INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Structural Design of a Building

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Extended Abstract

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ABBREVEVIATIONS LIST

LATIN CAPITAL LETTERS

A – Area

A_c – Total cross-sectional área of a concrete section

EC – Eurocode

IST – Instituto Superior Técnico

M_{Sd} – Design value of the applied internal bending moment

N_{Rd} – Design value of the resistant axial force (tension or compression)

N_{Sd} – Design value of the applied axial force (tension or compression)

P – Prestressing force

$REBAP$ – Pre-stressed and Reinforced Concrete Structures Regulation

RSA – Buildings and Bridges Structures Safety and Action Regulation

R_d – Design value of resistant effects

S_d – Design value of action effects

SLS – Serviceability Limit States

ULS – Ultimate Limit States

V_{Rd} – Design value of the resistant shear force

V_{Sd} – Design value of the applied shear force

LOWERCASE LATIN LETTERS

b – Overall width of a cross-section

b_w – Width of the web on T, I or L beams

d – Effective depth of a cross-section

f_{cd} – Design value of concrete cylinder compressive strength

h – Overall depth of a cross-section

l – Length; Span

w – Crack width

Lowercase Greek Letters

α – Seismicity coefficient

η – Performance coefficient

σ_{d} – Design applied stress

σ_r – Design resistant stress

ξ – Damping coefficient

STRUCTURAL DESIGN OF A BUILDING

EXTENDED ABSTRACT

This thesis presents the development of a building's structural design, based on an architectural project. The scope of this work is to create a structural solution that ensures the safety of the building when facing regulatory actions.

The purposed study object has a very irregular geometry, both in plan and in its height development. With an implantation area of approximately 975m^2, the building has 39.50m in its major extent. Featuring one underground floor and three more other above ground floor with different plan developments, its plan configuration shortens from floor to floor, until the top floor (2nd floor) shows a corresponding area of 33% of the ground floor area.

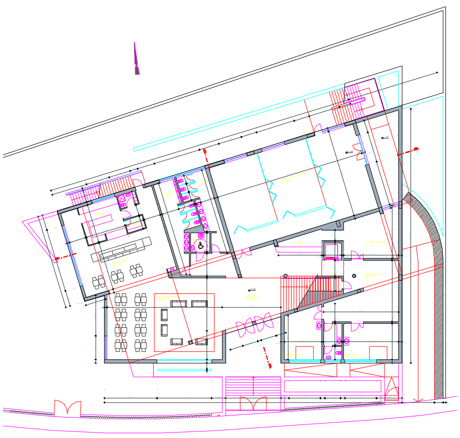


Image 1 – Architectural project's 1st floor plan

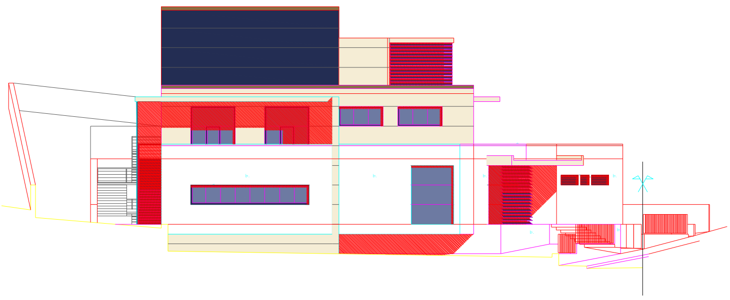


Image 2 – Architectural project's West elevation

Since in this work is used the theoretical knowledge platform gained over the IST's Structural Engineering course, its goal is to understand the applicability of this platform to the practical activity of structural design. Therefore, the different phases of a building's structural design, from its initial conception to the final design, are presented.

The first step of a building's structural design is the resolution of a Structural Solution with quality and economically viable that, according to its architecture, guarantees the safety of the building, its comfort of use and a proper functioning. It consists of choosing the location, size and arrangement of different structural elements, respecting the architectural project. The structural solution of the building in study consists of a grid of columns (that unloads on standalone foundations) composed by three main alignments. Slabs have a pre-stressed light weighted waffle slab with chapiters and solid bands due to large spans (nearly 10m of span) presented in architectural project. The roof slab is a pre-stressed massive slab with beams and the lower floor is surrounded by a earth retaining wall.

