INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MESTRADO EM ENGENHARIA CIVIL

BIM MODELLING AUTOMATION ON REINFORCEMENT DETAILING OF SLABS

MARGARIDA MAGALHÃES BORGES
agosto de 2018

POLITÉCNICO
DO PORTO

Instituto Superior de Engenharia do Porto

BIM MODELLING AUTOMATION ON THE REINFORCEMENT DETAILING OF SLABS

MARGARIDA MAGALHÃES BORGES

Internship Report submitted for partial satisfaction of degree of

Master in Civil Engineering – Structural Branch

Oriented by: Ricardo Manuel Pereira Santos

Supervised by: José Carlos Basto Lino (NEWTON – Consultores de Engenharia)

Patrício António Almeida Rocha (NEWTON – Consultores de Engenharia)

JUNE 2018

GENERAL INDEX

ABSTRACT

With the continuously undergoing development of new technologies, that lead to a gain of efficiency on daily processes, it is not surprising that, all around the world, one can face its increasing implementation even in an industry as old as Construction.

The range of possibilities in this technological age was seized by civil engineers resulting in the development of the BIM methodology. Its implementation, although slow, has taken place since the beginning of this century, easing the communication and coordination processes between professionals, required in the development of any type of construction. Arduous and time-consuming tasks are being aided by new automatizing software, thus decreasing the chance of human error and increasing the project performance.

One of the most difficult set of information to be transmitted between an engineering office and the construction site is the rebar detailing in reinforced concrete structures. Keeping in mind that the justification for extensive element detailing is the improvement of non-verbal communication between the structural engineer and the contractor, it is clear that this message must be passed as rigorously as possible. The development of a structural model with in depth representation of all reinforcement elements eases both the interpretation of the layout by the contractor as also the eventual detection of critical zones and optimization of the planning and construction processes by the engineer.

The present thesis takes advantage of BIM technology with the development of a set of intertwined routines in different software that automatically reproduce three-dimensional reinforcement elements in two-way orthogonal slabs supported on all sides. Thus, the introduction of slab related data into a developed Excel Worksheet will support its reinforcement design through various methods. Accordingly, via the visual programming software Dynamo, different selected reinforcement zones are represented as three dimensional elements within the global model in Revit.

To ascertain the application of the developed program routines compared to the traditional methods and representations, a case study is presented.

Keywords: Slabs, Reinforcement Dimensioning, Rebar Detailing, BIM Rebar Modelling

RESUMO

Com o desenvolvimento contínuo de novas tecnologias que levam ao aumento da eficiência dos processos diários, não é de surpreender que, em todo o mundo, se verifique a sua crescente implementação, mesmo num sector tão antigo como o da Construção.

A gama de possibilidades que acompanha a era tecnológica foi aproveitada por engenheiros civis, resultando no desenvolvimento da metodologia BIM. A sua implementação, embora lenta, tem ocorrido desde o início deste século, facilitando o processo de comunicação e coordenação entre todos os profissionais envolvidos no desenvolvimento de qualquer tipo de construção. Tarefas árduas e demoradas estão a ser apoiadas por novos *software* automáticos, diminuindo a ocorrência de erros humanos e aumentando o desempenho dos projetos.

Uma das informações mais difíceis de transmitir entre um escritório de engenharia e o estaleiro é a pormenorização de armaduras em estruturas de betão armado. Tendo em mente que o que justifica a extensiva pormenorização de elementos é a melhoria da comunicação não verbal entre o engenheiro estrutural e o construtor, fica claro que essa mensagem deve ser transmitida com o maior rigor possível. O desenvolvimento de um modelo estrutural com representação detalhada de todos os elementos de reforço facilita a interpretação do *layout* não apenas pelo construtor, mas também a eventual deteção de zonas críticas e a otimização do processo de planeamento e construção por parte do engenheiro.

A presente dissertação tira partido da tecnologia BIM com o desenvolvimento de um conjunto de rotinas interligadas em diferentes *softwares* que reproduzem automaticamente elementos de reforço tridimensionais em lajes retangulares armadas nas duas direções e com apoios em todos os bordos. Assim, a introdução dos dados relacionados com as lajes, diretamente numa folha de cálculo Excel, apoiará o dimensionamento das armaduras de reforço através de vários métodos. Consequentemente, através do *software* de programação visual Dynamo, as diferentes zonas de reforço selecionadas são representadas como elementos tridimensionais dentro do modelo global, no *software* Revit.

Para averiguar a aplicação das rotinas desenvolvidas e comparar os seus resultados com os métodos tradicionais de dimensionamento e representação, será apresentado um caso de estudo.

Palavras-chave: Lajes, Dimensionamento de Armaduras, Pormenorização de Armaduras, Modelação BIM de Armaduras

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisors at Newton – Consultores de Engenharia, Engineer José Lino and Engineer Patrício Rocha and mentor Professor Ricardo Santos, for the relentless knowledge, encouragement, inspiration and patience selflessly granted to me during my internship.

I would also like to thank all employees at the Newton offices for the kind welcome into their workspace, especially Henrique Pires for the important tips, advices and guidance given to me particularly, but not solely, during the development of the Dynamo routine.

A special thanks to my dear friend Raquel Correia not only for bearing with me through good and bad times in the years of my academic journey but also for giving me insight and advice into my thesis.

To my college roommates and friends Ana Castro and Teresa Carneiro, no words, they certainly know why, and to my cousin and first friend Diogo Martins for being the ears to both my problems and accomplishments all my life.

Last but, undoubtedly, not least to my family, especially my mom for all the immense kindness she has always given me and to the opportunities and sacrifices she made to get me to this stage of my life. To her, and to my beloved dad, I dedicate my Thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Building Information Modeling (BIM)

BIM is used as a verb or an adjective phrase to describe tools, processes and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction and later its operation.

BIM tool

A software with functionalities that allow the generation and manipulation of virtual models following the BIM methodology.

Interoperability

The ability to manage and communicate electronic product and project data from multiple vendors for the means of an efficient team collaboration.

Reinforcement Design

The quantification and planning of rebar elements within a concrete structural element in order to produce a structure capable of resisting all applied loads according to some regulation's criteria without failure during its intended life.

Structural Analysis

Is a process in which a mathematical model of a structure is analyzed in order to infer the real structure behavior based on the employed materials, the considered loading and the applied construction techniques.

LIST OF SYMBOLS AND ABBREVIATIONS

2D – Bidimensional

3D – Tridimensional

AECO - Architecture, Engineering, Construction and Operation

AIA - American Institute of Architects

$\mathrm{A_s}$ - Cross sectional area of reinforcement

b - Overall width of a cross-section

BIM – Building Information Modeling

CAD – Computer-Aided Design

COBIM – Common BIM Requirements

d - Effective depth of a cross-section.

EC2 – NP EN 1992 (Eurocode 2)

G – Permanent actions

h - Height

Kg – Kilogram

LNEC - Laboratório Nacional de Engenharia Civil

LOD – Level of Development

FEM - Finite Element Method

MEP - Mechanical, Electrical and Plumbing

NBIMS – National Building Information Model Standard

Q – Variable actions

REAE - Regulamento de Estruturas de Aço para Edifícios

REBAP - Regulamento de Estruturas de Betão Armado e Pré-esforçado

Robot – Robot Structural Analysis

RSA - Regulamento de Segurança e Acções para Estruturas de Edifícios e Pontes

XLSX - Excel Microsoft Office Open XML Format Spreadsheet file

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

It is staggering the under-accomplishment of the construction industry given its age and legacy compared to other newer big industries such as mechanical and automotive [1]. The high demand in what concerns civil engineering projects, lead the industry to accommodate on existing processes and stagnate in time, not taking full advantage of the promising technological developments during this modern age [2]. However, with the accelerated rhythm of technology and financial development the high demand justified the high offer, which lead engineers into a higher level of competition, and, consequently to the development of new means and methods to perform [3].

BIM methodology appeared in the end of the 20th century, trying an answer to the existing problems in the architecture, engineering, construction and operation industry, (normally referred as the AECO industry). It provides help not only in coordination between all professional involved in a construction project, as well in intricate project design and detailing [4]. Considering new constructions are becoming more and more complex, it is not enough to have a detailed methodology to lean on. Thus, this technological help keeps up trying to answer the challenges raised by more and more uncommon building shapes and functions.

Despite all advantages the new methodology brings, there is still a lackluster use of the BIM's abilities on some specific aspects and, in particular, on what concerns the concrete reinforcement modeling [5]. Having in mind that this field is heavily normalized and the solutions are usually repetitive, structural engineers should take advantage of BIM and focus on the development of tools that allow the automatic creation of certain objects with minor intervention from the engineer.

The present work pretends to give a contribution to the automation of rebar elements in two-way rectangular reinforced concrete slabs. Through a set of common software within the industry, intertwined routines were developed to culminate the modelling of rebar elements in a 3D environment. The process began with the development of an Excel worksheet containing traditional bending moment calculation methods, in addition to an option to manually introduce rebar solutions, in order to design the reinforcement zones of slabs. Once all reinforcement decisions were made, a Dynamo routine was developed to meet the data output of the Excel Worksheet and serve as an intermediate link between the first module and Autodesk's Revit, where the rebar elements will be generated. Taking into consideration that the developed algorithm targets slab panels with continuity, the program can be run multiple times in order to reinforce all panels, one at the time, provided they all have the same dimensions and load values.

1.2 MOTIVATION AND AIMS

The present document was developed under the internship that took place in the offices of Newton – Consultores de Engenharia in the context of the Master's in Civil Engineering – (structural branch), with this final work developed in a corporate environment.

The aim of this work is to develop a methodology based on BIM concepts that allows the automation of reinforcement modelling in the structural project of a rectangular two-way slab supported on all edges.

To fulfill these objectives the following actions needed to be accomplished:

- The development of a Microsoft Excel worksheet working as a dimensioning interface for any type of slab, regardless of its boundary conditions;
- The development of a Dynamo routine that would, in conformity with the Excel's output data, place all reinforcements in a slab in the original Revit Project.

To validate the routine set performance in a real environment, a case study regarding a previously dimensioned project was compared to the results of the automatic method developed.

1.3 REPORT SETUP

The present report is divided in 7 main chapters, beginning and including the present one:

- In Chapter 2 there's a comprehensive overview and description of the current matters concerning Dimensioning of slabs and BIM methodology;
- Chapter 3 offers a description of the developed worksheet, namely its inner works, components and functionalities;
- Chapter 4 introduces the thought-process in the development of the Dynamo routine, with a description of its correct use along with an adequate set of prints for better understanding of its functionalities;

- Chapter 5 presents the possibilities of converting the generated 3D model in varied detailed project elements;
- Chapter 6 illustrates the comparison between a real project design solution and the corresponding results using the developed routines, with the step-by-step description of the process;
- The final chapter offers some conclusions drawn from the work done.

CHAPTER 2

SUBJECT FRAMEWORK

2.1 SLABS

A Slab is a structural element that constitutes a floor of a building supporting loads normal to itself, causing out-of-plane bending. These elements are usually plane and horizontal with two main larger dimensions and a third one much smaller, the thickness. There are many types of slabs depending on their support type, manufacture method, materials and dimensions' ratio.

The supports are usually common structural elements in a construction, namely beams, columns or walls. As for the materials used in slabs, these have varied through ages and geographical location, but nowadays the most common material worldwide is reinforced concrete [6]. On what concerns the reinforced concrete itself, the manufacture method can be divided in two, "in situ" and precast. Finally, the dimensions ratio of the slab sides determines which way the slab will be reinforced in, distinguishing one-way of two-way slabs.

The present work will focus on the analysis of rectangular two-way reinforced concrete slabs.

2.1.1 Rectangular Two-way Slabs

These types of slabs are supported on all sides by beams and have rebars parallel to both axes. They transfer their load to the supports through both the shortest and longest slab directions.

The load causes the two-way slabs to have a so-called dished deformation, meaning that at any given point the slab is deformed in both principal directions. Considering curvatures are proportional to bending moments, these also exist in both directions, resulting in a need to be reinforced by at least two layers of perpendicular bars [7].

Boundary cases

Two-way slabs can be divided into simply-supported slabs, commonly known as an isolated slab panels, and restrained slabs, which are dependent on their edges whether they are continuous or fixed. The relative position of various slab panels to each other, and the dimension ratio of panel sides form continuous or fixed edges, culminating in nine boundary possible cases for two-way slabs, as demonstrated in Figure 2.1.

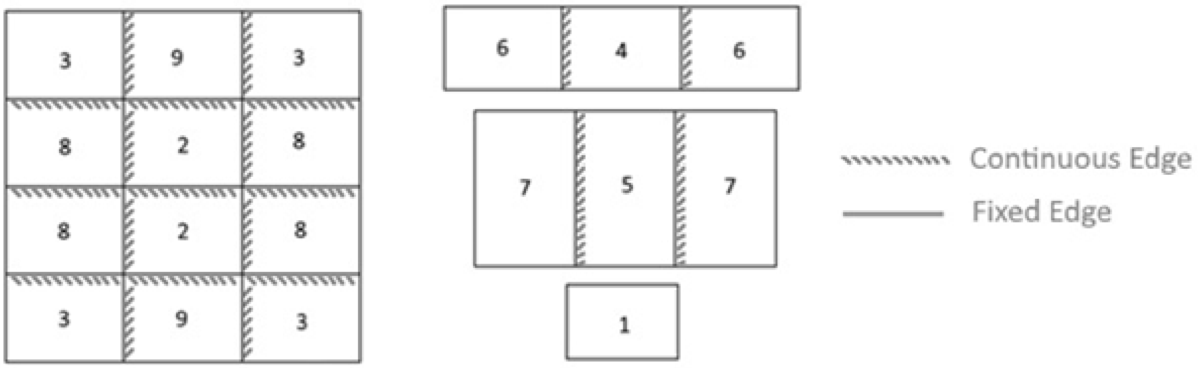


Figure 2.1 – Boundary Cases for Two-way Slabs

2.1.2 Structural analysis

History most celebrated scientists, from Galileu Galilei to Hardy Cross, have contributed to the advances on structural engineering. These individuals helped, one way or another, to develop methods, theories and mathematical formulas to better understand how structures behave. These efforts came together to develop Structural Analysis, the study of how loads affect physical structures and their components [8].

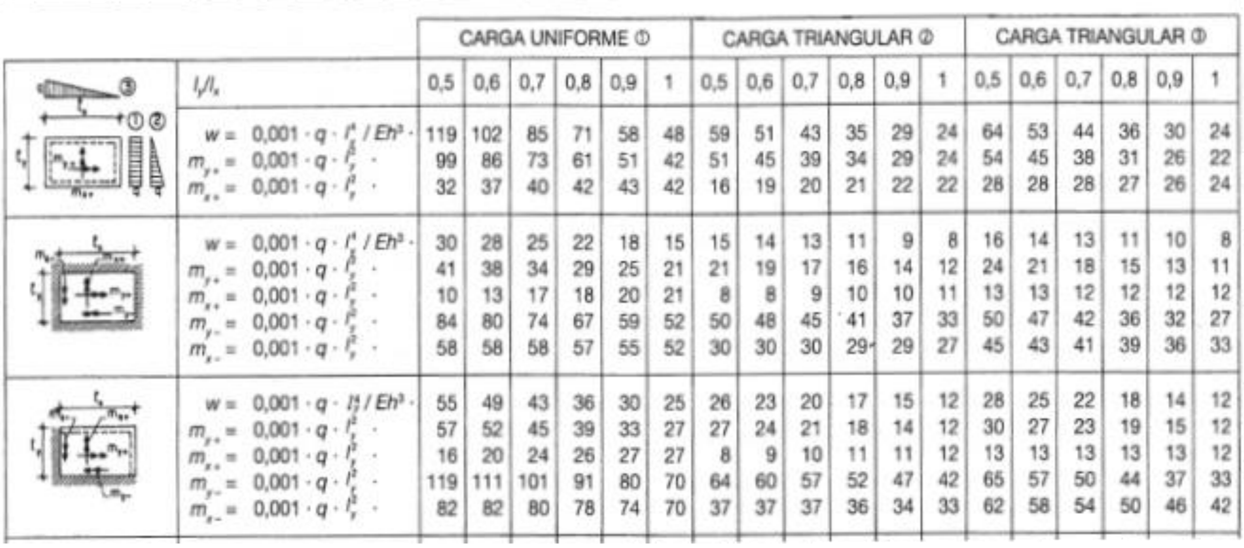
Years of research from different individuals resulted in a panoply of studies devising simplified methods to analyze any type of structures. Concerning two-way slabs, the most notably recognized works studied in Portugal, came from Jiménez Montoya et al in his work “Hormigón Armado” [9] and the British Standard – “Structural use of concrete —Part 1: Code of practice for design and construction” [10]. These type of approaches to structural analysis are called indirect methods.

Despite these great achievements, past engineers spent large amount of resources analyzing and determining loads and their resulting forces on structures. Fortunately, nowadays the process is simplified by computational analysis. This new way of work is called the direct method, where engineers can take advantage of software such as Robot Structural Analysis, ArchiCAD or Tekla, to provide them with a set of tools that model and analyze the most complex structures. Once the structure is simulated and the loads are attributed, the software calculates and returns all forces at once, avoiding time-consuming and error prone manual analysis. In Portugal, engineering offices widely use Autodesk’s Robot Structural Analysis on their projects, taking advantage of its simplified interface and interoperability with other Autodesk’s software [11].

Ahead a brief description of the software just mentioned will be presented, just after the following analysis of the Montoya and British Standard tables

2.1.2.1 Montoya Tables

“Hormingón Armado” came up with tables that determine internal structural forces and slab deflection based on loading, geometry and boundary conditions. These tables allow both uniformly distributed and triangular loads and are suited for rectangular two-way slabs supported on all sides, as shown below, as well as two-way slabs supported on only three sides.



	CARGA UNIFORME ①						CARGA TRIANGULAR ②						CARGA TRIANGULAR ③					
l_y/l_x	0,5	0,6	0,7	0,8	0,9	1	0,5	0,6	0,7	0,8	0,9	1	0,5	0,6	0,7	0,8	0,9	1
$w = 0{,}001 \cdot q \cdot l_y^4 / Eh^3 \cdot$	119	102	85	71	58	48	59	51	43	35	29	24	64	53	44	36	30	24
$m_{y+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	99	86	73	61	51	42	51	45	39	34	29	24	54	45	38	31	26	22
$m_{x+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	32	37	40	42	43	42	16	19	20	21	22	22	28	28	28	27	26	24
$w = 0{,}001 \cdot q \cdot l_y^4 / Eh^3 \cdot$	30	28	25	22	18	15	15	14	13	11	9	8	16	14	13	11	10	8
$m_{y+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	41	38	34	29	25	21	21	19	17	16	14	12	24	21	18	15	13	11
$m_{x+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	10	13	17	18	20	21	8	8	9	10	10	11	13	13	12	12	12	12
$m_{y-} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	84	80	74	67	59	52	50	48	45	41	37	33	50	47	42	36	32	27
$m_{x-} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	58	58	58	57	55	52	30	30	30	29	29	27	45	43	41	39	36	33
$w = 0{,}001 \cdot q \cdot l_y^4 / Eh^3 \cdot$	55	49	43	36	30	25	26	23	20	17	15	12	28	25	22	18	14	12
$m_{y+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	57	52	45	39	33	27	27	24	21	18	14	12	30	27	23	19	15	12
$m_{x+} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	16	20	24	26	27	27	8	9	10	11	11	12	13	13	13	13	13	12
$m_{y-} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	119	111	101	91	80	70	64	60	57	52	47	42	65	57	50	44	37	33
$m_{x-} = 0{,}001 \cdot q \cdot l_y^2 \cdot$	82	82	80	78	74	70	37	37	37	36	34	33	62	58	54	50	46	42

Figure 2.2 – Extract of the Montoya’s Tables for two-way slabs [9]

This set of tables have systematically the same consultation method. Firstly, the user needs to identify the boundary condition row, and the loading case columns correspondent to the slab in study. Guided by these two inputs, then the user divides, with decimal precision, the shorter span by the larger span of the slab and, in function of the result, retrieves the indicated coefficients. Finally, each coefficient needs to be applied in an indicated mathematical expression, and such expression is calculated, in order to obtain the values for either the final deflections or bending moments.

This study was based on elastic analysis that mimics a slab panel behavior and it is only considered a rough approximation of reality. This method relies on the conjuncture that slabs and other structural elements do not interact regarding their dimensions and stiffness, consequently two-way slabs are modeled overlooking the beams’ flexibility and torsional stiffness.

Where multiple continuous slabs exist, it is recommended to proceed, after obtaining the table’s final results, to pattern live load arrangements as well as redistribution of the support moments, and, if needed, their compatibilization. Ahead a summarized description of the concepts just mentioned is presented.

Pattern Live-Loading

The pattern live-load factor will allow the representation of the worst-case scenario of load distribution in different slab panels, needed to obtain the highest possible bending moment values in the structure.

The usual method to account for pattern live-loading is to alternate which slab panel receives live loads and develop an enveloped bending moment diagram of all the cases studied. This can be an arduous work, that can lead to endless possibilities for the analysis of a structure. It was considered, to account for the pattern live-loading factor, applied to the Montoya's Tables method, a known method in the Engineering Industry. It consists of recalculating, only, the positive moments by adding the resulting moments of two identical slabs. The first is a slab panel with the same boundary conditions as the original, but with half the permanent and variable loads. The second slab is a slab fixed on all sides and with only half the variable loads applied to it. A small example depicting the described is presented in Figure 2.3.

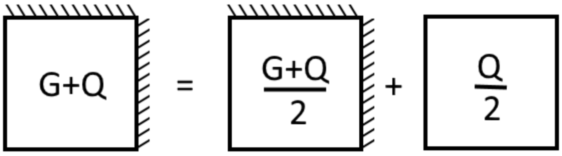


Figure 2.3 – Method for obtaining the positive moments considering pattern live-loading applied to Montoya's tables

It is important to stress that this process only influences the positive moments of a given slab. The maximum negative bending moments are obtained by applying the Montoya's tables normally.

Moments Redistribution

The redistribution reduces the densely reinforced zones in the upper surface of the slabs, by increasing reinforcement concentration in the lower surface. Moment redistribution has different limits depending on the norm in consideration. Portuguese national regulation in Reinforced Concrete, Regulamento de Estruturas de Betão Armado e Pré-Esforçado (REBAP), enforces in the 50th article that bending moment redistribution in slabs must never be greater than 25% in the support moments, while Eurocode 2 (EC2) presents a set of formulas in article 5.5 -Linear analysis with limited redistribution.

Compatibilization of Support Moments

Slab panels with concordant continuous edges usually have positive moments on most of their span and negative moments on the support zone. Specifically, if two neighbor slab panels, have different boundary cases, different loading or dimensions, the bending moments in the continuity edge will differ from panel to panel, as seen in Figure 2.4.

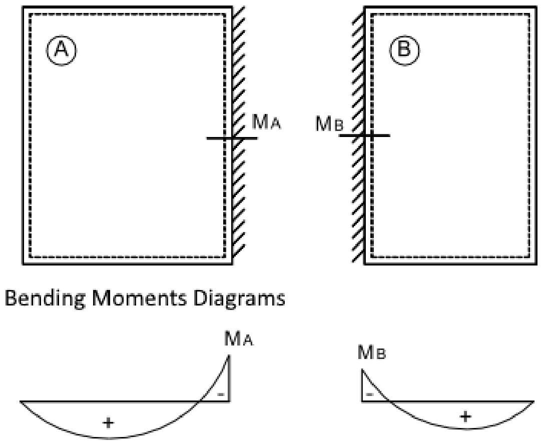


Figure 2.4 – Bending Moments Diagrams for two different consecutive panels (adapted from [12])

To have a harmonious analysis of the structure, negative bending moments need to match in value in both panels, a process called Support Moments Compatibilization.

There are many documented approaches for this process. In the present work it was adopted the compatibilization in regard to relative slab stiffness. In relation to Figure 2.4, the intermediate moment from the two specified will become M_{AB}, depending on the stiffness of the panels A and B.

Several structural analysis summary tables document numerous cases with varied support types and simplified formulas for the resulting moments based on the element's stiffness. Considering that a slab with fixed and continuous edges may be compared with a bar with simply and restrained supports, respectively, the following formulas are adequate to represents panel's A and B stiffness coefficient values:

$$\begin{aligned} \theta_A &= \frac{3EI}{L} \\ \theta_B &= \frac{4EI}{L} \end{aligned} \tag{2.1}$$

with:

θ_A— Panel A Stiffness;

θ_B— Panel B's Stiffness;

E — Elastic Modulus;

I — Second Moment of Area.

The next step is to calculate the difference between moments, ΔM, to evaluate how much each one of M_A and M_B will differ (ΔM_A and ΔM_B) in order to result in the same final moment, M_{AB}. The equation system demonstrates how to determine ΔM, by considering the relative stiffness of the slabs.

$$\begin{cases} \Delta\mathrm{M} = \Delta M_A \times \dfrac{\theta_A}{\theta_A + \theta_B} + \Delta M_B \times \dfrac{\theta_B}{\theta_A + \theta_B} \\ \Delta\mathrm{M} = \Delta M_A + \Delta M_B \end{cases} \tag{2.2}$$

with:

θ_A— Panel A Stiffness;

θ_B— Panel B Stiffness;

M_A— Panel A Maximum negative bending moment;

M_B— Panel B Maximum negative bending moment;

$\Delta\mathrm{M}$ – M_A and M_B difference;

ΔM_A – M_A variation;

ΔM_B - M_B variation.

Consequently, along with a negative bending moment variation, the maximum positive moment will also vary, usually by half the value of ΔM. These last considerations are illustrated on Figure 2.5.

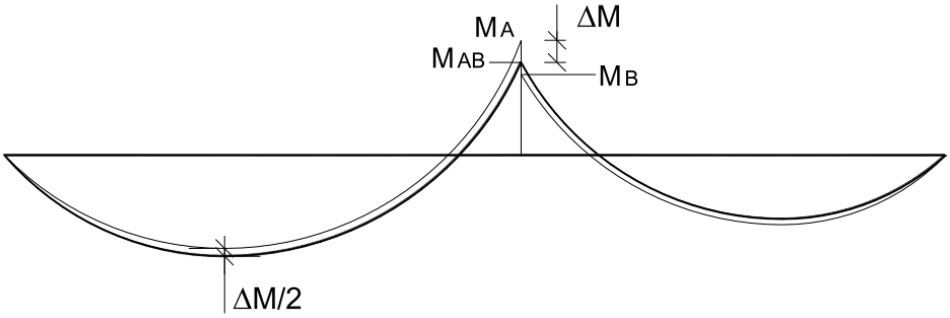
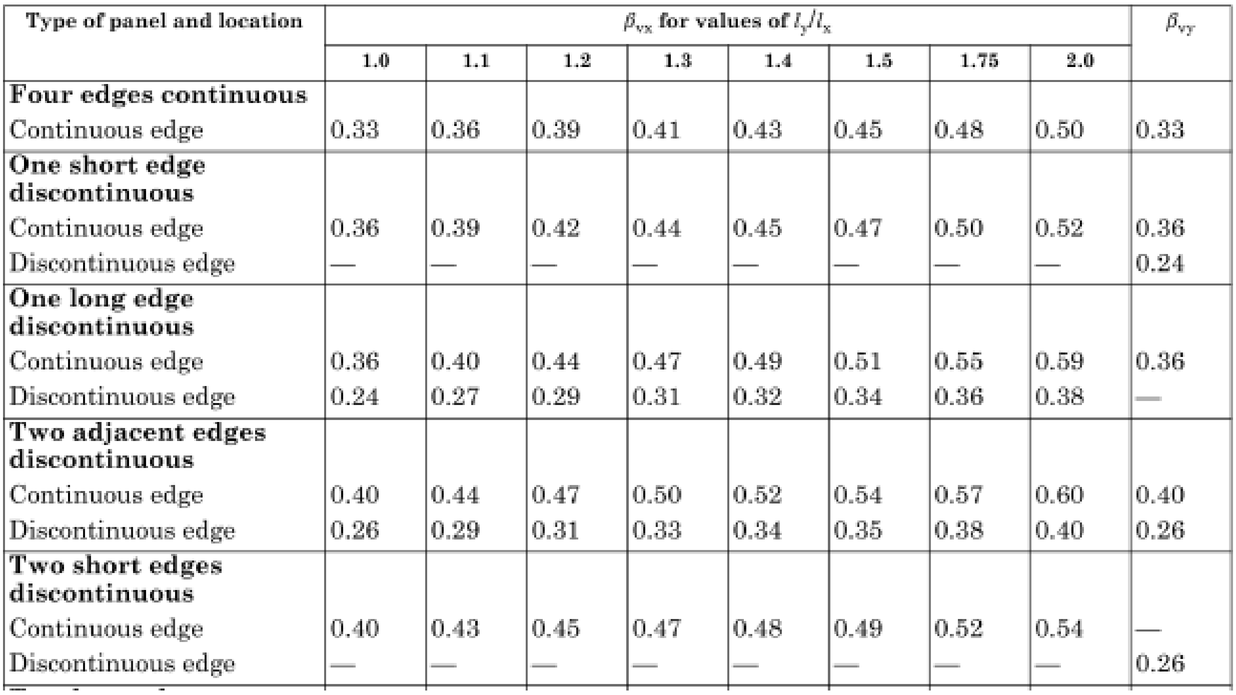


Figure 2.5 – Support Moment Compatibility diagram [12]

2.1.2.2 British Standard 8110

The BS 8110 is a British Standard produced by the BSI (British Standards Institution) Group and focuses on the design and construction of reinforced and prestress concrete structures. The section of that norm that specifies the best practices for reinforced slabs is BS 8110: Part 1: 1997 [10] .

In this standard, the method for obtaining bending moments values for two-way rectangular slabs is more limited than the one suggested by Montoya. BS 8110 documents a table with intermediate coefficients and its application is limited to slabs supported on all sides considering exclusively uniformly distributed loads, as shown in Figure 2.6.



