“COBIAX” Voided Slabs and Post-Tensioned Flat Slabs: Competitive Analyses

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Abstract

In building structures, slabs are one of the most essential elements regarding the final cost of the structure, due to the large amount of building materials used. Therefore, it is of value to compare some of the existing technologies on the market, aiming to make this element less costly or even improve its deformations. For that, Cobiax® and pre-stressed slabs appear as a suitable option. Based on this premise, this work focuses on showing the benefits and limitations of both Cobiax® and pre-stressed slabs, as well some of the most important aspects of the design of these solutions.

These solutions were compared with the traditional flat slab with drop panels in order to obtain the differences in both cost and deformation values. To perform this analysis two types of loads were used in a regular span of eight meters in length.

The first loading case refers to slabs applied in offices or habitations, and for this situation, the comparison was made between a Cobiax® slab and a solid flat slab with drop panels. The second one, simulating a parking area, three different slabs were compared, a flat slab with drop panels, a voided slab with drop panels and a pre-stressed slab with unbonded strands.

In the first loading cases, the Cobiax® solution showed better values of deformation and less quantity of used materials, although at a slightly higher cost. For the parking slabs, the pre-stressed solution is the one that presents better in-service behavior, however with an increased cost.

Keywords: Cobiax® slab, Post-tensioned slab, Deformations, Cost.

1 Introduction

The cost and the deformation are both parameters that must be taken into consideration when choosing the slab typology. Under those assumptions, this study compares both post-tensioned and Cobiax® slabs with a flat slab with drop panels regarding different load applications. The first load analyzed will simulate regular structures such as offices or apartment buildings. The second a one, parking area.

In this paper, firstly will be shown some criteria on the concept of slab thickness, according to its span, and also some design aspects of Cobiax® and post-tensioned slabs. The punching design in the post tensioned slab was performed according Ramos [1], an adapted method from EC2 [2].

The evaluation of deformations will be executed with a programmable methodology based on Method of the Global Coefficients, developed by Brandão [3], which doesn’t require the query of abacuses, making this process less subjectable to calculation errors. A direct control of the deformations will be performed according the EC2 [2].

2 Conceptual design of the slab thickness

Selecting the type of slab can be vital in the project's overall economy. With that in mind, Table 1 offers, in a preliminary state of the design, an idea of the flat slab's type and thickness $\boldsymbol{h}$ to use in relation to its span $\boldsymbol{L}$, never disregarding that the design is a continuous process that requires several attempts in order to achieve a good solution.

Table 1 - Preliminary thickness of flat slabs

Flat slab type	(L/h)	L [m] / h [m]								
		4	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**20**
Flat slab	25 to 30	0,15		0,2	0,25					
Flat slab with drop panels	35 to 40	0,15			0,2	0,25				
Voided flat slab	20 to 25		0,225	0,25		0,3	0,35			
Voided flat slab with drop panels	25 to 30			0,225		0,25	0,3	0,35		
Prestressed flat slab	40					0,2		0,25	0,3	
Voided Prestressed flat slab	35					0,225	0,25	0,3	0,35	0,6

3 Design concepts for flat slabs

3.1 Cobiax® Slab

A Cobiax® slab has rotationally void formers as is shown in Figure 1. The Cobiax® are retained inside rebar cages which make the placement of voids a simple and swift task.

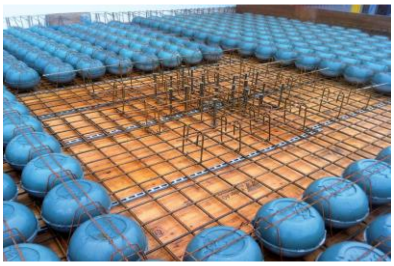
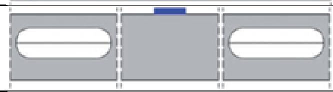
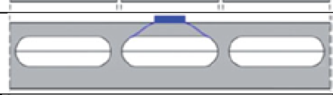
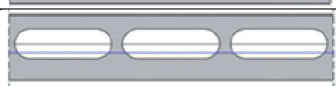


Figure 1 - Cobiax® void formers [4]

When designing the Cobiax® slab, the EC2 [2] does not include the design of slabs with flat rotationally void formers.

Although it could be analyzed as a ribbed slab, this would lead to a greater cost. Because of this, when using Cobiax® void formers, it is necessary to analyze different failure modes and adapt the design concepts. Table 2 presents the overview of the special features of this slab [4].