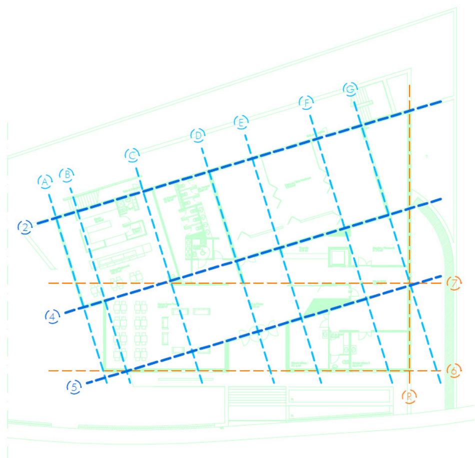


Image 3 – Column's grid

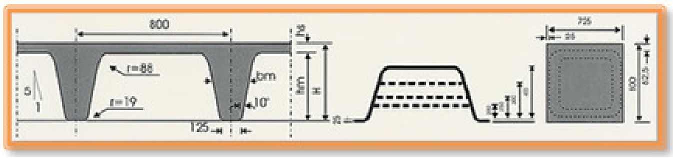


Image 4 –Light weighted waffle slab geometry

Safety Verification Criteria to Ultimate Limit States (ULS) and Serviceability Limit States (SLS) rules recommended in the Portuguese and European structures regulation, namely RSA, REBAP and Eurocodes, where adopted in the structure's analysis and design.

ULS are related to the collapse, or any other form of structural break, which determines the inability to use the structure. Their verification's principle determines the following condition:

$$S_d \leq R_d \qquad (1)$$

In section's resistance calculus the following hypothesis were considered: the inexistence of concrete's tensile strength capacity, plane sections after deformation and a perfect bond between rebar and concrete. The concrete and rebar design diagram extensions are limited to:

- Concrete's shortening extension: 3.5 ‰
- Rebar's elongation extension: 10.0 ‰

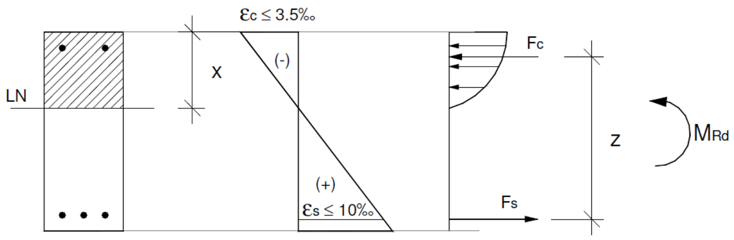


Image 5 – Limits to section's extensions

SLS correspond to the structure's impossibility of a normal use, being related to its durability, appearance, user comfort and its correct functionality concerning users and also equipments and possible existing machines. Their verification considers cracking and strain limit states as well as stress verification.

In reinforced concrete elements, cracking occurs when concrete's tensile strength (which is admitted as null) is reach. Its consideration is related to the type of structure and its purpose. For current buildings, excessive concrete's cracking can cause, besides aesthetic problems, structure deterioration due to rebar corrosion. Depending on the type of environment, crack's maximum opening was limited to $w = 0.3mm$ for the frequent combination. Reached this maximum specified value, durability and correct functionality of the concrete element is in jeopardy.

Strain limit state sets the maximum acceptable strain in order to guaranty structure's normal use. Strain should be controlled in order not to compromise structure, machinery or equipment functioning and the integrity of non-structural elements such as partition walls, windows or even the coatings and finishes.

Stress verification of the foundations was performed for the characteristic combination of actions, based on the following condition:

$$\sigma_d < \sigma_r \tag{2}$$

Structural analysis must consider the influence of all actions that might produce significant stress or strain to the structure's security. Depending on their variability in time and probability of occurrence, actions can be classified as permanent actions, variables actions, or accidental actions. Permanent and variables actions considered are quantified from the values listed in RSA. In the permanent actions range are listed the self weights of the structural elements and masonry walls, the remaining permanent loads related to coatings, finishes and earth pressures. In the variable actions range are listed overloads, depending on the type of usage, and seismic action.