Type of panel and location	β_{vx} for values of l_y/l_x								β_{vy}
	1.0	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.75**	**2.0**	
Four edges continuous									
Continuous edge	0.33	0.36	0.39	0.41	0.43	0.45	0.48	0.50	0.33
One short edge discontinuous									
Continuous edge	0.36	0.39	0.42	0.44	0.45	0.47	0.50	0.52	0.36
Discontinuous edge	—	—	—	—	—	—	—	—	0.24
One long edge discontinuous									
Continuous edge	0.36	0.40	0.44	0.47	0.49	0.51	0.55	0.59	0.36
Discontinuous edge	0.24	0.27	0.29	0.31	0.32	0.34	0.36	0.38	—
Two adjacent edges discontinuous									
Continuous edge	0.40	0.44	0.47	0.50	0.52	0.54	0.57	0.60	0.40
Discontinuous edge	0.26	0.29	0.31	0.33	0.34	0.35	0.38	0.40	0.26
Two short edges discontinuous									
Continuous edge	0.40	0.43	0.45	0.47	0.48	0.49	0.52	0.54	—
Discontinuous edge	—	—	—	—	—	—	—	—	0.26

Figure 2.6 - Excerpt of BS 8110 Tables for two-way slabs [10]

Aside from the division of the longer span by the shorter span to consult the table, the application method does not differ from Montoya's tables. The British Standard also developed these tables considering elastic theory but corrected the values through experimental results that account for the pattern live-load factor and negative moment redistribution. Given this, if needed, there's only the need to proceed to the negative moments compatibilization.

2.1.2.3 Robot Structural Analysis

Robot Structural Analysis is a software from Autodesk used to automatically structure models (Figure 2.7) with the distinct ability, compared to other similar software, of interacting with other Autodesk's frequently used tools in the AECO Industry, like AutoCAD or Revit.

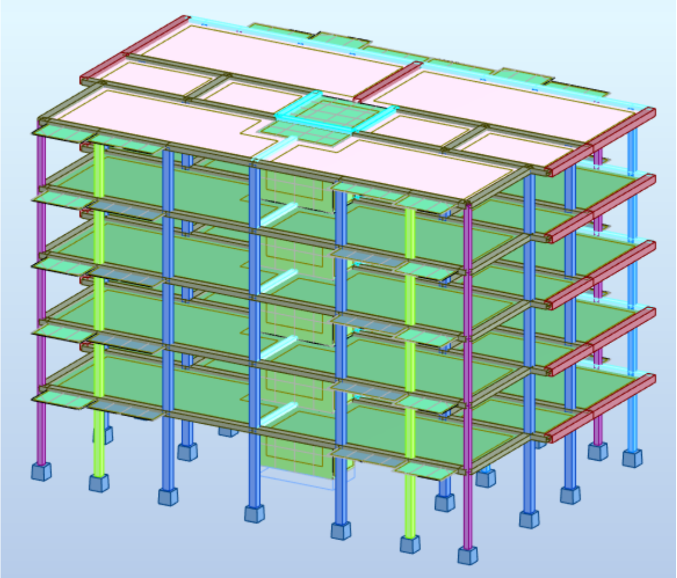


Figure 2.7 – Example of a building model in Robot

Robot provides linear, static non-linear and dynamic structural analysis through a tridimensional method based on the Finite Element Method (FEM). This method is based on the division of the structure in several smaller elements. These elements are defined by their nodes, allowing the determination of displacements between neighbor nodes and consequently estimated stress values, deformation and extension of different structural elements.

The software has built-in information and coded verifications dictated by different national and international norms.

2.1.3 Design Norms and Legislation

Currently Portugal is in a transition phase between norms concerning Structural Engineering. Currently the norms in force are REBAP Regulamento de Estuturas de Betão Armado e Pré-esforçado), RSA (Regulamento de Segurança e Acções em Edifícios e Pontes) and REAE (Regulamento de Estruturas de Aço para Edifícios). However, these three norms, besides being dated and incomplete, do not cover all the subjects concerning modern Structural Engineering [13]. This is where the Eurocodes come in to support and complete the current Portuguese legislation.

In the 70's, the European commission requested the European Committee for Standardization, CEN, the development of a set of documents to harmonize the technical rules in the field of construction among the member states [14]. A set of European Countries worked together to develop these documents, known as Eurocodes, and divided them in ten main standards, according to different subjects, as shown in Table 2.1. Each Eurocode, except EN 1990, is itself divided into a number of parts covering specific aspects of the subject, resulting in a total of 58 parts.

Table 2.1 – Eurocodes' norms and designations

European Norm	Designation
EN 1990	Eurocode 0: Basis of structural design
EN 1991	Eurocode 1: Actions on structures
EN 1992	Eurocode 2: Design of concrete structures
EN 1993	Eurocode 3: Design of steel structures
EN 1994	Eurocode 4: Design of composite steel and concrete structures
EN 1995	Eurocode 5: Design of timber structures
EN 1996	Eurocode 6: Design of masonry structures
EN 1997	Eurocode 7: Geotechnical design
EN 1998	Eurocode 8: Design of structures for earthquake resistance
EN 1999	Eurocode 9: Design of aluminum structures

In addition, each adherent country is required to have its own National Annex to the Eurocodes that takes into account distinguished characteristics and features of the country. In Portugal, the development of these National Annexes, as well as the Eurocodes' translation, is the responsibility of the Laboratório Nacional de Engenharia Civil (LNEC), that created a normalization technical committee called CT115 divided in ten groups, one for each Eurocode.

The most significantly applied norm in present document is Eurocode 2: Design of concrete structures, which corresponds most closely to Portuguese REBAP. Both these norms stipulate rules for structural reinforced concrete design, needed to be applied in the Excel Worksheet developed to design the reinforcement of two-way slabs.

2.1.4 Reinforcement Detailing

Reinforcement detailing in slabs must be precise, as they are normally heavily reinforced, resulting in complex and full drawings of mismatched rebars. The detailing must be easily read and well organized for there are many different zones of reinforcement, both in the upper and the lower surface of the slab.

EC2 has strict rules in what concerns the reinforcement design for two-way slabs, however its detailing rules and procedures are complex, as they were complemented with Montoya's suggestions in his work "Hormigón Armado" [9], to define and detail different reinforcement zones.

2.1.4.1 Anchorage

According to article 8.4.1 from EC2, the anchorage must be long enough so that the bond forces are correctly and safely transmitted to the concrete to avoid longitudinal cracking and spalling.

Article 8.4.4 from EC2 dictates that the design anchorage length, L_{bd}, must follow equation 2.3:

$$L_{bd} = \alpha_1 \times \alpha_2 \times \alpha_3 \times \alpha_4 \times \alpha_5 \times L_{b,rqd} \geq L_{min} \tag{2.3}$$

With:

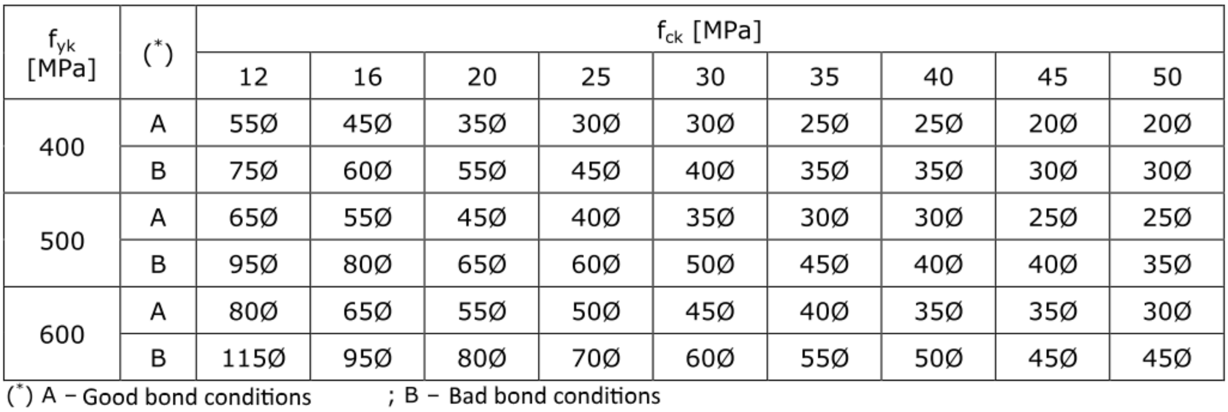
α_1 to α_5 – Coefficients from Table 8.2 from EC2;

$\mathrm{L_{b,rqd}}$ - basic required anchorage length;

$\mathrm{L_{min}}$ - minimum anchorage length;

Through the years simplified and approximate methods were developed to calculate such length. One of them is the application of a table, seen in Table 2.2 with equivalent anchorage lengths, $L_{b,eq}$, in function of steel and concrete class, rebar diameter and bond conditions.

Table 2.2 - Values for equivalent anchorage lengths, $L_{b,eq}$ (adapted from [15])



f_{yk} [MPa]	(*)	f_{ck} [MPa]								
		12	16	20	25	30	35	40	45	50
400	A	55Ø	45Ø	35Ø	30Ø	30Ø	25Ø	25Ø	20Ø	20Ø
	B	75Ø	60Ø	55Ø	45Ø	40Ø	35Ø	35Ø	30Ø	30Ø
500	A	65Ø	55Ø	45Ø	40Ø	35Ø	30Ø	30Ø	25Ø	25Ø
	B	95Ø	80Ø	65Ø	60Ø	50Ø	45Ø	40Ø	40Ø	35Ø
600	A	80Ø	65Ø	55Ø	50Ø	45Ø	40Ø	35Ø	35Ø	30Ø
	B	115Ø	95Ø	80Ø	70Ø	60Ø	55Ø	50Ø	45Ø	45Ø

(*) A – Good bond conditions ; B – Bad bond conditions

In the present document, two types of anchorage were applied, anchorage with a vertical 90 degrees hook and anchorage by rebar extending. Normally, in fixed edges a hook is made within the concrete cover distance from the beam's outer edge, while in other zones, such as continuity zones and rebar overlapping, there is simply the length extension of the rebar.

2.1.4.2 Reinforcement placement

Positive Main Reinforcement

The Main reinforcement is placed in the lower surface of the slab, with maximum rebar concentration in the central section of the panel. It usually has rebars in both x and y direction, always parallel to the edges, and their interruption details are dictated by practical rules.

In the present document the rebar interruptions on a given panel slab are made by firstly defining an edge strip all around the slab, with a distance of approximately 30% the shortest span of the slab, creating a central section. The first set of rebar will be placed covering all the area of the slab and the second set will only occupy the central section, extending to the edge of the slab, only if the particular edge is fixed. A representation of the described is schematically shown in Figure 2.8. In this figure, similarly to the next few in the present chapter concerning rebar placement, the longest span is characterized by "Lx" and the shortest one by "Ly".

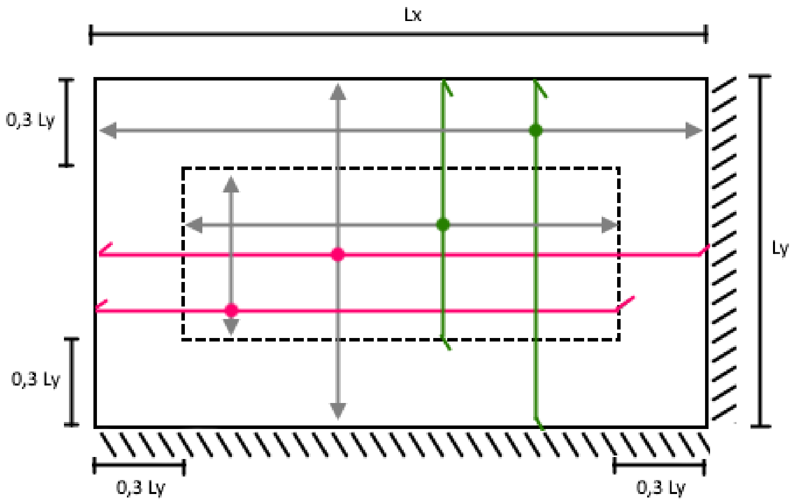


Figure 2.8 – Example of Positive Main Reinforcement areas of slabs

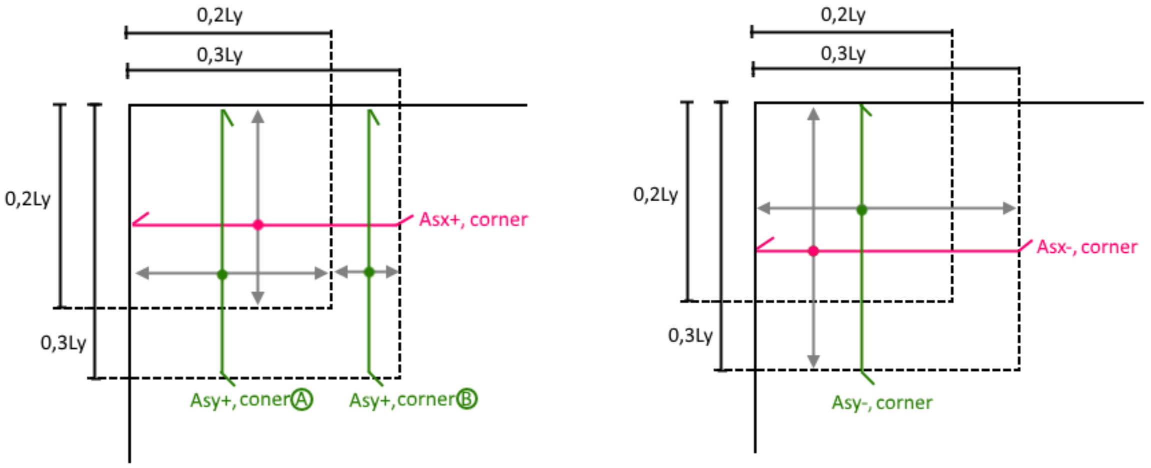
All rebars ends located in the fixed edge will be have a hook anchorage, and the ones in the continuity zone will be extended, while the rebars ends located in the interruption zone will be cut at the indicated distance.

Corner Reinforcement

Corner reinforcement correspond to the reinforcement on corners with two perpendicular fixed edges and they must be placed in the upper and lower surface.

These types of reinforcement zones, with freedom of rotation on the supports, tend to lift due to bending forces. To control these forces a reinforcement grid is needed with a rebar area per square meter equivalent to the maximum value of both positive main reinforcement areas.

The perpendicular bars must be placed in the correct corner with an approximate distance of 30% of the shortest span from the beam axis and should account for the existing main reinforcement in the design calculations, as suggested in the Figure 2.9.



a) Lower surface

b) Upper Surface

Figure 2.9 – Example of a fixed edge-fixed edge Corner Reinforcement in both slab surfaces

The rebars' anchorage in this reinforcement zone are done into a 90 degree hook on the fixed edge end of the rebar, while on the other end they are simply cut at the indicated distance.

Negative Main Reinforcement/ Support Reinforcement

This type of reinforcement is needed when there are two consecutive slab panels separated by a beam, to counteract the negative bending moments on these areas. This reinforcement must be designed to meet the maximum negative moment in the support zone, with the possibility of moments redistribution, to avoid excessive cracking.

The modeling of this type of reinforcement attended to one of the suggestions by Montoya [9], in which the rebar interruption is bi-phased and alternated between the 0,2Ly and 0,3Ly mark of the middle strip, as Figure 2.10 suggests.

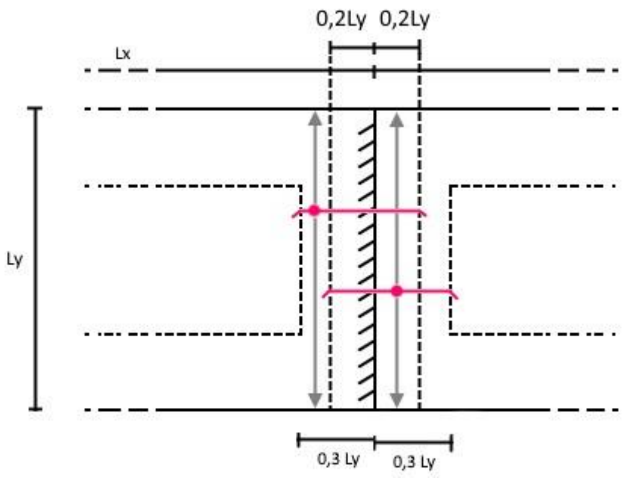


Figure 2.10 – Support Reinforcement placement

In this reinforcement zone no additional anchorage documented in the EC2 was applied.

Additional Reinforcement

The corner edge of type fixed edge-continuous edge is only applied to the upper surface and only accounts for rebars parallel to the continuous edge, as seen in Figure 2.11. This reinforcement zone must be designed to meet half the maximum main reinforcement. This type of reinforcement can be applied in any type of rectangular two-way slab except if it is continuous or fixed on all sides.

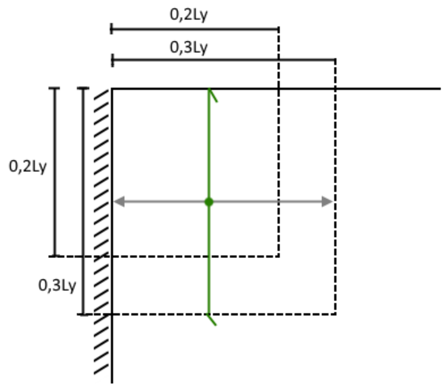


Figure 2.11 - Example of a fixed edge-continuous edge corner Reinforcement

The anchorage conditions in this zone is similar to the corner reinforcement.

Fixed strip Reinforcement

Even though this type of reinforcement is located in a zone of a fixed edge, where supposedly there are no negative moments, the rotation of the slab in relation to the beam provokes reciprocal forces originated by the beam's stiffness and consequently causing tensile strengths.

Rebars are placed on the upper surface of the slab perpendicular to the fixed edge with a length of 30% the shortest span starting from the beam axis and distributed between two corner reinforcement zones, as seen in Figure 2.12.

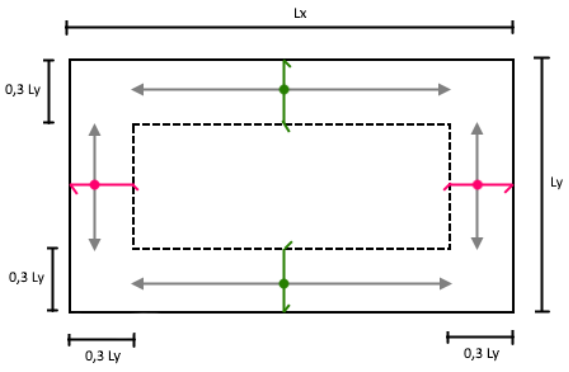
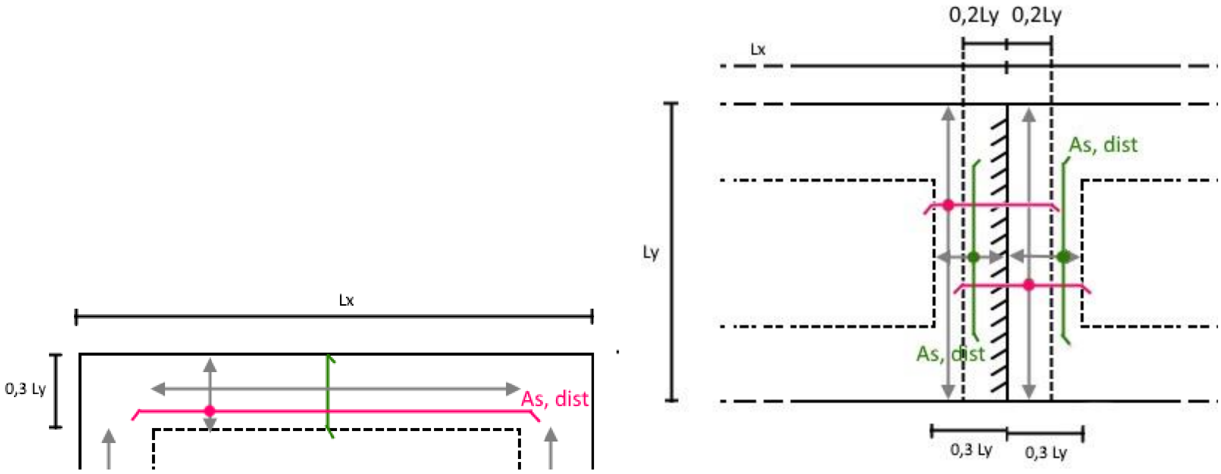


Figure 2.12 – Fixed Strip Reinforcement Placement

This reinforcement zone's anchorage is similar to the last zone.

Distribution Reinforcement

Distribution Reinforcement is mostly a practical set of rebars that not only help in the construction phase, by its parallel disposition to reinforcement with only one rebar directions, but also helps with crack controlling. In two way slabs this type of reinforcement is usually applied to the negative main reinforcement as well as the fixed strip reinforcement, depicted in Figure 2.13.



a) Distribution reinforcement for fixed edge reinforcement

b) Distribution reinforcement for support reinforcement

Figure 2.13 – Distribution reinforcement examples

The anchorage is made exclusively by the rebar extension method in both ends of the rebars.

2.2 BIM

BIM, which stands for Building Information Modeling is a new, modern and revolutionizing approach of design and documentation of building projects. The methodology has been gaining increasing attention in the architecture, engineering, construction and operation industry (AECO) with the technological development allowing planning, design, construction and operation simulation of a given facility [16], [17].

Even though the technological advances were a big contributing factor into the dissemination of BIM, the advantage of a high coordination between all participants of the project is also to acknowledge. These may include the client, architect, engineer, contractor, consultants, fabricators and operators. Their interaction allows a transparency in the project that makes possible to all stakeholders to participate on the result or insight on the different processing during all project phases [18]. In spite of the heavy use the virtual building model during the project and construction periods, BIM can cover future stages of a building's life-cycle (see Figure 2.14), such as logistics, maintenance and potentially even renovation and/or demolition [4].

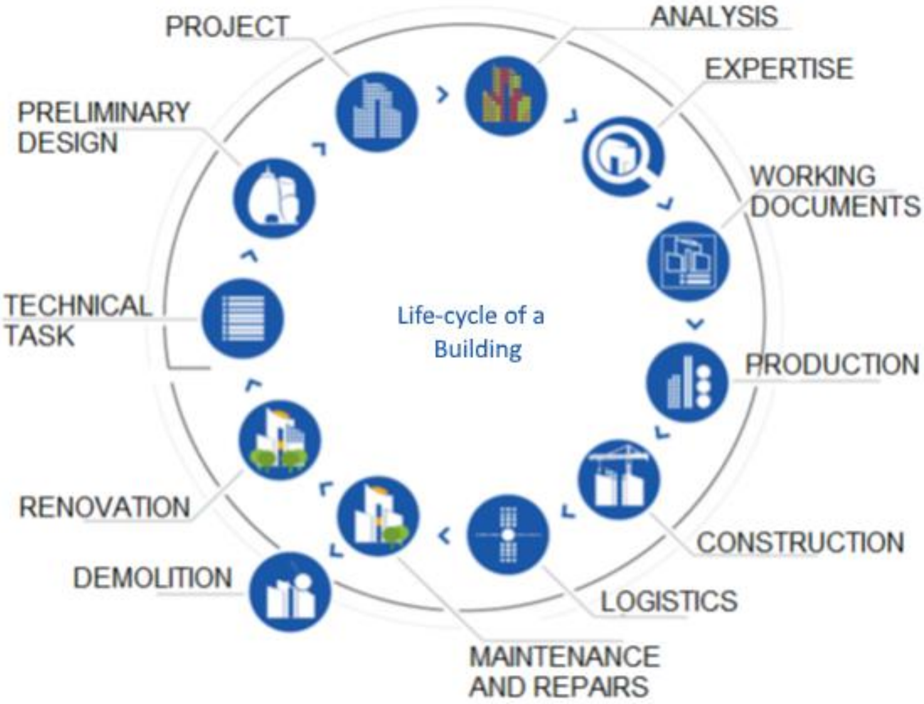


Figure 2.14 – Life-cycle of a building (adapted from [4])

2.2.1 History

The modern BIM concept started to develop as early as 1962 by Douglas C. Engelbart, in his published paper Augmenting Human Intellect, where he describes the transformation of a series of specifications and data input into a revised version of a structure [19]. This was the stepping stone for the methodology, followed by works such as Charles M. Eastman's "Building Description System", that criticizes the drawing as the only way of construction information communication, and G.A. van Nederveen and F. Tolman's "Modeling Multiple Views on Buildings", where was coined for the first time, in 1992, the term "Building Information Modelling" [20].

Decades have passed since this ideology were developed and documented, however a cheap and accessible software were still in need to satisfy the implementation of BIM technology. While this did not happen, the CAD software fulfilled the needs of AECO industry with its efficiency, slowing down the process and justifying the BIM circumvention.

2.2.2 CAD vs BIM

CAD and BIM represent two very different approaches to building, design and documentation. 2D-CAD drawings, similarly to traditional paper drawings, are created independently from each other and are the result of different individual and even specialty companies contributions [4].

Even though CAD software started with 2D objects, they evolved to offer 3D elements, which did not alter the industry's paradigm. Some of these drawings tools did, indeed, avoid some errors in the project process and eased the necessary time-consuming alterations, however the final result was used solely for representation purposes [21].

The BIM concept foresees not only objects with a 3D virtual representation but also its integration in a construction environment, mimicking a real building process. Such objects are called intelligent objects, characterized by their spatial properties linked with their physical representation. All the objects gather and form a single central virtual building model, where design changes are not considered a stumbling obstacle and are followed by updated individual drawings [21].

With all its advantages, BIM holds all necessary information to construction drawing, graphic expression, project analysis, inventory maps and budget estimates through the entire life-cycle of the project [4].

2.2.3 Level of Development (LOD)

When the term *Visual Model* is used to describe the BIM methodology, the receiving end may have a rather ambiguous understanding of it, causing confusion and frustration. This lack of accuracy can leave a lot of room for interpretation, hence the definition of levels of virtual modeling, commonly referred to as Level of Development (LOD) [11].

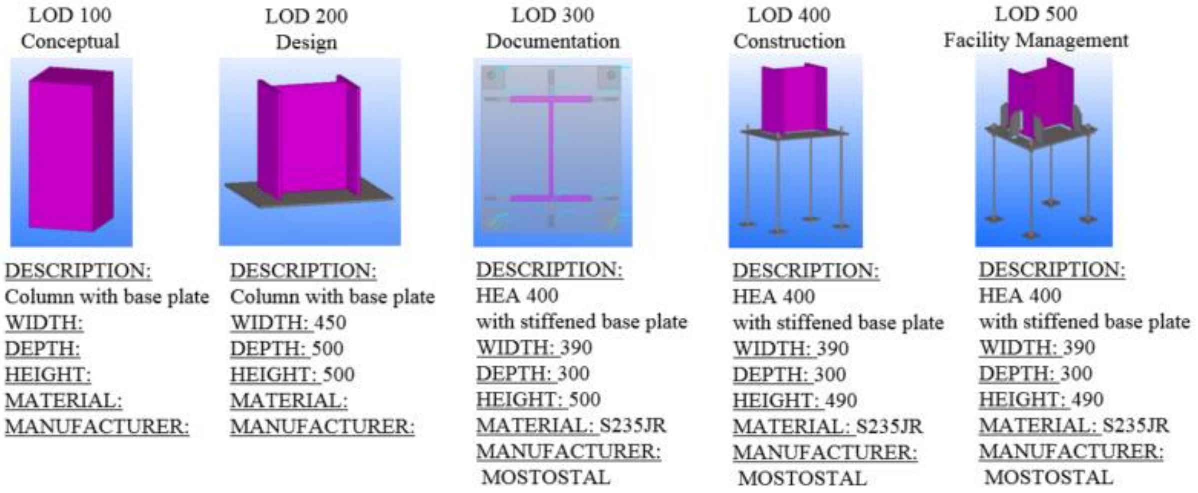
The LOD refers to the degree of detail and complexity of a BIM model, enabled by the development degree assigned to the objects that concern it. This means a LOD must be defined ahead of the model elaboration, so every party have knowledge of the level of information to be attached to each object within the model

[22]. Even though, sometimes, it is more useful to be simple than to include all the data, the higher the LOD, the more detailed information it contains in the model, making the effort to develop the model grow exponentially with the LOD levels [23].

The Structural Engineering Institute – Council of American Structural Engineers establishes and distinguishes five LOD's based on the publish document AIA Document E202, described as [24]:

- LOD 100 – This level is related to the conceptual project phase and provides information on the masses and volumes of objects. This basic info only restricts its use to the elemental disposition of spaces, calculations of volumes and areas and space orientation. This can potentially lead to a general estimation of the project planning and duration [24].
- LOD 200 – Comparable to a schematic drawing, this model contains objects with rough quantities, size, shape, location and orientation [25]. These specifications grant performance criteria analysis and can include a scaled appearance in time of the objects to assist the construction phasing and planning [24].
- LOD 300 – In this level of development the model needs to have the right amount of information to prepare the traditional construction documents at the execution project level [24]. It is possible to proceed to detailed simulations and analysis of system elements [22].
- LOD 400 – This level of development should include additional details and all the primary and secondary structures of support for it's used for the fabrication and assembly processes. The model contains precise object information about its size, shape, location, orientation and construction process. It is possible to estimate detailed costs and well as planning through the scaled appearance of specific elements [22], [24].
- LOD 500 – It is the final level and represents the project as it was constructed (as-built), reaching a level of realistic representation. The model has the same characteristics as the LOD 400 adding the maintenance ability when needed [22].

The graphic in Figure 2.15 shows a schematic example of the same element in different levels of development, along with the needed information for each one.



DESCRIPTION: Column with base plate
WIDTH:
DEPTH:
HEIGHT:
MATERIAL:
MANUFACTURER:

DESCRIPTION: Column with base plate
WIDTH: 450
DEPTH: 500
HEIGHT: 500
MATERIAL:
MANUFACTURER:

DESCRIPTION: HEA 400 with stiffened base plate
WIDTH: 390
DEPTH: 300
HEIGHT: 500
MATERIAL: S235JR
MANUFACTURER: MOSTOSTAL

DESCRIPTION: HEA 400 with stiffened base plate
WIDTH: 390
DEPTH: 300
HEIGHT: 490
MATERIAL: S235JR
MANUFACTURER: MOSTOSTAL

DESCRIPTION: HEA 400 with stiffened base plate
WIDTH: 390
DEPTH: 300
HEIGHT: 490
MATERIAL: S235JR
MANUFACTURER: MOSTOSTAL

Figure 2.15 – Example of LOD Levels [26]

2.2.4 Object-Based Parametric Modeling

BIM methodology utilizes a modulation approach oriented by its containing objects and their interaction with each other. On its turn, each object may contain information, more or less in depth, about its characteristics, but are also linked to the operators that create, manipulate, eliminate or update them, allowing their autonomy [27]. All this information is pertinent to gather meticulous inventory maps and budget estimates of a given project, culminating in a parametric model [28].

In Parametric Design, the user designs a model family or element class, representing a set of relations and rules for the object to follow. The relations grant the alteration of each instance of a model family according to its own parameters settings and context relations. On the other hand, the rules are qualified as requirements that the design must satisfy, allowing user manipulation all the while the rules update the altered details and check its legality, warning the user if the definitions are not met [29].

