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Prestressed concrete building floors

Pavimentos de edifícios de concreto protendido



F. M. Almeida Filho [a]
ffilho@sc.usp.br
M. R. S. Corrêa [b]
mcorrea@sc.usp.br
M.A. Ramalho [c]
ramalho@sc.usp.br

Abstract

The present work deals with the use of the prestressed concrete, bonded and unbonded, for residential buildings, pointing out aspects such as consumption of materials, construction time and structural performance. Three different structural systems are considered: flat plate and columns; waffle slab and columns and waffle slab supported by prestressed strip beams and columns. The studied structural systems are analyzed by the structural analysis program TQS®, using the so-called grillage analogy method. Initially, a numerical simulation is carried out in order to evaluate the behavior of an experimental model. After, a residential building floor case analysis is carried out, considering the different structural systems afore mentioned, adopting both bonded and unbonded tendons. After several considerations based on the obtained results one can say that the unbonded prestressed waffle slab on columns seems to be the most interesting system for this case.

Keywords: Prestressed concrete; structural system; materials consumption; unbonded prestress; bonded prestress.

Resumo

O presente trabalho aborda a utilização da protensão aderente e não-aderente em edifícios residenciais de concreto, com destaque para aspectos referentes ao consumo de materiais, tempo de execução e desempenho estrutural. São considerados três diferentes arranjos estruturais: laje plana maciça sobre pilares; laje plana nervurada sobre pilares e laje nervurada apoiada em vigas-faixa protendidas sobre pilares. As estruturas são analisadas com o programa TQS®, utilizando-se a "analogia de grelha". Inicialmente, é apresentada uma simulação numérica de um protótipo experimental em laje protendida, mostrando a adequação da simulação numérica adotada ao comportamento dos pavimentos estudados. Posteriormente, é estudado um caso de um pavimento de edifício residencial, considerando-se os três arranjos estruturais mencionados e ainda a protensão aderente e não-aderente. Com os resultados obtidos são feitas diversas considerações que levam à conclusão que, de forma geral, a laje nervurada sobre pilares com protensão não-aderente parece ser o sistema construtivo mais interessante.

Palavras-chave: Concreto protendido; Arranjos estruturais; Consumo de materiais; Protensão não-aderente; Protensão aderente.

[a,b,c] *Structural Engineering Department, São Carlos College of Engineering / USP , 13566-590, São Carlos, Brazil*

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1 Introduction

Concrete, since its creation, has been widely used in civil construction and the advent of prestressed concrete has made this material even more attractive to various structural systems. The following can be highlighted from among its main technical and economical advantages:

a) Viability of great spans and reduction of heights of angled components, turning the structures lighter and thus relieving also the very weight to be supported by the foundations;
b) Structures consumption conditions improvement .due to the fissures reduction in the concrete or their grooves limitations , thus increasing their protection related to the aggressiveness of the medium environment;
c) Greater possibility of structure recovery after an unexpected loading excess, with the closure of some eventual fissures after unloading.

In the 50's the first prestress patent emerged, which used to use individual extruded plastic sheaths. With this, structural solutions could be improved, with the reduction in the average thickness of the floors, decrease of the total building height and increase of speed in the execution process. All these conditions lead to reductions in the total project cost, turning this type of structural solution one of the most interesting choices for building projects.

In the present work a study of the structural prestress consumption aspect in building floors is presented and for this a relatively simple analysis procedure is used: the Grillage Analogy Method.

Building floors are evaluated more frequently in three structural arrangements:

a) Solid prestressed flat slab supported over columns;
b) Waffle (Ribbed) prestressed flat slab supported on columns;
c) Waffle slab without prestress supported over prestressed strip beams and columns;

The study involves system adaptation to the floor geometry, and taking advantage of the studies cases, it also compares bonded and unbonded prestress. The importance of this work is justified by the increasing unbonded prestress consumption in building floors and even by the reduced popularization of the matter in the country, especially in what refers to its possible economic advantages.

2 Numerical slab simulation

A comparative numerical analysis of an experimental prestressed flat slab model presented by Scordelis [1], Figure 1, was performed. The simulation was done, allowing a linear elastic behavior for a numerical model, which is a condition justifiable through the fact that the concrete, in this type of structure, maintains the greater part of its useful life in Stage I.

The objective of this analysis was to verify the acuity of the grillage analogy model in the representation of an in-service prestressed slab, where such verification is convenient since this was the numerical procedure used in all subsequent analyses. The choice of this procedure is justified because the adopted program for the analysis, TQS®, presents the quantities of materials used, considers automatically prestress influence and even executes efficiently structure detailing.

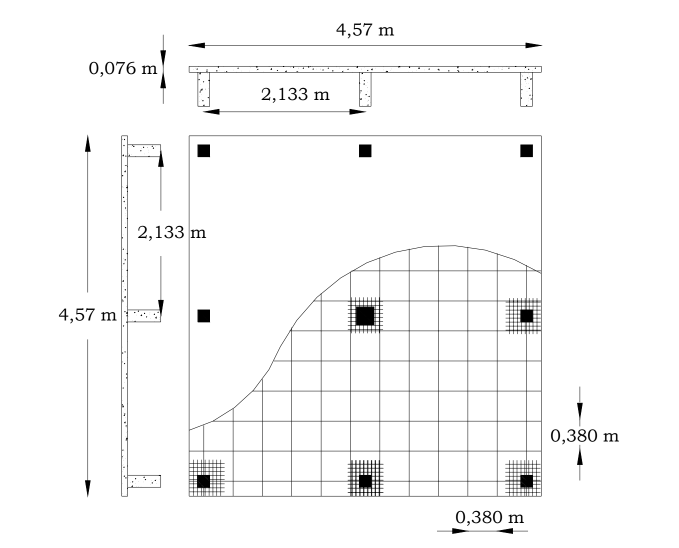

Figure 1 - Studied experimental model (Scordelis [1]).

Equivalent prestress action was calculated according to Lin's method [2] for load balancing, applying them as concentrated forces in cable intersection points.