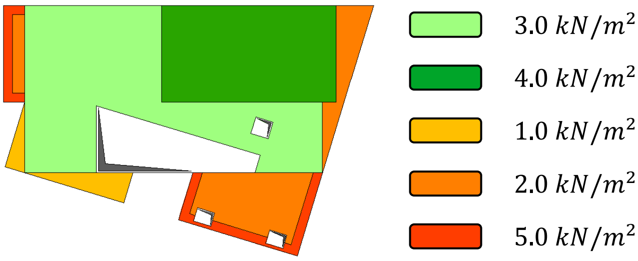
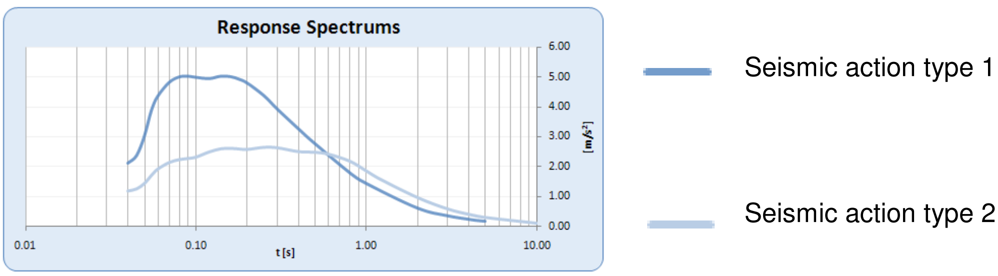


Image 6 – Overloads in 1st floor

For the seismic action, a seismicity coefficient value of $\alpha = 1.0$ was considered, corresponding to Portugal's area A. As the building's structural solution does not fit directly into any type of structure recommended in REBAP (frame, wall or mixed), an elastic analysis of the structure's deformed shape was needed to determine the performance coefficient to use, which resulted in $\eta = 1.75$. The response spectra used were those recommended in RSA for type 1 and type 2 seism correspondent to type I terrain and with a damping coefficient of $\xi = 5\%$.



Graph 1 – Considered response spectra

A load is defined by the combination of actions that have non-negligible probability of acting simultaneously on the structure, during a predetermined period of time. These combinations should cover the different possibilities of load's simultaneous occurrence in a plausible way, determining the most critical effects on the structure. In accordance with the recommendations in RSA, it was considered different combinations for the analysis of the ULS and ELS.

The materials adopted were C25/30 for concrete, A400 NR for ordinary rebar and A1600/1800 for pre-stressed rebar. Rebar cover was considered to be 3cm. According to the available report of the geological and geotechnical study of the work site, the terrain's design stress resistance was considered equal to 600 kPa.

After the structural solution is finalized, it is necessary to pre-design the structural elements in order to determine the dimensions that satisfy the required safety conditions.

Slabs were pre-design considering a ratio of "slab thickness / span" corresponding to $\frac{l}{h} = 30$. The large deformation that this type of slab presents (larger than the upper limit of 1.50cm on long term) led to the choice of a pre-stressed light weighted waffle slab.

Beam's pre-design was based on the condition that the value for "beam height / span" must be between $\frac{l}{10}$ and $\frac{l}{12}$. With the estimated beams height obtained, the next procedure is a simple verification of the following safety conditions for ULS:

$$\mu = \frac{M_{sd}}{b \times d^2 \times f_{cd}} < 0.25 \tag{3}$$

$$V_{sd} < 0.5 \times V_{Rd} \simeq 0.5 \times \tau_2 \times b_w \times d \tag{4}$$

These values were calculated according to the following beam's influence areas:

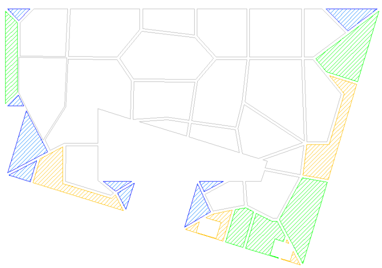


Image 7 – 1st floor beam's influence areas

Column's pre-design has a highly important role in structural design initial phase, since these are the elements that most interfere in architectural environments. Following REBAP's article 144º, the area required for each column to resist axial force can be obtained by the following expression:

$$A_c \geq \frac{N_{Sd}}{0.6 \times f_{cd}} \tag{5}$$

The axial forced unloaded into each column was based on the following column´s influence areas:

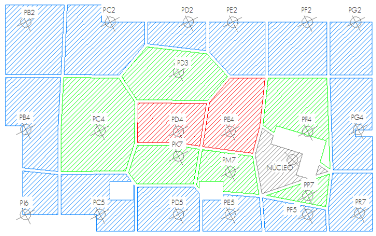


Image 8 –2nd floor column's influence areas

To pre-design standalone foundations it was ensured that the terrain was able to withstand the transmitted stresses. Knowing the axial force at the base of the columns, the minimum area of standalone foundations was determined by the following expression:

$$A_{min} \geq \frac{N_{column}}{\sigma_{adm}} \tag{6}$$

Since structural design is currently based on the application of automatic data processing tools, the three-dimensional finite elements program *SAP2000 – Structural Analysis Program 2000* was used to model the building's structure.

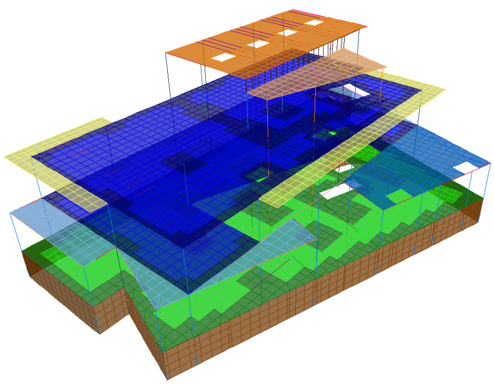


Image 9 – Three-dimensional finite elements model

Columns and beams were simulated as finite bar elements with two nodes, one at each end, with six freedom degrees each. Slabs and wall were simulated using finite shell elements with 3 and 4 nodes.

In the model's creation, mistakes can easily happen. Therefore, it is very important to validate the model in order to ensure full confidence in the results returned by the program, given that the design and safety of the structure depends on these results. Thus, a model validation was made through a comparison between the results returned by the program and the expected results by hand calculations.

The structural design of the building in study sought a solution that would endow a good dynamic behavior. Despite the unfavorable seismic characteristics of the architectural project such as the asymmetric localization of the core, the asymmetric and significant decrease of plan area in 2nd floor, among others, the solution provides an acceptable seismic behavior. The frequencies, mass participation factors and vibration modes are listed below:

Periods, Frequencies and Mass Participation Factors								
Mode	Period [s]	Frequencie [Hz]	Ux	Uy	sum Ux	sum Uy	Rz	sum Rz
1	0.48	2.08	23.2%	19.6%	23.2%	19.6%	0.2%	0.2%
2	0.40	2.50	12.7%	46.5%	35.9%	66.2%	54.5%	54.7%
3	0.32	3.13	34.5%	0.0%	70.5%	66.2%	0.0%	54.7%
10	0.13	7.69	4.5%	0.1%	88.7%	81.9%	0.1%	68.8%

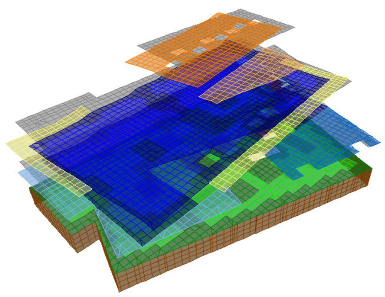


Image 10 – 3d view of 1st vibration mode

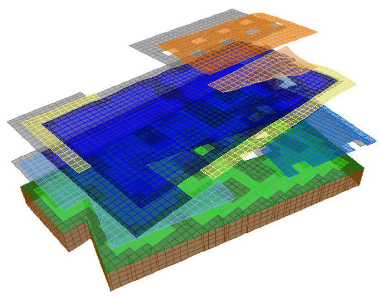


Image 11 – 3d view of 2nd vibration mode

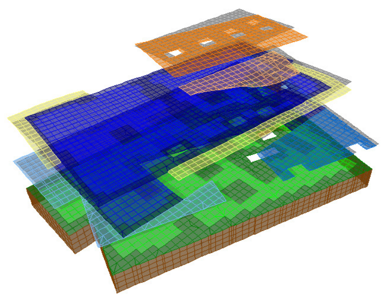


Image 12 – 3d view of 3rd vibration mode

The seismic coefficient was calculated by the following expression presented in RSA's Article 31º:

$$\beta = \frac{F_E}{F_V} \tag{7}$$

A structure or part of it, reaches a limit state when, in an effective or convention method, it becomes unusable or ceases to satisfy the conditions for its use. Therefore, when a structure fails to meet these conditions, it is reaching a limit state, which can be of structural (ULS) or functional (SLS) nature.

