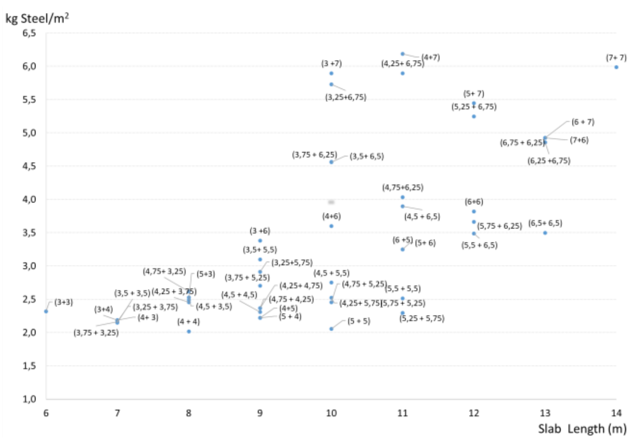

Figure 3. Steel used in the lattice joists for the different lights.

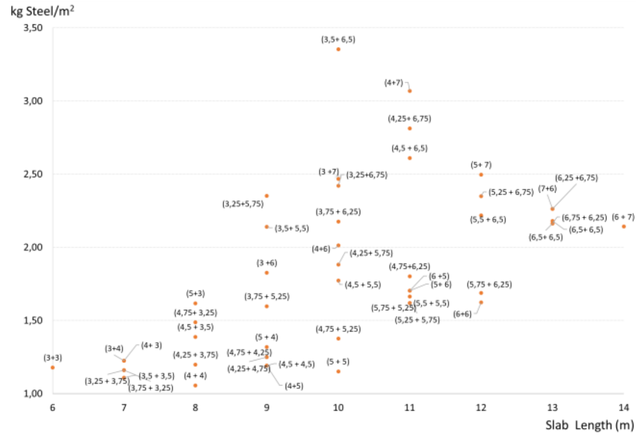

Figure 4. Steel used in the prestressed joists for the different spans.

A clear difference can be observed between the amount of steel used for the manufacture of reinforced joist and prestressed joist floors. For the 49 reinforced joist alternatives, they range from 2.02 to 6.18 kg/m2. On the other hand, the alternatives of prefabricated joists vary from 1.06 to 3.07 kg/m2. This means that the cost of steel in reinforced joists is up to 83% higher than in prestressed joists. In terms of cost per amount of steel used, a prestressed joist slab is much cheaper than one with a reinforced joist, so when selecting one type or another, the benefits offered by both types of reinforcement and identify which solutions offer the best value for money. The prestressed beam provides higher inertias, which produces a considerable reduction in deflection and provides a greater distance between supports, however, the prestressed concrete is more expensive, and the design of the structural elements is more complex and specialized. It is necessary to have specialized operators for its installation. We can also observe that the consumption of steel is lower when the spans of each of the two slabs is compensated. For example, for total spans of 10 meters between the two slabs, we have differences in consumption from the 5+5 alternative for a reinforced joist of 2.05 kg/m2 and 1.15 kg/m2 for a prestressed joist to the alternative 3.5+6.5 or 3+7 which has a consumption of 5.89kg/m2 and 3.35 kg/m2 respectively. Therefore, a poor choice of intermediate pillar design can lead to up to 191% more material used.

Figures 5 and 6 show the results obtained from the life cycle analysis, more specifically, the CO_2 emissions produced in the different treatment phases of the steel used. The figures have the same composition on the "X-axis" and at the scatter points. They change the “Y axis” where CO_2 emissions are shown in equivalent kg.

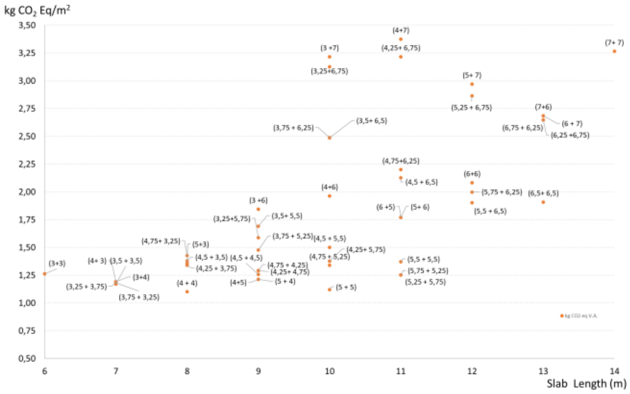

Figure 5. CO2 emissions in the lattice joists for the different lights.

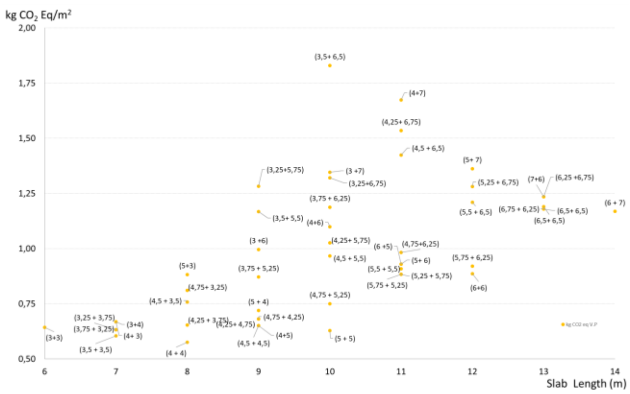

Figure 6. CO2 emissions in the prestressed joists for the different spans.

A clear difference can be observed between the CO2 emissions for the manufacture of reinforced joist and prestressed joist floors. The reinforced joists have a range between 1.10 to 3.37 kgCO2eq/m2. In contrast, the alternatives of prefabricated joists vary from 0.58 to 1.67 kgCO2eq/m2. This means that the emissions between the typologies can vary up to twice as much from choosing reinforced joists to prestressed joists. We can also observe that the consumption of steel is lower when the spans of each of the two slabs is compensated. For example, for total spans of 11 meters between the two slabs, we have differences in consumption from the 5.25+5.75 alternative for a reinforced joist of 1.25 kgCO2eq/m2 and 0.88 kgCO2eq/m2 for a prestressed joist to the 4+7 alternative, which has a consumption of 3.37 kgCO2eq/m2 and 1.67 kgCO2eq/m2. respectively. Therefore, a poor choice of intermediate pillar design can lead to a large increase in the emissions produced.

5. Conclusions

In this work, a methodology has been presented that allows the search for optimal solutions, balanced in cost and performance, of unidirectional concrete slabs with a slab with a depth of 25 + 5 cm and a center distance of 70 cm. Multiple combinations of designs were made, obtaining the efforts that determine the amount of steel per square meter and CO2 emissions.

From the results, the optimal ones are obtained and represented in graph form for the different types of light. The use of these graphs presents multiple advantages to the floor designer, since: the best solutions are presented together for each span and each type of reinforcement (reinforced and prestressed beam) that it is easy to make comparisons in terms of consumption and performance. Design time is reduced as lengthy trial and error is largely avoided. In addition, this methodology, if automated, can allow the rapid analysis of the optimal solutions in each future scenario where changes in the types of materials, loads or labor costs occur.

Finally, this methodology can be extended with the inclusion of other parameters such as the possibility of varying the depth and center distance, as well as the type of joist, offering a wider range of solutions.

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