Equation (1) shows the equivalent action proposed by Lin [2] for bi-directional systems. It incorporates the prestress forces in two directions that equilibrate the force q, portion of the distributed loading per unit of area to be balanced.

$$q = \frac{8 \cdot P_x \cdot e_x}{L_x^2} + \frac{8 \cdot P_y \cdot e_y}{L_y^2} \quad (1)$$

Still in equation (1), P_x and P_y correspond to the prestress forces, in the *x* and *y* directions, per unit of length. The values e_x and e_y correspond to the cable distances in relation to the average slab surface in the *x* and *y* directions, respectively. L_x and L_y correspond to the lengths of the cable parabolic intervals in the *x* and *y* directions, respectively.

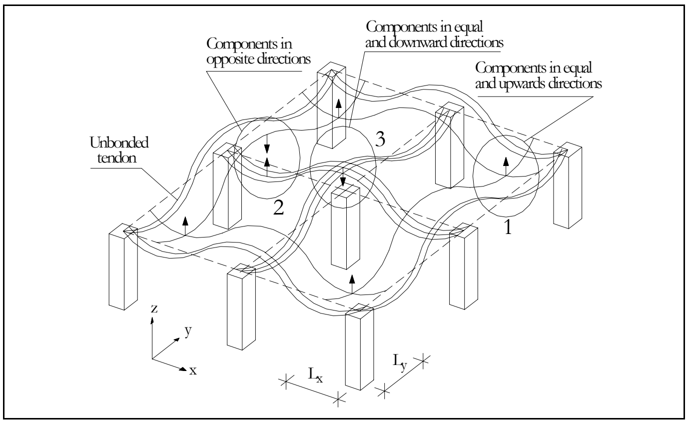

Figure 2 - Parabolic cable profiles in continuous prestressed slabs.

Figure 2 shows the disposition of the parabolic cables in the tested flat slab and even the schematization of the balanced load components.

For the load balancing, the value of the prestressed components is calculated so as to determine the value of the forces in the intersections of the cables.

Taking the rig profile, illustrated in Figure 3, Scordelis [1], can calculate the forces in the cable intersections. It should be pointed out that the units adopted herein are the same as the original work.

P = 6840.0 Lb; e = 1.0in.

S = 15 in. (spacing between tendons)

L_1 = 66 in.; L_2 = 48in.

Then:

$$q_1 = \frac{8.6840\,(\text{lb}).1\,(\text{in.})}{66^2\,(\text{in.}^2)} = 12,562\ \text{lb/in.}$$

$$q_2 = -\frac{8.6840\,(\text{lb}).1\,(\text{in.})}{48^2\,(\text{in.}^2)} = -23,75\,\text{lb/in.}$$

$q_1 = W_{bal1}$ = upward distributed force;

$q_2 = W_{bal2}$ = downward distributed force.

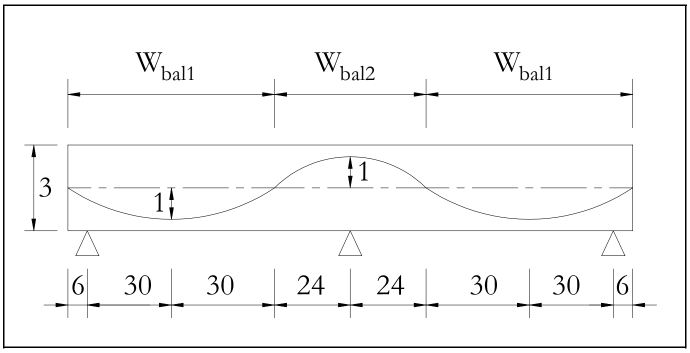

Figure 3 - Tendon profile (in.).

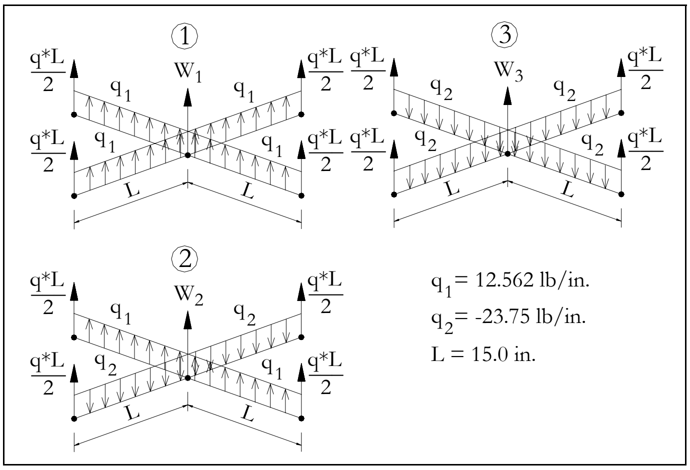

Figure 4 - Schema of nodal forces in the intersections of the cables.

Figure 4 illustrates the three possible situations for the calculation of forces that arise in the parabolic cable intersections, where the length L is the distance between the nodal points

Thus, the nodal force values for the cable intersections are:

W_1 = 376.86lb.

W_2 = -167.82lb.

W_3 = -712.50lb.

Where W_1, W_2 and W_3 are equivalent prestress forces for regions 1, 2 and 3, respectively, shown in Figure 2.

Lin's method [2] is based on the principle that the prestress can be understood as one action that balances part of an in-service structure loading, which explains its given denomination "equivalent prestress action". Thus, a structure under this condition can be considered one without prestress, but with a transversal loading decrease that is present due to this pre-compression introduced by the prestress. In this manner, the prestress can be designed to balance part of the load, or load combination, such that the traction stresses on the part may be cancelled or significantly reduced.

In accordance with Aalami [3], load balancing is the main analysis method of prestressed concrete structures. This procedure is even extremely advantageous in the calculation of statically undetermined systems because, even in this case, it maintains its simplicity.

Figure 5 shows the disposition of the cables in the experimental model, which was also the one adopted in the grillage analogy modeling.