ULS verification consists in verifying the load capacity of elements to deal with the actions that they are subject to. Throughout the corresponding chapter, verifications to guaranty the safety of elements subject to simple bending, compound bending, bi-axial bending, shear and punching are explained.

SLS are those states which correspond to the impossibility of normal use of a structure. Cracking and strain limit states are verified.

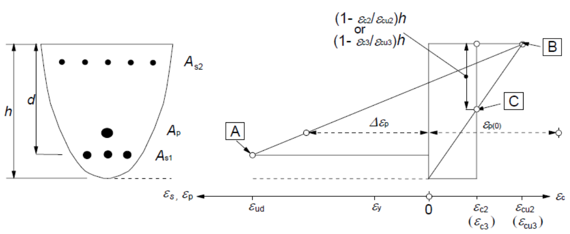


Image 13 – Material's extent limits

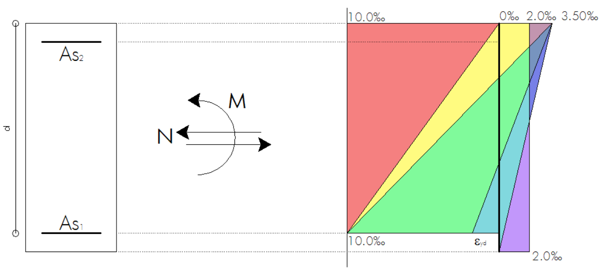
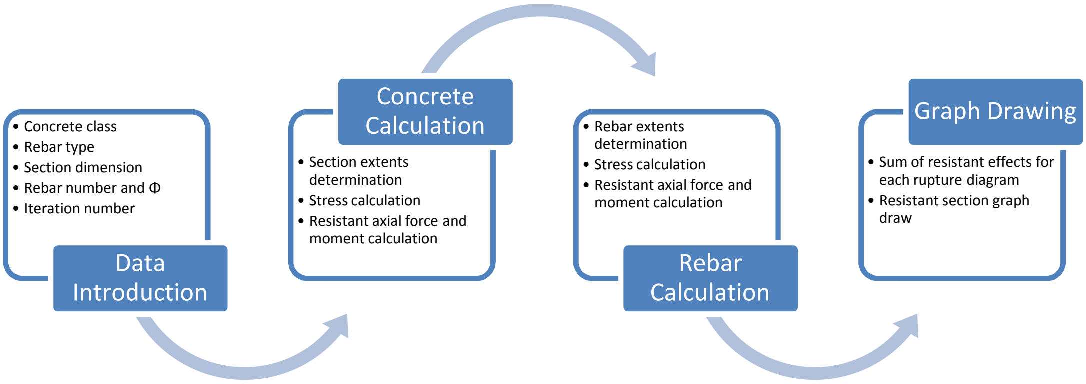