Table 2 – Special features of the Cobiax® slab [4]

Failure	Restriction	Illustration
Bending	Reduced flexural compression zone	
Shear	Reduced load bearing ability	
Global punching	Solid zones required	
Local punching	Restriction of concentrated load	
Shear force transfer reduction in the construction joint	Reduced bonding surface	

3.1.1 Bending

Usually, the regular design methods can be applied for the slab's rectangular cross-section regarding bending design. However, if the compression zone's height is not in the void free zone, in the ultimate limit state, a "T"-beam cross-section should be used [4].

3.1.2 Shear strength reduction

Due to the complex behavior of this slab, several experiments needed to be performed. In the tests conducted at Kaiserslautern University of Technology, the worst possible conditions were implemented to determine the experimental value of this slab. The ratio of shear resistance was determined by comparing the experimental value between a voided flat plate slab and a solid slab so that it can be designed in accordance with EC2, allowing for a reduction factor [4].

3.1.3 Mass and Inertia reduction

The fact that the Cobiax® void is placed between the two rebar layers (top and bottom) of the slab, so that the reduction of the slab inertia remains almost unaffected. The reduction of weight caused by the voids (in averaged of 33% depending on the type of void used) is significantly higher than the reduction of its inertia (approximately 10%), which results in a lower deformation when compared to other traditional ribbed slabs.

3.1.4 Constructability aspects

Because of the concrete displacement caused by the void formers, a significant upwards pressure will be created. Because of this, concreting needs to be divided in two stages, creating a construction joint. The first stage has the purpose of fixing the Cobiax® in place, and after this one had settled, the remaining concrete can be poured. However, this construction joint usually doesn't need additional calculations, due to the vertical rebar that forms the void support cages, which are anchored to the first concrete layer, connecting the two concrete layers.

3.1.5 Practical application

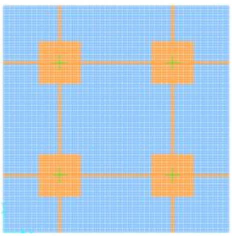


Figure 2 – Finite element model used in the calculations

The first step when designing a Cobiax® slab is to define the positioning of the voids. Figure 2 illustrates both Cobiax® (blue) and solid (orange) areas used in a slab with span of 8 meters. The voided areas have to take into account the self-weight and inertia reduction factors. The reinforcement can be calculated with the simplified rectangular diagram.

After longitudinal reinforcement is defined, punching and shear strength must be verified. The shear stress must be checked in the interface between solid and voided areas with the Cobiax® reduction factor. If necessary Cobiax® voids should be removed or the longitudinal reinforcement prolongated in order to increase the shear strength.

3.2 Post-tensioned Slab

3.2.1 Prestressing system

There are two methods of applying prestress to a slab, with an unbonded or a bonded system. The post-tensioning with unbonded tendons consists in a single strand tightly enclosed in plastic sheets needing lesser space than the multi-strand tendons with flat ducts that require room for grouting. Thus, the required concrete is minimum. Friction losses are also reduced because of the grease that allows relative movements between the tendon and the concrete. The other system refers to bonded tendons. This system, although less effective than unbonded tendons, due to their larger edge difference has some benefits regarding the ultimate limit state design [5].

3.2.2 Tendon arrangement distribution

There are three typical tendon arrangements in flat slabs. In all the layouts, it is recommended for a large amount (at least 50% [5]) to be distributed over the column strips to counteract the bending moments and high shear stress.

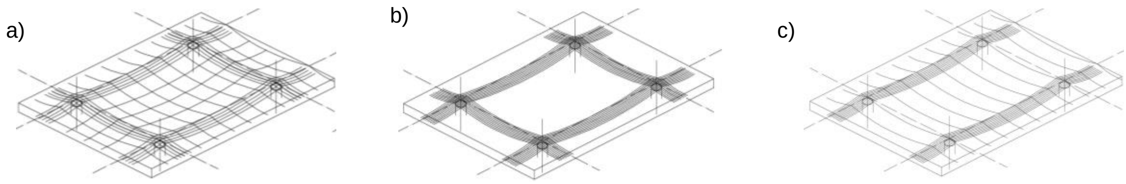


Figure 3 -Possible tendon arrangements: a); mixed distribution b) concentrated in both directions; c) – concentrated in one direction and distributed in the other.

