

Design of structures using BIM technology

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Abstract

The Building Information Modelling (BIM) concept has been implemented in the Architecture, Engineering and Construction (AEC) industry, imposing the establishment of government regulations on public works projects at a global level. The BIM methodology is based on the generation of a three-dimensional digital model that contains all the information underlying the development of a project. The BIM model supports the collaboration between the different stakeholders of a project, allowing the correct transfer of information between specialties, as it contributes to the reduction of design errors and time spent, leading to the achievement of a quality end product.

This study critically assesses the level of technological development of BIM tools applied in the design of structures. Using BIM base platforms: a single model is generated, with the architectural and structural components; the analytical model of the structure is obtained and transposed to the calculation program; the design is performed, followed by the detailing of the reinforcement. In this process, the existing level of interoperability is observed, provided by the current technological capacity, which is verified through the analysis of the quality of the information transferred between programs.

The study shows that, despite the limitations identified throughout the process, mainly due to interoperability problems, the methodology presents clear advantages in the development of the project, based on the ability to concentrate information, overlap of specialties, and transfer of results between stages, contributing positively to the implementation of BIM in the design of structures.

Keywords: BIM, design of structures, interoperability, data transfer, information extraction.

1 Introduction

The Building Information Modelling (BIM) methodology presents a new paradigm in the approach to the representation of buildings, using technologically more advanced computer systems, applied to the Architecture, Engineering and Construction (AEC) industry. This methodology enables the visualization of the 3D model representative of the building and the centralization of all the information associated with its design. The BIM project is built on a collaborative basis between all stakeholders in the design of a work, and throughout its entire life span, providing an adequate analysis of the compatibility between the different discipline projects [1]. The information created and reused throughout the design of the project is shared, from the project design to the use phase of the building. In this way, the design of projects becomes faster, with a high degree of associated trust, and evident gains in the accomplishment of each work.

The interoperability capacity, inherent to BIM-based tools, promotes the information flow between systems, a relevant aspect in the design of structures [2]. As so, the scope of this study concerns the demonstration of the application of the BIM methodology in the development of the design of structures, illustrating the collaboration between architecture and engineering. Throughout the work it's described the process of elaboration of the project and pointed out the main advantages identified as well as the limitations verified. The efficiency of the methodology relies heavily on the interoperability capacity established between software. The level of interoperability is analyzed in detail between the programs used in the development of the design of structures in relation to a case study.

2 Development of the BIM model

Initially, the BIM model component of the building architecture was designed in order to serve as a basis for the modeling of the structural component. Both components were designed based on a case study. The BIM tool used is Autodesk's Revit and the structural analysis is performed using Robot Structural Analysis software, also from Autodesk. The level of interoperability between the two is therefore expected to be high.

The building is situated in Tavira and consists of 2 floors and a basement. The basement floor is surrounded by containment walls that cover the entire construction area of the house, floor 0 comprises hall, kitchen, and living rooms, and on the 1st floor is the bedroom area. The roof is terrace. All information relevant to the modeling was obtained from the documentation provided in pdf format.

The first step when start modeling is to define the initial information, regarding aspects like the template (architectural), the levels of each floor and the grid of auxiliary axes. The grid helps defining the wall distribution and the levels define the different floors location. The grid established corresponds to the structural project, and the architectonical elements were adapted in their location representing the architecture.

The modeling of the architecture component is initiated by the implementation of walls, followed by floors and stairs. In Revit, it's selected a parametric object representative of a wall element from the project's library and then adapted to each wall of the architecture project. The same procedure is used for the other elements of the model. Figure 1 illustrates 3D perspectives of the architectural model.

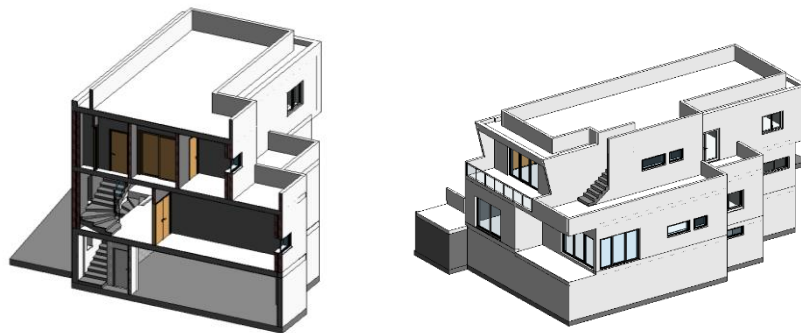


Figure 1 - 3D model of the architecture and representation of a vertical cut on it.