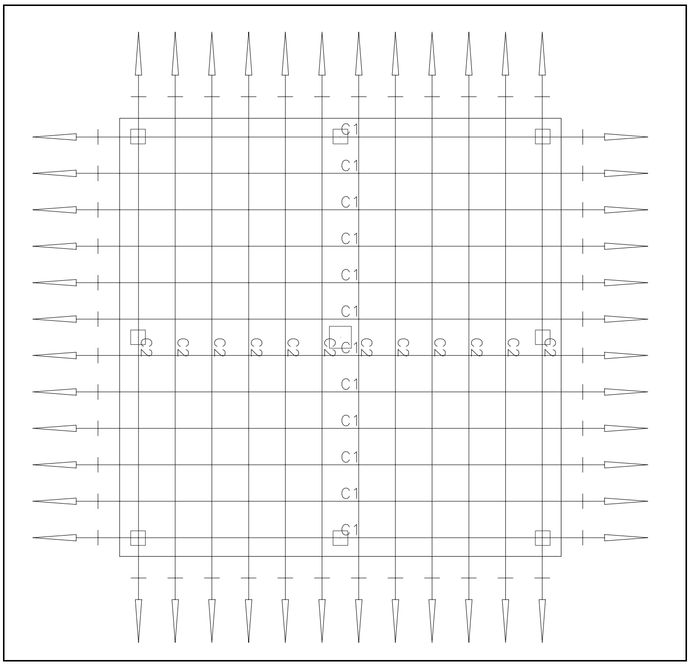

Figure 5 - Disposition of the cables for the grillage model.

For the numerical modeling of the example in question, the same loadings and the same concrete characteristics were taken into account, as presented by the authors of the experimental work.

For the concrete, the following has been adopted:

- Poisson's Coefficient = 0.14;
- Longitudinal Modulus of Elasticity (E_c) = 2413 kN/cm²;
- Transversal Modulus of Elasticity (G_c) = 965 kN/cm².

For the unbonded tendon, the following parameters were adopted:

a) Yield limit = 1533 kN/cm²;
b) Rupture limit = 1744 kN/cm²;
c) Longitudinal Modulus of Elasticity (E_p) = 20670 kN/cm²;
d) Cable section area (A_s) = 0.32 cm²

In Table 1 the maximum displacements in the central point of the slab are presented. In this table, loading 1 corresponds just to the prestress force applied in the model; loading 2 is equivalent to the cracking limit that is equal to 9.6×10^{-4} kN/cm² and loading 3 to the distributed vertical action equal to 1.7×10^{3} kN/cm², representing the rupture of the model.

Table 1 - Displacements for the numerical and experimental models (in centimeters).

Loading	Exp.	Numerical
1	-0.11	-0.08
2	0.12	0.13
3	0.39	0.28

Numerical modeling with the TQS® program presented good results, with differences in the order of 9% concerning the experimental model in the elastic phase, revealing adequate precision for the analyses to be performed in the present work. Concerning the rupture loading, which did not constitute as objective of this work to evaluate, the difference was 29%, showing a greater deviation between the experimental and numerical results. This difference was already expected, since the numerical simulation is just a linear procedure and, after the cracking, the experimental model's behavior is typically non-linear.

From the resulted obtained in the example can be concluded that the grillage analogy procedure is sufficiently precise for the analyses to be performed. Meanwhile, for the analysis of localized effects, a more refined discretization can be required.

3 Pavement example for study

For the present case study, a residential building floor was taken as example, previously analyzed by Albuquerque [4] in a work that presented an analysis similar to the study performed herein, however, with the focus towards armed concrete structures.

In Figure 6 the building's floor architecture is shown.

It is a 20-floor residential building with an area of 254 m² on every floor. The numerical modeling was performed in accordance with the parameters discussed in the previous item, that is, grillage analogy analysis with the use of the TQS® program.

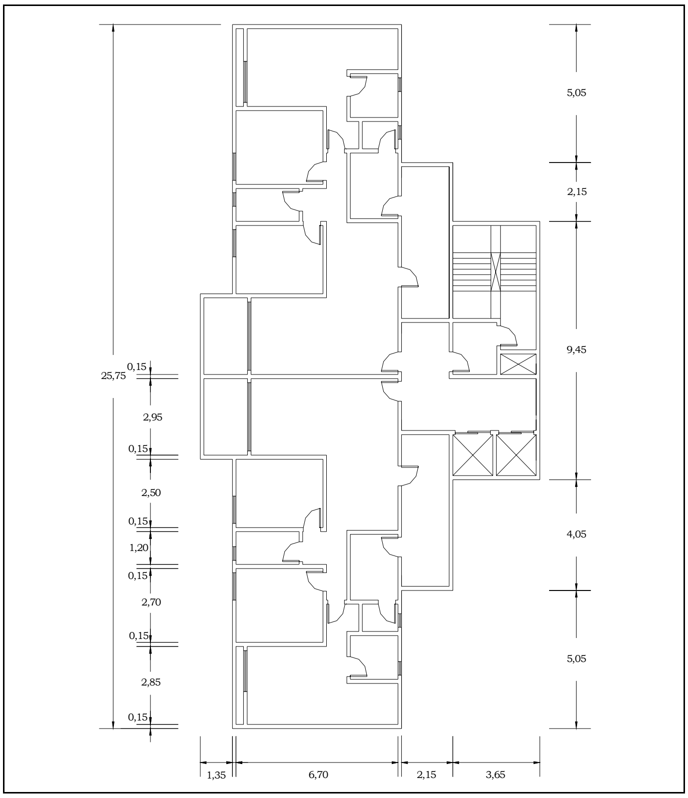

Figure 6 - Pavement type (Albuquerque [4]).

4 Analyzed structural arrangements

For the intended comparisons, six prestressed concrete structural arrangements, three with bonded prestress and three with unbonded prestress, were studied. The general description of their characteristics is given in table 2.

Table 2 - Analyzed structural arrangements.

Arrangement	Description
E01	Solid flat slab with unbonded prestress.
E02	Solid flat slab with bonded prestress.
E03	Waffle flat slab with unbonded prestress.
E04	Waffle flat slab with bonded prestress.
E05	Waffle flat slab with strip beams with unbonded prestress.
E06	Waffle flat slab with strip beams with bonded prestress.