Given the tendon arrangements the most commonly used tendon arrangement is depicted in Figure 2 c) because it allows to get the full benefit of the eccentricity in both directions mid-span although b) as a better punching behavior.

3.2.1 Ultimate limit state

For bonded tendons, they can be elongated between cracks. This results in a higher strain and correspondingly stress increase, therefore, the full strength of prestressed steel can be used. For the unbonded tendons, they are instead elongated uniformly between the anchorages and, as a result, stress increase at failure is limited. A value of $100\ MPa$ can be used in the absence of a more detailed calculation [5].

3.2.2 Practical application

In this work, the tendon arrangement shown in Figure 3 c) was used with unbonded monostands.

The criteria used to determine a preliminary number of strands was the balancing of 70% of the quasi-permanent load. In favor of optimizing this solution cost-wise, successive iterations lead to 12 monostands in each direction. A tendon layout with strait parts was used to simplify the execution and maximize the effect of prestress on the slab. In this work, for the bending reinforcement calculations, the axial effect was not taken into consideration due to the uncertainty of the boundary conditions.

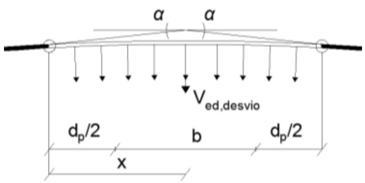


Figure 4 – decompression force in punching resistance

The punching resistance was calculated by an adapted method developed by Ramos [1], based on the EC2 [2]. This method takes into account the reinforcement rate, the eccentricity effect of the cable, and the compression imposed by the tendons.

The effective punching strength is calculated by reducing the transverse effect of the tendons as it is exemplified in Figure 4.

4 Competitive analysis of flat slabs

The competitive analyses of the slabs were performed for two different loadings, one simulating current building and other a parking area. A flat Cobiax® (in the case of the parking loads with drop panels) and a flat slab with drop panels were compared for both loadings, with the add solution of the post-tensioned slab for the parking loads. A summary of the compared solution's geometry is shown in Table 3.

Table 3 – Slab types analyzed

	Apartment/Office buildings		Parking areas		
Type	**Flat**	**Cobiax®**	**Flat**	**Cobiax®**	**Post-Tensioned**
Slab tackiness [m]	0,22	0,275	0,2	0,2	0,22
Drop panel thickness [m]	0,35	-	0,32	0,32	-

This paper analysed, for each solution, three different slab panels: a central panel with continuity, meaning that this panel had no edges, a lateral panel with a free edge and a corner panel with two free edges, as ilustrated in Figure 5.

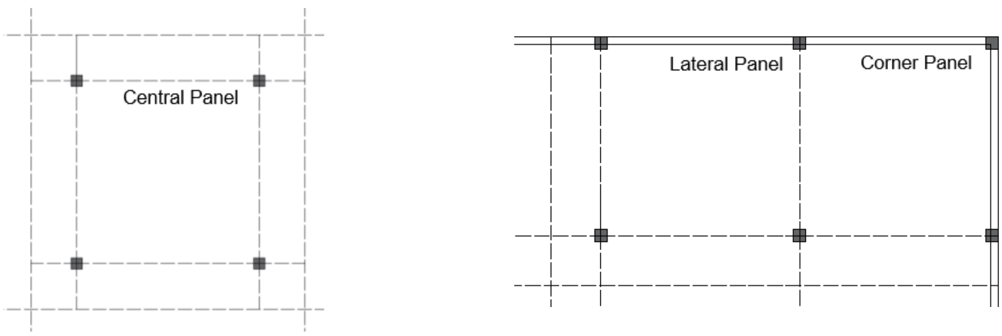


Figure 5 - Panels analyzed

In the egde panels, for the case of appartment loads, a boundary beam is designed with 0,65 m height and 0,3 m width, as it is the most common typology to improve the building behaviour to seismic actions. The same was done for the parking loads' scenario, although with a height of 0,55 m because the loading was less demanding. In this case, the post-tensioned slab was designed with an aditional four tendons relatively to the central panels, to avoid cracking at the top of the columns.

The materials used are in relation to the bending reinforcement of the slabs and beams, the shear reinforcement of the beams and even punching of the slabs.

The material amount is in reference of the structural drawing developed by Viana [6].