This modelling method is not limited to the built-in families or classes in the used software. Nowadays there is an array of algorithm development tools that allow the manipulation of objects in order to create new geometries in any project phase [5]. As the algorithms are created through programming language, direct or indirectly, the shapes possibilities are next to endless, complementing any demanding request.

2.2.5 BIM in Structural Engineering

Traditionally, structural engineers start a new project by analyzing the drawings done by the architect, and, following directions about materials, layout, section properties and loading, create a design documentation along with numerous analytical models [30].

In the analysis and design stages, the approach on the model process could be divided in two, namely the global model and the local model. Being the first less detailed than the second, these models can have the need to be developed in different software, that may have next to none interoperability between them [31]. A single design change to the project requires a one-by-one alteration to all the models, which can end up in both faulty, time-consuming projects [4], along with the resulting added costs. This results in a highly disturbed workflow, that depend heavily in human resources to manipulate and coordinate [31].

By taking advantage of BIM, these models can all be merged into one central model, containing both physical and analytical representation of the structural model. The physical information contains data used in the analysis applications, while the analytical information matches the model used in the structural analysis. These take two different views of the same model and interconnected, allow not only the structural analyses of the project, but also the production of construction documents [32].

The graph in Figure 2.16 shows the level of effort required over the life of a typical structural design project in terms of cost and performance impact, cost value and workflow effort in both BIM and traditional processes.

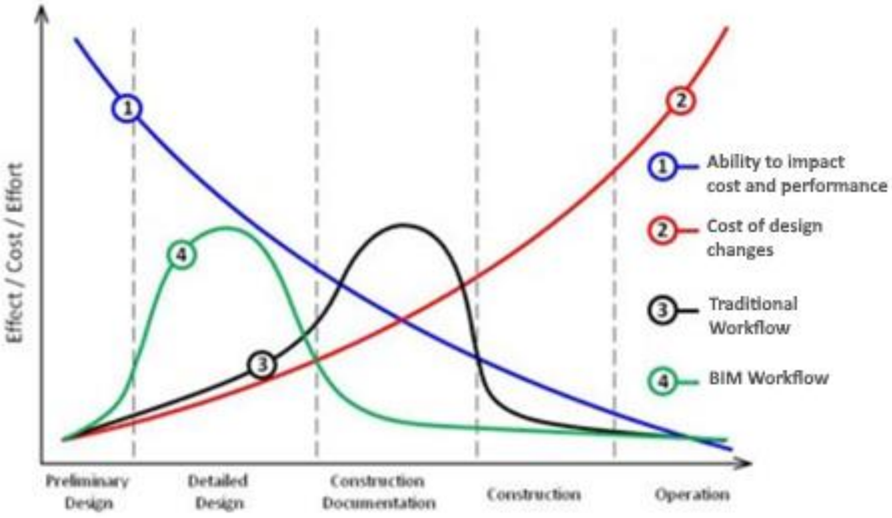
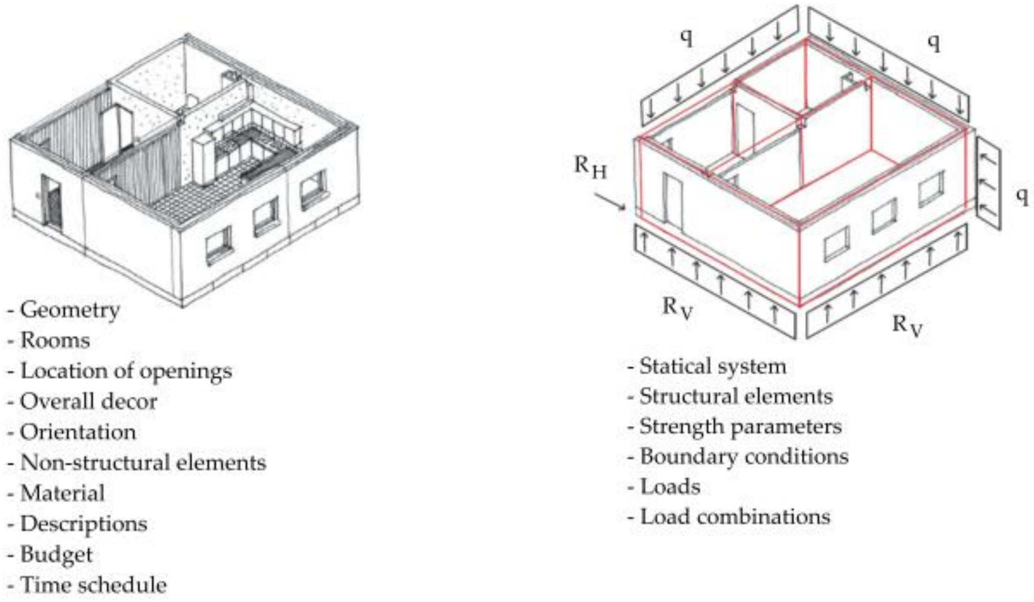


Figure 2.16 – Level of effort required with respect to time in BIM (adapted from [33])

In the early stages of the project the engineer has a high impact and influence over the cost and performance of the project, but increasingly loses its control over time. The cost of design changes behaves in opposite way, while the black line (traditional workflow effort) peaks in the middle, during the construction documentation phase, where civil engineers and designers expend their most effort in the traditional process. This level of effort, combined with a high cost of design change and low ability to impact cost and performance, is counterproductive and depicts the limitations of the traditional process compared to BIM. The methodology workflow effort, represented by the green line, peaks in the detailed design stage of the process, where the ability to impact cost and performance is still relatively high and the cost of design changes still present a low value. This a result of a high dynamically connecting design, analysis, and documentation, allowing engineers to spend more time evaluating problematic scenarios and less generating construction documentation [33], [34].

The structural engineering role in BIM is becoming so prevalent in the AECO industry, that Hejnfelt and Øksengaard coined a term to identify it through the acronym S-BIM. The major difference between the main and subset methodologies is that the BIM model can focus a lot of resources, important to almost all the professionals involved in the project, while S-BIM only has information relevant to structural engineers [35]. A simple example for this paradigm is shown in Figure 2.17.



a) BIM model

b) S-BIM model

Figure 2.17 – Differences between BIM and S-BIM model (adapted from [35])

The structural engineer takes the BIM models and assigns to it relevant information, such as geometry material properties, loads and boundary conditions, allowing its structural analysis through structural BIM tools [35].

2.2.6 BIM tools

There is a panoply of BIM tools that satisfy the needs of both engineers and architects, however these professionals have different focuses, and so do the tools they use within a particular software. The need to answer some problems structural engineers face, led the industry to develop computer applications that allow a faster and easier project development. In an age of daring and complex construction, a high information management, in respect to updating and coordination between different models and platforms is crucial [24].

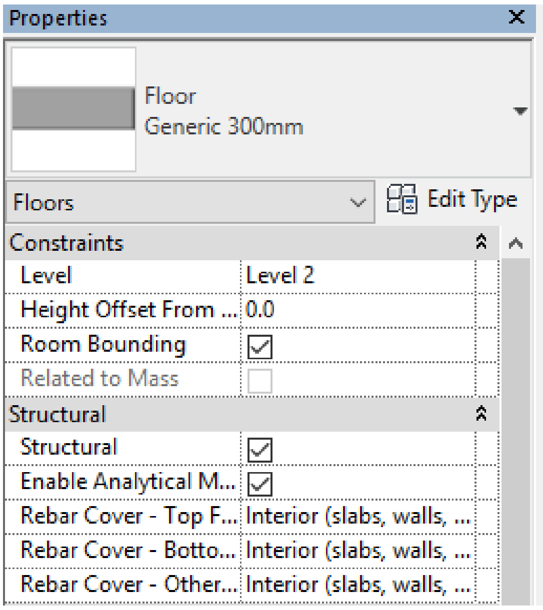
The first BIM software in the world for a personal computer was Radar CH in 1984, developed by Gábor Bojár, that later became Archilab [20]. This software was, most notably, followed by Parametric Technology Corporation (PTC), it conquered the AECO industry with its graphic interface with the user, convenient Unix windows, and fast solid processing [36]. In 2000, Irwin Jungreis and Leonid Raiz created a software named Revit, later sold to Autodesk [19].

2.2.6.1 Autodesk Revit

By introducing sophisticated parametric families, construction phase control, schedules and visual programming environments, Revit grants the implementation of the BIM methodology worldwide [19].

Even though Revit was originally built by architects for architects [18], the software's 3D modelling properties called its use by not only civil and structural engineers, but also mechanical, electric and hydraulic engineers. With its success and professional demands, this software is almost annually updated, multiplying its tools and properties in such a way that it is now divided in three main branches: Revit Architecture, Revit MEP and Revit Structure [37].

The Revit Structure branch focus on aiding structural engineers, where the user can design a project, perform its analysis, plan structural reinforcement and generally guarantee the structural stability of a building [37]. To take full advantage of all the potentialities Revit has, it is important to easily distinguish all elements involved with structural engineering from elements concerning other specialties, not only to maintain a harmonious coordination between the project specialties, but also to obtain correct inventory maps. Structural Engineers must pinpoint all elements as structural elements, otherwise it will be considered a regular element that will not have the necessary property fields [38]. For example, slabs are easy elements to model the wrong way, since they can be either part of the architectural branch or the structural one. This action can be maneuvered in the Revit interface, within the element's properties, similarly for every type, as the Figure 2.18 shows.



Floor
Generic 300mm

Constraints	
Level	Level 2
Height Offset From ...	0.0
Room Bounding	☑
Related to Mass	☐
Structural	
Structural	☑
Enable Analytical M...	☑
Rebar Cover - Top F...	Interior (slabs, walls, ...
Rebar Cover - Botto...	Interior (slabs, walls, ...
Rebar Cover - Other...	Interior (slabs, walls, ...

Figure 2.18 – Properties of Slabs

In slabs this distinction is especially important because if the floor is not marked as structural, Revit will not allow its reinforcement modeling. The definition of diameters, steel classes, concrete cover values, not to mention the possibility of activating the analytical model of the slabs will be locked.

It is also important to note that there is not only a separation of specialties by also modelling types. There is the “Revit Project” that addresses the modelling of the project itself, different from “Revit Families” that provide the development of new BIM objects not integrated in the “Revit Project”. Within this one there is also a tool called “Model in Place”, that allows the creation of an object exclusive to the model it was created in [39].

In “Revit Families” there are many partitions meant to the creation of different objects, with properties meant for either architectural, structural, mechanical or even neutral elements. The creation of such families provides the user the possibility for storage of edited elements in a library for its use in future models, avoiding a continuous edition of frequently used elements [38]. In the structural branch, “Revit families” are particularly useful, for they provide an analytical model for all newly created elements through the “Model in Place” tool. However, as this tool consists in an arduous and time-consuming, manual introduction of analytical lines, this process can result in an incomplete analytical model and inadequate interpretation of project.

One of the most focused “Revit Families” is the Rebar Bar family, utilized for the reinforcement of rectangular two-way slabs. The 2D and 3D visualization of the reinforcement aids in the evaluation of the chosen solution, by identifying errors in rebar spacing, overlapping and other conflicts [38]. Small details such as anchorage types, seen in Figure 2.19, and lengths can be easily identified and effectively reproduced in site.

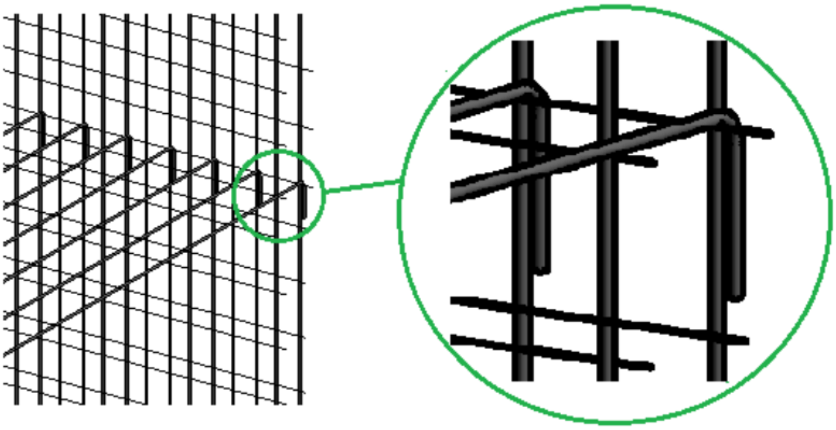


Figure 2.19 – Anchorage Detailing in Revit [38]

In what concerns slabs as structural elements, Revit has a built-in option to semi-automatically reinforce slabs with a set of functionalities such as Area reinforcement, Path reinforcement, Fabric area reinforcement, concrete cover and rebar couplers definition, as Figure 2.20 shows.

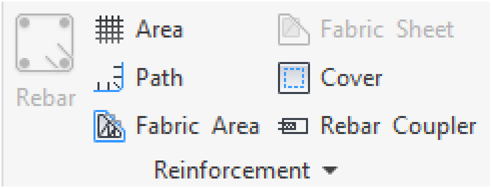


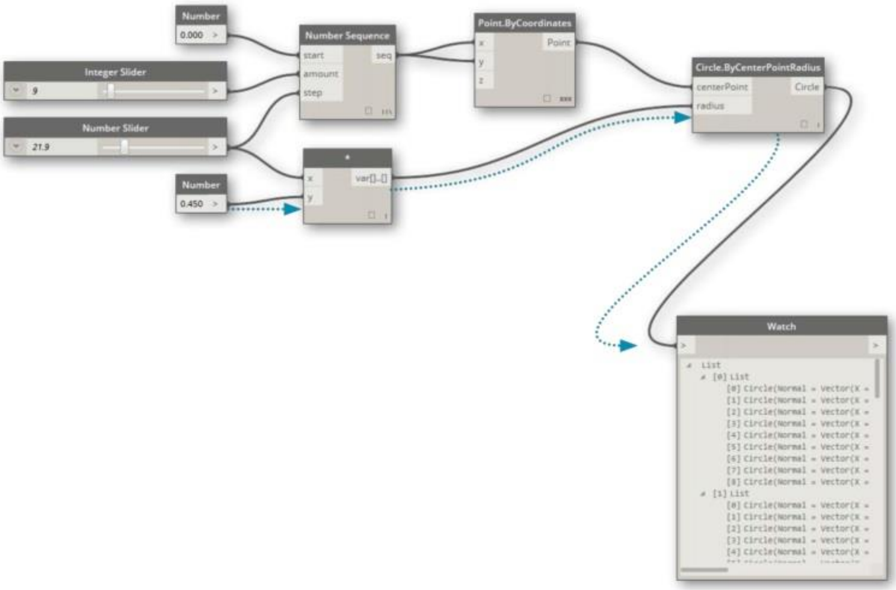
Figure 2.20 – Revit's Reinforcement tools

Even though these tools are of significant help for a structural engineer it is still not enough, as slabs still have a lot of different reinforcement both in the upper as lower surface that may have different diameters, lengths or even materials. For this reason, in what concerns reinforcement detailing, BIM methodology still does not convince most structural engineering offices to completely discard of CAD drawings, for it is still faster. To circumvent the problem of time the most notorious downside in the field of BIM reinforcement, there is a need to develop automatic routines that do standardized reinforcement rapidly. Nowadays a way to do it is to take advantage of a Revit extension called Dynamo, that automatizes some processes though Visual Programming.

2.2.6.2 Dynamo

Starting as a plug-in for Revit, Dynamo became such a prevalent tool that it grew into a built-in extension in the main software. It is a visual programming tool of relatively easy comprehension for non-programmers, by giving the user the ability to visually script behavior and create custom elements and pieces [18].

Several studies corroborate that professional engineers not specialized in programing have an easier time learning visual programing instead of the conventional programing language [18]. Dynamo replaces the complex programming language syntax with simple blocks or nodes, connected with each other by virtual strings. These nodes can be manually created through PYTHON language or, more frequently, used as pre-packed nodes, either built-in by Dynamo or downloaded by a third party, to represent various commands and functionalities [17]. Taking issuing node's outputs and transforming them into a receiver node's input, as well as moving and grouping the nodes as wanted, allows the creation of a user-manipulated workflow, as Figure 2.21 exemplifies.



```
List
  [0] List
    [0] Circle(Normal = Vector(X =
    [1] Circle(Normal = Vector(X =
    [2] Circle(Normal = Vector(X =
    [3] Circle(Normal = Vector(X =
    [4] Circle(Normal = Vector(X =
    [5] Circle(Normal = Vector(X =
    [6] Circle(Normal = Vector(X =
    [7] Circle(Normal = Vector(X =
    [8] Circle(Normal = Vector(X =
  [1] List
    [0] Circle(Normal = Vector(X =
    [1] Circle(Normal = Vector(X =
    [2] Circle(Normal = Vector(X =
    [3] Circle(Normal = Vector(X =
    [4] Circle(Normal = Vector(X =
```

Figure 2.21 – Typical Dynamo workflow [18]

In the development of this work, it was resorted the use of MS Excel as mean to design slab reinforcements, for it is the Dynamo's duty to convert the data related into Revit elements. This choice of workflow allows a control over the calculations and, consequently, of reinforcement selection within Excel, in ways Revit is still not capable of doing. Besides storing most information in Excel, this option releases the need for a heavy Dynamo routine containing all calculations and conditional formatting involved in reinforcement design. This brings augmented information control with the creation of intertwined and systematic relations between model elements and its easy alteration through Excel, hardly possible with the conventional Dynamo and Revit tools.

It is important to stress that Dynamo is still relatively new in the market and it is constantly detecting and eliminating the most worrying problems/bugs as well as implementing new functionalities to the software. These constant updates assure corporations to the use of Dynamo and take them to explore all of its potentialities, even though, with its current state, structural engineers can take advantage of next to endless possibilities to substitute a significant workload [17].

2.2.7 BIM in the World

In Portugal it is up to the engineering company to decide at which stage of the life-cycle of a building to apply the BIM methodology however in some countries its implementation is already mandatory by legislation. [28] The United States of America have several organizations and universities that come out with many norms publications, most notably the National BIM Standard (NBIMS) while in Europe the BIM advocates are the Scandinavian countries. Finland, with the Common BIM Requirement 2012 (COBIM) norm, and Norway, with the Statsbygg Building Information Modeling Manual of 2012, show great commitment in converting the use of this methodology in numerous processes [25].

Evidently, in order to develop a good and sustainable BIM practice it is necessary, not only the access to good hardware and software, but also grant the workers with the needed training. All the BIM advantages are slowly overshadowing the disadvantages as the symbiotic use of this methodology is increasingly taking place by all project parties.

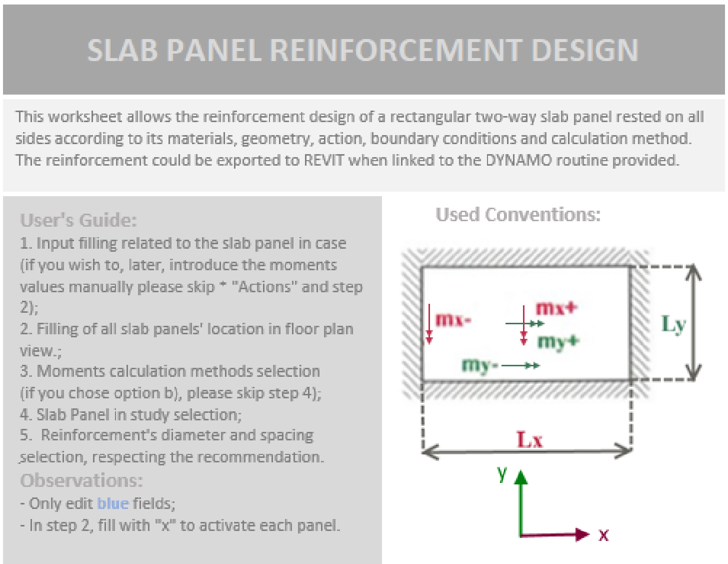
CHAPTER 3

REINFORCEMENT DESIGN PLATFORM

This chapter concerns the presentation and intricacies of the developed MS Excel worksheet for reinforcement design. It resorts to macros as well as general cell programming and constitutes the core of the associated Dynamo program, calculating the necessary reinforcement for any given rectangular two-way slab rested on beams on all sides. Rebars are reproduced in the 3D models by reading diameters, lengths, distribution, quantity and location in Excel. All these parameters are automatically generated according to the data of the slab regarding its materials, geometry, actions, boundary conditions and calculation methods.

The programmed spreadsheet is constituted by 13 internal sheets, 3 of which are editable and directed at the user in order to collect the necessary data needed to generate a reinforcement solution. The remaining 10 sheets tie in the input treatment and intermediate calculations.

The opening sheet presents firstly an introductory section, seen in Figure 3.1, that clarifies the functionalities and limitations of the program and its outputs, as well as a brief user's guide, divided in five steps, some observations to have in consideration, the bending moments convention used in the worksheet, and, finally, an indication of the slab borders designations.



SLAB PANEL REINFORCEMENT DESIGN

This worksheet allows the reinforcement design of a rectangular two-way slab panel rested on all sides according to its materials, geometry, action, boundary conditions and calculation method. The reinforcement could be exported to REVIT when linked to the DYNAMO routine provided.

User's Guide:

1. Input filling related to the slab panel in case (if you wish to, later, introduce the moments values manually please skip * "Actions" and step 2);
2. Filling of all slab panels' location in floor plan view.;
3. Moments calculation methods selection (if you chose option b), please skip step 4);
4. Slab Panel in study selection;
5. Reinforcement's diameter and spacing selection, respecting the recommendation.

Observations:

- Only edit blue fields;
- In step 2, fill with "x" to activate each panel.

Used Conventions:

Figure 3.1 – Opening sheet extract

The sheet is prepared to receive structural analysis through the direct and indirect methods mentioned in 2.1.2., for the steps depicted in the user's guide will determine the workflow of the Excel program itself. The user guide reads:

1. *Input filling related to the slab panel in case (if you wish to, later, introduce the moments values manually please skip * "Actions" and step 2);*
2. *Filling of all slab panels' location in floor plan view.;*
3. *Moments calculation methods selection (if you chose option b), please skip step 4);*
4. *Slab Panel in study selection;*
5. *Reinforcement's diameter and spacing selection, respecting the recommendation.*

It is important to stress the slab convention used in the worksheet (Figure 3.2). Usually the Lx and Ly side of a rectangular two-way slab tends to distinguish the larger from the smaller span, regardless of slab orientation. However, in the worksheet, the formulas and calculations are programmed to consider that the Lx edge refers to the side parallel to the X axis and the Ly to the Y axis.

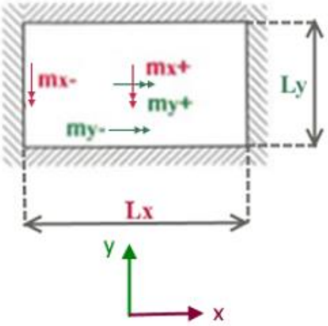
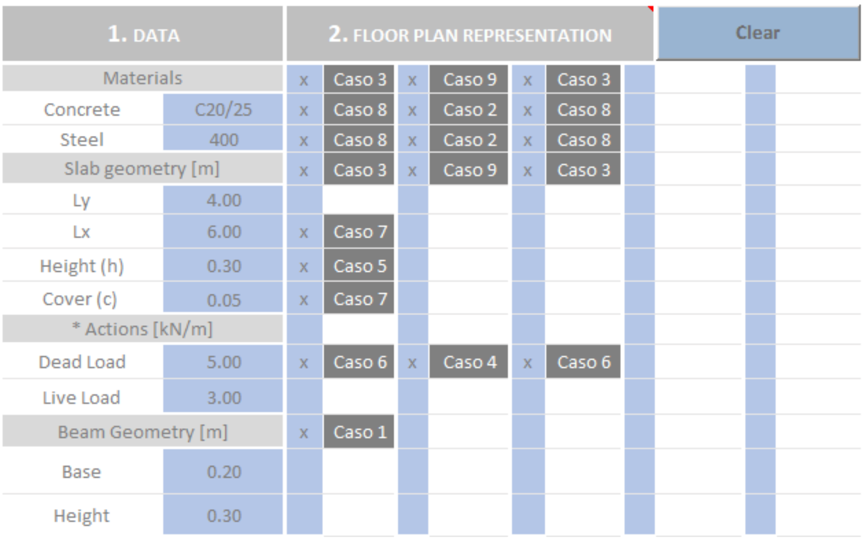


Figure 3.2 – Bending moments, edge and axes convention

It is of significant importance the acknowledgement of the color scheme featured in the worksheet as well as in the Dynamo program, since it provides a simpler user interaction. The user can only edit and/or click on the blue fields, being that the grey toned ones are not to be interfered with. The pink and green elements are linked to all the data and information that concerns reinforcement parallel to the Lx and Ly slab border, respectively.

3.1 SLAB DATA GATHERING

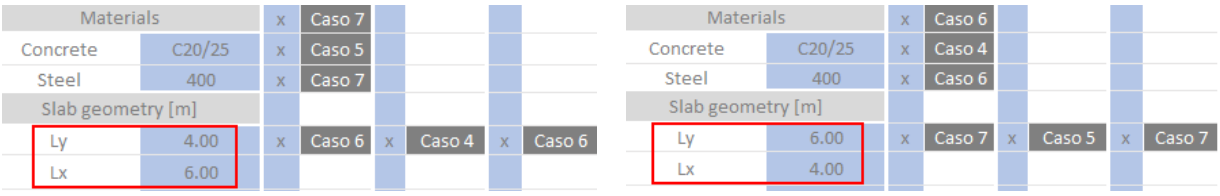
Succeeding the introductory section, and still in the opening spreadsheet, the first two steps featured in the user's guide take place with the title of "Data" and "Floor Plan Representation". The first has, as its objective, the material, geometry and actions definition related to the slab panel in study, as well as its beams' geometry. The second step represents, schematically, the quantity and relative location of panel slabs through Excel cell activation, symbolic of the slab panels themselves.



1. DATA		2. FLOOR PLAN REPRESENTATION						Clear
Materials		x	Caso 3	x	Caso 9	x	Caso 3	
Concrete	C20/25	x	Caso 8	x	Caso 2	x	Caso 8	
Steel	400	x	Caso 8	x	Caso 2	x	Caso 8	
Slab geometry [m]		x	Caso 3	x	Caso 9	x	Caso 3	
Ly	4.00							
Lx	6.00	x	Caso 7					
Height (h)	0.30	x	Caso 5					
Cover (c)	0.05	x	Caso 7					
* Actions [kN/m]								
Dead Load	5.00	x	Caso 6	x	Caso 4	x	Caso 6	
Live Load	3.00							
Beam Geometry [m]		x	Caso 1					
Base	0.20							
Height	0.30							

Figure 3.3 – Step 1 and 2 of the Excel Program

This activation, achieved with the insertion of the letter "x" in the blue cells, as indicated in "Observations" in the introductory section, creates a gray cell on its right side, with its boundary conditions case ("Caso" in Portuguese) written on it, with the same number setup indicated in Figure 2.1. These suggested cases, as explained before, consider all the predicted borders continuity conditions, including the border dimension itself. Considering the axis and edge convention used in the worksheet and the definition of the Lx and Ly in the first step "Data", their relative dimensions influences the automatic case establishment as can be more clearly seen in Figure 3.4 below.



Materials		x	Caso 7				
Concrete	C20/25	x	Caso 5				
Steel	400	x	Caso 7				
Slab geometry [m]							
Ly	4.00	x	Caso 6	x	Caso 4	x	Caso 6
Lx	6.00						

a) If Ly<Lx

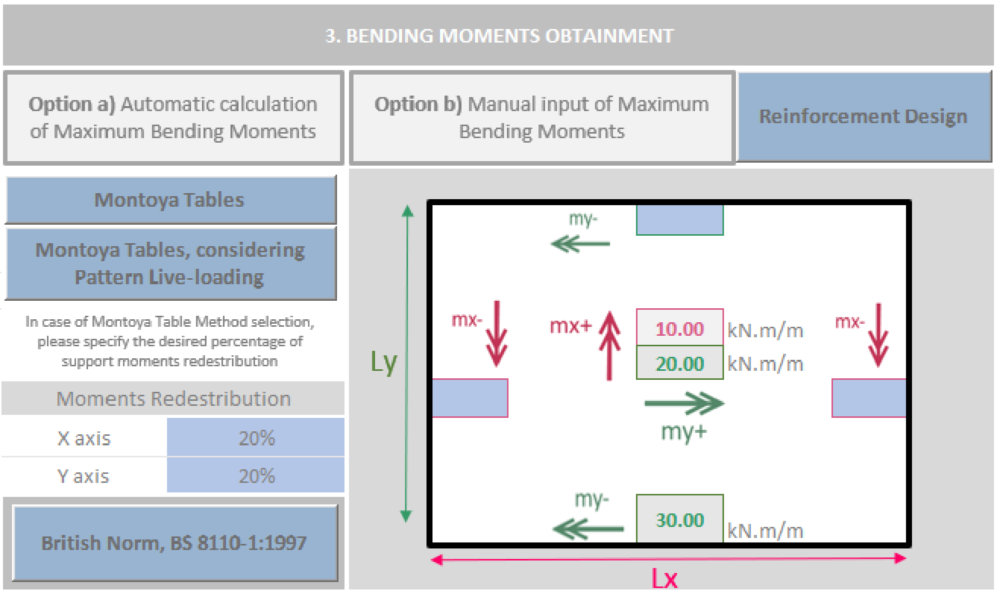
Materials		x	Caso 6				
Concrete	C20/25	x	Caso 4				
Steel	400	x	Caso 6				
Slab geometry [m]							
Ly	6.00	x	Caso 7	x	Caso 5	x	Caso 7
Lx	4.00						

a) If Ly>Lx

Figure 3.4 – Boundary Cases dependent on Lx and Ly definition

3.2 STRUCTURAL ANALYSIS

The last step within the initial spreadsheet is designated as "Bending Moments Obtainment" and splits itself into two options a*) Automatic calculation of maximum Bending Moments* and *b) Manual input of maximum Bending Moments,* as Figure 3.5 shows.



In case of Montoya Table Method selection, please specify the desired percentage of support moments redestribution

Moments Redestribution	
X axis	20%
Y axis	20%

10.00 kN.m/m
20.00 kN.m/m
30.00 kN.m/m

Figure 3.5 – Step 3 of the Excel Program

3.2.1 Ultimate Limit State

Both methods use the Ultimate Limit State featured in Eurocode 0 to obtain the resulting bending moments values.

ULS is a type of actions combination related to collapse, or any type of structural routine, which determines the incapacity for structure use. The application of this method to a structure design grants a margin of error for the structural resistance to the applied loads. Its verification guarantees that the resistant forces of a certain structural element are larger than the characteristic values induced by the applied loads thus providing a necessary safety margin.