More details on these arrangements are provided in the following items. Meanwhile, it is pointed out that for all cases of analyzed waffle slabs, the waffles have the following characteristics: average thickness equal to 7 cm, total height of 25cm (4-cm layer) and distance between axes equal to 60cm.

Since the pavements are flat slabs, even in the case of the arrangements in strip beams, there are little trestles in the diagonal brace structures, which, however, present adequate rigidity as it could be verified in Table 4 and in Table 5.

4.1 Prestressed flat slab

In Figure 7 shows the adopted structure for the pavement, taking into account both prestress systems: bonded and unbonded. The slabs have a thickness of 16cm.

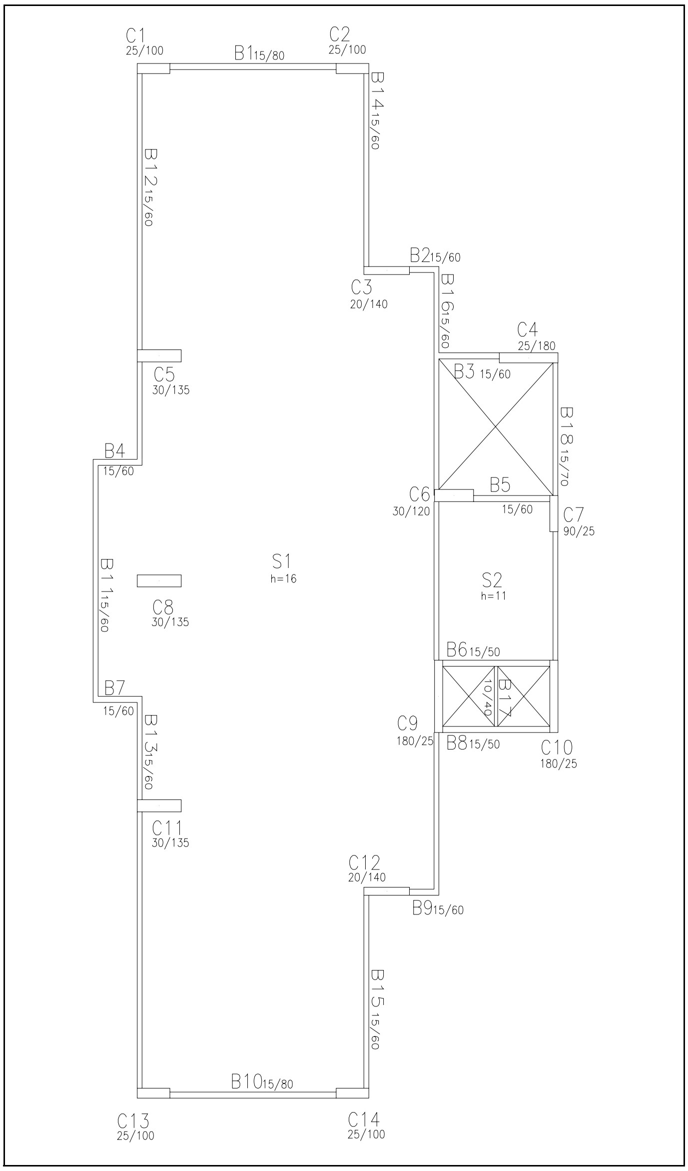

Figure 7 - Prestressed solid flat slab.

4.2 Prestressed waffle slab

Figure 8 shows the second adopted structural arrangement, that it is valid for the bonded prestress as well as for the unbonded prestress. The span / thickness ratio of to 30 was adopted, which results in a slab with waffles of 25cm high.

4.3 Waffle slab with prestressed strip beams

For this case, as presented in Figure 9, a span/thickness ratio equal to 30 would lead to a structure thickness equal to 27cm. A thickness equal to 25cm was adopted as initial pre-sizing attempt in function of its adaptation to the plastic molds usually found in the market.

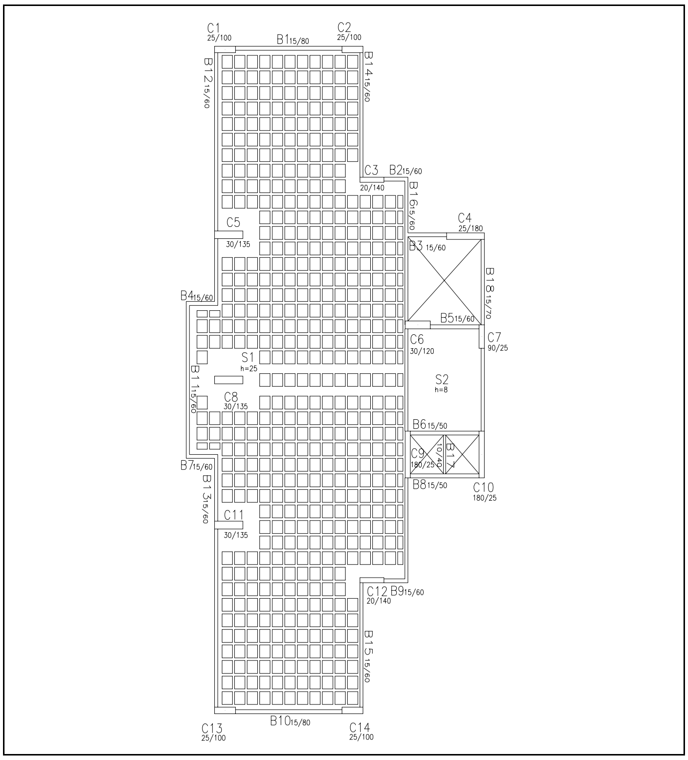

Figure 8- Prestressed waffle flat slab.