4.1 Calculation of deformation

The methodology used to calculate the deformations was developed by Brandão [3]. The equations used to evaluate the short-term a_0 and the long-term a_t deformations, are as follows:

$$a_0 = \left[(1-\zeta)\frac{E_{c_0}I_c}{E_{c_0}I_I} + \zeta\frac{E_{c_0}I_c}{E_{c_0}I_{II}}\right]a_c = \left[(1-\zeta).K_{0_1} + \zeta.K_{0_2}\right].a_c = K_0 \times a_{c_0} \quad (1)$$

$$a_t = \left[(1-\zeta)\frac{E_{c_0}I_c}{E_{c,eff}I_{I,eff}} + \zeta\frac{E_{c_0}I_c}{E_{c,eff}I_{II,eff}}\right]a_c = \left[(1-\zeta).K_{t_1} + \zeta.K_{t_2}\right].a_c = K_t \times a_{c_t} \quad (2)$$

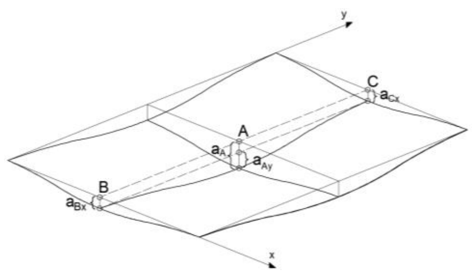


Figure 6 - Orthogonal bands

To evaluate slab's deformations, the used method was the Orthogonal Bands' Method. The deformations were calculated through a "path" defined by the bands which are always with their relative deflections. The mid-spam deformation in this work was calculated by the bands represented in Figure 6.

4.2 Direct control of deformation

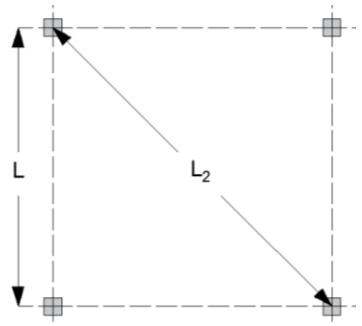


Figure 7 – Considered spans for direct control of deformation

The direct control of deformation, acording to the EC2, imposes limit values for long term and incremental deformations of L/250 and L/500, respectively. For long term deformations, measured in the middle of the slab, the limit must be calculated using the diagonal span L_2 (between two supports).

The incremental value of deformation limit should be calculated in the aligment of masonary walls' columns to avoid non-structural damages.

It is worth mentioning that the limit values of deformation are not absolute, and may vary due to the building purpose

The long term and the incremental deformations, presented in the chapters 0 and 4.4.2, represent the difference, percentage wise, between the calculated deformations with the limit stipulated in the EC2, in order to see if the deformations are in check.

The elastic deformations are obtained using the finite elements program *SAP2000.*

4.3 Loading in apartment and office buildings

The comparison for regular apartment or office buildings is made between a Cobiax® slab and a flat slab with drop panels.

4.3.1 Amount of Materials

The amount of materials was quantified in the equivalent thickness of the slab, which gives an idea of the concrete volume used and the rate of reinforcement in each panel.

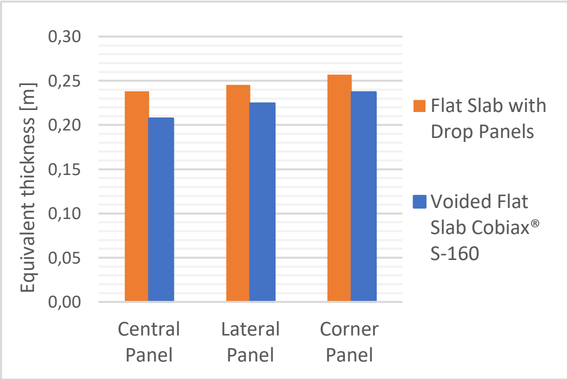


Figure 8 – Equivalent thickness in apartment buildings

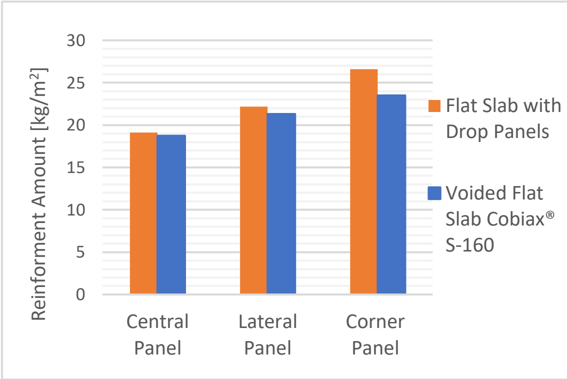


Figure 9 – Reinforcement amount in apartment buildings

Regarding the equivalent thickness of concrete, although the Cobiax® slab shows a higher thickness in the span, it shows an inferior consumption of concrete due to the volume reduction caused by the void formers. Relatively to the amount of reinforcement, the Cobiax® slab also shows better results. The reason for this is the increase in static height that leads to less reinforcement in the spans areas that are needed to verify bending in the ultimate limit state.

