1. INTRODUCTION

This Final Project was written to confront the need of reducing the economic costs of execution of projected works and the environmental effects during the process. The main motivation is to optimize the execution of the structure through analysing the chosen structural systems while evaluating other options. Therefore the original project, as well as other proposals, was modelled with Cypecad, software specialized in calculation of reinforced concrete structures.

Nowadays the need of mastering software tools for the development and scaling of structures is essential when providing professionalism and competitiveness. Consequently, choosing and learning to use this program became a challenge and an advantage in the process of writing this Final Project.

On the other hand, the work, which is by now a project will be executed by the end of 2014 and will offer, to the author of this essay, the opportunity to collaborate as an assistant site manager. In consequence, the results and benefits obtained during this research may become directly applicable to the execution of the work, with economic and sustainable improvements.

Direct influence on the project through optimisation, cost savings and improvements in environmental effects during execution are the main goal to achieve. This is the challenge.
Avaluació de diferents solucions estructurals per als sostres d'un aparcament soterrat, amb la intenció d'optimitzar-los.
2. CORE OF THE PROJECT

2.1. PRESENTATION OF THE PROJECT AND SOFTWARE

2.1.1. Introduction to the project
The research project is an underground public car park situated within the premises of the Hospital Plató of Barcelona. The final project was designed in 2012 and is expected to be executed in late 2014 and early 2015.

The car park offers 170 spaces and has three underground floors, a ground floor with area of access for ambulances, mezzanine floor and a garden floor (roof) where the external access to the hospital is found. The built area is 6.070'21m² and the execution budget amounts to €3.253.769'71.

The area where the car park is projected is currently the garden and the main access, both for cars and pedestrians, to the hospital. This garden, bordered by the streets Marc Aureli, Plató and Tavern, is located opposite the building, therefore the car park will be an outbuilding attached to the lobby and emergency room, which when completed will have an exterior look resembling the current one, where the garden floor will be also used as a main gate, but where ambulances will have a separate entrance, covered and connected to the access to the underground car park.

The project takes into account the demands for parking spaces in the area, both for users and for neighbours, suffering from a lack of parking spaces, both public and private.

2.1.2. Car park description
The car park consists of three underground floors for parking of cars, which are accessed from the ground floor through two one-way slopes, one going up and the other going down. The ground floor, above ground level and with less vehicle capacity than the previous floors, which offer 55, 50 and 49 spaces each, has room for 16 cars and 3 ambulances. It is therefore the level where access from Marc Aureli street to the car park and emergency room for ambulances is located. There is also the garden floor that serves as a cover, a mezzanine floor located between the ground floor and the garden floor, and finally the cover of the area of the access to the hospital.

The external access, either for vehicles or pedestrians, is located at the junction between Tavern and Plató streets, where currently the main entrance is found. Taxis and, in case of an emergency, fire fighters, will use this access as well. There are also entries for users of the car park in Tavern and Marc Aureli streets that allow access to the stairs and elevator (see Appendix 1).
The internal vertical communication will be via two fire protection blocks containing two stairs, three elevators and a lift for gurneys. The connection with the hospital’s building is through direct stairs coming from Marc Aureli Street to the offices or via stairs and lifts that take you to the garden floor connecting with the emergency exit.

The outer space of the car park is the garden floor, above the ground floor, which offers a wide garden space where the main entrance to the hospital is located. The mezzanine is kept privately for an office and a maintenance room.
2.1.3. Description of the structure

The car park has been designed with a system of solid slabs and concrete columns, surrounded by an earth retaining wall perimeter consisting of 256 columns of 45cm of diameter every 70cm. The foundations consist of isolated footings of reinforced concrete for the columns, and a descending wall working on tip and friction rooted at three heights. Rolled steel columns have also been used in the union between the parking area and the building of the hospital.

The hyperstatic structure consists, in its entirety, of embedded joints, except the ones between the retaining wall and the structural floor in the underground floors, which become joints. The absence of earthquakes in the area and the high resistance of the ground, which grants an allowable tension of 5,00Kp/m², allow the structure to be considered highly stable and monolithic.

The construction materials used for the implementation of the structure are basically reinforced concrete HA-25-F-20-I/IIa with 25N/mm² of nominal resistance and corrugated steel B500 with a elastic limit of 500N/mm².

The floors have been projected as slabs with an edge of 35cm of thickness, except for the joining area with the Hospital on the ground floor, mezzanine floor and stairs roof, which has a thickness of 24cm, and 18cm in the hanging floor where the car park’s office is situated. The spans between the columns are of 7m and the height between floors is of 2,65m and variable up to 5m on the ground floor, among others.
The nominal coating for the project is 30mm, 50mm in the case of lateral excavation and 35mm (plus 10cm of concrete layer) at the bottom of the same. This coating is specified by the regulations (justified later).