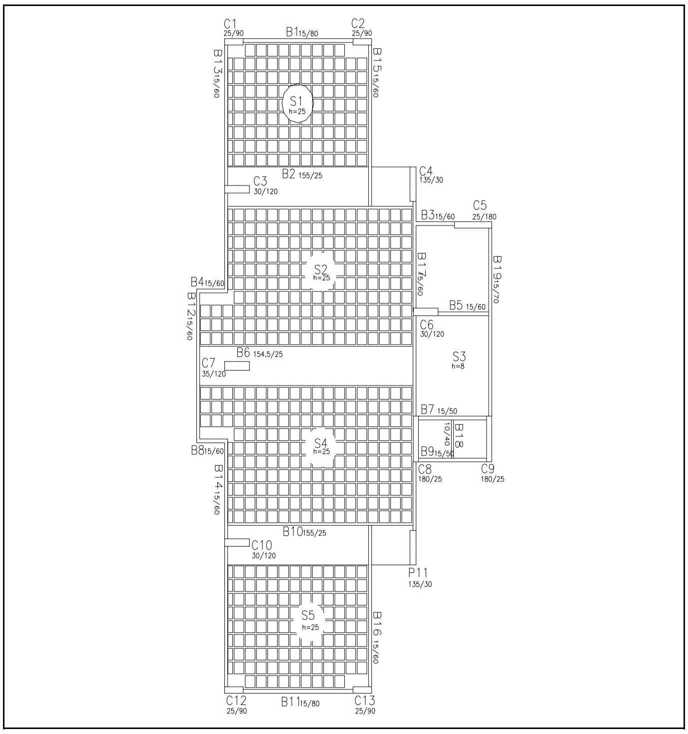

Figure 9 - Waffle slab with prestressed strip beams.

5 Material consumption comparative analysis

From Figure 10 to Figure 13, graphs with material consumptions are presented for the considered structural alternatives, which allow the proper comparisons to be established.

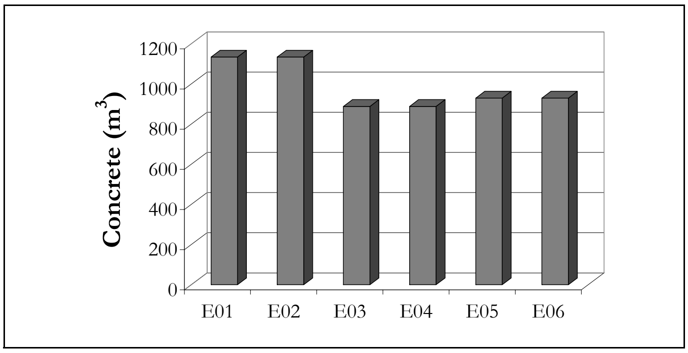

Figure 10 - Concrete consumption.

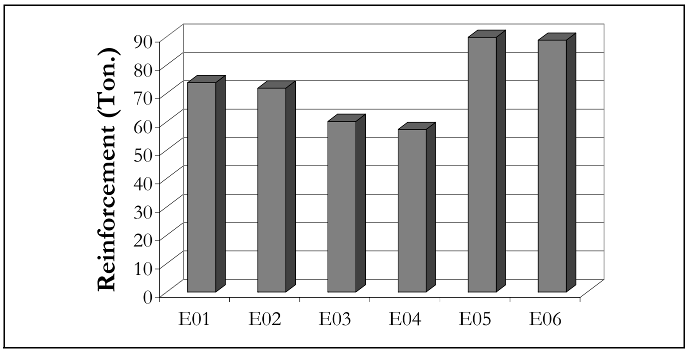

Figure 11 - Passive reinforcement.

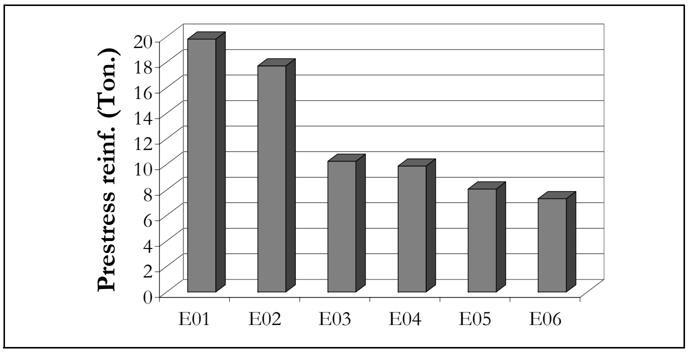

Figure 12 - Prestressed reinforcement.

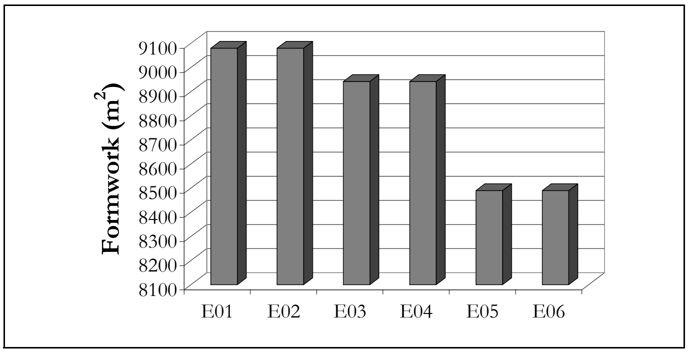

Figure 13 - Formwork consumption.

In all comparisons that are presented as follows the same procedure is used: the base value is that of the alternative that leads to the least consumption, where the values of the others are referenced to it.

Figure 14 presents the differences for concrete consumption. Related to this requirement, the waffle flat slab arrangements, E03 and E04, are a little more economical than those in waffle slab and strip beams, E05 and E06, and significantly more economical than those in the solid flat slab, E01 and E02. These results are not different from those that would be obtained without prestress and, therefore, they were already expected.

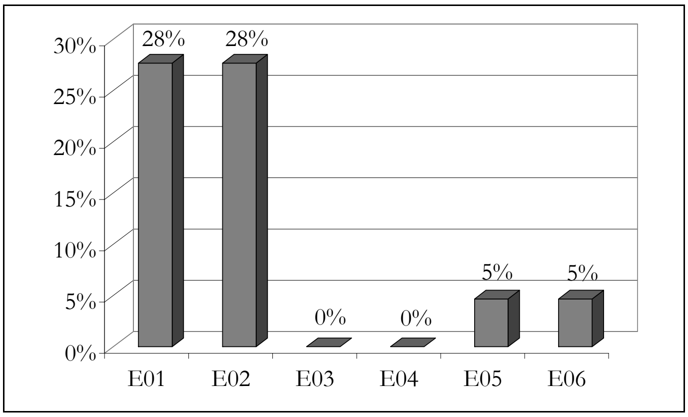

Figure 14 - Difference of concrete consumption.