4.3.2 Deformations

The deformations in apartment building are as follows:

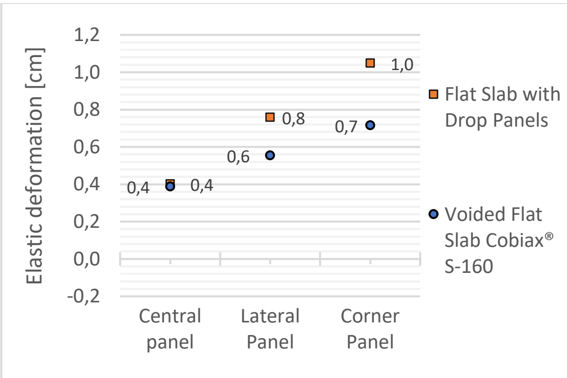


Figure 10 - Elastic deformations in apartment buildings

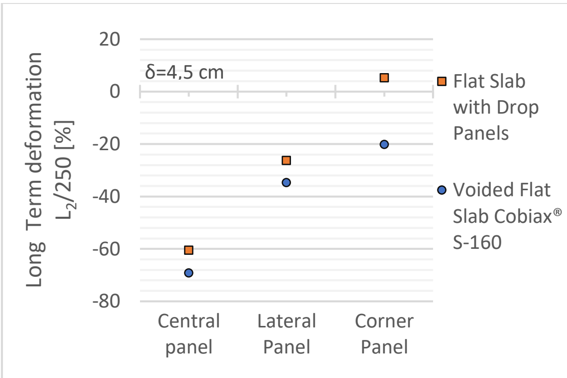


Figure 11 – Long-term deformations of apartment buildings

Figure 10 shows almost no difference between these two slabs regarding the central panel. The same does not occur in the other panels, since there is an increase of deformations directly proportional to the number of free edges. In the lateral and corner panels, the Cobiax® slab presents significantly better results in comparison to the flat slab with drop panels.

For the long-term deformations, Figure 11 depicts the same result as the elastic ones. It is worth mentioning that the corner panel does not exceed the maximum value, whereas the flat one is slightly above the limit.

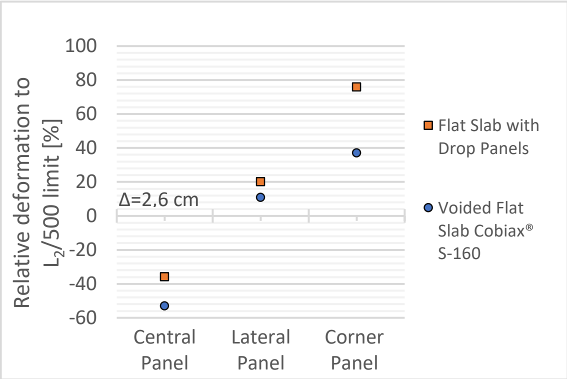


Figure 12 – Relative deformation to L/500 limit

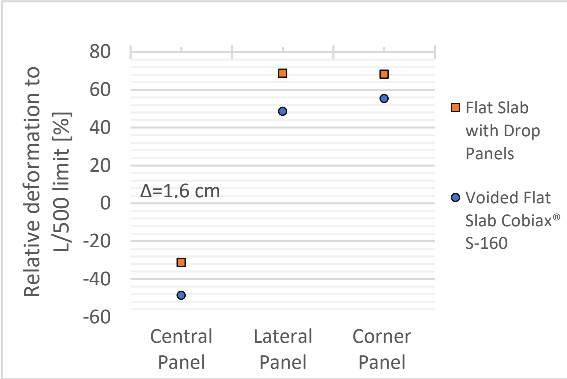


Figure 13– Relative deformation to L/500 limit

The incremental values of deformations in mid-span (Figure 12) and for the alignment of the columns (Figure 13) illustrate that the Cobiax® slab presents a favorable behavior. In the lateral panel, the flat slab shows a slight increase comparatively to the corner panel. This is a consequence of the lesser amount of reinforcement needed for the bending moments to verify safety, resulting in slightly increased deformations in this panel.