The design applied forces are obtained through fundamental action combination based on safety coefficients suggested by EC2. The fundamental combination used in the present work has, as the main load, the live load, in agreement with following equation

$$E_d = \gamma_G \times G_k + \gamma_{Q,1} \times Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \times \psi_{0,i} \times Q_{k,i} \tag{3.1}$$

With:

γ_G –Partial factor for permanent actions;

G_k – Permanent actions characteristic value;

$\gamma_{Q,1}$ –Partial factor for variable action 1;

$Q_{k,1}$ –Characteristic value of the leading variable action 1;

$Q_{k,i}$ –Characteristic value of the accompanying variable action i;

$\psi_{0,i}$ –Factor for combination value of a variable action i.

3.2.2 Automatic calculation of maximum Bending Moments

On the worksheet option a) has a process of bending moments obtainment based on the published tables of Pedro Jiménez Montoya et al in his work "Hormigón Armado" [9], followed by its adaptation for the case of pattern live loading, in addition to tables of the British norm BS 8110-1:1997 – "Structural use of concrete" [10]. This option contains three macro-programmed buttons, one for each of the calculation methods specified, as well as an editable field.

Montoya Tables

The "Montoya Tables" button runs a macro that retributes all moments resulting from the Montoya's tables in relation to the boundary cases set in step 2, redistributes the maximum bending moments according to the indicated percentage and recurs to negative bending moments compatibility on neighbor panels, if needed.

To make the excel worksheet fully automatic Montoya's tables were also programmed into it. All values from the original tables were copied into a worksheet to obtain an identical table in digital format.

As explained in 2.1.2.1, the Montoya table interpretation requires the division of the dimension value of the shortest span divided by the longest span, as well as the identification of the slabs boundary cases to get an intermediate coefficient. This sides ratio, in the original tables, are set for 0,5, 0,6, 0,7, 0,8, 0,9 and 1. However this approximation does not grant an exact value of the division nor of its correspondent coefficient. Usually structural engineers take advantage of a linear approach to obtain a final coefficient with more decimal places and not restricted by the six possibilities in the Lx/Ly columns. This approach was reproduced in the worksheet to acquire a bending moment value as approximate as possible to reality. Therefore, the introduction of values for Lx/Ly were approximated to the second decimal place, and the resulting coefficients to the first decimal place. This resulted in a table with fifty Lx/Ly factors for the four types of moments, Mx+, My+, Mx- and My- for each of the 9 boundary cases.

The negative moments redistribution is set manually, in the two available editable cells, since its verification is the user responsibility according to his choice of the applicable norms. Excel will not issue any warning or verify any values and will conduct the calculations either the percentage is adequate or not.

The redistribution field regards the percentage value of the negative moments redistribution the user wishes to apply in the x and y axes, which influence the Mx- and My- values, respectively.

Montoya Tables, considering Pattern Live-Loading

This button runs the calculations of both positive and negative maximum moments according to the description in 2.1.2.1, redistribute the negative ones according to the percentage specified and, if necessary, proceeds to the compatibilization of the negative moments.

British Norm, BS 8110:1997

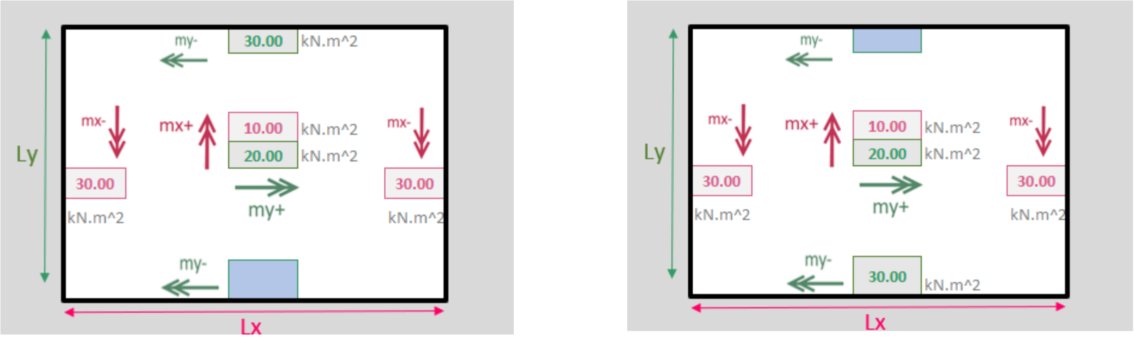
The programming of the British norms tables concerning the obtainment of maximum bending moments in rectangular two -way slabs was aided by an existing separate worksheet within Newton – Consultores de Engenharia office. The said worksheet took the values suggested by the standard and developed several polynomial regressions, one for each boundary case and moment type.

The macro associated with this button is similar to the last two, with the main different of not resorting to the redistribution of the support moments, it only runs the compatibility routine as the last step of the macro.

3.2.3 Manual input of maximum Bending Moments

Worksheet option b) allows the user to manually introduce the slab panel maximum moments, when these are provided from structural analysis software, such as Robot, or others. Taking this into consideration, this second option renders the second step, “Floor Plan Representation”, irrelevant.

This option contains six editable cells, corresponding to the potential negative moments in each edge and the two positive main bending moments. The filling of the negative moments will not only dictate the boundary case applied to the slab as well as the continuity edge location. In other words, two panels can have the same boundary case but have continuity edges in different borders. Consequently, if the user fills a bending moment value on the right side there will be a continuity edge there and in due course a support reinforcement will be placed on the right side of the slab panel. This system of relative locations uses the terms “Left”, “Right”, “Up” and “Down” recurrently within the worksheet for it is needed to pinpoint and organize reinforcement zones. Exemplifying, if the boundary case number 9 (see Figure 2.1) is to be recreated through this method, there are two possibilities for negative bending moments values input, assuming that Lx is greater than Ly, shown in Figure 3.6.



a) – Continuity in the “Up” Edge b) – Continuity in the “Down” Edge

Figure 3.6 – Example of the reproduction of case 9 boundary case for a slab panel

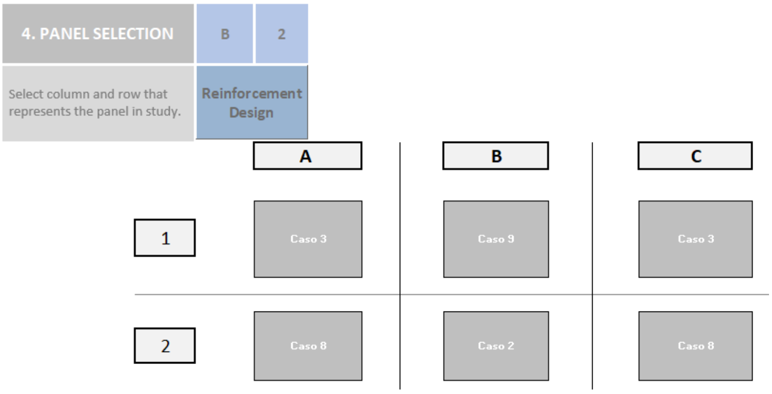
By filling the negative moments fields, the user should not use the negative sign before the value, for the program is only prepared to deal with positive values and will malfunction otherwise.

Once every bending moment is filled in to recreate a particular slab the user should “press” the command button “Reinforcement Design”, just above the slab panel representation, that will redirect the worksheet to the fifth step on the user’s guide, once the moments values are set.

3.3 SLAB SELECTION

In case option a) was chosen, the selection of one of the three buttons conducts the program to a new sheet within Excel, towards the fourth step “Panel Selection”, seen in Figure 3.7, which allows the selection of one of the panels generated in the second step.

Such panels declared in “Floor Plan Representation” are here represented by a set of merged cells with its boundary case written on it. The layout is organized by a grid system, represented by letters on the X axis and numbers on the Y axis, used to pinpoint the slab panel the user wishes to study. By clicking the button “Reinforcement Design”, the program will redirect the program to the third spreadsheet and last step of the program.


4. PANEL SELECTION

Select column and row that represents the panel in study.

Figure 3.7 – Step 4 of the Excel Program

3.4 REINFORCEMENT INTERFACE

The fifth and final step in the user's guide, called "Reinforcement Selection" provides handpicked options for reinforcement zones guided by design values for all reinforcement zones in a two-way rectangular slab. The user's decisions are limited to diameter and spacing selection for each reinforcement zones, meaning the user has no interference in what concerns rebar placement and quantity. Such decisions can be converted into a 3D model, if the provided Dynamo routine is applied to an existing Revit Model.

Bellow a comprehensive overview of the thought process and applied regulations in the development of this step is presented.

3.4.1 Reinforcement Design

All reinforcement design, regardless of reinforcement zone, go through an initial treatment of transforming bending moments values into areas of reinforcement steel and finally, into reinforcement solutions. This process, in the present work was aided by the verification of the Limit State Design for Bending suggested by EC2. [40]

As mentioned before, two-way slabs suffer and deform from applied bending forces. In order to apply the Limit State Design for Bending and determine the resistance of sections, one needs first to assume the following hypothesis:

- Plane sections remain plane
- Tensile strength of concrete is ignored
- Limit state design is reached when one of the below conditions verify:
    - $\varepsilon_c = 3{,}5‰$
    - $\varepsilon_s = \varepsilon_{ud}$

To solve the bending impact on a slab, EC2 suggests the application of the stress distribution diagram, presented in article 3.1.7 of EC2; however for simplicity and familiarity with the method, such diagram was simplified to a rectangular stress distribution diagram, seen in Figure 3.8.

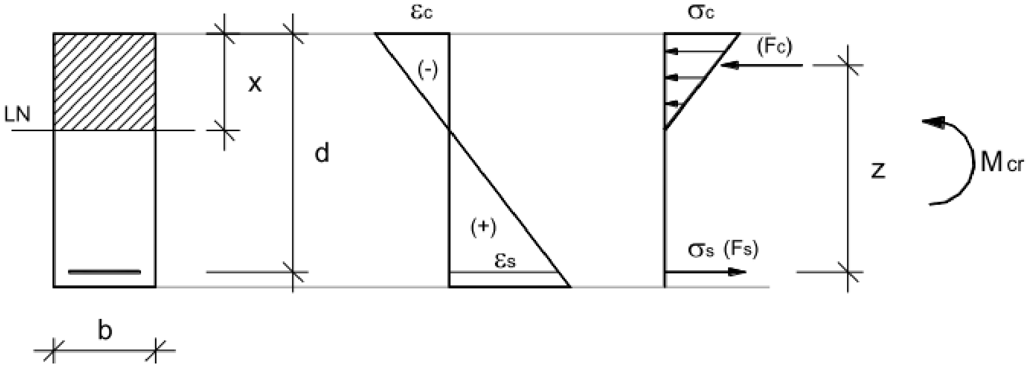


Figure 3.8 -Simplified Rectangular stress distribution for concrete up to class C50/60 [41]

Taking this hypothesis and applying its concepts, the following equation system depicts the section balance.

$$\begin{cases} \sum F = 0 \\ \sum M = 0 \end{cases} \Leftrightarrow \begin{cases} F_c - F_s = 0 \\ M_{rd} = F_c \times z \end{cases} \tag{3.2}$$

with:

F_c— Concrete Force;

F_s— Steel Force;

M_{rd} — Bending Moment.

The reduced bending moment controls the neutral axis depth (x) and is defined by the following mathematical formula.

$$\mu = \frac{M_{ed}}{b \times h^2 \times f_{cd}} \tag{3.3}$$

With:

μ – Reduced bending moment;

M_{ed} - Design value of the applied internal bending moment;

b - Overall width of a cross-section;

h - height;

f_{cd} — Design value of concrete compressive strength.

The bending moment value is calculated or filled-in in step 3, depending on the reinforcement zone in study. Considering reinforcement slabs are designed per meter, b takes the value of 1, while the height and concrete class, that f_{cd} depends on. In the same conjuncture of keeping the program as automatic as possible, f_{cd} values were programmed as well as f_{cm}, f_{ctm} and ε_{cm}, needed in future calculations, for concrete classes from C12/15 all the way up to C90/105.

Next step on the calculation process is the determination of the reinforcement mechanical percentage, that can be obtained through a formula developed by Júlio Appleton [42].

$$\omega = \frac{1 - \sqrt{1 - 2{,}42 \times \mu}}{1{,}21} \tag{3.4}$$

ω – Reinforcement Mechanical Percentage;

μ – Reduced Bending Moment.

Finally, to calculate the design area of reinforcement, the following expression was used.

$$A_S = \frac{\omega \times b \times h \times f_{cd}}{f_{yd}} \tag{3.5}$$

With:

ω – Reinforcement quantity;

A_s – Reinforcement Cross sectional area;

f_{yd} - Reinforcement design yield strength;

f_{cd} — Concrete compressive strength design value;

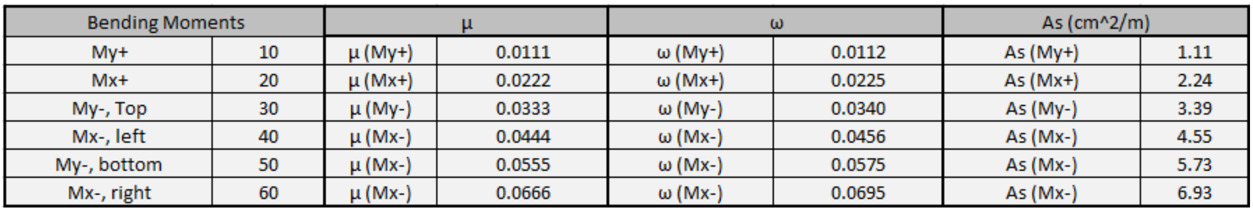
b - Overall width of the cross-section;

h - height.

The f_{yd} value also depends on the user input in “Data”, for its value depends on the steel class and was adequately programmed in the worksheet, along with the steel’s ε_s, needed in future calculations within the worksheet.

The last three formulas were manually introduced in the worksheet to retrieve each area of reinforcement correspondent to each defined maximum bending moment, as seen in Table 3.1.

Table 3.1 - Calculation in MS-Excel of the areas of reinforcement



Bending Moments		μ		ω		As (cm^2/m)	
My+	10	μ (My+)	0.0111	ω (My+)	0.0112	As (My+)	1.11
Mx+	20	μ (Mx+)	0.0222	ω (Mx+)	0.0225	As (Mx+)	2.24
My-, Top	30	μ (My-)	0.0333	ω (My-)	0.0340	As (My-)	3.39
Mx-, left	40	μ (Mx-)	0.0444	ω (Mx-)	0.0456	As (Mx-)	4.55
My-, bottom	50	μ (Mx-)	0.0555	ω (Mx-)	0.0575	As (Mx-)	5.73
Mx-, right	60	μ (Mx-)	0.0666	ω (Mx-)	0.0695	As (Mx-)	6.93

To achieve a comparation method between reinforcement solutions and area of reinforcement values within the Excel worksheet, it was needed to define some reinforcement types. These are defined as result of a combination of six different rebar diameters and nine spacing lengths, as shown in Table 3.2.

Table 3.2 – List of Rebar Diameters and Spacing used

Rebar Diameter [mm]	Spacing [m]
6	0.1
8	0.125
10	0.15
12	0.175
16	0.2
20	0.225
-	0.25
-	0.275
-	0.3

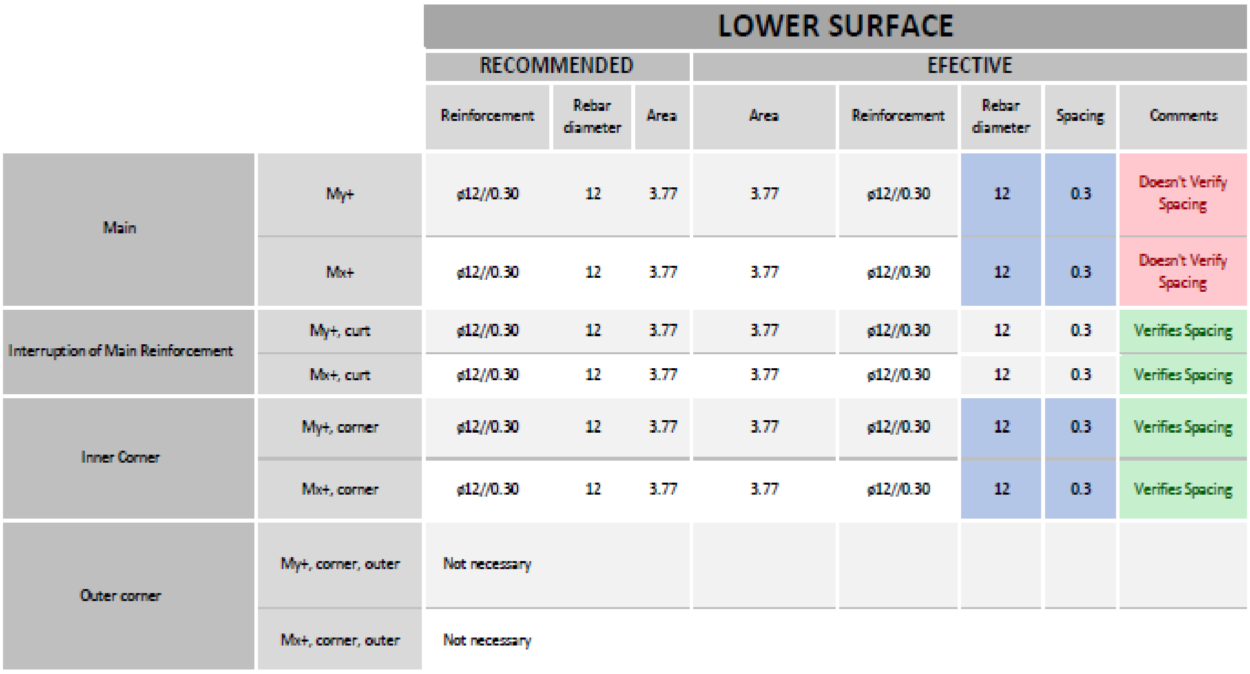
The area that each rebar, spaced at a given distance, occupies in a square meter is the parameter the program uses to determine which reinforcement type is the first to comply the design value.

The design value differs from reinforcement zone, for some are regulated by strict standards and other are defined by practical rules.

3.4.1.1 Lower Surface Reinforcement

The lower surface reinforcement responds to and contradicts positive moments within a given slab. it is usually constituted of two distinct reinforcement zones: the main positive reinforcement and the corner reinforcement. While the main reinforcement is always represented regardless of the boundary case, the corner reinforcement depends on the continuity edges, for it may not be place at all or it can be placed on four corners of the slab.

Figure 3.9 shows the layout for the selection table of the lower surface reinforcement, divided by rows for all the reinforcement zones, and by columns on the recommended and effective values.



		LOWER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	My+	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Doesn't Verify Spacing
	Mx+	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Doesn't Verify Spacing
Interruption of Main Reinforcement	My+, curt	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
	Mx+, curt	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
Inner Corner	My+, corner	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
	Mx+, corner	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
Outer corner	My+, corner, outer	Not necessary							
	Mx+, corner, outer	Not necessary							

Figure 3.9 – Selection table for the reinforcements of the Lower Surface

Just for the lower surface as for the upper one, the program specifies the recommended reinforcement solution through calculations made in reinforcing design. The reinforcement design itself is not made directly in the present spreadsheet but in a separate one within the same worksheet, for the table is simply a condensed interface to show final results.

According to article number 9.3.1 from EC2, the main positive reinforcement, as well as its interruption, and corner reinforcement must be designed to meet minimum and maximum areas of reinforcement and maximum spacing. Guided by these rules, the following four formulas were programmed into the worksheet.

Minimum area of reinforcement

$$A_{S,min} \geq \begin{cases} 0{,}26 \times \dfrac{f_{ctm}}{f_{yk}} \times b_t \times d \\ 0{,}0013 \times b_t \times d \end{cases} \tag{3.6}$$

With:

$A_{S,\mathrm{min}}$ - minimum cross-sectional area of reinforcement;

$\mathrm{b_t}$ - denotes the mean width of the tension zone;

f_{ctm} - Mean value of axial tensile strength of concrete;

f_{yk} - Characteristic yield strength of reinforcement;

d - Effective depth of a cross-section.

Maximum area of reinforcement

$$A_{S,max} = 0{,}04 \times Ac \tag{3.7}$$

with:

$A_{S,\max}$ - Maximum cross-sectional area of reinforcement;

Ac - Cross-sectional area of concrete.

Maximum Spacing for main reinforcement

$$S_{max,slabs} \leq \begin{cases} 2 \times h \\ 250\ mm \end{cases} \tag{3.8}$$

with:

$S_{max,slabs}$ – Maximum spacing in slabs;

h – Height.

Maximum Spacing for secondary reinforcement

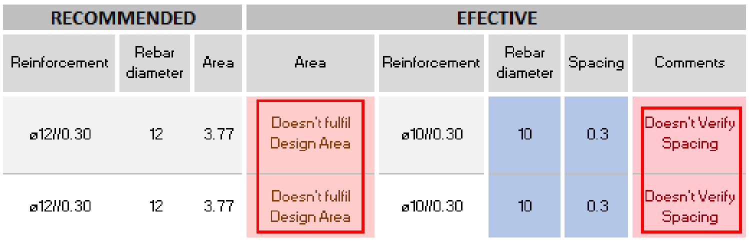
$$S_{max,slabs} \leq \begin{cases} 3 \times h \\ 400\ mm \end{cases} \tag{3.9}$$

with:

$S_{max,slabs}$ – Maximum spacing in slabs;

h – Height.

The program runs the formulas and returns the first programmed reinforcement type, solely, to fulfill the design reinforcement area. Having this said the design reinforcement solutions found do not have in consideration other type of criteria, for example diameter uniformity or maximum spacing, only conferring the minimum and maximum areas. Consequently, the recommended reinforcement type is not always suited for practical and everyday construction, resulting in the implementation of the "Effective" columns in the reinforcement selection tables. In two of the columns the user can choose the effective reinforcement through the selection of rebar diameters and spacing, provided its area is equal or greater than the recommended one. By default, the program always adopts the recommend reinforcement type, therefore it is the user responsibility to choose a reinforcement type that complies both with the design values and the maximum spacing. The selection is facilitated by written warnings in the same table, as those shown in Figure 3.10.



RECOMMENDED			EFECTIVE				
Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
ø12//0.30	12	3.77	Doesn't fulfil Design Area	ø10//0.30	10	0.3	Doesn't Verify Spacing
ø12//0.30	12	3.77	Doesn't fulfil Design Area	ø10//0.30	10	0.3	Doesn't Verify Spacing

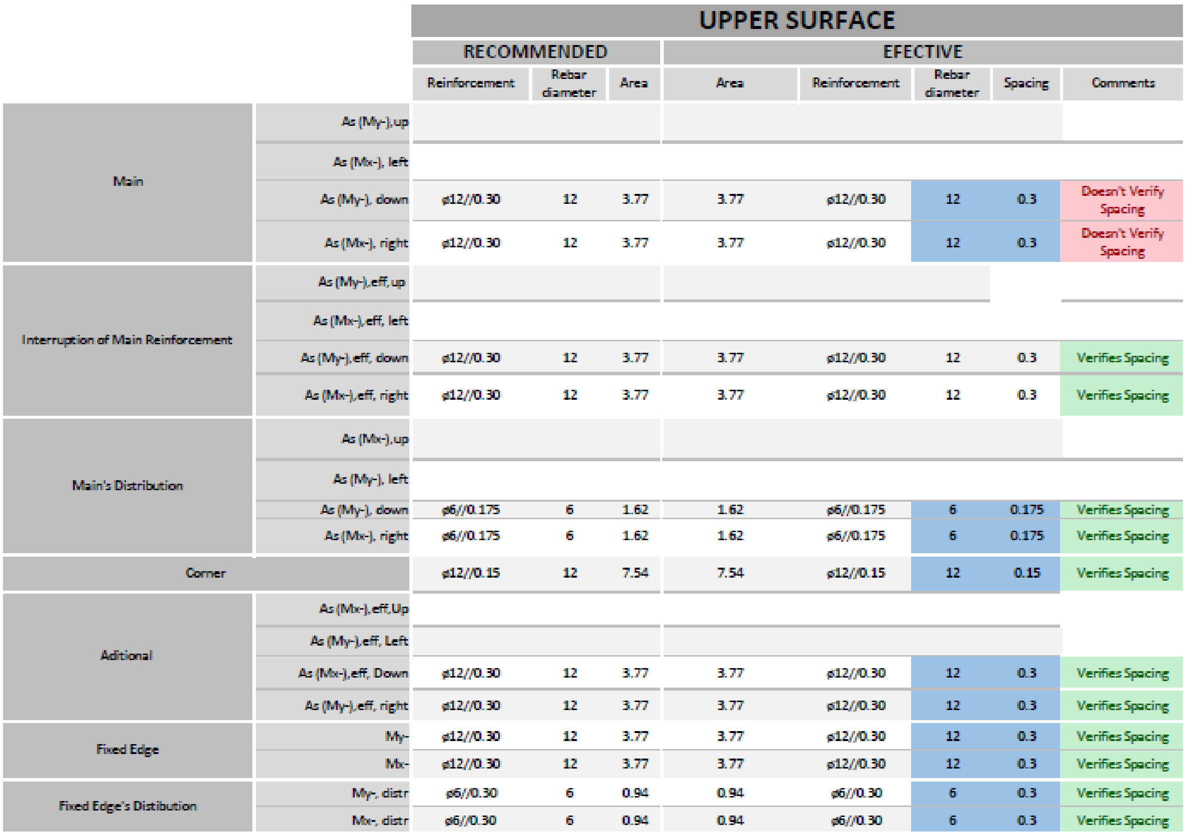
Figure 3.10 – Written warnings about Design Area of Reinforcement and Maximum Spacing

The interruption zone of the main positive reinforcement is not editable in the table, since the program assumes the same reinforcement type as the main reinforcement. This is because both reinforcement zones, main and interruption, are modelled as separate even though they are distributed through the same central panel zone. Keeping in mind that the interruption zone is programmed to have half the area of reinforcement steel of the main one, the overlap zone contains the right area designed for the main reinforcement zone.

3.4.1.2 Upper Surface Reinforcement

The upper surface reinforcement mainly resists the negative bending moments in a slab. Usually it has more reinforcement zones than the lower surface's, with more intricate details and design calculations.

The Excel table represented in the Figure 3.11 contains all the potential reinforcement zones in the upper surface of a two-way slab.



		UPPER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	As (My-),up								
	As (Mx-), left								
	As (My-), down	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Doesn't Verify Spacing
	As (Mx-), right	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Doesn't Verify Spacing
Interruption of Main Reinforcement	As (My-),eff, up								
	As (Mx-),eff, left								
	As (My-),eff, down	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
	As (Mx-),eff, right	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
Main's Distribution	As (Mx-),up								
	As (My-), left								
	As (My-), down	ø6//0.175	6	1.62	1.62	ø6//0.175	6	0.175	Verifies Spacing
	As (Mx-), right	ø6//0.175	6	1.62	1.62	ø6//0.175	6	0.175	Verifies Spacing
Corner		ø12//0.15	12	7.54	7.54	ø12//0.15	12	0.15	Verifies Spacing
Aditional	As (Mx-),eff,Up								
	As (My-),eff, Left								
	As (Mx-),eff, Down	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
	As (My-),eff, right	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
Fixed Edge	My-	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
	Mx-	ø12//0.30	12	3.77	3.77	ø12//0.30	12	0.3	Verifies Spacing
Fixed Edge's Distibution	My-, distr	ø6//0.30	6	0.94	0.94	ø6//0.30	6	0.3	Verifies Spacing
	Mx-, distr	ø6//0.30	6	0.94	0.94	ø6//0.30	6	0.3	Verifies Spacing

Figure 3.11 – Selection table for the reinforcements of the Upper Surface

The main negative reinforcement, or support reinforcement, as well as its respective interruption and corner reinforcements of the upper surface follow the same verifications as the lower surface main and corner reinforcements.

According to EC2's article 9.3.1.1 (2) the distribution reinforcements are considered secondary reinforcements and they should respect the maximum spacing depicted in equation 3.9, while its design must meet at least 20% of the reinforcement it corresponds to.

Both the additional reinforcement zones and fixed edge reinforcement design verification are suggested by Montoya [9], and completed with the EC2. The additional reinforcement must have at least the same area as the larger main positive reinforcement, while the fixed edge reinforcement must meet at least 15% of the area of the main positive reinforcement on the same direction. Through EC2 standards, these may be considered secondary reinforcements as it was decided and programmed that they shall meet the maximum and minimum area of reinforcement and maximum spacing set in equation 3.9.

The following table describes all the EC2 verifications made in the present work.

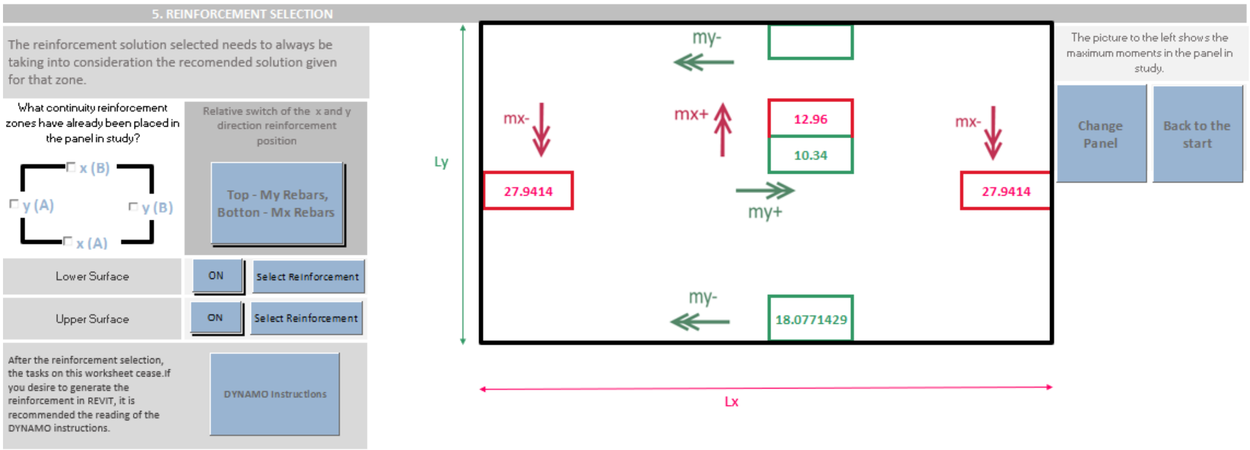
Table 3.3 – EC2 Verifications made in both upper and lower surfaces' reinforcement zones

	Equation 3.6	Equation 3.7	Equation 3.8	Equation 3.9
Main Reinforcement / Support Reinforcement	✓	✓	✓	✗
Corner reinforcement	✓	✓	✗	✓
Additional Reinforcement	✓	✓	✗	✓
Fixed Edge Reinforcement	✓	✓	✗	✓
Distribution Reinforcement	✗	✗	✗	✓

All these limitations are also set as formulas in the worksheet as to give a guideline for which reinforcement type to choose. Observing Figure 3.11, some rows are blank; these are all the reinforcement zones that are not applicable to the slab panel in study, wherefor its forced implementation in the "Effective" columns are not encouraged. This action can bring the program to malfunction and furthermore the reinforcement will not be converted to the 3D Revit model, if attempted.