There is no phreatic level affecting the development of the implementation, and involvement snow will be corresponding to the area of the city of Barcelona and therefore at a height of less than 1000m, or a maximum load of 0.4KN/m². There is also no remarkable affection for the wind.

2.1.4. Applicable regulations

For the final design, completed in 2012, the following rules were applied. These rules will be later justified in those areas that have undergone significant modifications to the original project:

- EHE 08: Regulation of reinforced concrete
- NCSR-02: Standard for earthquake resistant construction
- DB-SI: Safety in case of fire
- DB-SE-AE: Activities in the building process
- DB-SE-A: Steel
- DB-SE-F: Brick wall
- DB-SE-C: Laying of foundations

2.1.5. Introduction to computer tool Cypecad

Cypecad the software employed for this assignment. It is used for the calculation and dimensioning of the structure and it is part of Cype software, which includes other tools to give a price quote, facility sizing, development of civil engineering, drafting and specifications, etc.

Cypecad allows introducing elements such as columns, beams, walls, floors, foundations, etc. of a structure both of reinforced concrete and of steel. Concentrated loads, linear or superficial, were applied; determine the type of material and its resistance was determined, the allowable stress of the land, the possible effects of the wind or seismic zone, as well as all the implicit features in a given structure.

Once the structure is calculated, the program detects and notifies inconsistencies and errors of size, lack of steel so as to be corrected. The deformations in the beams or slabs, depicted as sags, are only detected by the program when they are really big. These deformations should be checked manually when the goal is to reach reduced horizontal surfaces with, consequently, sags close to the limits set by the regulation.
This sag testing is linked to the length between the columns, whether it bears partition walls or not, and the relationship between the total load, weight, permanent loads and overload use. For this reason a previous calculation must be done through the use of tables which may determine what the acceptable maximum sag is in each particular case and verify that the obtained sag in the model is found within the projected limits.

Once the final sizing of the structure is obtained, Cypecad summarises the measurements of the necessary materials for its execution and allows one to print customized maps facilitating the development of a complete executive project. It also offers 3D view and a summary of the applied regulation and data.

Cypecad, therefore, helps develop construction projects free of errors and quick to alter and dimension.
2.2. STUDY OF ROOFING TYPES ORIGINALLY DESIGNED AND ALTERNATIVE FLOORS

2.2.1. Introduction to structural floors

A floor is a horizontal constructive element capable of transmitting the loads that supports its own weight as well as other elements of the structure as beams, columns and walls. It is a part of the horizontal structure of the different floors of a building, allowing to join horizontally various structural elements and thus transmitting both vertical and horizontal loads. It offers rigidity and reduces the possibility of shifting in the building.

The floors can be classified in accordance to the transmission of loads:

- Unidirectional floors: loads are transmitted unidirectionally on linear supports as beams or bearing walls. Unidirectional floors are only reinforced towards the direction of flexion.
- Bidirectional floors: loads are transmitted in two directions, usually orthogonal, and can be supported on linear elements or on specific elements such as columns and they do not have to necessarily be arranged in an orderly manner.

Multidirectional floors can also be considered when loads are transmitted in all directions in the plane, but these will be understood as a case of bidirectional floors.

There is a second method to classify floors depending on the construction process. These can be:

- Prefabricated floors: those that are divided into pieces ready to be placed, either by order or made in a factory line.
- "In situ" floors: those floors that are built in the site.

Floors act as an architectural vertically dividing space, with the constructive role of protecting from fire and isolate noise and heat, and the structural function of bearing loads and transmitting them. The following conditions are necessary to satisfy these features:

- Flexural rigidity: determined by the ratio f/L, where f (sag) is the elevation's maximum difference caused by deformation between the floor farthest point to the horizontal plane and the floor itself, and L (span) is the distance between columns.
- Monolithical: the floor aims, despite being made up of several individual elements, at acting as a single piece. It is usually achieved with a compression layer.
- Chained: it must ensure the correct transmission of loads through floor, beams and columns to the foundations, that is why hoops or perimeter beams are placed in the floors.
- Performance of service actions: during the building’s lifetime the structure must be maintained at an acceptable level of conditions of service such as deformation, elongation of reinforcements, cracks in elements, etc.

2.2.2. Type of studied floors: "in situ" bidirectional floors

The construction system employed in the Hospital's car park uses a structure of concrete made "in situ" consisting on columns, retaining walls and solid slabs that form the floors. Therefore this study will focus on the "in situ" bidirectional floors. Solid slabs have a multidirectional transfer of loads in the horizontal plane, their main use is torsion and bending, and because of their, usually, orthogonal disposition of the reinforcement they are considered "in situ" bidirectional floors. These slabs have a great simplicity and the benefit of not needing a strictly ordered disposition of the columns. The downside is the heavy weight. It is for this reason that the reticular floor and the lightened slab exist.