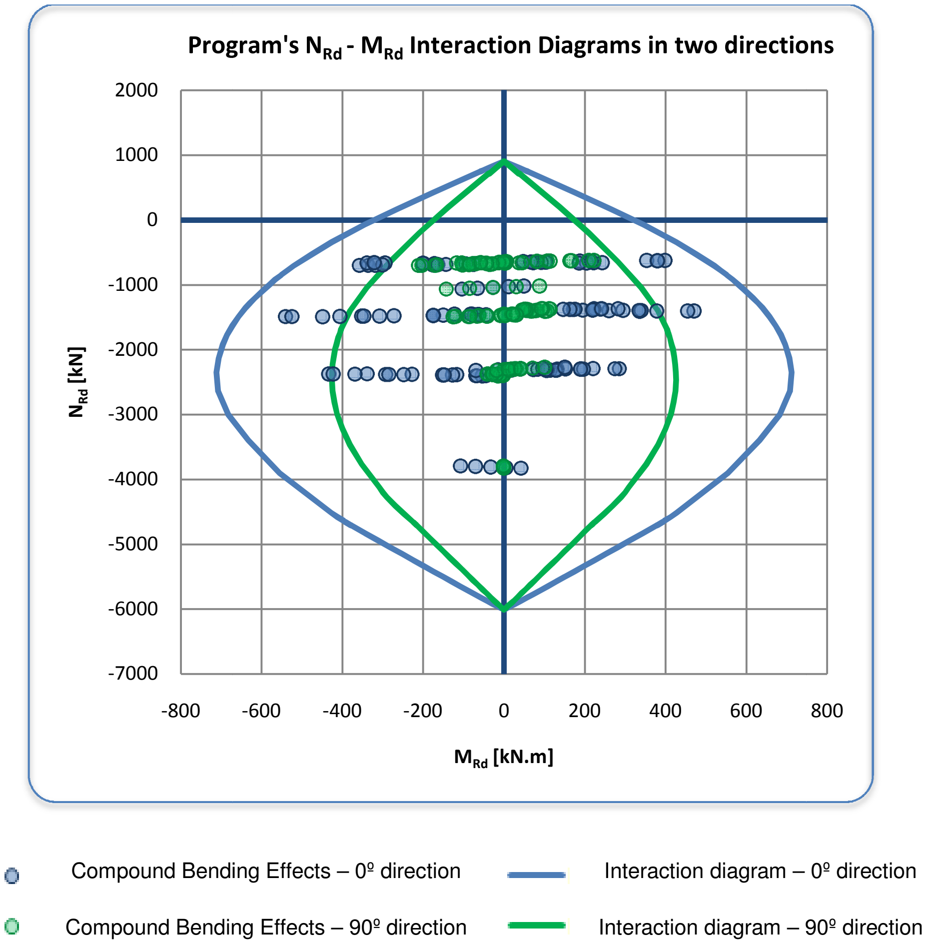
Image 14 – Diagram zones associated to rupture

A post-processing program that verifies the safety of rectangular cross-sections with symmetrical rebar subject to compound bending in both directions and also “H” or “T” cross-sections subject to compound bending in one direction, was developed. Image 14 shows the 5 different zones associate to rupture considered in the program, depending on material’s extent limits presented in EC2.

Programmed in *Visual Basic* programming language through *Microsoft Office Excel*, the program follows the following procedure:



Thus, elements subject to compound bending, were designed using the developed program whose results are returned in an A4 sheet which features section’s characteristics, including considered materials, section‘s dimensions, rebar and rebar percentage, maximum and minimum N_{Rd} and M_{Rd} values, design resistant effects and the N_{Rd} - M_{Rd} interaction diagram above.



Nowadays, the application of pre-stressed slabs is a competitive solution in common structures, representing an economic and efficient solution. Its application can reduce slab's thickness and, consequently, its own weight, resulting on the reduction of the structure is overall weight and allows the construction of larger spans. The solution adopted is composed by post-tensioned non adherent mono-strands. Since these slabs consist of a recoverable waffle slab formwork blocks solution, its configuration limits mono-strands number to 2 per rib.

Image 15 – Pre-stressed strands distribution in ground floor

Image 16 – Pre-stressed strands distribution in 1st floor

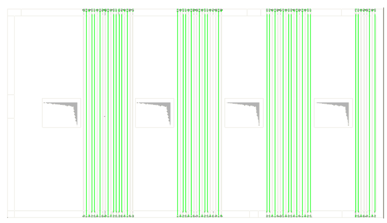


Image *17* – Pre-stressed strands distribution in roof's slab

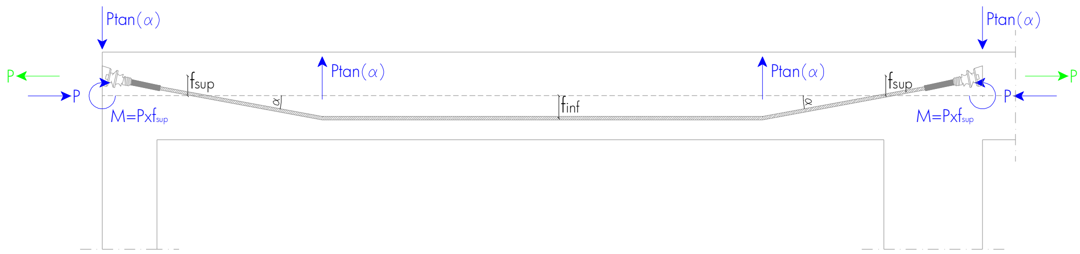


Image 18 – Schematic pre-stressed cable trace, with green pulling loads and blue equivalent punctual loads