3.4.2 Additional functionalities

Apart from the reinforcement selection tables, the last step of the Excel program contains a schematic representation of the panel being studied with the maximum bending moments values, as well as a few command and toggle buttons that aid the reinforcement modelling in Revit through Dynamo, all seen in Figure 3.12.



The reinforcement solution selected needs to always be taking into consideration the recomended solution given for that zone.

What continuity reinforcement zones have already been placed in the panel in study?

Relative switch of the x and y direction reinforcement position

After the reinforcement selection, the tasks on this worksheet cease.If you desire to generate the reinforcement in REVIT, it is recommended the reading of the DYNAMO instructions.

The picture to the left shows the maximum moments in the panel in study.

Figure 3.12 – Partial interface of Step 5 "Reinforcement Selection"

In the middle of the interface there is the schematic representation of the slab, with the bending moments originating from manual or automatic structural analysis. On its right side there are two command buttons with the options to change panels or restart the program from the beginning.

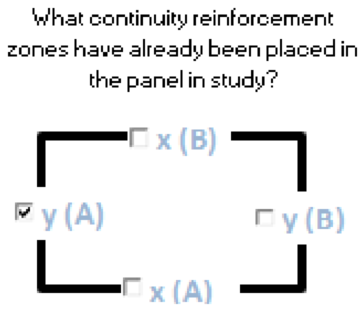
On the far left of the interface there's an introductory text box with some indications about the present step and two fields that help avoid rebar intersection within Revit. Below follow options to either turn on and off the upper and lower reinforcements of the slab in the 3D model and redirecting buttons to the reinforcement selection tables. To finish, a button will redirect the user to a spreadsheet with some indications for the correct utilization of the developed Dynamo routine.

Rebar overlapping

Since the paramount purpose of the development of the worksheet at hand is rebar representation on the software Revit, and having the possibility to reinforce neighbor slab panels, the second and so forth run of the Dynamo program might bring overlapping rebar problems in continuity zones within the Revit model.

The overlapping of negative moments reinforcement in the continuity region is a reality, for each slab panel is modeled individually, and there is only one support reinforcement zone between neighbor panels. Under this circumstances, it was developed a system that restrains said rebars to be represented in the 3D model, in case these already exist.

This system consists in recognizing the existing reinforcement in terms of relative location through manual filing of four check boxes. To exemplify, considering the panels represented in Figure 3.7, if the A1 panel is already fully reinforced in the Revit model, in the midst of reinforcing the B1 panel, it is necessary the activation of the checkbox marked as "y (A)", as shown in Figure 3.13.



What continuity reinforcement zones have already been placed in the panel in study?

☐ x (B)

☑ y (A)

☐ y (B)

☐ x (A)

Figure 3.13 – Support Reinforcement zones Check Boxes

Additionally, and to also avoid rebar overlapping, now of the positive reinforcement bars, it was introduced a Toggle button that switches the relative position of rebars along the x and y axes in height.

In continuity edge zones the positive main reinforcement bars are extended beyond the beam's edge about 20 cm. Considering that both main lower reinforcements of neighbor slabs extend beyond its continuity edge, they might overlap in that zone; as this overlapping always happens with same direction rebars, switching the relative position between Mx+ and My+ main reinforcement would resolve the problem. To control the reinforcement position switch, it was introduced a toggle button in Excel, as seen in the following figure.

a) -My Rebars on top and Mx rebars on bottom

b) Mx Rebars on top and My rebars on bottom.

Figure 3.14 – Toggle button to switch main positive reinforcement relative positions

3.5 DATA SORTING AND ORGANIZATION

Once again, all these rules were programmed into the worksheet in order to give the user a guideline for which reinforcement to select as a final reinforcement solution. Once all the effective reinforcements are selected the activities in the Excel worksheet cease in the user's stand view.

Congruent to the user's inputs and choices, the program is prepared to calculate all the necessary data to the Dynamo routine. This data processing is compiled in a sheet called "Saída" (means "Output") and its information mostly concerns measurements and quantities needed to define reinforcement bars.

As a mean to standardize all the data, all calculations use a coordinate system with origin in the slab upper surface bottom left corner, with the X and Y axes parallel to the Lx and Ly borders, respectively, as seen in the Figure 3.15.

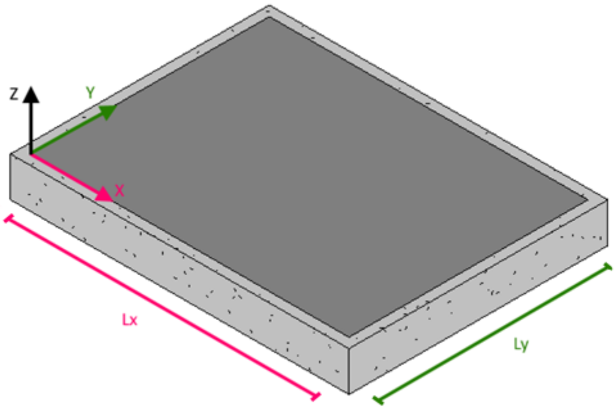


Figure 3.15 – Coordinate system used in Excel

CHAPTER 4

DYNAMO ROUTINE

The present chapter gathers the procedures made in the visual programming software Dynamo to transform Excel data into 3D reinforcement elements within Revit. The Dynamo routine will place the reinforcement elements provided the slabs are previously modeled and will run the routine as many times as needed in conformity with the Excel Worksheet. With this in mind, it is vital that a geometrical match between the study panel in Revit and the inputs made in Excel exists, as the Dynamo routine is not programmed to verify or compare any parameters between the two models, and it will run regardless of geometric inconsistencies.

During the development of the Dynamo routine it was noticed the built-in nodes did not have all the functionalities to grant the desired final purpose. In agreement with the spirit underlying the cooperative development of software subjacent to Dynamo and other new programming languages, it was decided that the best solution would be to resort to node packages developed by third parties. For the correct use of the routine, apart from the installation of Dynamo and Revit 2018 software, the user must download and install the following packages: “Beaker”, “BIM4Struct”, “Bumblebee” “Dynamo for Rebar” and “LunchBox”.

For the purpose of a simpler and more comprehensive reading of the program, the routine was divided into four major sections based on their functions, as presented in Figure 4.1. Still trying to follow the color scheme used in the Excel worksheet, the first section, with blue colored groups, is the only one the user can intervene in. The second group with gray groups are a set of general information that serves the remaining last two sections. The third section deals with the lower surface reinforcements while the fourth and last section perform calculations related with the upper surface reinforcements. Both these sections are divided, into green and pink groups of nodes, concerning the creation of My and Mx reinforcement, respectively.

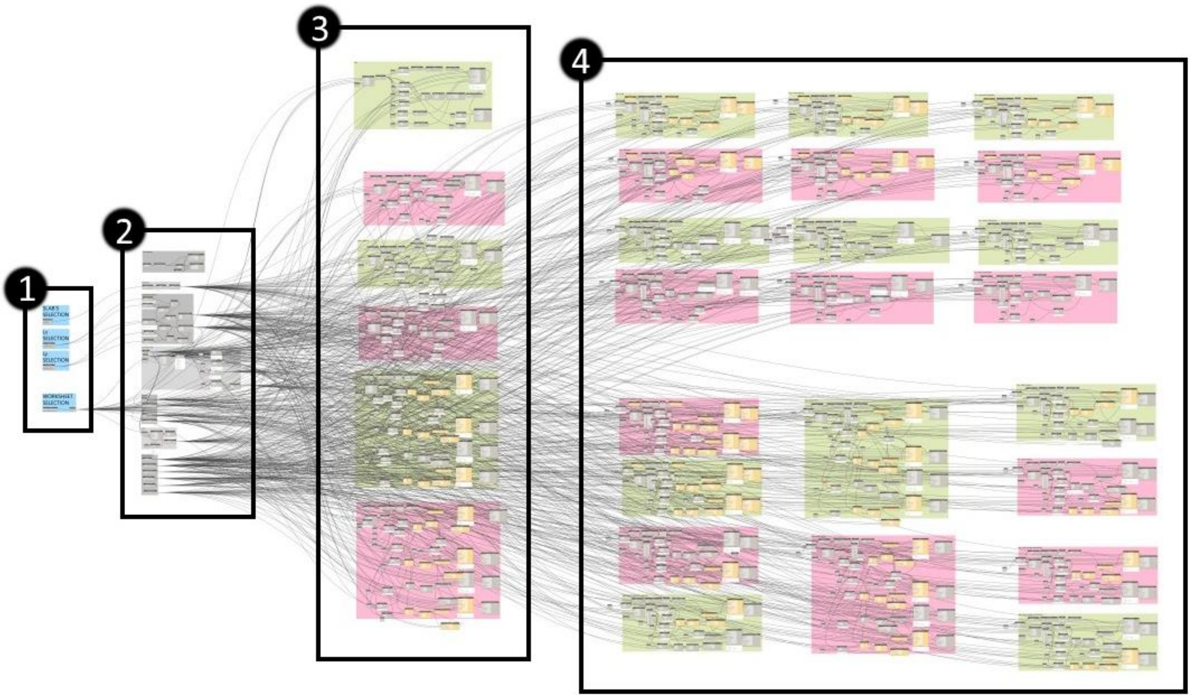


Figure 4.1 – Dynamo Routine layout

4.1 INPUT SECTION

First section is established by four groups with five nodes (Figure 4.2). One of the groups is used to determine the file path of the Excel spreadsheet, and the other three are the slab and borders selection nodes.

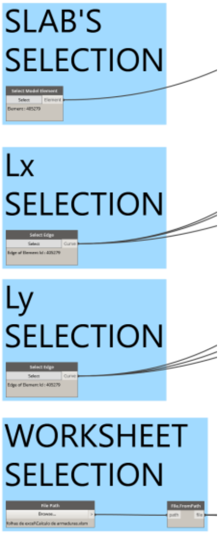
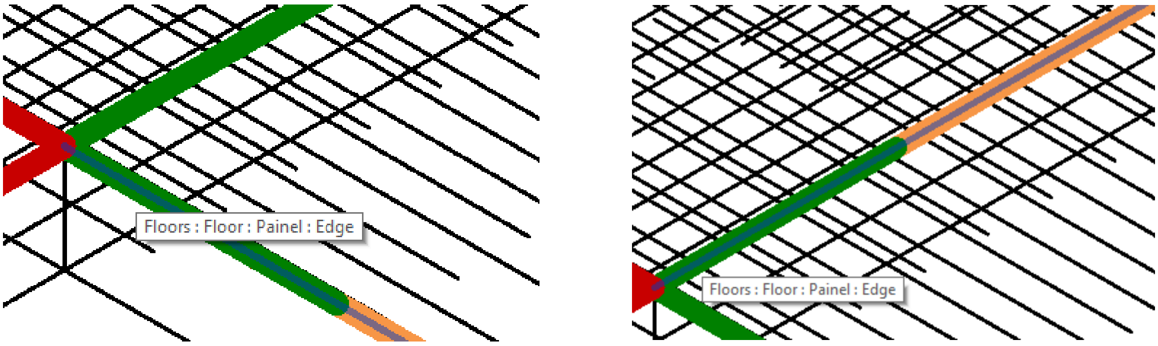


Figure 4.2 – Dynamo’s input section

The group named “Worksheet Selection” contains two nodes, one of them is purely responsible for the selection of the file path within the user’s computer, while the second one grants the user multiple runs of the program as long as the Excel File is saved. The panel selection node returns the Revit element ID, a necessary input of the rebar creation nodes, serving as a link between the rebars and its panel host. The remaining two nodes, the borders' selection nodes, are related to specific edges of the panel. It is important that the Lx and the Ly edges will correspond to the bottom Lx and the left Ly of the upper surface of the slab, as seen in Figure 4.3.



a) Lx Selection

b) Ly Selection

Figure 4.3 – Edge Selection

4.2 GENERAL DATA PROCESSING

The second section of the Dynamo routine prepares and summarizes information that will serve as repetitive inputs for reinforcement creation. Considering a single node output can be used as multiple nodes inputs, this section was isolated to take an efficient advantage of Dynamo's performance when processing systematic and repetitive data.

In this section there are seven groups of nodes that define:

1. The steel grade;
2. The concrete cover;
3. The reinforcement orientation;
4. Reinforcement and anchorage type;
5. Revit element ID of the slab;
6. New coordinate system definition;
7. Preservation guarantee of previously generated elements.

While the first five groups of nodes are relatively straightforward, reading and processing either Excel or user's input defined parameters, the last two are more intricate.

The new coordinate system definition is going to transpose the coordinate system used in the Excel worksheet to a new one within Revit, allowing a correct placement of the reinforcement bars, as schematically presented in Figure 4.4.

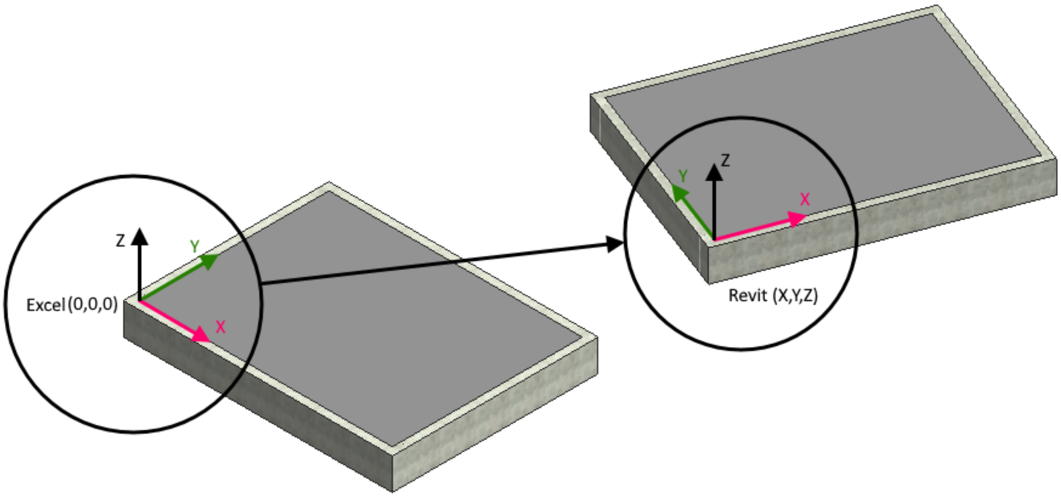


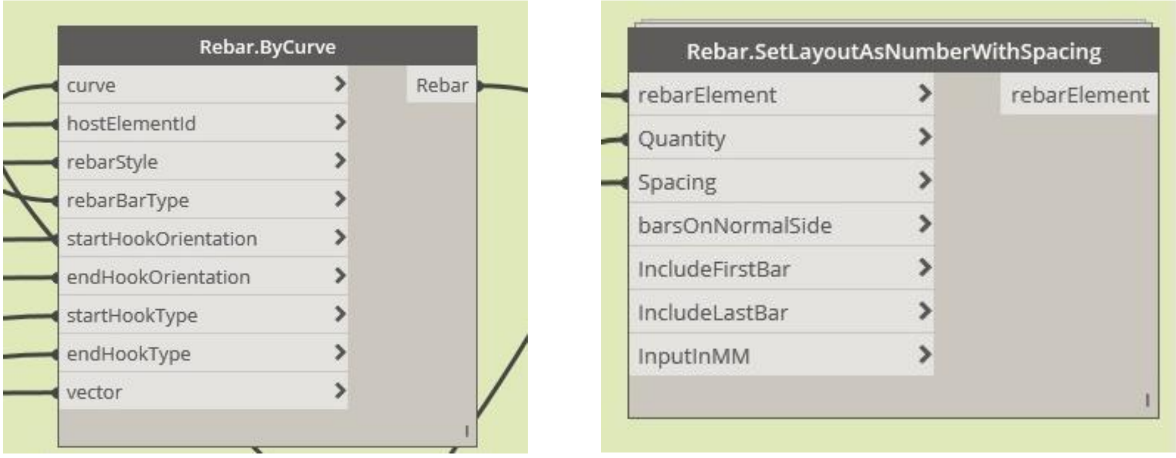
Figure 4.4 – Coordinate system transformation

This process is aided by the borders selections made in the first section (see Figure 4.3), for the new coordinate system will have the X and Y axes coinciding with the selection made of the Lx and Ly mentioned, respectively. The Z axis definition does not need manual aid as the Dynamo nodes used will automatically generate it as perpendicular to the other two and on an upward direction.

The group guaranteeing the preservation of elements generated by previous routines was introduced into the routine as result of a recent Dynamo software update that deletes any previously generated elements by the same routine automatically when a rerun occurs. This concerns a problem given that multiple slab panels within the same model can be reinforced, and that the Dynamo routines only runs one slab at a time. The mentioned group contain nodes created by the Dynamo community to help recognize elements and preserve them, allowing a full exploitation of the present routine.

4.3 REINFORCEMENT CREATION ROUTINE

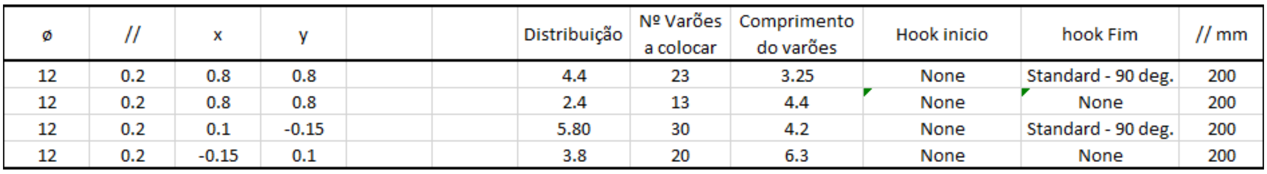
The third and fourth sections are constituted of twenty-eight groups of nodes in total; six of them create the reinforcement for the lower surfaces of the slabs and the remaining, the reinforcements for the upper surfaces. Even though they all result in different reinforcement bars, all groups have similar creation processes because they all converge in the same two final nodes. These two nodes belong to a third party's node package, "Dynamo for Rebar", with the title "Rebar.ByCurve" and "Rebar.SetLayoutAsNumberWithSpacing", seen in Figure 4.5. The first is responsible for the definition of one rebar and the second node replicates it *n* times according to a defined spacing.



a) “Rebar.ByCurve” b) “Rebar.SetLayoutAsNumberWithSpacing”,

Figure 4.5 – Rebar creating nodes

In its majority, the inputs for these nodes are read, direct or indirectly, in the developed Excel worksheet, while the remaining information comes from the second section of the routine or even from default inputs within the nodes. Every single one of the groups is responsible for the creation of one set of rebars on one single direction, hence the group colors, as mentioned before. Although the process is identical from group to group, what makes them unique in order to create different rebars with various placement, is the analysis of different Excel rows with 12 cells each. These cells values gather all information needed to distinguish particular reinforcement zones, even though not all groups need all 12 cells to fulfil its duty. This set of rows compose a table within the spreadsheet “Saída”, mentioned in the previous chapter, with a small excerpt shown in Figure 4.6.



ø	//	x	y			Distribuição	Nº Varões a colocar	Comprimento do varões	Hook inicio	hook Fim	// mm
12	0.2	0.8	0.8			4.4	23	3.25	None	Standard - 90 deg.	200
12	0.2	0.8	0.8			2.4	13	4.4	None	None	200
12	0.2	0.1	-0.15			5.80	30	4.2	None	Standard - 90 deg.	200
12	0.2	-0.15	0.1			3.8	20	6.3	None	None	200

Figure 4.6 – Excel Outputs

4.3.1 Single Rebar creation

Generally speaking, the Dynamo process used to the creation of an only rebar, simply passes for defining a line segment and applying to it rebar characteristics. In turn, to define a line segment the approach was to apply a certain distance to a point through a vector and move it to its place according to its host coordinate system. Considering this, usually, every reinforcement zone contains more than one rebar and in order to use two replicating vectors in total, the line segment always represents the rebar closer to the panel bottom left corner. The nodes used in the visual programing software to create this first rebar, shown in Figure 4.7, were a point and a line creating node, followed by a coordinate system transformation and lastly a node that transforms the line segment into a curve from a program code stand view, needed to run the "Rebar.byCurve" node.

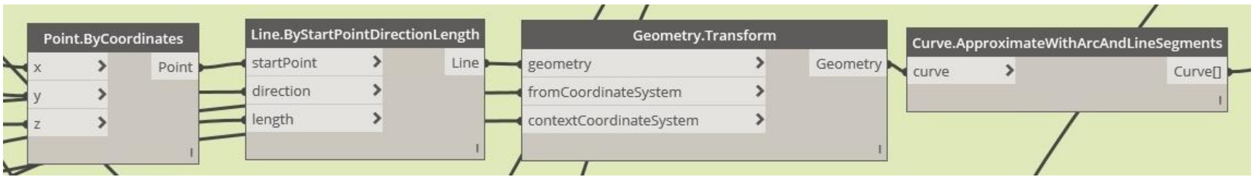


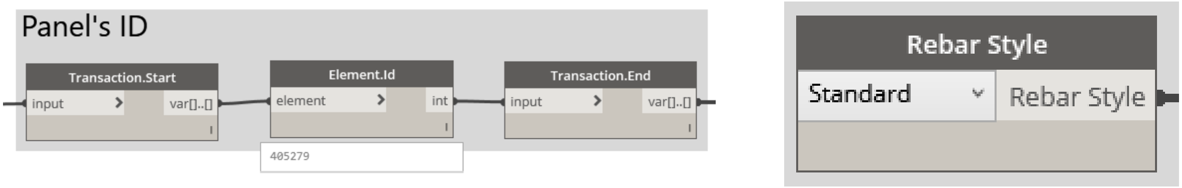
Figure 4.7 – Line creation nodes

The point creating node requires the input of three coordinates, being x and y read in the third and fourth cells of the rows in Figure 4.6, while the z coordinate is read separately in the second section of the routine. The elevation goes in line with the concrete structural cover, given as an input by the user in Excel. In concerns of overlapping perpendicular rebars, as it was decided to separate the Mx and My reinforcements in each surface by 2 cm. Since Revit considers the upper surface spot elevation of a given panel as its highest value, all the inputs given in the Z parameter of the node will have negative values. As an example, a slab panel with a thickness of 30 cm and 5 cm of concrete cover can have, if not switched in Excel (see Figure 3.14), Z coordinates of the My^+, Mx^+, My^- and Mx^- reinforcements with values of -0,23 m, -0,25 m, -0,05 m and -0,07 m, respectively.

Once a point is defined, it will become an input to the line segment creation node with the aid of a vector and a distance. This last one is also read in the mentioned row, occupying its ninth position, while the vector takes the direction of Revit's base axes X and Y in case the reinforcement is parallel to the Lx or Ly borders, respectively. Following the creation of the line segment a relocation is needed because, at this stage, the segment is located near Revit's origin point and parallel to one of its axis. As said, this action is guaranteed by converting coordinate systems, defined in the second section, through the "Geometry.Transform" node.

Even though the segment is created and properly located, the Dynamo code does not agree with the "Rebar.byCurve" first parameter, "Curve", that, as the name suggests, requires a curve code. To circumvent this issue, it was used a node that converts the "Line" code to a "Curve", with the name of "Curve.AproximateWithArcAndLineSegments".

The "Rebar.byCurve" next two parameters, "hostElementID" and "rebarStyle", are constant throughout all types of reinforcement creation groups, making its inputs part of the second section of the Dynamo routine. These parameters require the hosts element IDs and a "Standard" rebar style, as seen in Figure 4.8.

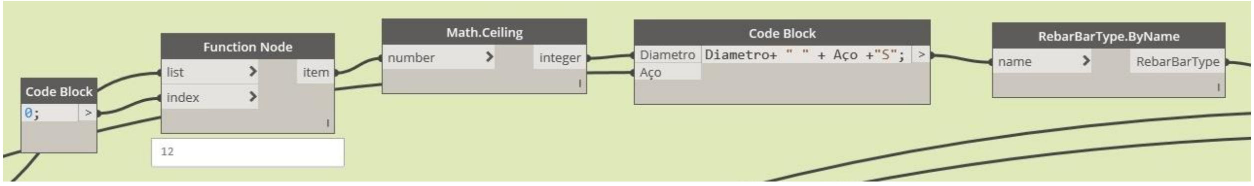


a) Panel ID nodes

b) Rebar Style Node

Figure 4.8 – Extra required nodes for “Rebar.byCurve”

The fourth parameter, “RebarBarType”, defines the type of rebar to be applied to the line created, in terms of diameter and steel grade. The diameter is selected by the user in Excel, occupying the first column in the Excel output table and, is used on Dynamo to assemble an expression that defines the rebar bar types in Revit. For instance, a rebar bar graded S400 with a diameter of 12 mm is named, in Revit, as “12 400S”. Thus, by putting together the number read in the Excel and joining the steel grade defined in the second section of the Dynamo routine second section, it can be avoided a repeated manual input of the rebar bar type to apply (see Figure 4.9).



```
0;
```

```
Diametro+ " " + Aço +"S";
```

Figure 4.9 – Rebar type generating nodes

The fifth through the ninth “Rebar.ByCurve”’s parameters allow the definition of the reinforcement anchorage. The first two nodes establish the rebar start and end orientation and the remaining two nodes define its type. While most of reinforcement start and end hook types are constant regardless of the panel, in main reinforcement of the lower surface a potential continuity influences the anchorage type, as explained in 2.1.4. Under these circumstances, the anchorage of the positive main reinforcement varies from panel to panel and its rebar’s start and end need to be programmed in Excel and later read by Dynamo. In this software, the hook types used are “None”, in a continuity zone, and “Standard – 90 deg.”, making the rebar bend 90 degrees. All lower surface reinforcements will bend upwards into the beam, and the upper surface reinforcements downwards, defined by the expressions “Left” and “Right” in the hook orientation parameters, respectively, as seen in Figure 4.10.

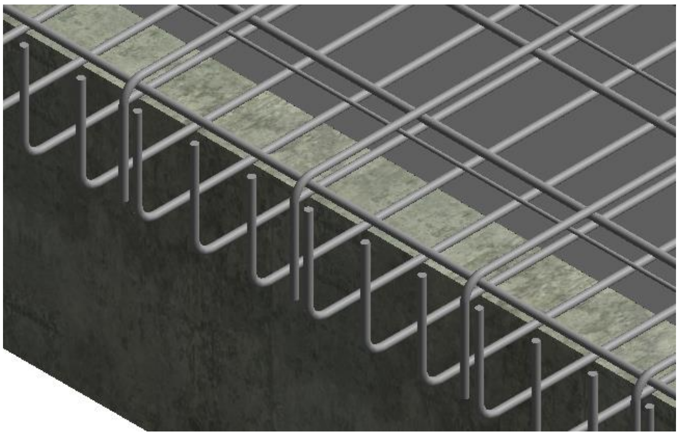


Figure 4.10 – Revit Hooks

The last parameter needed to create the first rebar is called "Vector", which will dictate the direction the rebar will be replicated. Within this Dynamo routine this vector can only take two perpendicular directions, because in a rectangle slab all reinforcements parallel to the panel's Lx side will be replicated along the Ly side and vice-versa. Considering the first rebar corresponds to the one nearest to the left bottom corner, the vector at issue is either the x or y axes of the new coordinate system.

4.3.2 Rebar Replication

The "Rebar.SetLayoutAsNumberWithSpacing" node only has three parameters that potentially diversify in its input value, while the last four have a programmed default option that fits the current routine on all reinforcement types. As said before, this node replicates the initial rebar element a certain number of times with a fixed spacing, so the 3 editable parameters mentioned correspond to "RebarElement", "Quantity" and "Spacing". The first input corresponds to the "Rebar.ByCurve" output, and the next two are read in Excel. The quantity is calculated by dividing the reinforcement distribution length by the user's defined spacing and adding one the result, so to account with the first rebar. As seen in Figure 4.6, the spacing between bars is defined in both the second and last position of the Excel table, in meters and millimeters, since the meter unit is used throughout all the worksheet while its thousandth unit is needed for the "Rebar.SetLayoutAsNumberWithSpacing" last parameter. That being said, the value in meters is still read in Dynamo, even though it is not used as input in any node.

This node marks the end of the 3D generation of each reinforcement zone, creating a Revit Rebar Family constituted of rebars for each zones. Nonetheless, these families can be edited within Revit if there is the need, either by adding or removing rebars, editing their length, position or hook type and length.

CHAPTER 5

SYSTEMATIC PRODUCTION OF PROJECT ELEMENTS

Construction projects consist of sophisticated and complex processes often carried out by a number of different individuals and professionals, who focus their efforts into different skills and knowledge [43].

The Structural Engineers' contribution to the project does not stop at the end of design, for it needs to be comprehensively and effectively interpreted by other involved professionals. Even though the 3D modelling of the reinforcement of a slab has its advantages in terms of overall visualization and error detection by its author, one should not forget that Revit has much more potentialities that can further explore the newly added structural elements and help on the message transmission.

In the following sub-chapters a description of some Revit built-in functionalities can be found, that help in the field of project management and detailing.

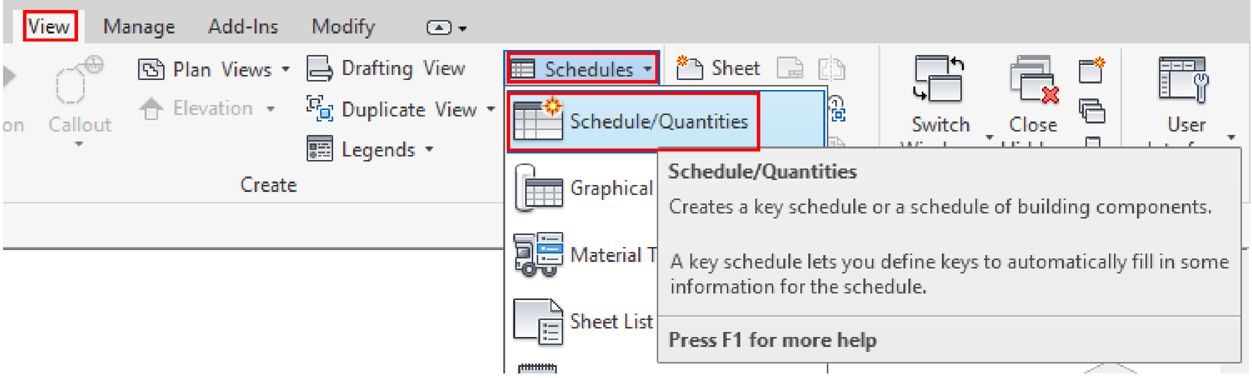
5.1 INVENTORY MAPS

Inventory maps make a big part of the materials management system, which attempts to conveniently deliver the right quantity of materials, in its best quality, through appropriate selection and on-time purchase and delivery. [44].