4.4 Parking loads

The slab and drop panel thickness in both Cobiax® and flat slabs are similar. So, it is possible to observe the direct impact that the Cobiax® void formers have in both the amount of used concrete and in rebar quantities.

4.4.1 Amount of materials

In parking post-tensioned slabs, the amount of prestressed steel is added to the regular one, in order to show the total use of steel.

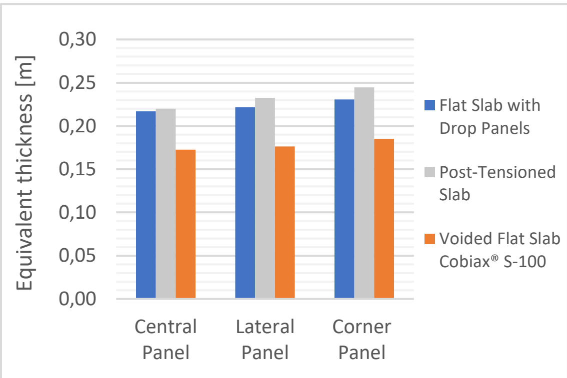


Figure 14 – Equivalent thickness for parking loads

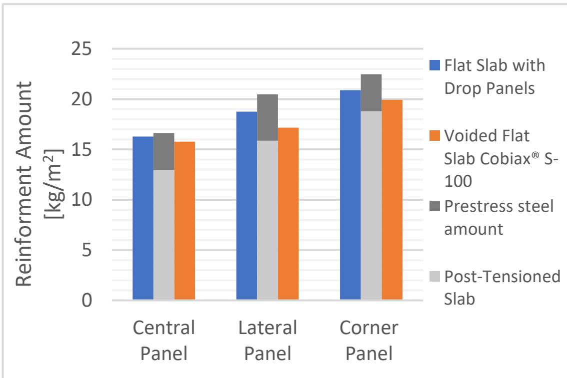


Figure 15 – Reinforcement amount for parking loads

As it is expected, the addition of the Cobiax® in slabs reduces significantly the consumption of concrete (approximately 20% in all panels) in comparison with flat slabs. The post-tensioned slab shows the highest amount of concrete used, and while this value could be reduced, that design option was not considered because of possible construction errors that may occur, causing the loss of the prestresses effect.

Regarding the amount of reinforcement needed, the self-weight reduction of the Cobiax® void formers reveal that less reinforcement is needed to provide safety in the ultimate limit state. The post-tensioned slab also does not show the expected reduction in the reinforcement because of uncertainty of the support conditions. However, this value could be reduced by 30% by using the axial force applied in the bending verifications and in the minimum reinforcement required by the codes.

4.4.2 Deformations

For the parking areas, the limits of deformation are not as strict as for apartment buildings. The incremental value of deformation is not applicable because there aren't masonry walls dividing the panels.

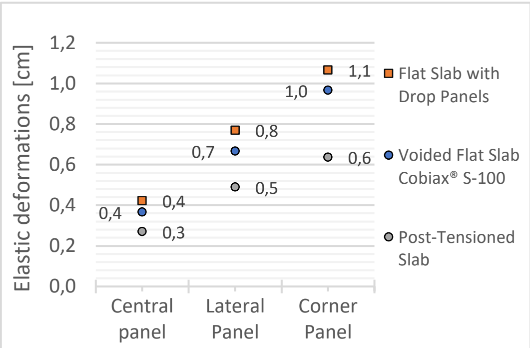


Figure 16 – Elastic deformations in parking structures

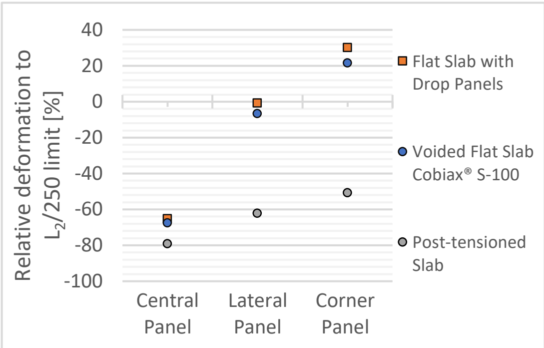


Figure 17 – long term deformation in parking structures

Comparing the values between the flat and Cobiax® slab with drop panels, in terms of elastic deformation, the flat slab shows the largest deformations. Regarding the long-term deformations, the relative difference between these two is not so pronounced. The reason behind this is the less reinforcement needed to fulfil ultimate limit state that causes cracking.