Related to the secondary reinforcement consumption, Figure 15 shows the differences obtained. As base value, the arrangement that leads to the least consumption was once again chosen, in this case E04, waffle slab with bonded prestress. It must be pointed out that the difference between the bonded and unbonded prestress is not very significant, representing only 5% more consumption in every case. Clearly less economical in this requirement are the waffle slabs with strip beams: approximately 50% more consumption.

The differences of prestressed reinforcement consumption are quite significant, as it can be verified in Figure 16. In this case, the waffle slabs with strip beams arrangements are the most economical, where it can be observed that all cases of flat slabs presented an even greater consumption in this item. Similarly to what was verified for prestressed reinforcements, the difference between the bonded and unbonded prestress systems is relatively small, between 5% and 10% only for every case.

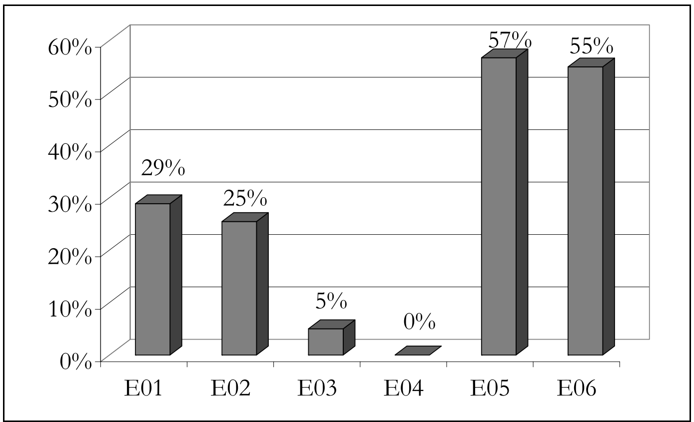

Figure 15 - Difference of passive reinforcement consumption.

For the consumption of the formworks, the values obtained for all structural arrangements were, obviously, very close to each other. In Figure 17, the maximum difference obtained was 7%, where this is, therefore, a less significant parameter.

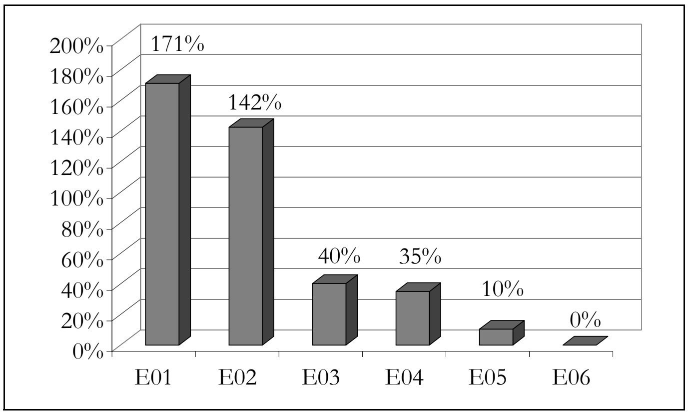

Figure 16 - Difference of prestressed reinforcement consumption.

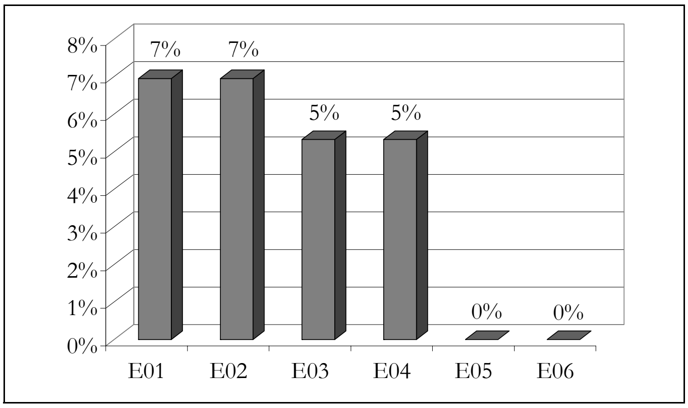

Figure 17 - Difference of formwork consumption.

6 Execution time

In this item, search whether to evaluate the expected execution time for the studied examples. The interest in this aspect can be explained due to its direct relation with the applied labor cost for the execution of each one of the studied alternatives. Concerning this requirement, two main aspects are focused: comparison between the different structural systems; solid flat slab, waffle flat slab with and without strip beams; and comparison between bonded and unbonded prestress.

In accordance with the experience of various project engineers accustomed to the execution of this type of structure, and that were consulted on this requirement, the execution time for the pavement considered as example can be estimated, in workdays, in accordance with what is presented in Table 3. For this evaluation, the actuation of a well-sized and well-trained team was taken as basis, like those that are normally used by good construction companies.

It can be pointed out that there are no significant differences for the execution of waffle slabs with or without strip beams. Therefore, in this item, only waffle slabs will be mentioned, independently of whether they are supported over columns or strip beams.

It is worth recalling that the arrangements with waffle slab demand greater execution time in function of the assembly of the formwork for waffle concreting.

Table 3 - Time (days) for pavement execution.

Prestress	Bonded	Unbonded
Solid flat slab	6	5
Waffle Slab	7 to 8	6 to 7

Details on these evaluations will be discussed in the next two sub-items. It is important to mention, however, that this discussion is given in more qualitative terms than in the evaluation on material consumption. Unfortunately, in this requirement it was not possible to present really precise data, since most of them were the factors that can influence this evaluation of execution times, and consequently the expected labor costs for the production of various analyzed structural arrangements.