As material represent a major expense in construction —60 to 70% of the direct cost of a project [44]—, minimal material waste conducts to a significant reduction of the overall project cost. According to Gamil [45], some of the main causes for material waste in the construction industry are changes in design, poor design management, inaccurate dimensions in early stage design and poor communication.

Structural engineers can contribute to minimal material waste and an efficient material management system by developing a thorough inventory of structural elements. Henceforth, taking advantage of the developed 3D modelling routine and Revit properties, rebars can be quantified in an exact manner through organized tables of information.

Once the project model is fully reinforced and all rebar elements are selected, the table of information can be generated by opening the Revit's tab "View", clicking "Schedule" followed by "Schedule/Quantities", as seen ahead.



Schedule/Quantities

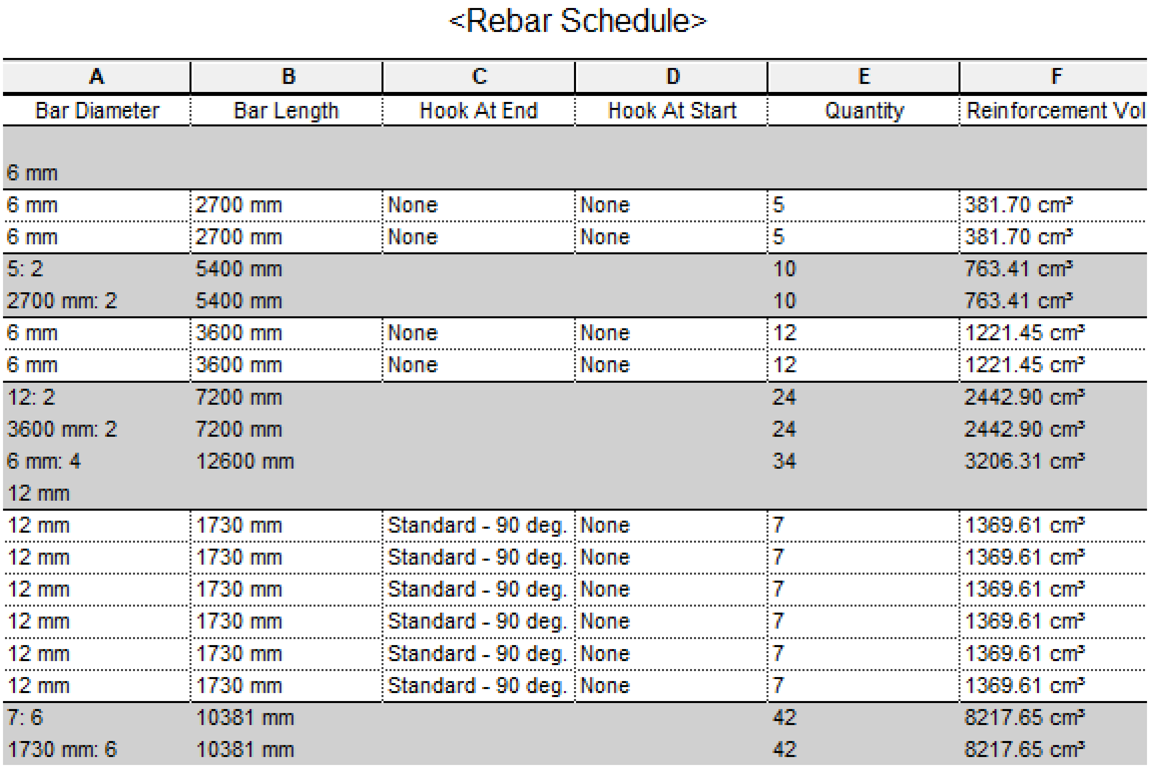
Creates a key schedule or a schedule of building components.

A key schedule lets you define keys to automatically fill in some information for the schedule.

Press F1 for more help

Figure 5.1 – Material Quantities functionality in Revit

This functionality allows access to a panoply of information relevant for all types of elements quantification and organization. Nonetheless in what concerns structural rebars, the most important fields to analyze are the bar diameter, length, hook at start and end, quantity and reinforcement volume. Their selection can be made in an intermediate interface, along with a set of sorting and filter functionalities, to define the columns present at the desired inventory table. An example of an inventory table concerning reinforcement can be seen on Figure 5.2.



<Rebar Schedule>

A	B	C	D	E	F
Bar Diameter	Bar Length	Hook At End	Hook At Start	Quantity	Reinforcement Vol
6 mm					
6 mm	2700 mm	None	None	5	381.70 cm^3
6 mm	2700 mm	None	None	5	381.70 cm^3
5: 2	5400 mm			10	763.41 cm^3
2700 mm: 2	5400 mm			10	763.41 cm^3
6 mm	3600 mm	None	None	12	1221.45 cm^3
6 mm	3600 mm	None	None	12	1221.45 cm^3
12: 2	7200 mm			24	2442.90 cm^3
3600 mm: 2	7200 mm			24	2442.90 cm^3
6 mm: 4	12600 mm			34	3206.31 cm^3
12 mm					
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
12 mm	1730 mm	Standard - 90 deg.	None	7	1369.61 cm^3
7: 6	10381 mm			42	8217.65 cm^3
1730 mm: 6	10381 mm			42	8217.65 cm^3

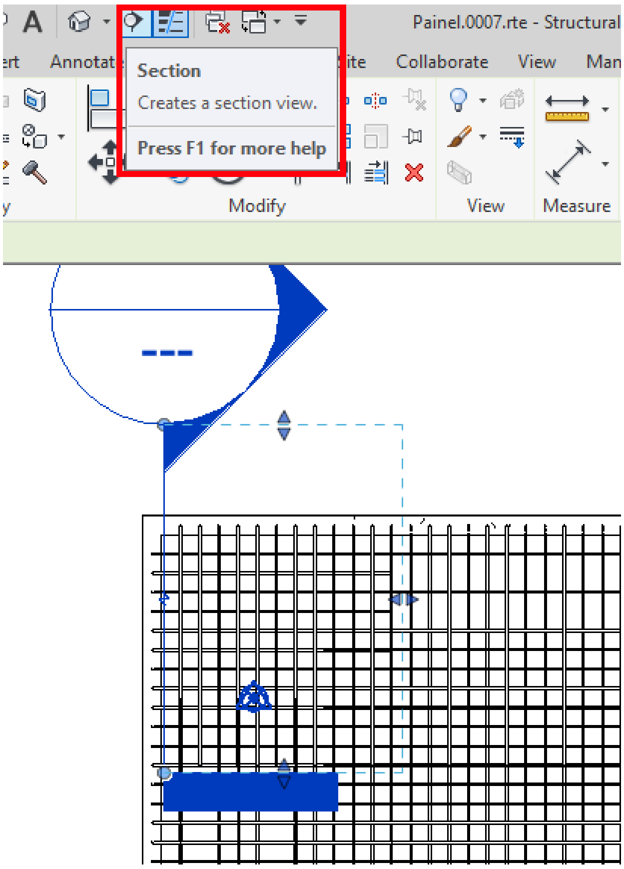
Figure 5.2 – Example of a reinforcement inventory table

5.2 SECTIONAL VIEWS

Sections and details of all structural and non-structural elements are usually requested by the client or contractor to better perceive their exact constitution, placement, relationship and interconnection to other elements.

Sectional views are drawings that graphically represent the projection of a vertical section, or plane, of a building or specific element. These drawings should also provide adequate dimensions to allow a proper installation and assembly of the building structure. Structural Engineers are responsible for, and shall assist in, coordinating the dimensions needed for the accurate location and construction of the building structure. Its purpose is to clarify the observer of the project through plans of longitudinal and transverse intersections, giving a third dimension to the reading and interpretation of the project [46].

As slabs are quite extensive and heavily reinforced structural elements, a large number of sectional views are usually required to illustrate perfectly rebar detailing and positioning. Consequently, slab sectional views can occupy a considerable amount of time in the project development. The use of the developed routine combined with Revit section properties can significantly reduce the time spent on these tasks. By taking advantage of the “Section” tool, engineers can pinpoint the most intricate reinforcement zones, like the corner reinforcement zone, and retrieve a detailed section view, as seen in Figure 5.3.



Section

Creates a section view.

Press F1 for more help

Figure 5.3 – Section view selection for a corner reinforcement zone

The depicted action will provide the engineer an exact and fast section view of this zone of the slab, with the potentiality of adding tags to selected elements, as seen in the following figure.

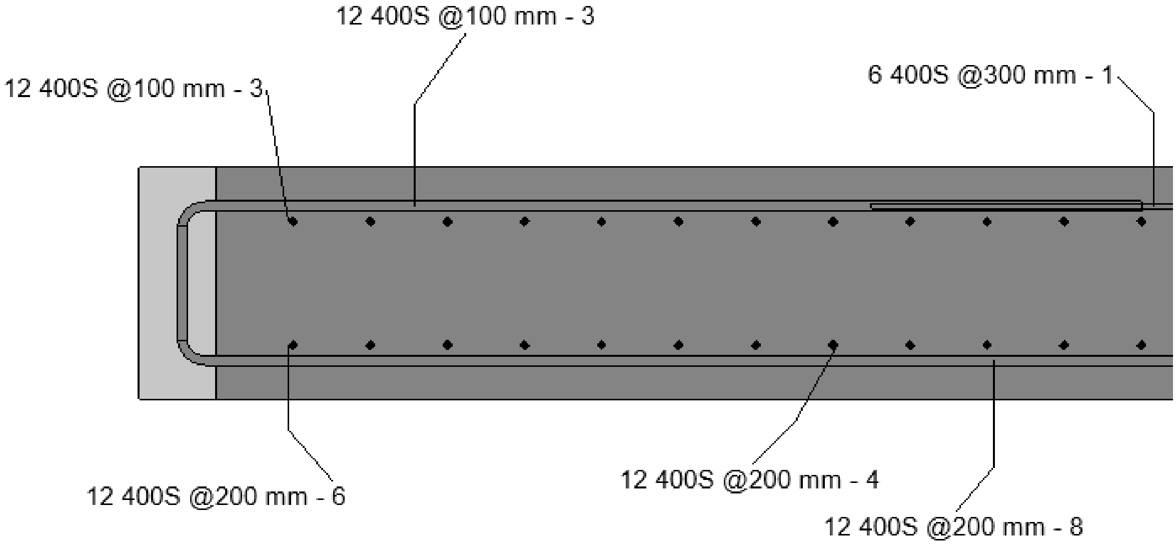
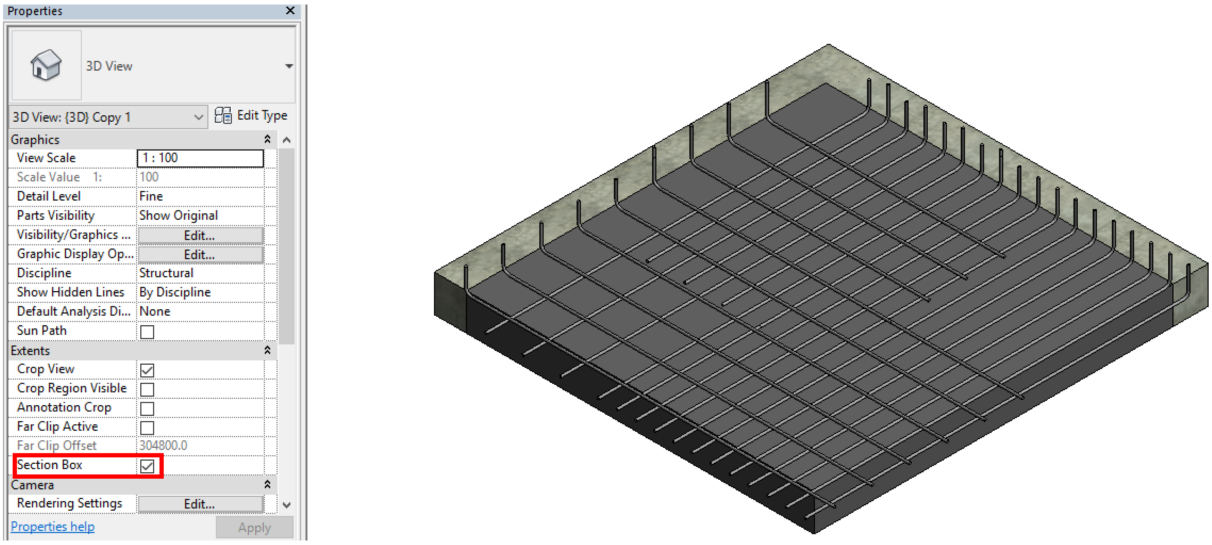


Figure 5.4 – Section view of a corner reinforcement zone

In addiction, and to complete the last section view, the Revit "Section Box" can be used to make area section views of the element in a 3D way, to clearly visualize rebar placement in more detail. The section box allows many views of the elements, for instance, the box can be positioned to demonstrate only lower surface reinforcement, as seen in the next figure.



3D View: {3D} Copy 1

Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics ...	Edit...
Graphic Display Op...	Edit...
Discipline	Structural
Show Hidden Lines	By Discipline
Default Analysis Di...	None
Sun Path	☐
Extents	
Crop View	☑
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304800.0
Section Box	☑
Camera	
Rendering Settings	Edit...

Figure 5.5 – Area section view of a lower surface corner reinforcement zone

CHAPTER 6

CASE STUDY

The present chapter will describe the application of the developed Excel worksheet and Dynamo routine into a residential house previously designed by Newton – Consultores de Engenharia.

The structural project of the building is represented in AutoCAD while the routine's outputs will be 3D elements within Revit. However, this will not constitute a problem for the main goal is to compare reinforcement design and placement in two-way rectangular slabs so to understand the applicability and functionalities of the developed programs.

6.1 CASE DESCRIPTION

The building studied is constituted by two floors of diverse types of slabs, with only three of these slabs complying with the target type: rectangular two-way slabs. These slabs all have a consistent height of 20 cm, with spans of 7 and 7,10 m, with 5 cm of concrete structural cover. These three panels, placed consecutively in the first floor of the building, have concrete beams between and all around them with 50 cm in height and 25 cm of width.

The slabs have a dead load of 3 kN/m applied to them, not considering its self-weight, and a live load of 2 kN/m. The materials considered were concrete of class C20/25 and a steel grade S400.

The structural analysis of the original project was made via the software Robot Structural Analysis, while the reinforcement design and detailing relied on both the Eurocode 2 [40] rules and Montoya's suggestions [9]. The reinforcement zones placed do not correspond entirely with the zones defined in the developed program, however the study will be conducted by evaluating the area of reinforcement present in missing reinforcement zones and comparing it to the Excel's solution. For a more comprehensive overview and analysis of the three slabs, they will be defined by the letters "A", "B" and "C", from left to right, seen in Figure 6.1 along with the final original reinforcement design. Both surfaces reinforcements are represented in the figure either in the plant or in the section cut, with the upper surface reinforcement defined by blue dashed lines and the lower surface reinforcement with solid blue lines.

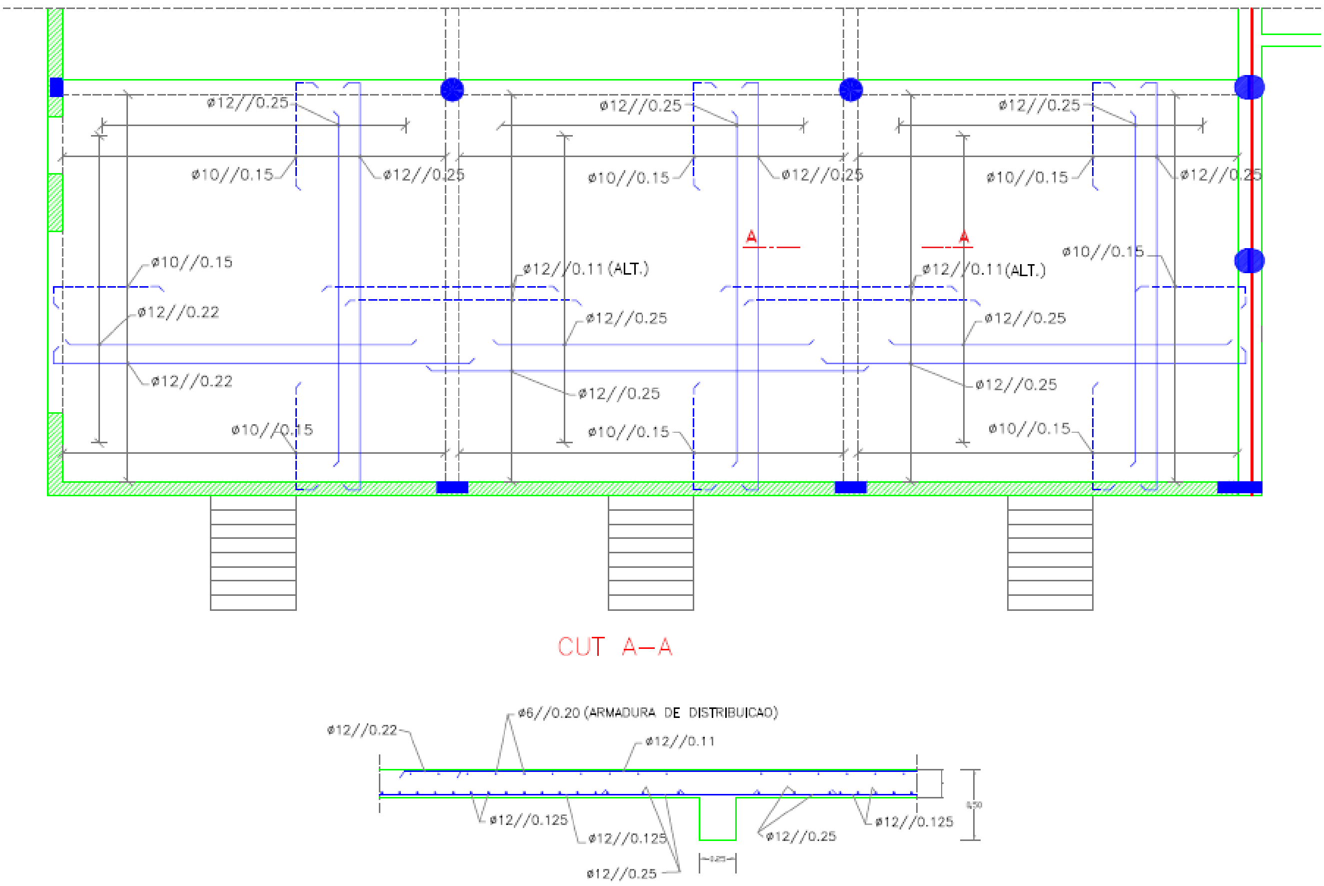


Figure 6.1 – Original reinforcement design for the targeted two-way rectangular slabs

The lower surface of the panels does not contain specific corner reinforcement zones in neither A nor C panels. The B panel, in terms of lower reinforcement, is the one that closely approximates to the placement and interruption zones considered in the present work. The upper surface also presents a similar rebar placement in the support reinforcement zone as its corresponding distribution reinforcement, however both additional and corner reinforcements zones are not specifically represented, for the fixed edge reinforcement seems to replace the last two. Even though it is not represented in Figure 6.1, a note in the drawing suggests that the fixed edge distribution of the reinforcements is ø6//0.20.

Table 6.1 summarizes the reinforcement solutions and their respective areas of reinforcement placed in the original reinforcement design.

Table 6.1 – Summary of original Reinforcement design solution

			Lower Surface	Upper Surface											
			Main Reinforcement	Support Reinforcement		Distribution of Support Reinforcement		Fixed Edge Reinforcement				Fixed Edge Reinforcement Distribution			
				Left	Right	Left	Right	Left	Right	Top	Bottom	Left	Right	Top	Bottom
Panel A	Type	Mx	ø12//0.11	-	ø12//0.11	-	-	ø10//0.15	-	-	-	-	-	ø6//0.20	ø6//0.20
		My	ø12//0.125	-	-	-	ø6//0.20	-	-	ø10//0.15	ø10//0.15	ø6//0.20	-	-	-
	Area cm^2/m	Mx	10.28	-	10.28	-	-	5.24	-	-	-	-	-	1.41	1.41
		My	9.05	-	-	-	1.41	-	-	5.24	5.24	1.41	-	-	-
Panel B	Type	Mx	ø12//0.125	ø12//0.11	ø12//0.11	-	-	-	-	-	-	-	-	ø6//0.20	ø6//0.20
		My	ø12//0.125	-	-	ø6//0.20	ø6//0.20	-	-	ø10//0.15	ø10//0.15	-	-	-	-
	Area cm^2/m	Mx	9.05	10.28	10.28	-	-	-	-	-	-	-	-	1.41	1.41
		My	9.05	-	-	1.41	1.41	-	-	5.24	5.24	-	-	-	-
Panel C	Type	Mx	ø12//0.125	ø12//0.11	-	-	-	-	ø10//0.15	-	-	-	-	ø6//0.20	ø6//0.20
		My	ø12//0.125	-	-	ø6//0.20	-	-	-	ø10//0.15	ø10//0.15	-	ø6//0.20	-	-
	Area cm^2/m	Mx	9.05	10.28	-	-	-	-	5.24	-	-	-	-	1.41	1.41
		My	9.05	-	-	1.41	-	-	-	5.24	5.24	-	1.41	-	-

6.2 REVIT MODELING

First and foremost, it is important to have a Revit Model in order to apply the described BIM reinforcement modeling.

The model geometry should correspond exactly to the 2D drawings to make a correct assessment of the final results. As the current study is being conducted only in what concerns the two-way rectangular slabs, only these, with the addition of the beams, were added to the model. The Revit model can be seen on Figure 6.2.

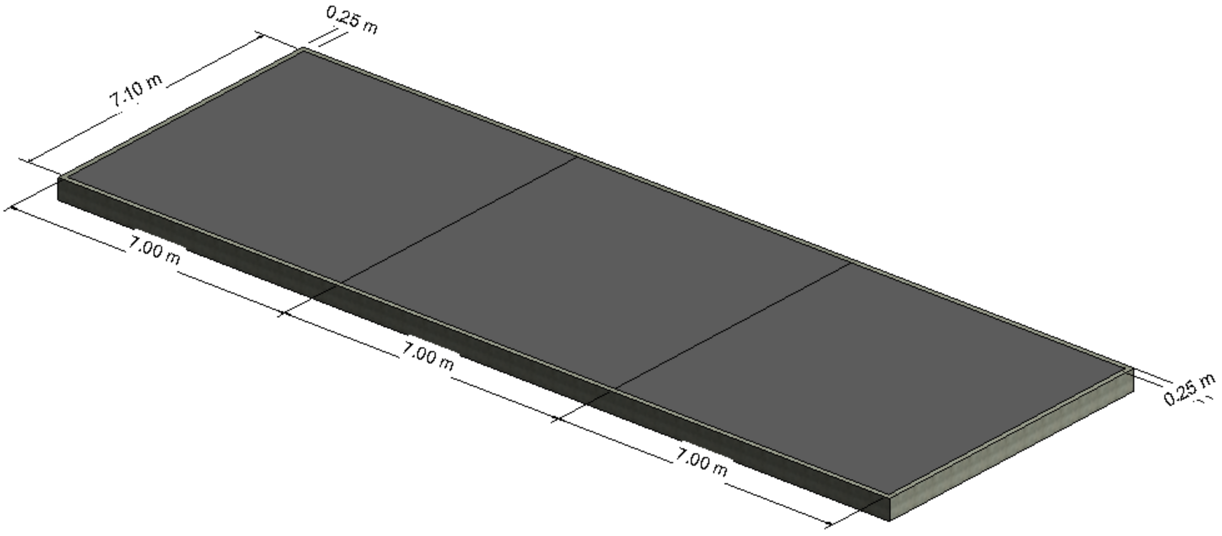


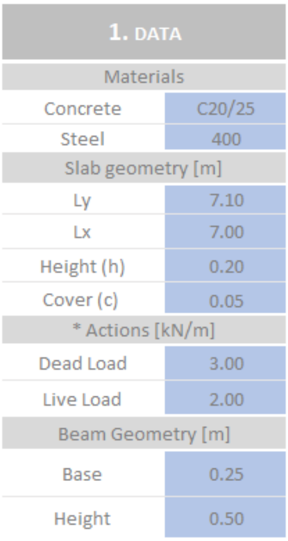
Figure 6.2 – Simplified Revit Model of the Case study

6.3 SLAB DATA INPUT

The Excel Worksheet should be the first program to be used to round up all information about the slab in study and provide uniformity between the reinforcement elements and the Revit Model.

Guided by the Excel's user's guide, cited in 3.1, some data about the slabs must be filled-in, for the information provided last sub-chapter fulfills all fields, namely the materials, geometry of the slab and beam and action. It is important to stress the adequate filling of the Lx and Ly values in accordance to the convention used in Excel (see Figure 3.2), in which the edge parallel to the X axis is the Lx and the one parallel to Y axis will take the Ly value.

Figure 6.3 shows the information filled-in in step 1 of the user's guide according to the slabs under study.



1. DATA	
Materials	
Concrete	C20/25
Steel	400
Slab geometry [m]	
Ly	7.10
Lx	7.00
Height (h)	0.20
Cover (c)	0.05
* Actions [kN/m]	
Dead Load	3.00
Live Load	2.00
Beam Geometry [m]	
Base	0.25
Height	0.50

Figure 6.3 – Data input in Excel

6.4 STRUCTURAL ANALYSIS RESULTS

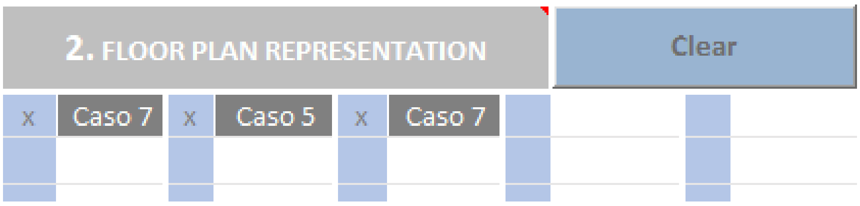
As explained before the Excel Worksheet is prepared to run the structural analysis via built-in Montoya and British Standard tables or via manual input of maximum positive and negative bending moments.

Considering that both tables results are a rough approximation of reality and that Robot Structural analysis provide a more reliable set of values, both the automatic and manual approach will be run and compared for the panels in study.

6.4.1 Excel Worksheet Automatic Approach

To take advantage of the built-in automatic set of tables, the user's guide states that step 2 should be filled-in, corresponding to the relative representation of the slabs in study.

Following the indication given at the worksheet introductory section, the introduction of the letter "x" within the blue cells will activate symbolic panels within Excel and consequently its boundary cases. In the study case the three slab panels are consecutively placed in a row, resulting in a relatively straightforward fulfillment, as seen below.



x Caso 7 x Caso 5 x Caso 7

Figure 6.4 – Floor span representation of the three slab panels in study

The boundary cases number 7, 5 and 7 (see Figure 2.1) are now associated with the panels A, B, and C, respectively, for the continuity edges correspond to the largest span.

The procedure for calculating the maximum bending moments in the three slab panels through this method implies choosing one of the buttons within user's guide step 3 a) *Automatic calculation of maximum Bending Moment.* By clicking one of the three available buttons the program redirects into the forth step – Slab Selection, and second spreadsheet. In there, the bending moments of the slab cannot be visualized, for it is necessary the individual selection of panel A, B and C. This is done by indicating the location of the slab relative to the grid presented, in case of the present case study: A1, B1 and C1 (see Figure 6.5) and clicking in the button "Reinforcement Design". Doing so will redirect the program to the last step of the worksheet and the bending moments will be shown.

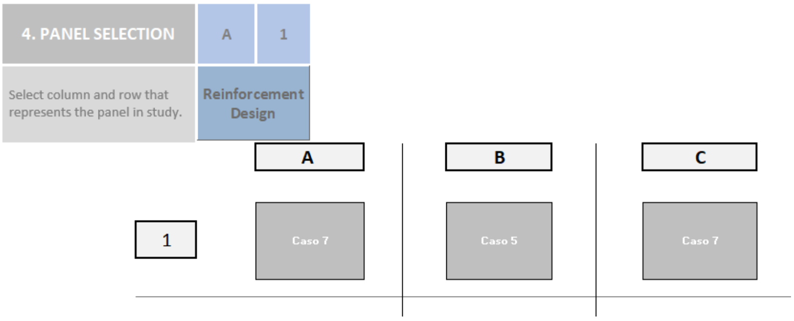


Figure 6.5 – Panel Selection Process

6.4.1.1 Montoya Tables

The first button in the user's guide step 3 a), runs the Montoya's tables in respect to the boundary cases indicated in the "Floor Plan Representation", actions defined in the first step and the negative moments redistribution. Within the scope of this option two percentage values were tested for the redistribution: 0% and 25%. This will provide a good analysis of the absolute maximum negative bending moments and their repercussions on the positive ones after redistribution. A recollection of the maximum bending moments values (in kN.m/m) for all 3 panels are represented, using 0% and 25% redistribution are represented in Figure 6.6 and Figure 6.7, respectively.