For long-term deformations, the post-tensioned solution illustrates the clear advantaged of this slab. The flat and Cobiax® slab present a higher value than the EC2 [2] establishes.

4.5 Final cost

The unitary cost used to perform the cost comparison between the slabs were: reinforced steel 0,9 €/kg, concrete C30/37 90,0 €/m^3; prestressed steel 4,0 €/kg; Cobiax® 13,5 €/m^2. The formwork used add a cost of 15 €/m^2 with an increase of 15 %, in the case of slabs with drop panels.

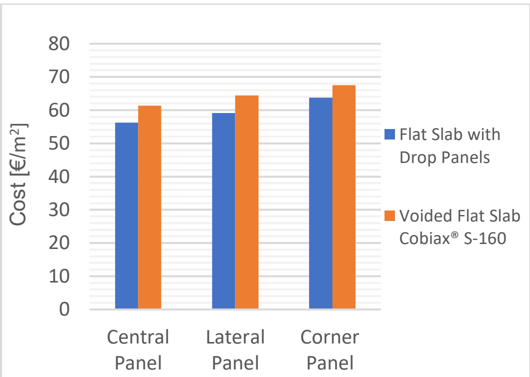


Figure 18 - Slab cost/m^2 for apartment buildings

For the apartment building it is illustrated, in Figure 18, that the most economical solution is the flat slab. However, the Cobiax® slab offers an array of improvements such as better results in terms of deformations, that in return will have a direct impact on the maintenance cost. Also, the linear finish of the celling provides for simpler structural drawing and rebar placement.

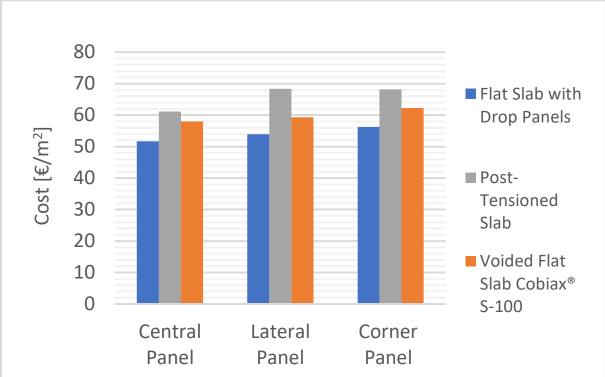


Figure 19 - Slab cost/m^2 for parking buildings

In Figure 19, the comparison of both Cobiax® and flat slab, it is clearly visible that the cost of the Cobiax® does not compensate the reduction in concrete and reinforcement, showing a difference of approximately 6 €/m^2 versus the flat slab. The cost of the post-tensioned slab, is the highest of the three but with a greatly improved behavior in service. The considerations taken were not favorable as the axial compression has a large impact in the bending and minimum reinforce needed. In a project scenario with the vertical elements placed and with the knowledge about their stiffness, a more precise calculation of the quantity of reinforcement would take place, lowering the total cost of this slab.

5 Conclusions

The comparisons made in this paper aim to provide the cost, deformations and the amount of material used in Cobiax® and post-tensioned slabs versus the flat slabs.

In the case of apartment buildings, the Cobiax® slab shows a significantly better behavior in the serviceability state with a slightly increase in the final cost. In terms of structural drawings, the Cobiax® slab with the absence of drop panels also presents a simpler construction with less formwork required.

In the parking load cases, the Cobiax® slab doesn't show a sufficient improvement in serviceability state to compensate the higher cost of the Cobiax® voids when compared to the reduction of the amount of material used. This shows that the main advantage of the Cobiax® is when no drop panels and linear formwork are used. The post-tensioned slab exhibits the best deformation results. This is due to the prestress effect of the slab that prevents cracking, therefore the increase in the long-term deformations is only affected by creep. It's also worth mentioning that the tendon arrangement adopted dispenses the need of reinforcement and drop panels in the punching verification.

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