The equivalent punctual loads were calculated using the following expression:

$$q = Ptan(\alpha) \tag{8}$$

Pre-stressed solutions are divided into two distinct techniques, pre-tensioned and post-tensioned, being the latest one subdivided into adherent and non adherent cables. Post-tensioned pre-stress is applied after the concrete has acquired sufficient strength, being stress transfer assured by anchorage in the extreme ends of the piece. Compared to other systems, non adherent pre-stress has, among others, the following advantages: for thinner slabs the adoption of mono-strands allows to conduct better eccentricity; flexible strands allows a simple cable tracing (trapezoidal) for easy placement and also adaptable to complex geometries; no need for injection and allows adjustment at any instant of life of the structure.

Once established a structural solution with a three-dimensional static and dynamic analysis realized, and considering safety criteria listed, as well as calculation hypotheses to verify, building's structure elements such as columns, core, slabs and beams are designed. Results of this design are presented in *Appendix*, such as pre-stress drawings, reinforced concrete drawings and global structure drawings. Some of these drawings are showed below:

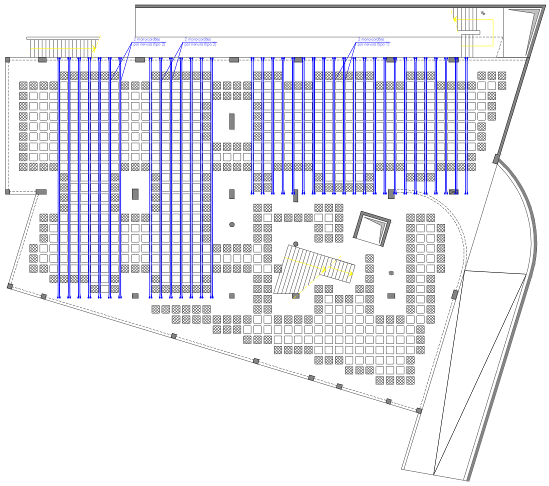


Image 19 – 1st floor plan

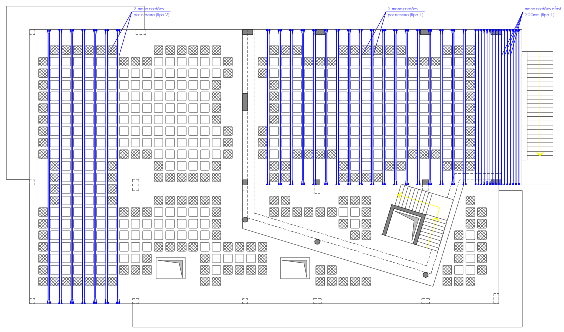


Image 20 – 2nd floor plan

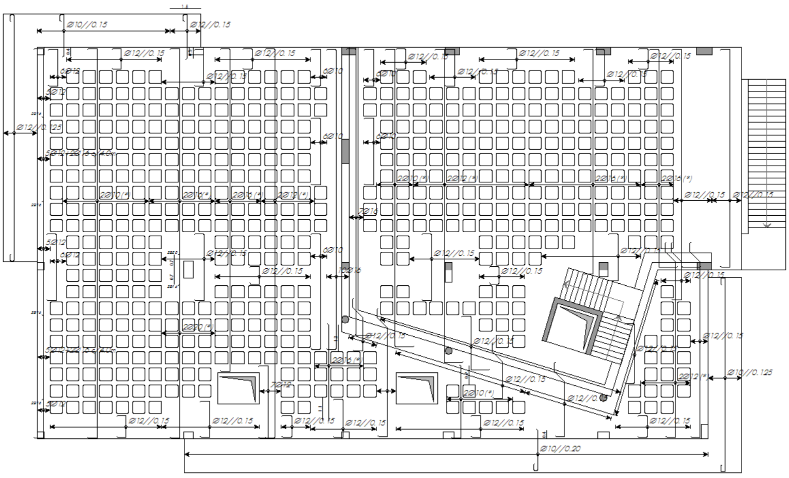


Image 21 – 2nd floor slab's inferior side reinforced concrete

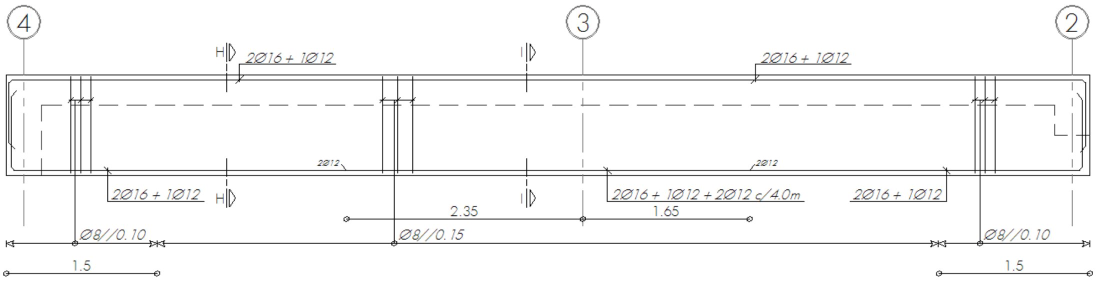


Image 22 – Beam's reinforced concrete