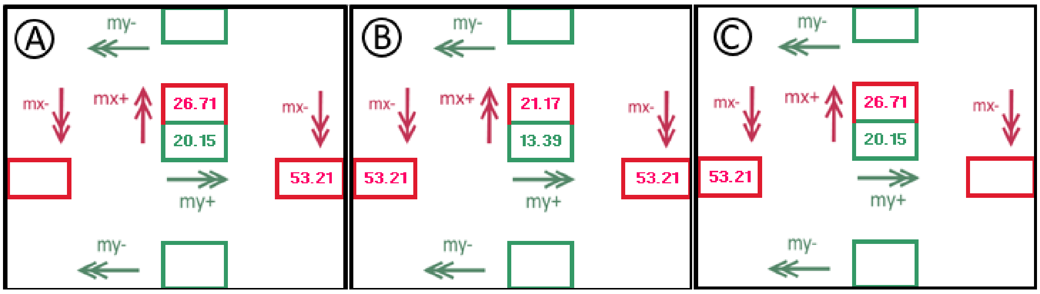


Figure 6.6 – Maximum bending moments in respect to Montoya's tables application and considering 0% Redistribution

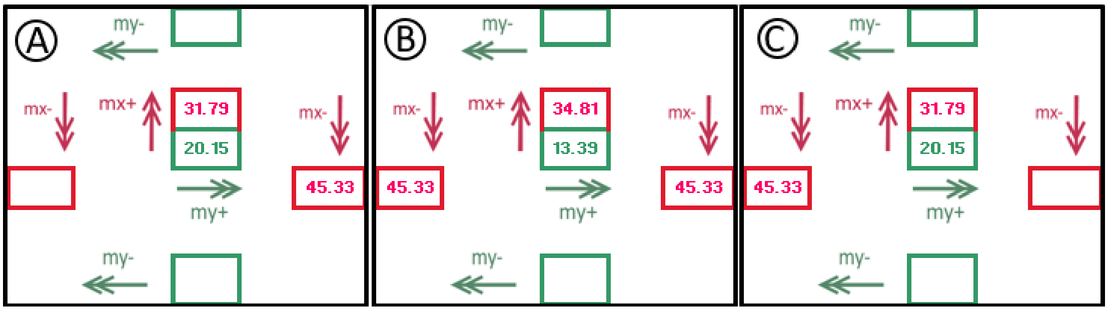


Figure 6.7 - Maximum bending moments in respect to Montoya's tables application and considering 25% Redistribution

The maximum negative moment of 53,21 kN.m/m, seen in Figure 6.6, depicts the peak of the bending moments diagram, when there is no moment redistribution. The maximum falls to 45,33 kN.m/m justifying the need for a coherent redistribution of the negative moments, for the peak of the bending moments diagram does not portray the effective forces in the zone.

In what concerns the remainder of the bending moments values in both analysis, it can be noticed that the ones corresponding to My do not vary in value. Only Mx values change as the redistribution is made solely on X axis direction, imposing new values not only on the negative bending moments values as in the positive ones.

6.4.1.2 Montoya tables with pattern live-loading

Figure 6.8, similarly to the last two, shows the bending moments in the three slab panels in study, only this time considering the pattern live-loading factor combined with 25% redistribution. It can be noticed that the application of the pattern live-loading factor does not interfere with the negative bending moments values for it influences the positive ones. Compared to Figure 6.7, the values of the positive bending moments increased in both directions, justifying the factor's purpose of illustrating the worst-case scenarios in consecutive panel slabs.

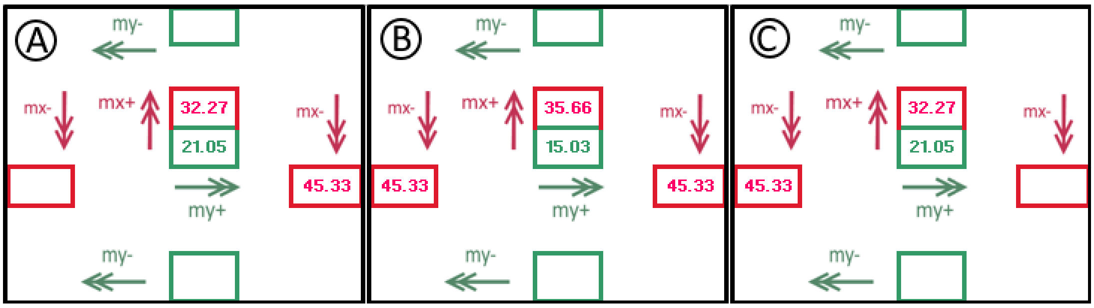


Figure 6.8 - Maximum bending moments in respect to Montoya's tables application considering pattern live-loading and 25% Redistribution

6.4.1.3 British Standard, BS 8110-1:1997

The results for the positive and negative maximum bending moments for the three slabs in study, resorting to the British standard tables described in 2.1.2.2 are represented in the following figure (Figure 6.9).

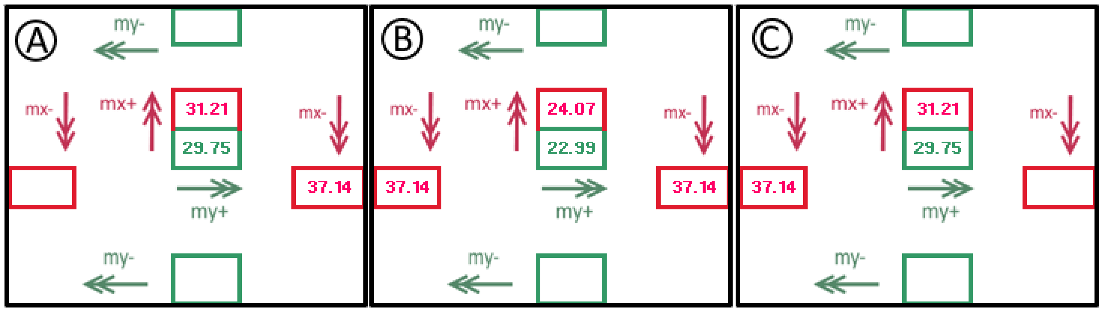


Figure 6.9 –Maximum bending moments in respect to the British Standard's tables application

As can be seen the values are in the same order of magnitude as the last case analyzed, differentiating most significantly in the negative moments. However, it is important to stress that these tables account for the pattern live-loading factor, and the negative moments redistribution in a non-disclosed way, making it difficult to make assumptions on the values compared to the previously described methods. The values discrepancy in this order of magnitude are prone to happen with the application of different methods, for its validity is not questioned.

6.4.2 Excel Worksheet Manual Approach

To exploit the user's guide step 3 b) *Manual input of maximum Bending Moments* it is important the use of reliable methods to enact the behavior of two-way slabs. The chosen procedure in the case study at hand was to make a structural analysis of the three slabs resorting to the functionalities in the software Robot Structural Analysis.

The slab panels A, B and C were reproduced in the program with the original 7 and 7,10 m spans, using RC shell, 20 cm panels and a mesh constituted of 25x25 cm elements. The beams and structural walls were represented with linear pinned supports on all edges. The final analytical model can be seen below (Figure 6.10).

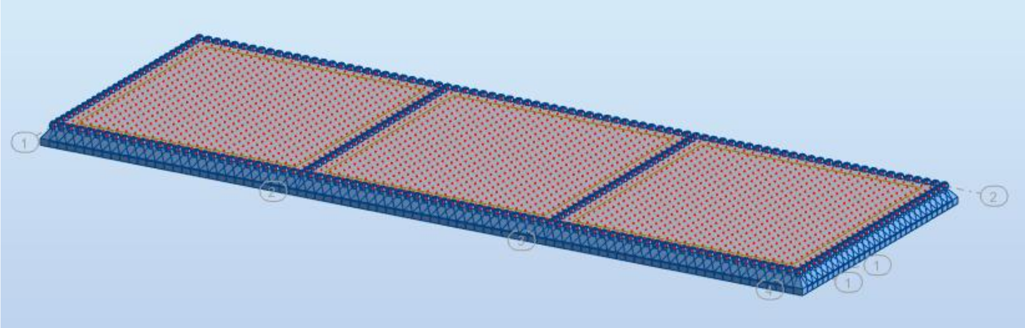


Figure 6.10 – Robot analytical model of the slabs in study

The software recognized the self-weight of the slabs, for it was only needed to add the remaining dead and live loads of 3 kN/m^2 and 2 kN/m^2, respectively. Upon load definition it was applied to them the Ultimate Limit State and run the calculations within the software.

The bending moments planar maps in XX and YY are represented in Figure 6.11 and Figure 6.12, respectively. They both show the evident, minimum and maximum values for positive and negative moments within various zones of the three slabs. It is important to note that, in contrast with the usual convention, Robot represents the usual negative bending moments with positive values and positive bending moments with negative values (American convention).

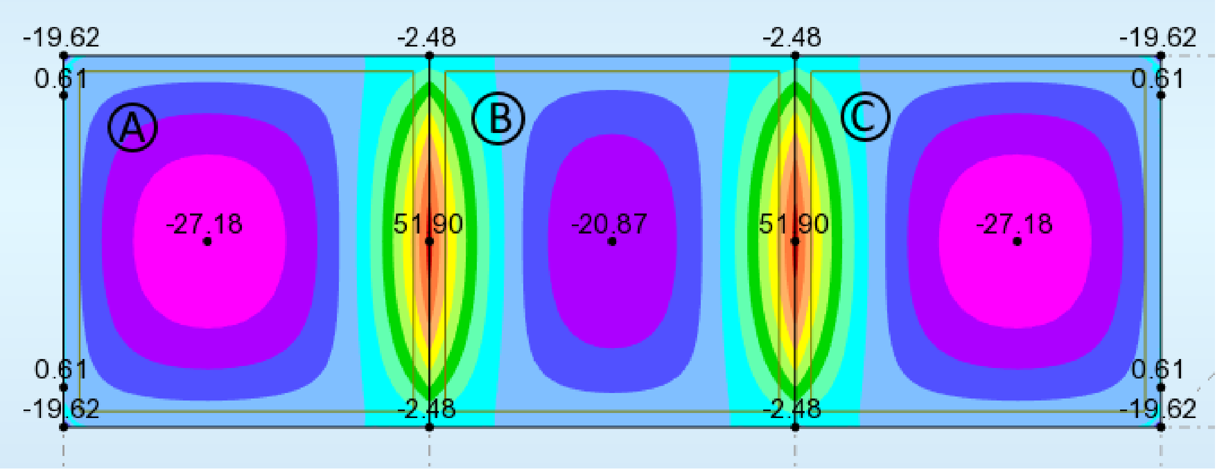


Figure 6.11 – Bending moments map in XX direction

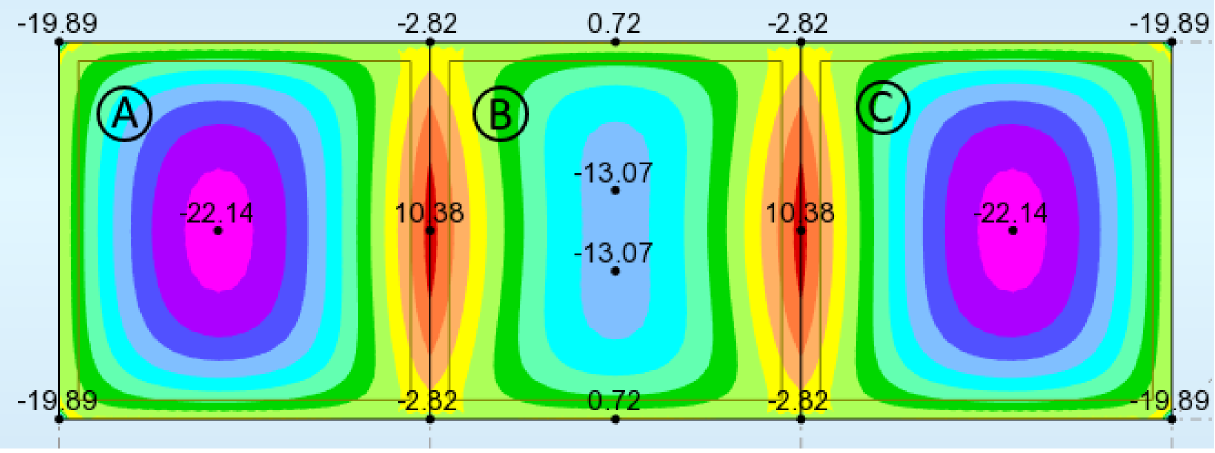


Figure 6.12 -Bending moments map in YY direction

The bending moments values in both directions originated by Robot Structural analysis have a striking resemblance to the Montoya's results with 0% Redistribution, with an average discrepancy of approximately 4%, according to the table below.

Table 6.2 – Maximum bending moments through Montoya's tables and Robot Structural Analysis

	Montoya, 0% Redistribution			Robot Structural analysis			
	Panel A	Panel B	Panel C	Panel A	Panel B	Panel C	Disparity (%)
Mx+ [kN.m^2]	26.71	21.17	26.71	28.18	20.87	27.18	2.79
My+ [kN.m^2]	20.15	13.39	20.15	22.14	13.07	22.14	6.79
Mx- [kN.m^2]	53.21			51.90			2.46

This means that the maximum negative bending moments values, even coming from Robot, should not be accounted for in the reinforcement design for they correspond to the peak of the bending moments, and the redistribution should still be carried out.

Once everything is ready the values should be manually introduced within the Excel Worksheet. The Figure 6.13 suggests values for the filling of the manual approach within Excel, corresponding to the bending moments obtained from the British standard. This method was chosen as it account for both pattern live-loading and negative moment redistribution, which may correspond to the bending moments obtained from a more in depth treatment of the Robot results.

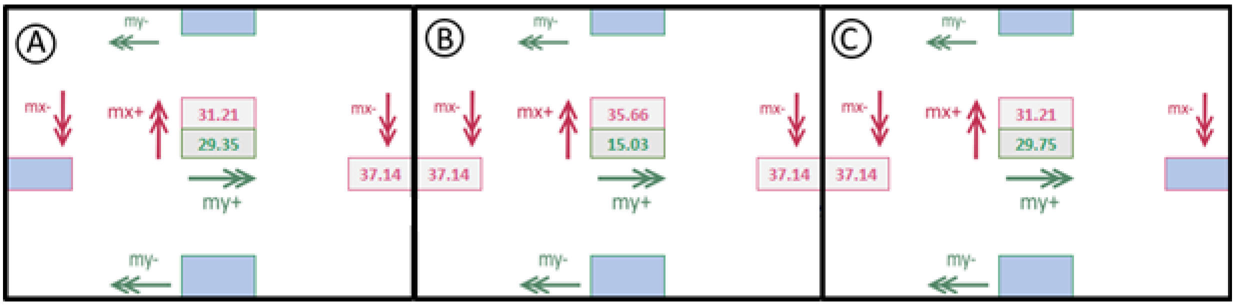


Figure 6.13 – Manual filling of the maximum bending moments within Excel

6.5 REINFORCEMENT SELECTION

The reinforcement selection resorting to the present Excel Worksheet will generate more reinforcement zones than the ones established in the original project. Still the goal of the case study is not to recreate as close as possible the original solution but to guide the design with what reinforcement the program gives back.

To make a realistic selection of the reinforcement zones it is advised to analyze both reinforcement zones simultaneously so that, mainly, the rebar diameter match in both surfaces of the slab as much as possible. This decision respects a practical rule in the AECO Industry, that aids the building process in the construction site to avoid mistakes in rebar placing.

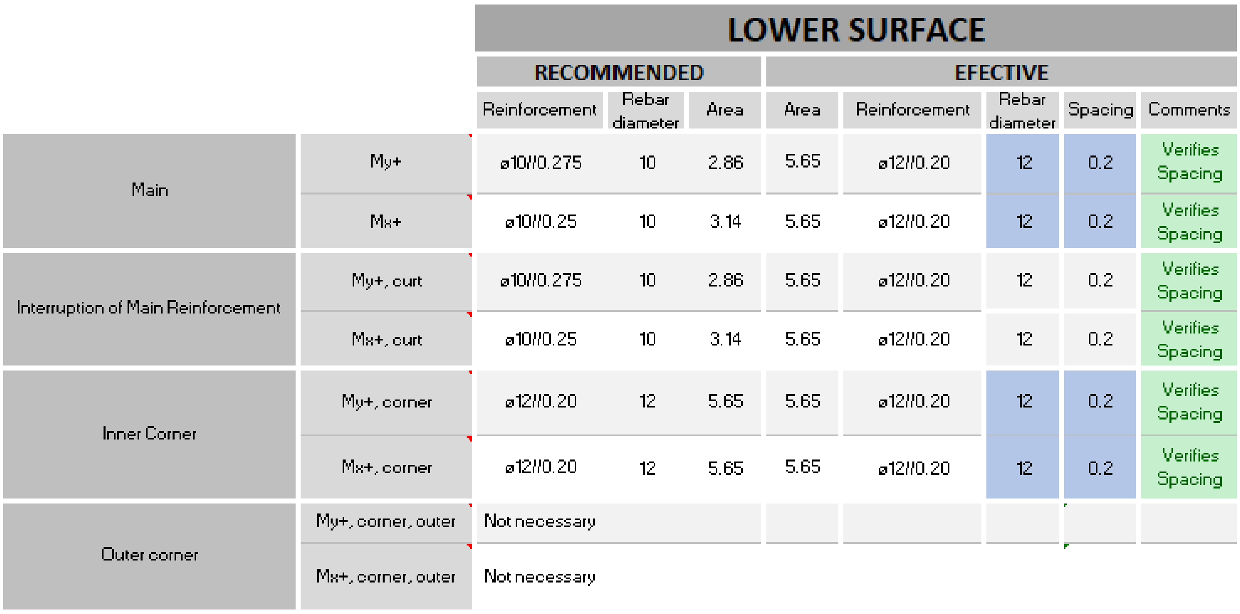
It was decided that the bending moments used in the reinforcement design would be the ones resulting from the application of the British standard (see Figure 6.9), since these have the most homogenous values.

Ahead follows the thought process in the reinforcement selection of the three slab panels in study.

6.5.1 Panel A and C

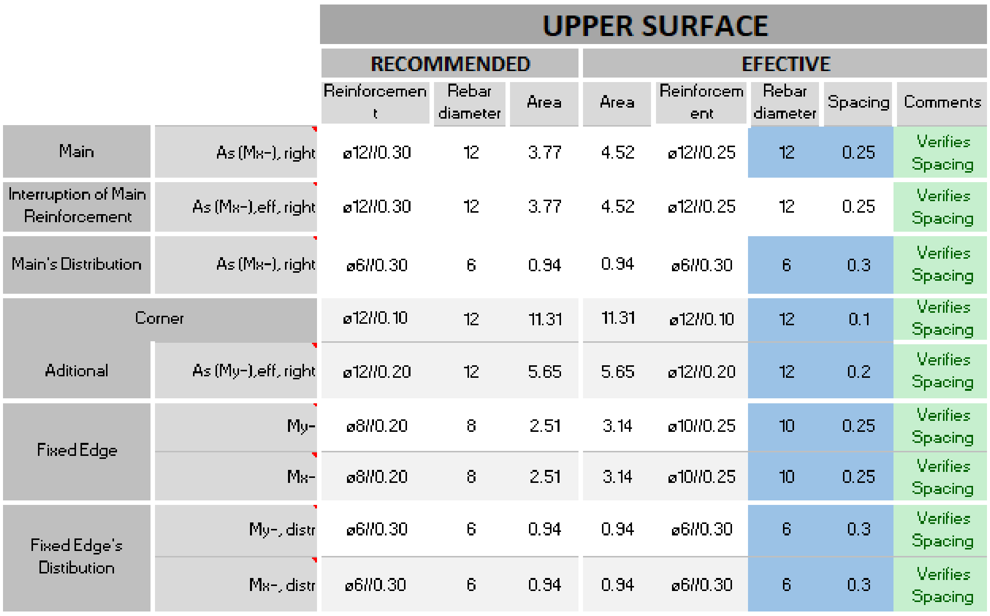
As Panels A and C have the same boundary case (number 7), and the same bending moments values for the reinforcement zones will be same as well as their solutions, as it is not necessary to analyze them separately. Having this said all reinforcement destined to panel A right side will correspond with panel C left side.

The figures below (Figure 6.14 and Figure 6.15) show the lower and upper reinforcement selection tables within step 5 of the program user’s guide for Panel A.



		LOWER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	My+	⌀10//0.275	10	2.86	5.65	⌀12//0.20	12	0.2	Verifies Spacing
	Mx+	⌀10//0.25	10	3.14	5.65	⌀12//0.20	12	0.2	Verifies Spacing
Interruption of Main Reinforcement	My+, curt	⌀10//0.275	10	2.86	5.65	⌀12//0.20	12	0.2	Verifies Spacing
	Mx+, curt	⌀10//0.25	10	3.14	5.65	⌀12//0.20	12	0.2	Verifies Spacing
Inner Corner	My+, corner	⌀12//0.20	12	5.65	5.65	⌀12//0.20	12	0.2	Verifies Spacing
	Mx+, corner	⌀12//0.20	12	5.65	5.65	⌀12//0.20	12	0.2	Verifies Spacing
Outer corner	My+, corner, outer	Not necessary							
	Mx+, corner, outer	Not necessary							

Figure 6.14 – Panel A Lower Surface reinforcement selection tables



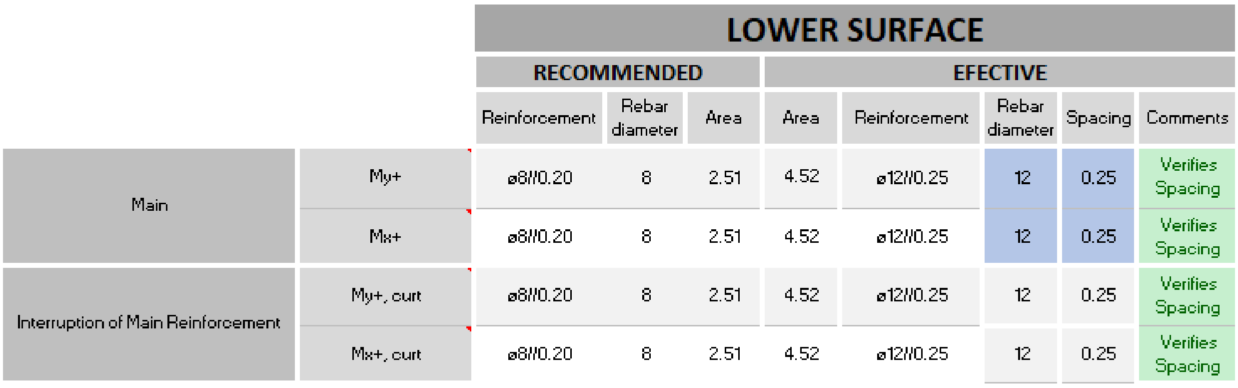
		UPPER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	As (Mx-), right	⌀12//0.30	12	3.77	4.52	⌀12//0.25	12	0.25	Verifies Spacing
Interruption of Main Reinforcement	As (Mx-),eff, right	⌀12//0.30	12	3.77	4.52	⌀12//0.25	12	0.25	Verifies Spacing
Main's Distribution	As (Mx-), right	⌀6//0.30	6	0.94	0.94	⌀6//0.30	6	0.3	Verifies Spacing
Corner		⌀12//0.10	12	11.31	11.31	⌀12//0.10	12	0.1	Verifies Spacing
Aditional	As (My-),eff, right	⌀12//0.20	12	5.65	5.65	⌀12//0.20	12	0.2	Verifies Spacing
Fixed Edge	My-	⌀8//0.20	8	2.51	3.14	⌀10//0.25	10	0.25	Verifies Spacing
	Mx-	⌀8//0.20	8	2.51	3.14	⌀10//0.25	10	0.25	Verifies Spacing
Fixed Edge's Distibution	My-, distr	⌀6//0.30	6	0.94	0.94	⌀6//0.30	6	0.3	Verifies Spacing
	Mx-, distr	⌀6//0.30	6	0.94	0.94	⌀6//0.30	6	0.3	Verifies Spacing

Figure 6.15 - Panel A upper Surface reinforcement selection tables

6.5.2 Panel B

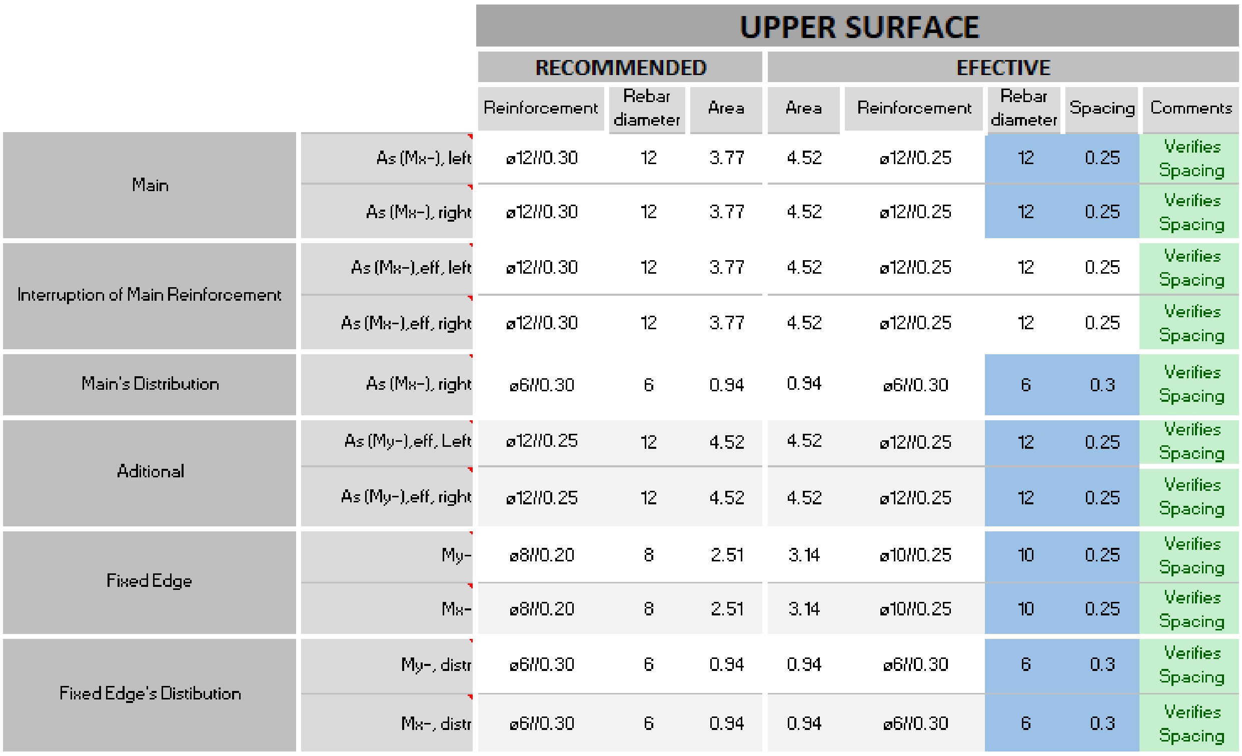
The reinforcement selection chosen for panel B follows diameter uniformity in accordance with the remaining panels, hence some of areas disparities between the recommended and effective reinforcement.

Careful attention is needed when selecting the main negative reinforcement type, for it needs to be the same as the ones chosen for panel A and C. As the panels are reinforced one at a time in Revit, the support reinforcement will only be modeled twice in three panels, but not their respective distribution reinforcement, for it needs to be in conformity with the main zone. Reinforcement tables for the panel are shown in Figure 6.16 and Figure 6.17.



		LOWER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	My+	ø8//0.20	8	2.51	4.52	ø12//0.25	12	0.25	Verifies Spacing
	Mx+	ø8//0.20	8	2.51	4.52	ø12//0.25	12	0.25	Verifies Spacing
Interruption of Main Reinforcement	My+, curt	ø8//0.20	8	2.51	4.52	ø12//0.25	12	0.25	Verifies Spacing
	Mx+, curt	ø8//0.20	8	2.51	4.52	ø12//0.25	12	0.25	Verifies Spacing

Figure 6.16 - Panel B Lower Surface reinforcement selection tables



		UPPER SURFACE							
		RECOMMENDED			EFECTIVE				
		Reinforcement	Rebar diameter	Area	Area	Reinforcement	Rebar diameter	Spacing	Comments
Main	As (Mx-), left	ø12//0.30	12	3.77	4.52	ø12//0.25	12	0.25	Verifies Spacing
	As (Mx-), right	ø12//0.30	12	3.77	4.52	ø12//0.25	12	0.25	Verifies Spacing
Interruption of Main Reinforcement	As (Mx-),eff, left	ø12//0.30	12	3.77	4.52	ø12//0.25	12	0.25	Verifies Spacing
	As (Mx-),eff, right	ø12//0.30	12	3.77	4.52	ø12//0.25	12	0.25	Verifies Spacing
Main's Distribution	As (Mx-), right	ø6//0.30	6	0.94	0.94	ø6//0.30	6	0.3	Verifies Spacing
Aditional	As (My-),eff, Left	ø12//0.25	12	4.52	4.52	ø12//0.25	12	0.25	Verifies Spacing
	As (My-),eff, right	ø12//0.25	12	4.52	4.52	ø12//0.25	12	0.25	Verifies Spacing
Fixed Edge	My-	ø8//0.20	8	2.51	3.14	ø10//0.25	10	0.25	Verifies Spacing
	Mx-	ø8//0.20	8	2.51	3.14	ø10//0.25	10	0.25	Verifies Spacing
Fixed Edge's Distibution	My-, distr	ø6//0.30	6	0.94	0.94	ø6//0.30	6	0.3	Verifies Spacing
	Mx-, distr	ø6//0.30	6	0.94	0.94	ø6//0.30	6	0.3	Verifies Spacing

Figure 6.17 - Panel B Upper Surface reinforcement selection tables

6.6 REINFORCEMENT MODELLING

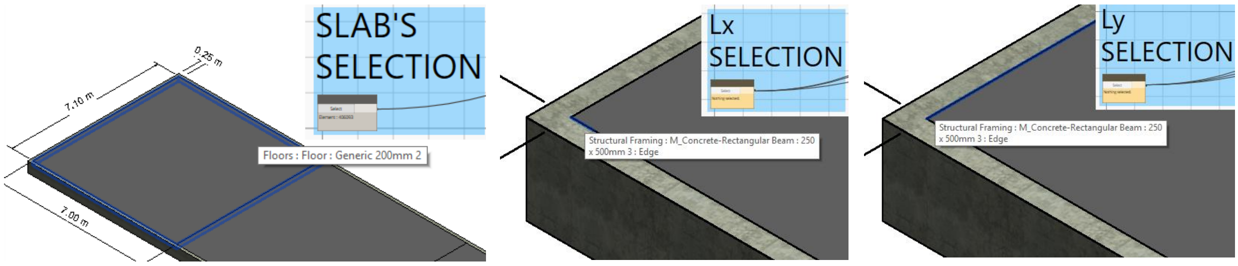
The reinforcement model in 3D environment will be aided by Dynamo through the open model in Revit. It is important the latter is opened first and through it, its extension is opened, so that Dynamo properly recognizes the model the routine will be applied to.

On the opening of the Dynamo file, as said in 4.1, the only editable nodes are the ones enveloped by blue colored groups. Within this first section it was selected first and foremost the Excel Worksheet file path within the personal computer; only then Dynamo is ready to receive information.

The reinforcement modelling will be generated panel by panel, beginning with A, followed by B and C. However, this is not the only way to reinforce the set of slabs, as they can be reinforced on any order, as long as their information is compatible with the Excel Worksheet. For example, it is absolutely necessary that the functionality presented in 3.4.2 is used in what concerns, at least, the support reinforcement or else there two elements of the same kind will be overlapped. It is also mandatory the saving of the Excel Worksheet every time a change is made, for Dynamo only reads the last saved version.