6.1 Adopted structural systems comparison

Generally, the structures that demand more execution time were those present a large number of beams and columns. Related to this, the structural systems analyzed herein, can be considered interesting, since all present a relatively small number of beams and columns, where its main characteristic is the use of relatively large-sized slabs.

Meanwhile, the waffle flat slab systems, whether they are with or without strip beams, present a disadvantage that can be considered significant in comparison with the solid flat slab. Concerning the constructive process, these waffle slab solutions become more difficult due to the difficulties found in the correct positioning of plastic molds used for the obtaining of waffles and posterior assembly of reinforcements. On the contrary, the execution of solid slabs ends up being even simpler, having only the need of the correct positioning of the reinforcements. In general, it can be affirmed that waffle flat slabs demand 20% more time in relation to solid flat slabs.

6.2 Comparison between bonded and unbonded prestress

Concerning the execution time for the cables with or without bonding, two factors can be compared: the time for positioning of the cables in the forms and the time needed for stretching of the cable.

In general, the unbonded tendon presents greater facilities for its positioning in the mold as well as for the posterior prestress application. The facility in positioning is explained because the unbonded tendon are lighter, not having the metallic sheaths that characterize bonded prestress. Besides, the proper prestress application is facilitated since the jack is much lighter, turning easier its transport and positioning.

As a matter of illustration, it can be mentioned that a query performed on the MAC's catalog, Brazilian Prestress System (*Sistema Brasileiro de Protensão*), indicated that a hydraulic jack for 4 bonded rigs would weigh approximately 70 kgf, while the hydraulic jack for unbonded prestress only weighs approximately 20 kgf.

In this study, it was established, along with engineers with experience in prestress projects, that usual pavements with bonded prestress require from 15% to 20% more execution time than those similar with unbonded prestress. In the case of the adopted pavement as example for the analyses performed herein, this would represent approximately a day more for its execution.

7 Structural performance evaluation

As simplified structural performance criteria, it was opted to adopt the maximum displacements obtained for every structural arrangement considered.

For this vertical displacements were calculated that include an estimate of the increases due to cracking and creep (Figure 18). It is important that these values were obtained for the same point in all arrangements and are below the limits prescribed by NBR 6118 [6].

The Figure 19 presents the differences obtained between the considered arrangements, such that the adopted basic value is that of arrangement E04, waffle slab with bonded prestress, that is, the least value obtained. Observing the Figure 19 it can be noticed that the arrangements in waffle slab with strip beams present displacements that are approximately twice the values obtained for the waffle slabs without strip beams, where the values obtained are a little worse for the solid flat slabs.

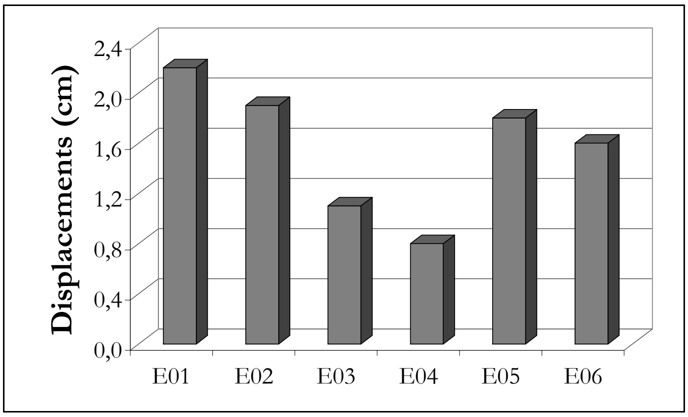

Figure 18 - Maximum vertical displacements.

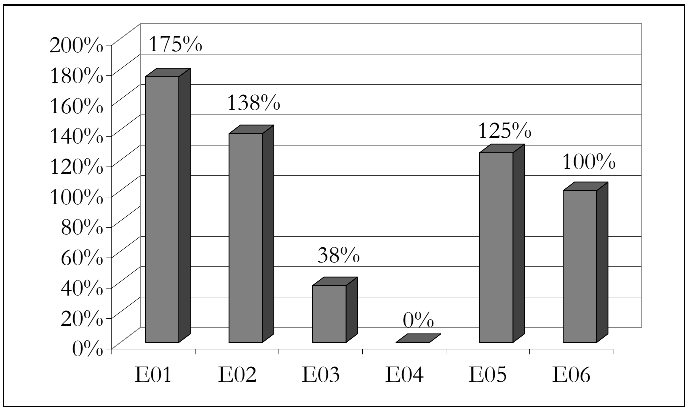

Figure 19 - Differences of maximum vertical displacements.

An estimate of the values obtained for the building top is done already for horizontal displacements, considering only the cracking effects. The results obtained for every analyzed arrangement are presented in Figure 20. For every case the wind action was considered according to the directions X, greatest size in plant, and Y, smaller size in plant.

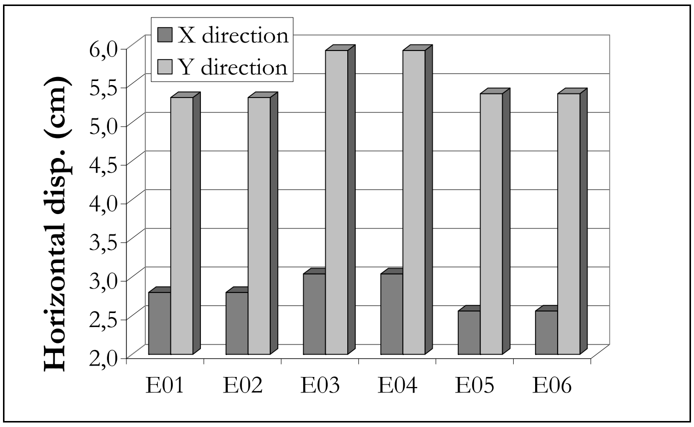

Figure 20 - Horizontal displacement in X and Y directions.

In order to perform the comparison between the various analyzed constructive systems the graph presented in Figure 21 was prepared. In this case the basic adopted value is the limit H/500, where H is the total building height. This limit, adopted by some authors as the maximum horizontal displacement to be admitted for the building top, must be seen with certain caution, but it can be adopted for the simple comparison purposes of this work.