2.1 Structural component

Finished the architecture component of the BIM model, the modeling of the structural solution was proceeded. The parametric objects to be considered are of a structural nature allowing the automatic obtaining of the discretized model, associated with physical properties required in the calculation. The analytical model serves as the basis for structural calculation, being transferred to Robot. Previously, the analytical model is checked for consistency. In Robot, the structural design is performed.

Within the framework of collaboration between disciplines, Revit allows the connection among different files through the *Revit Link* Tool. Thus, it was created a new file and selected the structural template. Through this tool, a link was created between the file with the architecture component, and the file with the structure component. The link established provides the visualization of the architecture model in the structure file, allowing the reading of all its information, without the possibility of it being manipulated. The advantage of this option in relation to the modelling of the two components within the same file, is related to a better performance of the program during the modelling, since it is not overloaded with the information related to the two specialties. In this way it is possible to easily model and manage the various structural elements, respecting the constraints imposed by the architectural elements.

In Revit, levels were defined for the modeling of the structural project. The levels considered were defined with different vertical heights of the admitted levels of the architecture project. This option was taken in order to consider the difference in architectural and structural dimensions, due to the thickness of the layer of coverings of the architectural slab. The slabs of each model are associated with the level corresponding to their top elevation. Once the work levels were defined, the structural elements were created and placed. For each category of parametric objects, the geometry and the associated analytical model are analyzed:

- The structural columns were defined with the necessary sections for the project. Since the project also required the use of "L" section columns, there was a necessity to explore the capacity to create families in Revit, since the program library does not have this type of section. The insertion of the pillars into the model is done floor by floor and supported on the grid. The analytical axis of each type of structural column is automatically associated with the geometric axis of the section.
- At the basement level, the project admits the existence of resistant walls with the function of soil containment. The analytical model is of the Shell type and its plane is located in the middle of the wall thickness.
- The beams are modeled interconnecting the already created columns. Their extreme points are fixed using the top of the columns or resistant walls. Continuous beams, of constant section, were modeled as a continuous element, constituting a single object. This option of modelling a continuous element transposing several spans, aims to turn the modelling process more expeditious. By default, when modelling a beam supported on two columns, the program keeps the analytical axes of the columns in the geometric center of their sections, connecting the analytical ends of the beam to them.
- The structural solution provided contemplates two types of foundation, isolated footings (*Isolated foundation*) and strip footings (*Wall foundation*). The modeling of the wall foundations requires that the element be associated with an adjacent wall element (*Host*). Once placed, its analytical model corresponds to a fixed linear support condition, which is connected to the base of the shell model of the wall. The use of isolated foundations satisfies the support of the columns in geometric terms. However, for some cases, the analytical discretization may not be fully satisfactory. Since this element generates a punctual support condition at its geometric center, the structural column will only be supported in terms of the analytical model, if the base of its axis coincides with the support point, concluding that Revit is not yet prepared for slightly more complex situations.
- Structural slabs were generated using the capacity of collaboration between linked projects of Revit, taking advantage of the geometry of the architectural slabs. From the *Copy/Monitor* tool, Revit allows to copy the slabs from the architecture project to the structures project. In this process is associated a new object of slab created, with a thickness of 16 cm, transforming the architectural slab into a structural slab with active analytical model. Subsequently, the positioning of the structural slabs in height is changed in relation to the defined structural levels, resulting on the disposition showed in Figure 2. In the figure we can also see the structural model created.