6.6.1 Panel A

To correctly reinforce the panel A, it is first necessary to save the Excel Worksheet with the decided reinforcement selected. Upon this step, and already within Dynamo's first section the selection of the slab panel element in Revit is needed, followed by its respective Lx and Ly edges, as the following image suggests (see Figure 6.18).



a) – Slab Selection b) – Lx Selection c) – Ly Selection

Figure 6.18 – Dynamo Inputs concerning a specific slab

By clicking the button "Run" Dynamo recreates the chosen reinforcements, from both upper and lower surfaces, and places them on their respective positions within Revit, resulting in the model represented in Figure 6.19.

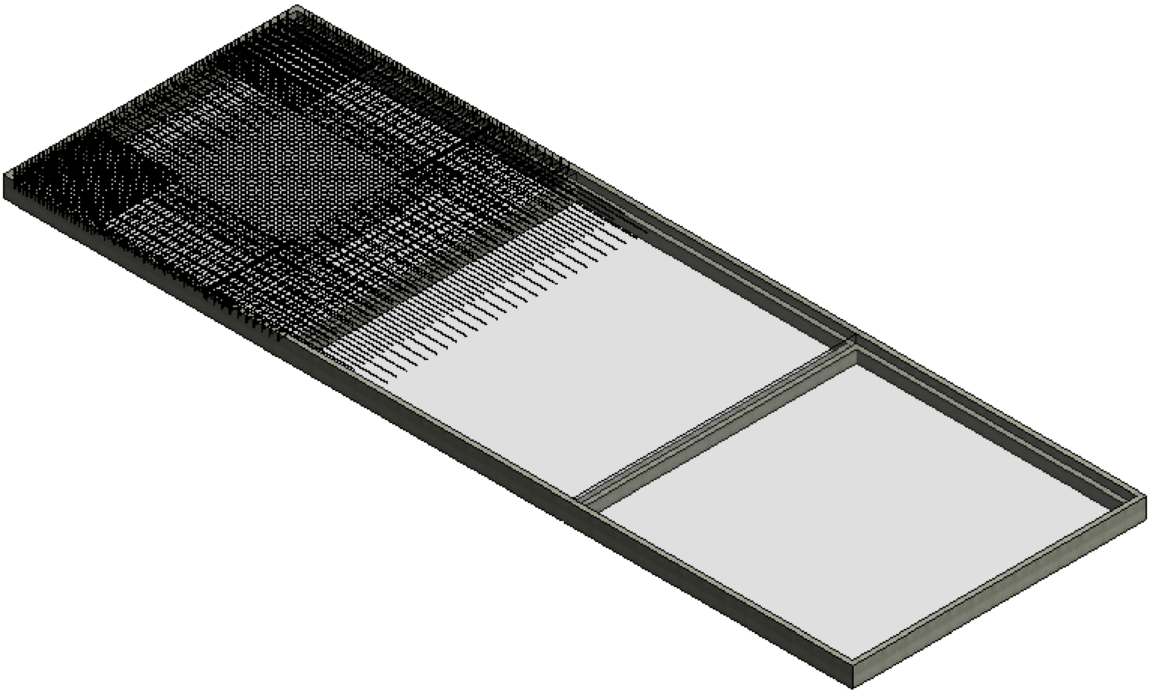
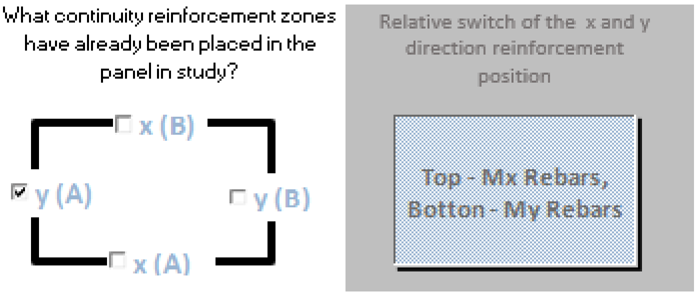


Figure 6.19 – Reinforcement modeling in Panel A

6.6.2 Panel B

To reinforce Panel B using the Excel's automatic approach there is the need to return to Step 4 – Slab Selection and select the B1 combination and click "Reinforcement Design", that will redirect the program to step 5.

As can be observed in the last figure, Panel A generated a support reinforcement that occupies some of Panel B's left strip, for the adequate measures must be applied. Still in step 5 the Check Box labeled "Y(a)" must be activated, and to avoid overlap of the positive main reinforcement the toggled button was also activated. These actions are represented in the figure below.



What continuity reinforcement zones have already been placed in the panel in study?

☐ x (B)

☑ y (A)

☐ y (B)

☐ x (A)

Figure 6.20 – Overlapping functionalities in Excel

Once the file is saved and the similar selections for Panel B are made in Dynamo, everything is ready for the reinforcement modelling of the second panel. The results can be seen in the Figure 6.21.

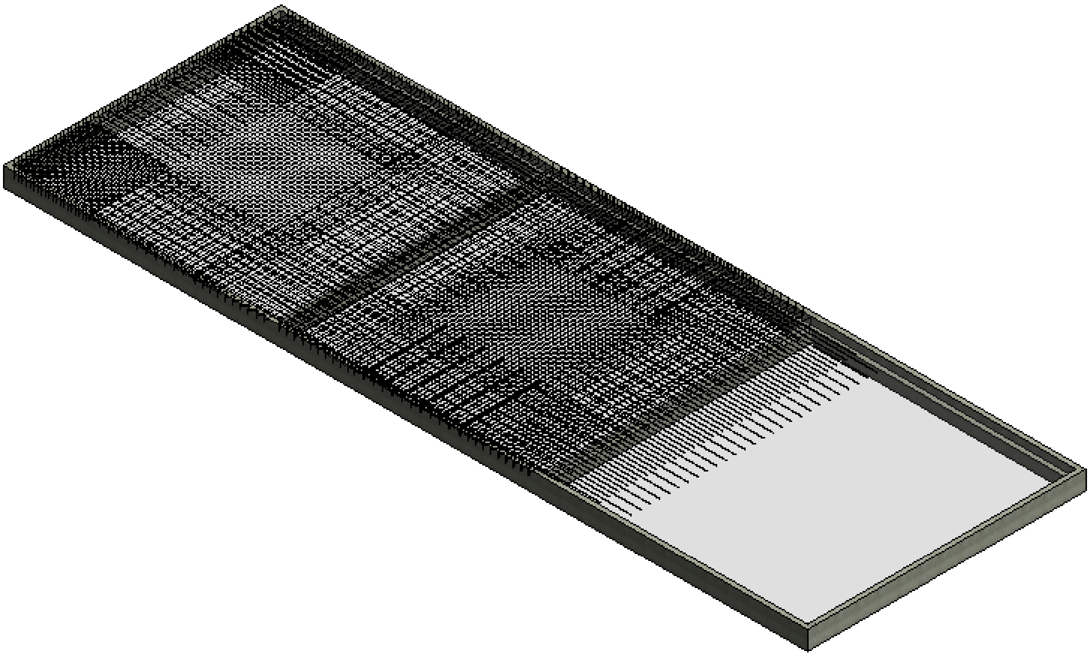


Figure 6.21 – Reinforcement modeling in Panel A and B

6.6.3 Panel C

The panel C reinforcement modeling procedure compares to the latter, as the panel in the step “Floor Plan Representation” was switched to “C1”, the overlapping precautions were repeated, the Excel file was saved, and the Dynamo inputs made. The fully reinforced set of panels are represented below.

Figure 6.22 - Reinforcement modeling in Panel A, B and C

6.7 INVENTORY MAPS

The inventory map related to the reinforcement in the three studied slab panels can be seen bellow.

Table 6.3 – Inventory Map for Rebar

Rebar Schedule						Rebar Schedule					
Bar Diameter	Bar Length	Hook At End	Hook At Start	Quantity	Reinforcement Volume	Bar Diameter	Bar Length	Hook At End	Hook At Start	Quantity	Reinforcement Volume
						12 mm	2220 mm	None	Standard - 90 deg.	13	3263.99 cm³
6 mm	3300 mm	None	None	7	653.14 cm³	12 mm	2220 mm	None	Standard - 90 deg.	13	3263.99 cm³
6 mm	3300 mm	None	None	7	653.14 cm³	12 mm	2220 mm	None	Standard - 90 deg.	13	3263.99 cm³
6 mm	3300 mm	None	None	7	653.14 cm³	12 mm	2220 mm	None	Standard - 90 deg.	13	3263.99 cm³
6 mm	3300 mm	None	None	7	653.14 cm³					52	13055.96 cm³
				28	2612.55 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3400 mm	None	None	7	672.93 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
				42	4037.57 cm³	12 mm	2270 mm	None	Standard - 90 deg.	20	5134.62 cm³
6 mm	3300 mm	None	None	8	746.44 cm³					160	41076.95 cm³
6 mm	3300 mm	None	None	8	746.44 cm³	12 mm	4000 mm	None	None	17	7690.62 cm³
				16	1492.88 cm³					17	7690.62 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³	12 mm	3500 mm	None	None	27	10687.70 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³	12 mm	3500 mm	None	None	27	10687.70 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³					54	21375.40 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³	12 mm	3500 mm	None	None	28	11083.54 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³	12 mm	3500 mm	None	None	28	11083.54 cm³
10 mm	2280 mm	None	Standard - 90 deg.	12	2148.85 cm³					56	22167.08 cm³
				72	12893.10 cm³	12 mm	5920 mm	None	Standard - 90 deg.	19	12721.19 cm³
10 mm	2280 mm	None	Standard - 90 deg.	19	3402.34 cm³	12 mm	5920 mm	None	Standard - 90 deg.	19	12721.19 cm³
10 mm	2280 mm	None	Standard - 90 deg.	19	3402.34 cm³					38	25442.38 cm³
				38	6804.69 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	17	14304.55 cm³
12 mm	2220 mm	None	Standard - 90 deg.	6	1506.46 cm³					17	14304.55 cm³
12 mm	2220 mm	None	Standard - 90 deg.	6	1506.46 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	21	17670.33 cm³
12 mm	2220 mm	None	Standard - 90 deg.	6	1506.46 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	21	17670.33 cm³
12 mm	2220 mm	None	Standard - 90 deg.	6	1506.46 cm³					42	35340.66 cm³
				24	6025.83 cm³	12 mm	7350 mm	None	Standard - 90 deg.	28	23275.43 cm³
12 mm	2270 mm	None	Standard - 90 deg.	8	2053.85 cm³	12 mm	7350 mm	None	None	28	23275.43 cm³
12 mm	2270 mm	None	Standard - 90 deg.	8	2053.85 cm³	12 mm	7350 mm	None	Standard - 90 deg.	28	23275.43 cm³
12 mm	2270 mm	None	Standard - 90 deg.	8	2053.85 cm³					84	69826.29 cm³
12 mm	2270 mm	None	Standard - 90 deg.	8	2053.85 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	28	23560.44 cm³
				32	8215.39 cm³					28	23560.44 cm³
12 mm	2270 mm	None	Standard - 90 deg.	10	2567.31 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	34	28609.10 cm³
12 mm	2270 mm	None	Standard - 90 deg.	10	2567.31 cm³	12 mm	7440 mm	Standard - 90 deg.	Standard - 90 deg.	34	28609.10 cm³
12 mm	2270 mm	None	Standard - 90 deg.	10	2567.31 cm³					68	57218.20 cm³
12 mm	2270 mm	None	Standard - 90 deg.	10	2567.31 cm³						
				40	10269.24 cm³						

6.8 SECTION VIEWS

An example of a section view can be seen below (Figure 6.23) related to the zone of the fixed edge strip of panel B, marked in red.

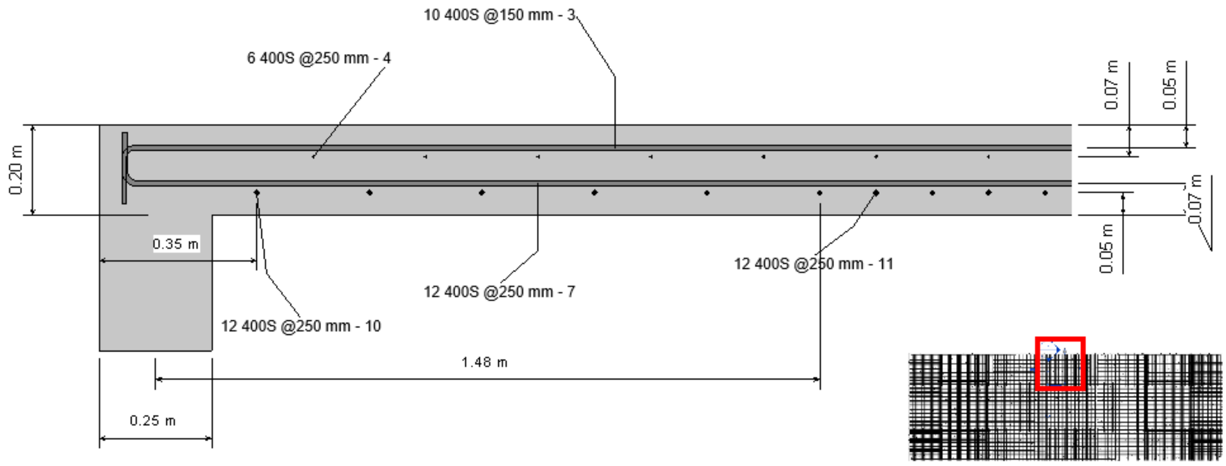
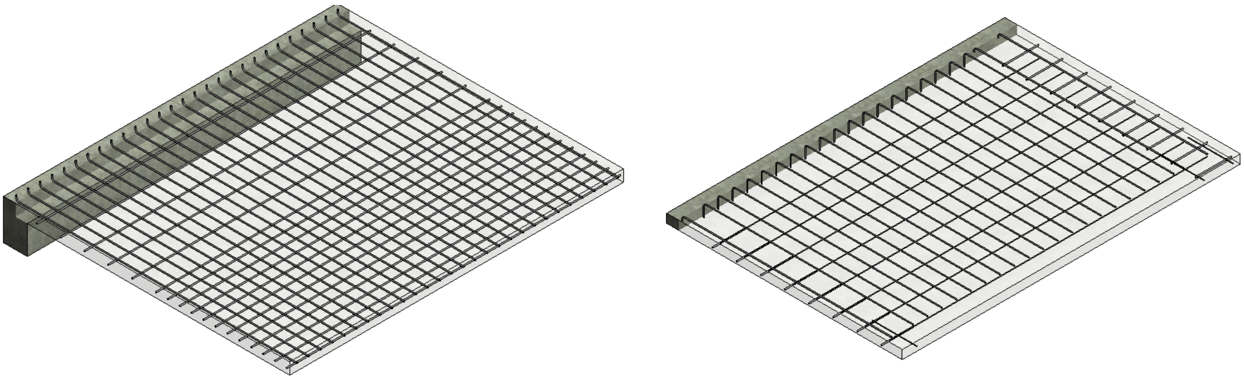


Figure 6.23 – Section View detail of the fixed edge strip of panel B

To complement the section view above, Figure 6.24 shows the lower and upper reinforcement area view of the same zone.



a) Lower surface reinforcement

b) Upper surface reinforcement

Figure 6.24 – Area section view of lower and upper reinforcement of the fixed edge strip of panel B

The depicted sections can be repeated as many times as necessary to detail all reinforcement zones in the three panels.

6.9 COMPARISONS

It seems that, in the original project presented few fluctuations between either placement and rebar type, justifying a route of simplicity and transparency in site. In the automatic model, while the diameter homogenization is still possible with the proper reinforcement selection, the reinforcement zones cannot be avoided, for the Excel Worksheet does not allow such functionality. Consequently, the most differences between the two project solutions are mainly in the quantity of zones of reinforcement applied, and not the effective reinforcement types.

6.9.1 Lower surface

Excluding the fact that the original reinforcement design did not account for detailed corner reinforcement, the lower surface, between the two, is the one with most resemblance with the automatic solution (see Figure 6.25). Having this said, the choices made for the main positive reinforcement were led by the diameter uniformity criteria, ruled by the main negative reinforcement with a recommended diameter of 12 mm. This fact leads to believe that the original choice of 12//0,11 and 12//0,125 correspondent to the main positive reinforcement was also guided by diameter uniformity in site.

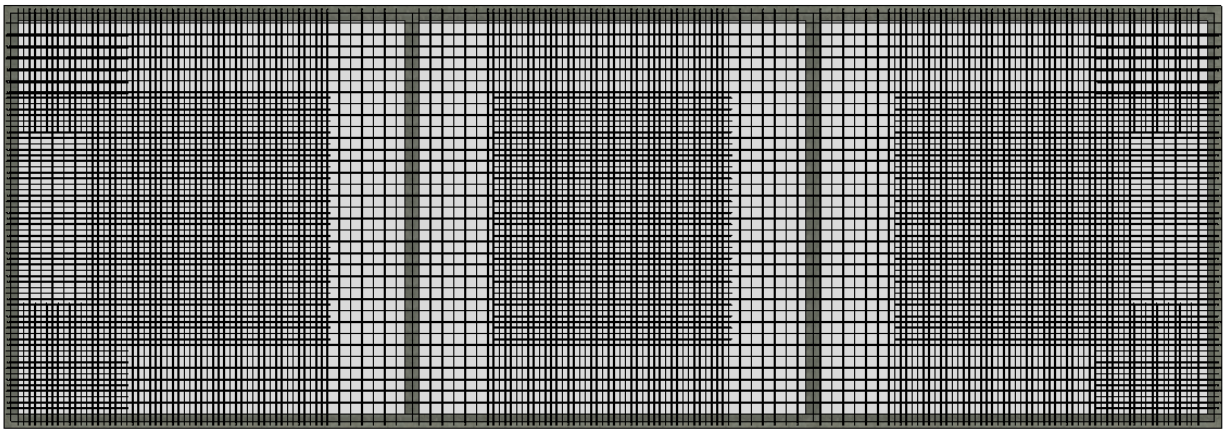


Figure 6.25 – Lower surface reinforcement for panels A, B and C

6.9.2 Upper Surface

As explained before both the corner and additional reinforcement zones were neglected, in detail, from the original project. Instead, what was presented was some kind of fixed edge reinforcement distributed from edge to edge, on all fixed borders. This covers both neglected zones with an area of reinforcement of 5,24 cm^2/m in X and Y directions, which would be enough to meet the design requirements for both zones, if they did not refer to effective, but the design area of reinforcement.

The remainder of the zones applied through automatic modelling, namely the support and fixed edge reinforcement and their respective distribution reinforcement, correspond almost with no significant variation to the original project, either in reinforcement type as in placement.

All upper surface reinforcement zones can be seen in Figure 6.26.

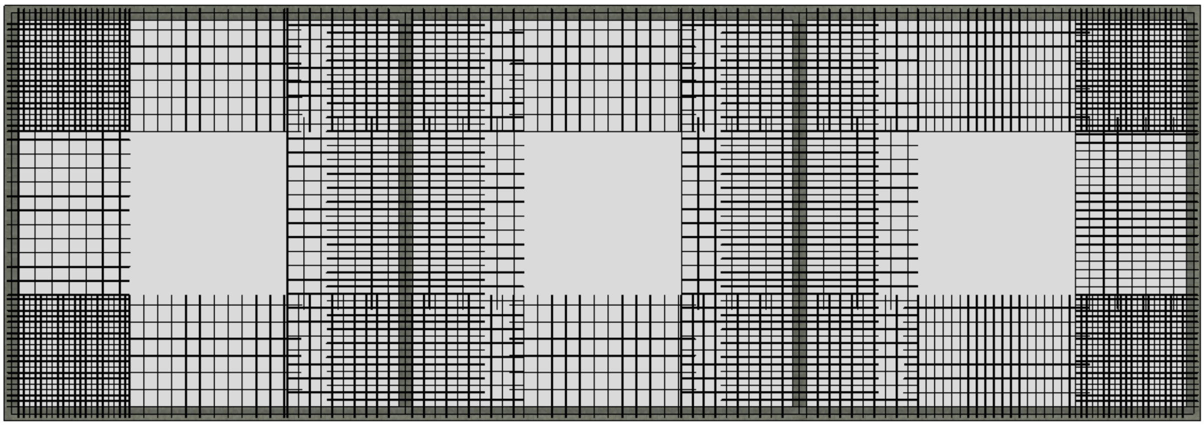


Figure 6.26 – Upper surface reinforcement for panels A, B and C

CHAPTER 7

CONCLUSIONS

7.1 GENERAL CONSIDERATIONS

The development of the present work shows the advantages of the introduction of visual programming into the AECO industry. The link between structural engineering knowledge to programming skills, that do not often overlap, creates a powerful tool to fulfill almost any functionality gap.

The use of Dynamo did not constitute a barrier to the main objective of this thesis, for it is no longer a brand-new software and there is significant quantity of information available as well as continuous third party's node package launches that fulfil almost every need. The almost complete dependence of Dynamo in the Excel worksheet also eased the workload associated with the visual programming, shifting it to the basic programming that almost every Engineers dominates. Given the quantity of boundary cases for the slabs and reinforcement zones at stake the Excel cell formatting and macro programming offer a variety of conditional paradigms that Dynamo is just not yet to efficiently host.

Even though the developed routines are limited to rectangular two-way slabs, this kind of work can be a stepping stone to more intricate slab cases or even some of its contents adaptation into other structural elements. The widespread of the incorporation of visual programming into structural engineering should be a norm, not the exception. The only barrier preventing it from being resorted to more often is the time spent in the development of the routines and the added amount of time needed for Dynamo to process and reproduce reinforcement elements. Despite this, the effort in manually detailing any structural project, does not compare to the advantages of using BIM methodology to adapt, manage and adjust the needs of the structural engineer to fit every project, regardless of specialty.

The continuous craving for better and more efficient tools within the AECO industry needs to be maintained, for the BIM mandatory implementation is spreading and might someday target Portugal. If Portuguese Industries want to accompany their practices with more developed countries in the field and follow the latest industry trends, lots of facts point to the need of shifting away from the 2D drawings into a full-on 3D environment.

7.2 FUTURE DEVELOPMENTS

Even though the main objectives for this thesis were met, there is still a lot that could be done to improve the developed routine, not only to encompass more functionalities as for increase its performance. The future recommended developments for this thesis contain:

- Further development of the Excel worksheet to accommodate different dimension consecutive slab panels as well as the integration of slabs supported on three edges as well as flat slabs;
- Further and more in-depth manipulation into the options for the rebar anchorage, either within Dynamo or in Excel;
- Optimizing the performance of the Dynamo routine by reducing the number of nodes.

Although challenging, the development of a program from the ground up was a very gratifying experience, as for the final result has reasonable applicability potentialities in the AECO industry. Considering the key to all the accomplishments of the present thesis was the experience obtained during the time spent at Newton – Consultores de Engenharia, the author’s future carrier will always seek the BIM methodology used during the internship.

REFERENCES

[1] John McManus,What Construction Can Learn From Other Industries 2017. [Online]. Available: http://www.builderonline.com/builder-100/strategy/what-construction-can-learn-from-other-industries_o. [Accessed: 24-Jun-2018].

[2] Lidija Grozdanic, Thoughts on Disrupting the AEC Industry 2016. [Online]. Available: https://archipreneur.com/thoughts-on-disrupting-the-aec-industry/. [Accessed: 24-Jun-2018].

[3] "A (Very) Brief History of the Construction Industr Constructible, 2018. [Online]. Available: https://constructible.trimble.com/construction-industry/a-very-brief-history-of-the-construction-industry. [Accessed: 24-Jun-2018].

[4] A. Sharafutdinova, BIM in Practice: BIM Education" Saimaa University of Applied Sciences, 2012.

[5] H. PIRES, Automatização da Modelação Bim de Armaduras no Projeto de Estruturas, Instituto Superior de Engenharia do Porto, 2017.

[6] N. Sivakugan, C. T. Gnanendran, R. Tuladhar, and M. B. Kannan, Civil Engineering Materials, 1º. Cengage Learning, 2017.

[7] A. H. Nilson, D. Darwin, and C. W. Dolan, Design of concrete structures. The Mcgraw-Hill Companies, Inc., 2010.

[8] GRAITEC, The Robot Structural Analysis Story 05/03/2014, 2014. [Online]. Available: https://www.youtube.com/watch?v=blfTXLuYMbA. [Accessed: 24-Jun-2018].

[9] P. J. Montoya, Á. G. Meseguer, and F. M. Cabré, Hormigón Armado, 14º. Barcelona: Editorial Gustavo Gili, SA, 2000.

[10] BS 8110 – British Standard for the design and construction of reinforced and prestressed concrete structures. London: British Standard Institution, 1985.

[11] B. Hardin and D. McCool, BIM and Construction Management - Proven tools, methods, and workflows, 2º., no. 1. Wiley, 2015.

[12] S. Cruz and M. Azenha, Estruturas de Betão II Subject Notes, Técnico de Lisboa, Departamento de Engenharia Civil e Arquitetura, Lisboa, 2013.

[13] LNEC, CT 115 – Eurocódigos Estruturais. [Online]. Available: http://www.lnec.pt/pt/servicos/normalizacao-e-regulamentacao/normalizacao/ct-115-eurocodigos-estruturais/. [Accessed: 24-Jun-2018].

[14] A. Dahlgren and L. Svensson, Guidelines and Rules for Detailing of Reinforcement in Concrete Structures, 2013.

[15] C. Félix, Disposições construtivas relativas a armaduras. Instituto Superior de Engenharia do Porto, 2010.

[16] S. Azhar, M. Hein, and B. Sketo, Building Information Modeling (BIM): Benefits , Risks and Challenges, BIM-benefit measurement, vol. 18, no. 9, p. 11, 2007.

[17] P. Pavlov, Automation of Information Flow From Revit To Bsim Using Dynamo, Aalborg university, 2015.

[18] T. Mousiadis and S. Mengana, Parametric BIM: Energy Performance Analysis Using Dynamo for Revit, KTH Royal Institute of Technology, 2016.

[19] N. Korqa, T. Frederica, T. De, and V. Heitor, GENERATIVE DESIGN FOR BIM Its Influence in the Design Process Examination Committee, no. November, 2015.

[20] J. Ter Maaten, BIM and its Envisioned Use in Engineering Infrastructure, Delft University of Technology, 2015.

[21] J. G. A. Freitas, Metodologia BIM – Uma nova abordagem , uma nova esperança, Universidade da Madeira, 2014.

[22] I. F. do V. Gonçalves, Aplicação do BIM ao Projeto de Estruturas, Instituto Politécnico de Viana, 2014.

[23] Y. Li, Automated Code-checking of BIM models, Universidad de Cantebria, Faculdade de Engenharia da Universidade do Porto, 2015.

[24] J. Silva, Princípios para o Desenvolvimento de Projeto com Recurso a Ferramentas BIM, Faculdade de Engenharia da Universidade do Porto, 2013.

[25] M. R. B. de Almeida, Análise da interoperabilidade aplicada ao projeto BIM de Estruturas Metálicas, Instituto Superior de Engenharia do Porto, 2015.

[26] W. S. FLEMING, BIM modelling for structural analysis, Poznan University of Technology, 2016.

[27] A. Monteiro and J. Martins, Building Information Modeling (BIM) - teoria e aplicação, Int. Conf. Eng. UBI, p. 10, 2011.

[28] J. C. Lino, M. Azenha, and P. Lourenço, Integração da Metodologia BIM na Engenharia de

Estruturas, Encontro Nac. Betão Estrutural -BE2012, no. November, p. 10, 2012.

[29] C. Eastman, K. Liston, R. Sacks, and K. Liston, BIM Handbook Paul Teicholz Rafael Sacks. 2008.

[30] V. Roberti, Implementing BIM Standards in a Structural Engineering Firm, Western Michigan University, 2016.

[31] B. Ferreira, J. Lima, J. Rio, and J. P. Martins, Integração da Tecnologia BIM no Projeto de Estruturas de Betão, Encontro Nac. Betão Estrutural, pp. 24–26, 2012.

[32] C. A. Hunt, The Benefits of Using Building Information Modeling in Structural Engineering, Utah State University, 2013.

[33] A. Strafaci, What does BIM mean for civil engineers? - Civil + Structural Engineer magazine, What Does BIM mean for Civil Engineers?, 2014. [Online]. Available: https://csengineermag.com/article/what-does-bim-mean-for-civil-engineers/. [Accessed: 24-May-2018].

[34] A. A. Bhusar and A. R. Akhare, Application of BIM in Structural Engineering, SSRG Int. J. Civ. Eng., vol. 1, no. 5, pp. 12–20, 2014.

[35] A. K. Nielsen and S. Madsen, Structural modelling and analysis using BIM tools, Civ. Eng., no. June, p. 19, 2010.

[36] R. Gomes and D. D. E. Lima, Tecnologia BIM na Arquitetura, Universidade Presbiteriana Mackenzie, 2011.

[37] G. Dimov, Analysis of Revit 2014 based on the Modeling of a TU Munich Building, Technical University of Munich, 2014.

[38] D. G. P. Tarrafa, Aplicabilidade prática do conceito BIM em projeto de estruturas, Faculdade de Ciências e Técnologia, Universidade de Coimbra, 2012.

[39] L. Maia, P. Mêda, and J. G. Freitas, “BIM Methodology, a New Approach - Case Study of Structural Elements Creation,” Procedia Eng., vol. 114, pp. 816–823, 2015.

[40] NP EN 1992-1-1 2010, Eurocódigo 2 – Projeto de estruturas de betão: Parte 1-1 : Regras gerais e regras para edifícios. Portugal: IPQ, 2010.

[41] J. F. Almeida, J. N. Camara, A. Costa, E. Júlio, and R. Rodrigues, Estruturas de Betão I, Folhas de apoio às aulas. Técnico de Lisboa, Departamento de Engenharia Civil e Arquitetura, 2014.

[42] J. Appleton, Estruturas de Betão, Volume 1. Edições Orion, 2013.

[43] Z. Ahmed, The impact of material management on construction project delivery in Maldives, Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 2017.

[44] B. V. Mahavidyalaya, V. Vidhyanagar, and N. V. Vidhyanagar, Construction Material Management, National Conference on Recent Trends in Engineering & Technology,Gujrat,India, no. May, pp. 1–5, 2011.

[45] M. Gamil, Mapping between BIM and Lean-Construction, Hochschule für Technik und Wirtschaft Berlin University of Applied Sciences, 2017.

[46] K. Chessman, D. Ireland, N. Kennedy, J. Mark, R. Morrison, and R. Radonjic-Vuksanovic, Structural Engineering Design Services for Buildings Guideline, no. June. Ontario: Professional Engineers, 2017.