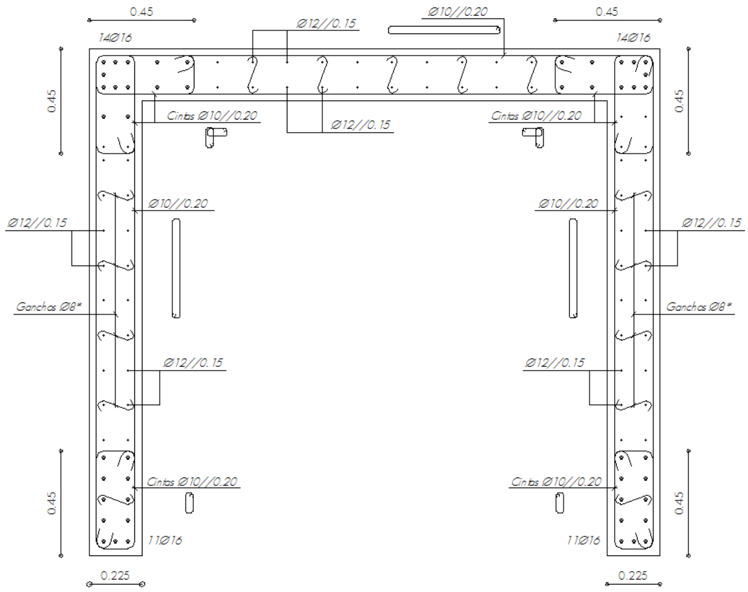


Image 23 – Core's reinforced concrete

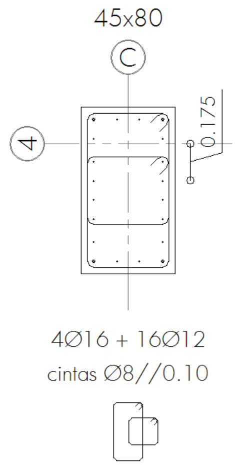


Image 24 – Column's reinforced concrete

Throughout the work was tested the knowledge acquired along the course of Structural Engineering, which allowed an analysis of all different types of structural elements, although not all were completely designed.

Comparing pre-design values to the model's results, it is conclusive that results associated to columns were proved similar. As to beams, these values were not so close even though they allowed to obtain reasonable results. In fact, this initial analysis is of high importance, since it allows to obtain a reasonable idea of initial dimensions required for structural elements.

As for the structure's dynamic behavior, considering its irregular geometry both in plan and in its height development, this has proved difficult to interpret, particularly vibration mode analysis, where modal participation factors led to a different expected dynamic behavior from what observed in the overall structure deformed shape. This happens because the building's geometry leads to a seismic behavior hard to predict.

Concrete cross section verification to compound bending program developed turned out to be very useful, since it allows an automatic verification of a significant number of columns, walls and core, and also the determination of resistant bending moment for pre-stressed slabs.

Keywords: Structural Design; Bending with Axial Force; Pre-Design; Modeling; Seismic Analysis; Design.

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