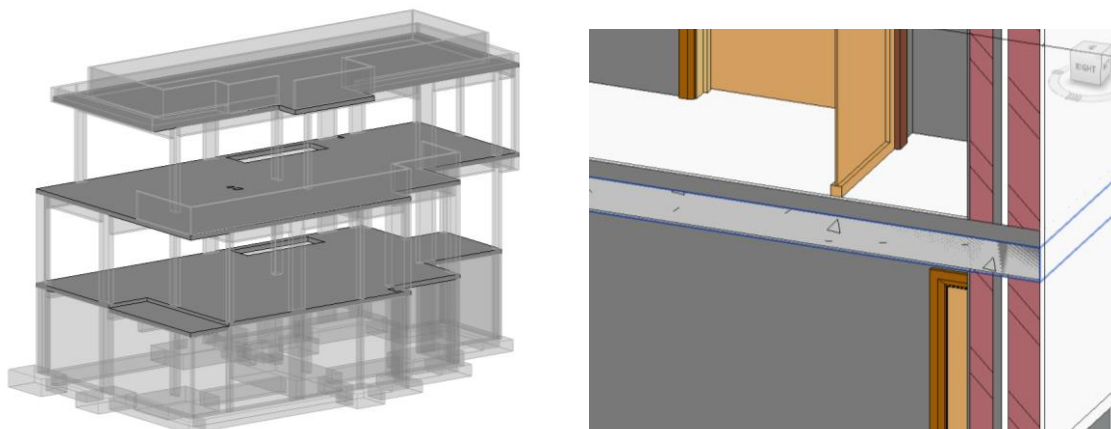


Figure 2 - 3D model of the structure and relative positioning of the structural slab in relation to the architectural slab

2.2 Interference check

The interference check or detection of conflicts is one of the best known and most used BIM modeling software features. This procedure identifies the occurrence of collisions or interferences between elements belonging to the various disciplines that coexist in a project. Within the scope of this study, this capacity was used in the analysis of possible conflicts between elements of the architecture and structure components of the BIM model. One of the conflicts detected is the overlapping of one of the lower walls of the 1st floor (*Wall*) with the guard of the balcony of that same floor (*Railings*). To solve the conflict the structural wall was selected, and its length was redefined, adapting it to the extension of the wall defined by the architecture. Figure 3 illustrates the conflict before and after the resolution of the interference.

These conflicts can lead to significant problems during construction, leading to increased costs and time in the development of the works. Both models were built based on the provided documentation of the structural design and architecture of the building, which were carried out using the traditional methodology. This example shows the advantage of this tool based on the BIM methodology, for those involved in the preparation of the project, compared to the traditional way, by allowing to avoid future errors in the construction phase in a simple and automated way.



Figure 3 - Interferência entre murete estrutural e guarda da varanda

2.3 Verification of the analytical model

For an adequate direct transposition of the model created in Revit to the analysis program, the analytical model must admit regularity and coherence, in order to avoid inconsistency errors in the calculation model. As mentioned, the analytical model of the beams is automatically connected to the analytical axis of the

columns. In Figure 4 the image on the left illustrates the result of the automatic detection. These elements were adjusted in order to achieve an orthogonal arrangement between all the elements, allowing subsequently, an adequate discretization of the finite element mesh in the slabs by the calculation program and therefore, a good approximation of results. Thus, the analytical axes of the beams were aligned with the corresponding Grid alignments, and the analytical axes of the columns with the intersection of alignments, as can be seen in the image on the right. The correct connection between these elements was also checked.

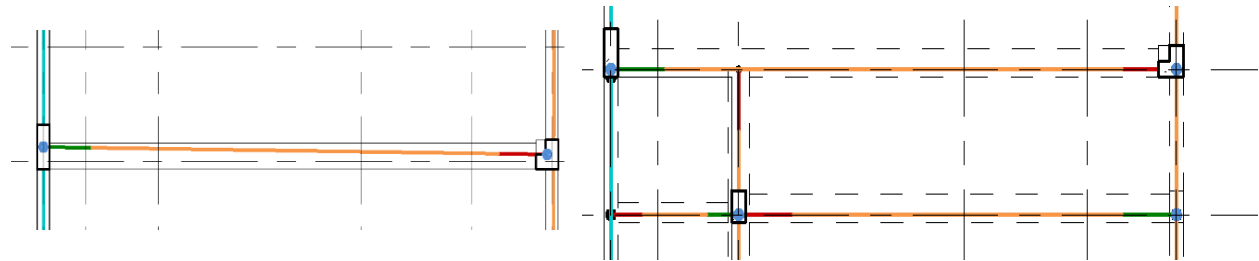


Figure 4 - Analytical model before and after readjustment of beams and columns

It was also ensured the alignment of the outline of the analytical surface of the slabs with the grid lines coinciding in its perimeter with the analytical axes of the beams or with the top of the analytical surface of the retaining walls. After these changes, it was necessary to resolve the connection between two unaligned beams and the column that supports them. As can be seen in the Figure 5 the beams are supported at the ends of the column section, without creating an analytical connection to it. The solution for this connection was to model analytical rigid bars (Analytical link) connecting the ends of the beams to the analytical axis of the column. In addition to providing support for the beams, it also introduces stiffness to the connection, bringing the model closer to the real situation.