Image 2.2.2.1: Example: Solid slab

The reticular floor is a concrete not homogeneous slab, lightweight and reinforced in two orthogonal directions, thus forming a ribbed plate. Around the pillar the slab turns into a solid slab to resist the force of punching and forming the abacus, usually cross reinforced which can sometimes exceed the bottom of the slab, being called the capital. Generally, the edge is bigger than that of a solid slab, but its weight is substantially lower.
Two different types of reticular floor may be found, the lost coffer and the recoverable coffer. The coffer is commonly used to reduce the weight, and it can be made of plastic or metal in the recoverable case, or concrete and expanded polystyrene if it is lost. Only in the case of a concrete lost coffer its role is, among others, protecting the armours in the event of fire. In other cases the slenderness of the nerves and compression layer leaves, to a higher degree, armours with only nominal coating exposed. So the best choice for public buildings that need to be thoroughly fire protected, as the case of a car park may be, is to use the lost concrete coffer, despite being the heaviest one.

2.2.3. Criteria for choosing the different structural solutions

The main goal of this essay is the optimization of the floors or ceilings of the analysed car park. Therefore, the most interesting options are those that do not involve significant modifications in terms of the structural characteristics and space arrangement and vertical elements of the structure. Thus, the criteria are:

- Build the reinforced concrete structure "in situ".
- Get a bidirectional mechanical behaviour similar or better than the projected structure.
- Maintain or increase the span between columns.
- Reduce the depth of floors.
- Reduce the economic expenses.
Avaluació de diferents solucions estructurals per als sostres d’un aparcament soterrat, amb la intenció d’optimitzar-los.

- Reduce the environmental effects and make implementation more sustainable.
- Maintain or improve the layout of vertical elements of the structure for a better accessibility while reducing the number of columns.
- Keep the compartmentalization of space and design of the facilities.
- Improving the option chosen for the roof of the building.

2.2.4. Evaluated options. Models:

Given the aforementioned criteria the options for evaluation are:

- Solid slab.
- Reticular floor.
- Lightened slab.

In order to assess and obtain trustworthy results models were performed with Cypecad, allowing us to calculate and dimension the structure by analysing forces and deformations. These models were developed with an equal layout of columns and edges to the original project (Model 1 & 2) and other models, proposals A, B and C with a new columns layout and reduced edges. The models are:

MODELS

Model 1. Current Status (the original project).
Model 2. Current Status edge optimized.
Model 5. Proposal B: Reticular floor.
Model 6. Proposal B: Reticular floor edge optimized.
Model 7. Proposal C: Lightened slab.
Model 8. Proposal C: Lightened slab edge optimized.

Once models and results are obtained each model (current and proposed) will be compared with its optimized versions. Later, optimized and non-optimized models will also be compared to draw conclusions and to choose the most appropriate.

These comparisons include the observation of deformations, edges, amount of material for the execution, budget and the environment effects.

No modifications of the characteristics of the planned work such as lining, material properties, land tensions, state of loads, functionality of each area, type of joints, arrangement of architectural elements, etc.
The program also allows you to generate 3D views. The following images correspond to model number 1, or the original project. But the 3D views of the other models are very similar, so these are valid examples for creating a general idea of the structure.

3D IMAGES

![Image 2.2.4.1: Edification above gradient](image_url)

![Image 2.2.4.2: Edification above gradient](image_url)

![Image 2.2.4.3: Edification under gradient](image_url)
Avaluació de diferents solucions estructurals per als sostres d’un aparcament soterrat, amb la intenció d’optimitzar-los.

Image 2.2.4.4: Complete edification

Image 2.2.4.5: Acces areas to the car park and to the hospital

Image 2.2.4.6: Vertical structure
2.2.4. Methodology for the study of the projected models
The method for the comparison and optimization of the designed models was based on the observation of the maximum sags produced in the floors of each studied structural system. The economic relationship between edges of the floors of 35cm originally designed and the ones obtained by the optimized models will also be taken into account. Seeking minor edges taking the maximum edges to the limit so as to logically balance the spending in concrete and steel. This ratio penalizes economically and quantitatively the excess or lack of edges for floors, hence the excessive minimisation of excessive floor, although it gives acceptable maximum sags, may cause the need to provide a high amount of steel and therefore represent an expense almost equal to the cost of the original floor. The maximum sags are observed by applying a multiplying factor of instant sags resulting from the calculation that relates the state of the loads with amplifying coefficients depending on whether or not the floor supports partition walls. These factors and calculations are justified on the following points.
It is also taken into account and checked that the columns withstand in the projected proposals in which there are a decrease of the number of columns, and therefore it is verified that it does not involve a resizing of the vertical structure.