Observing Figure 21 it is noticed that the performance of various arrangements is similar and must not cause greater preoccupations. Even in the Y direction, the more deformable, the values obtained in the 50% range of the value H/500. Another detail to be mentioned is that, in this case, there is no difference between the bonded and unbonded prestress, since the non-linear effects relative to the cracking were considered in a simplified form in accordance with NBR 6118 [6].

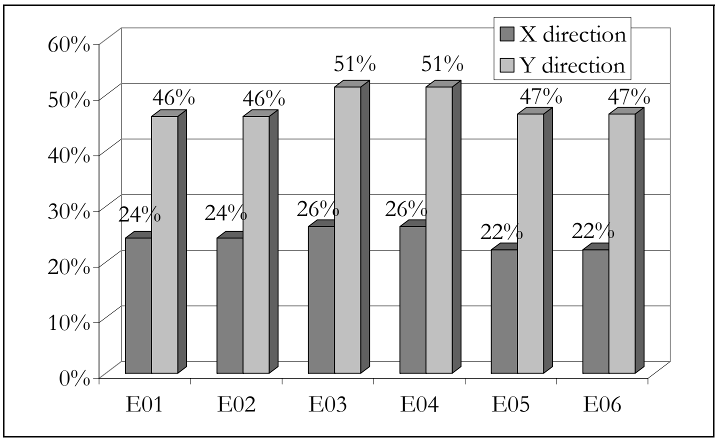

Figure 21 - Horizontal displacement percentage in relation to the value H/500.

Table 4 and Table 5 illustrate the γ and α values for the prestressed concrete structure arrangements.

Table 4 - Global instability parameters – X direction.

	E01	E02	E03	E04	E05	E06
γ_x	1.12		1.13		1.12	
α	0.77		0.78		0.72	

Thus, although the overall structure of the buildings of every structural arrangement were deformable by the lack of internal frames, the overall behavior of all examples was satisfactory.

8 General evaluation for analyzed arrangements

For a general evaluation on the best solution, the three previously mentioned main factors must be considered: material consumption, execution time and structural performance.

Also in this general evaluation, in a similar form to what has been done on the item on execution time, two main aspects are focused: comparison between the different structural arrangements, solid flat slab, waffle flat slab with and without strip beams; and comparison between bonded and unbonded prestress.

Initially the more complex aspect is approached, that is, the comparison between the different adopted structural systems. Within this focus, analyzing in the first place material consumption, it is verified that the waffle slabs lead to a certain advantage over the solid flat slab. Mainly related to the dimension of concrete and use of prestressed reinforcements, this advantage becomes well evident. Meanwhile, this advantage is even more evident when the waffle slab without strip beams is considered, which presents the least consumption in all the evaluated items.

Related to the execution time the situation is inverted and under this point of view the solid flat slab is that it presents a clear advantage over the waffle slabs. This obviously is reflected in a least labor cost that does not eliminate the difference obtained related to material consumption, but at least reduces significantly this disadvantage.

Even with respect to the vertical displacements, it can be observed that the arrangements with bonded prestress are a little more rigid than those that use unbonded prestress, presenting values for 25% to 40% lesser displacements.

Finally, as for the structural performance, the waffle slab without strip beams is clearly pointed out in regards to the vertical displacement, producing even more rigid pavements related to this important parameter. When the horizontal displacements of the building top are considered, all systems behave similarly and satisfactorily.

Therefore, in a general evaluation on the three adopted structural arrangements, it can be affirmed that the waffle slab without strip beams seem to be the most indicated for the usual cases. The only doubt that can remain is when the speed of execution or labor cost is really very important, such that it may be thought of in the use of solid flat slabs that present a better performance exclusively under this aspect.

Thereof, the question of the bonded or unbonded prestress, the differences over material consumption are not very significant, where these differences are restricted to passive and prestressed reinforcements. For example, for waffle slabs, with or without strip beams, the difference varies between 5% to 10%, with slight advantage for the bonded prestress.

A different situation, although more accentuated, is verified when execution time is discussed. In this case, the unbonded prestress is more interesting than the bonded prestress, where the differences are more significant than in the previous case and putting it within the 15% to 20% range. Since the execution time is found directly related to labor cost, it can be concluded that the unbonded prestress presents a certain advantage in relation to the total cost, where this difference must be within the 10% to 15% range when material consumption and labor are considered as a whole.

Meanwhile, when structural performance is considered, bonded prestress is more interestingly revealed, obtaining smaller vertical displacements, where the differences are of the order from 25% to 40%. It is important to verify hat these differences are verified in the portions corresponding to the creep and that, therefore, could only be evaluated using a non-linear analysis procedure, although in a simplified form.

Thus, considering then, the question of the type of prestress to be adopted, it seems that the unbonded prestress is revealed more interesting, although it may present greater vertical displacements when creep is considered. But, unless this detail is really very important for a determined specific case, the use of unbonded prestress seems to be more adequate to the usual cases.

Therefore, in a general form and respecting particular conditions that can occur, the waffle slab without strip beams with unbonded prestress an be considered the structural system that presented the best general performance. This is what was concluded when the adopted pavement was considered in this study. Evidently, for other cases with significantly different spans other conclusions can be obtained.

9 Conclusions

In this study six different structural systems were analyzed, including arrangements in solid flat slab, waffle slab without strip beams and waffle slab with strip beams, all considered with bonded and unbonded prestress.

In general, it can be concluded that the waffle slab without strip beams and with unbonded prestress is the most interesting when concerning the total cost, presenting even good indicators related to structural performance, in accordance with a simplified verification criteria of maximum values obtained for displacements, also with respect to execution time.

The arrangement in solid flat slab already presents a more elevated material consumption and a poor structural performance than the waffle slabs. Only in the execution time requirement, and consequently labor cost, is that it presents some advantages.

Finally, in the comparison between bonded and unbonded prestress, this last system seems to be more interesting, nevertheless the fact that the expected maximum displacements are a little greater, when the portion is considered due to creep.

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