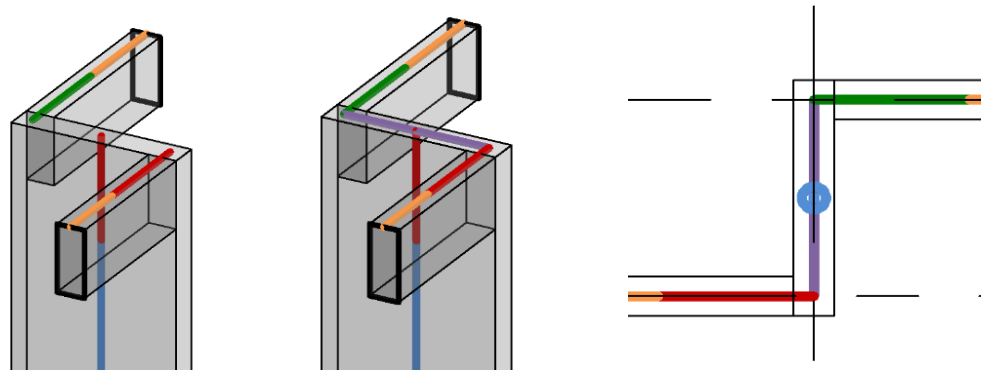


Figure 5 - Analytical link between beams and column.

Through the image of the Figure 6 it is possible to have a clear idea of the model, and the elements that will be transferred to Robot, such as the bars corresponding to the beams and columns, and the surfaces corresponding to the slabs and walls. It was also activated the visualization of analytical nodes, in order to verify the correct connection between the different elements. These capacities are inherent to the BIM modeling tools and constitute strong support to the structural designer.

In Revit, load cases were defined in order to transfer them to Robot. The actions considered were the permanent loads and the live load. These loads were applied in the form of area and linear loads, as appropriate. The structural elements considered active in the analytical model, automatically introduce the action relative to their own weight in the model. The quantification of this action is based on the parametric information associated to each element.

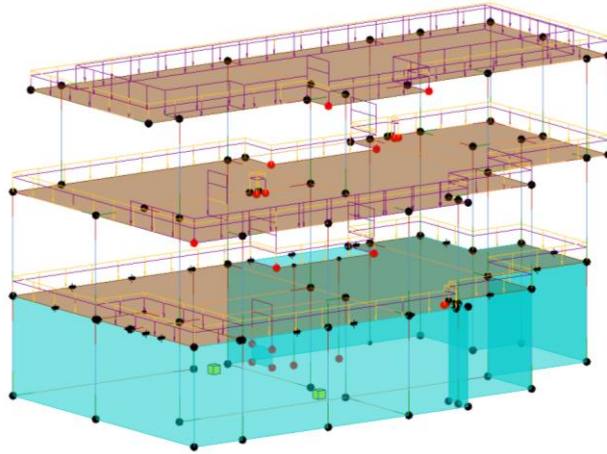


Figure 6 - Perspective of the analytical model in Revit with the applied loads.

3 Structural analysis

This section discusses the process of transferring the analytical model, created in Revit, to the structural calculation program, Robot Structural Analysis. The level of compatibility between the two programs is evaluated, based on the verification of the correction of the transferred information. The definitions imposed in Revit are verified and, additionally, are established the combinations required in the Eurocode, necessary for the structural calculation, including the definition of the seismic action. Once the calculation model has been validated, some structural elements are calculated and detailed. Subsequently, the model created will be transposed again to Revit, in order to assess the level of interoperability between the programs, in relation to the inverse information flow.

3.1 Transferring from Revit to Robot

It was verified that the model transfer to Robot occurred without errors. All the analytical elements were correctly transposed maintaining their information, namely their geometry, the characteristics of the constituent materials, as well as the alignment grid and the defined actions (Figure 7).