2.2.5. Implementation of regulations
The size of the floors is given by the following parameters, concerning estimations by the Limit State of Service (EHE Chapter 11.-08. Instruction of Structural Concrete):

Limit State of Deformation

The limit state of deformation is satisfied if the movements (sags or turns) in the structure are lower than the maximum limit values. The total deformation produced in a concrete element
is the sum of several partial deformations which occur over time as a result of the inserted loads, yield and retraction of concrete and the relaxation of the armours.

We can distinguish between:

- **Total sag**: due to the total amount of loads acting throughout its lifespan. It is formed by the instant sag produced by the loads plus the deferred sag for the permanent and almost permanent loads in its performance.

- **Active sag**: in regards an item liable to be damaged, caused in the moment in which the element is constructed, like a partition wall. Its value is equal to the total sag minus the one produced until the moment of construction of the partition wall.

The maximum allowable values of the sag for buildings are established by the Technical Building Code (CTE). Usually in normal buildings, if there are no particular demands more precise, the following values are established:

- **Floors without partition walls**:
  - For span \( L \) or \( \leq 5m \): \( F_{\text{Total}} \leq \frac{L}{250} \)
  - For span \( L > 5m \): \( F_{\text{Total}} \leq \frac{L}{500} + 1 \text{ cm} \)

- **Floors with partition walls**:
  - \( F_{\text{activa}} \leq \frac{L}{400} \)

  ➢ **Simplified method**:

It is applicable to beams, concrete slabs and unidirectional floors. The sag is considered composed by the sum of instant sag and deferred sag caused by permanent loads.

- **Minimum Edges**: The sag is not necessary to be checked in beams and slabs when the relationship useful span/edge is equal to or lower than the one shown in the following table:

<table>
<thead>
<tr>
<th>Sistema estructural</th>
<th>( K )</th>
<th>Elementos fuertemente armados (( \beta = 1.5% ))</th>
<th>Elementos débilmente armados (( \beta = 0.5% ))</th>
</tr>
</thead>
</table>
| Viga simplemente apoyada. Losa unidireccional o bidireccional
| \( L/d \)                                             |        |                                 |                                 |
| 1.00                                                   | 14     | 20                              |                                 |
| Viga continua en un extremo. Losa unidireccional o bidireccional
| \( L/d \)                                             | 1.39   | 18                              | 26                              |
| Viga continua en ambos extremos. Losa unidireccional o bidireccional
| \( L/d \)                                             | 1.50   | 20                              | 30                              |
| Recuadros exteriores y de esquina en lasos sin vigas sobre apoyos aislados
| \( L/d \)                                             | 1.15   | 16                              | 23                              |
| Recuadros inferiores en lasos sin vigas sobre apoyos aislados
| \( L/d \)                                             | 1.20   | 17                              | 24                              |
| Voladizo                                               | 0.49   | 6                               | 8                               |

Table 2.2.6.1: Table 50.2.2.1.a of EHE 08 – Structural concrete regulation
Avaluació de diferents solucions estructurals per als sostres d’un aparcament soterrat, amb la intenció d’optimitzar-los.

The examined work is considered weakly reinforced and its inner and outer locks are, therefore, for 7 meters span and the minimum useful edge would be 700cm/23=30,43cm. As the edge of the floors of the original project is 35cm, minus 3cm of lining, it can be deduced that the structure has been sized according to the limitation of the simplified method.

The main goal of the optimization goes beyond this edge limit. Therefore the limit should be sought in each case observing the maximum sags produced in different floors with different loads, in the computer generated models.

Fire Protection
The regulation regarding fire protection set by the CTE for the exclusive use of a car park determines a fire resistance R90. This means that the structural elements must resist all cases a minimum of 90 minutes exposed to fire.

<table>
<thead>
<tr>
<th>Table 3.1 Resistencia al fuego suficiente de los elementos estructurales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uso del sector de incendio considerado</td>
</tr>
<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Vivienda unifamiliar</td>
</tr>
<tr>
<td>Residencial Vivienda, Residencial Público, Docente, Administrativo</td>
</tr>
<tr>
<td>Comercial, Pública Concurrencia, Hospitalario</td>
</tr>
<tr>
<td>Aparcamiento (edificio de uso exclusivo o situado sobre otro uso)</td>
</tr>
<tr>
<td>Aparcamiento (situado bajo un uso distinto)</td>
</tr>
</tbody>
</table>

Table 2.2.6.2: Table 3.1 of CTE – DB SI (Fire safety measures)
This will set the minimum linings and the quality of the materials used in the structure.