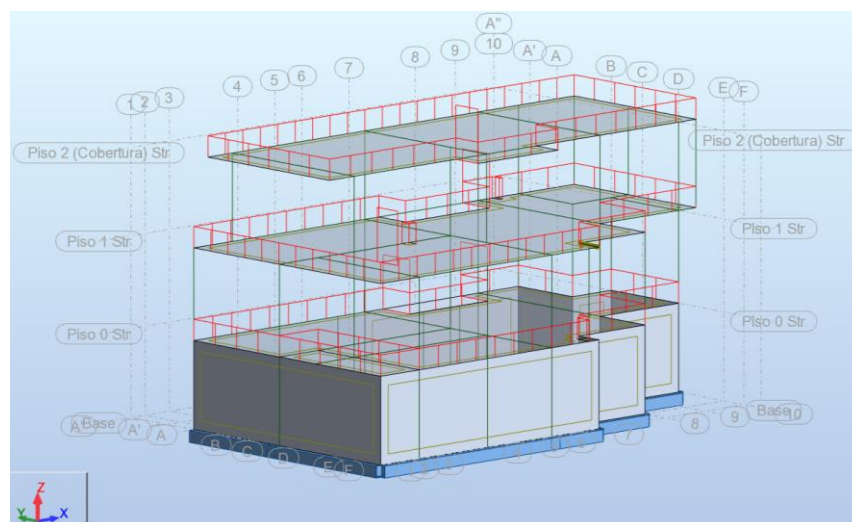


Figure 7 - Analytical model in Robot

When describing the structural elements, it was mentioned that isolated foundations only offers analytical support if the base of the columns analytical axis coincides with the support point, located at the geometric center of each footing. Therefore, in order to complete the modelling of the structure's supports, in relation to the isolated foundations that support two columns, a rigid connection must be created between the lower extremities of the analytical bars of the columns and the support point of the foundation. This procedure is performed in Robot through the *Rigid Links* tool, because Revit does not allow creating this type of connections with the isolated supports.

Since the seismic analysis of the building is performed, there is a necessity to carry out the following procedures: In relation to the reinforced concrete walls located in the underground basement, springs with high stiffness are placed in their contour, in order to restrict the displacements resulting from the horizontal action of the earthquake in the horizontal plane at the level of the Floor 0; in order to consider the low torsional strength of reinforced concrete beams and columns in the structural analysis, it's necessary to reduce the value of the moment of inertia of torsional rotation in all columns and beams of the model.

3.2 Structural calculation

In Robot, once the seismic action has been defined based on the guidelines in the Eurocode 8 regulations [3] and in the National Annex, the combinations of actions are introduced. All combinations are automatically generated in Robot through *Automatic Combinations*, indicating the source of the guidelines. The safety check is performed on Robot, which shows the ability to design and define the reinforcement area for each element, complying with the guidelines defined in the Eurocode and some conditions that can be specified by the user.

- Based on the results diagram, obtained from the application of the combinations of actions considered, two different cases of reinforcement detailing of continuous beams were performed: of constant section, and of variable section. The *Provided Reinforcement* option was used to perform the automatic calculation of reinforcement. In this process was observed some inconsistencies that were solved by adequate adjustments of the reinforcement detailing in a manual way, after the automatic calculation. Figure 8 illustrates an example of the beam reinforcement detail on Robot.
- The verification of the column design is performed in a similar way to the beams. The verification of safety is illustrated in relation to two columns with different cross-section shapes (rectangular and "L" cross-section columns). An error was detected by the program related to the dimension of the cross section and the distance between the point of inflection and the ends of the column (5.4.1.2.2 of EC8 [29]). To solve the situation, it was necessary to increase the section width of the column in question. Thus, a new cross section was created in the Robot, assigned to the column, and the calculation of the reinforcement was performed again, where it was found that no errors occurred. In relation to the second case of the "L" section column, when detailing, an error related to the spacing between straps was detected. After analyzing the error in question, it's realized that the detailing performed complies with the defined standards. Therefore, it must be a defect in the analysis by the program, in relation to this type of columns.
- Using the *Required Reinforcement for Slabs* tool, some of the most relevant parameters to consider were indicated prior to the calculation of the reinforcement area required for the safety check of the slab located on the 1st floor. It's important to mention the option of reducing the forces on the slab supports, in order not to oversize the structure. Subsequently, using the *Provided Reinforcement* tool, Robot calculated the detailing of the reinforcement for the slab.
- The transfer of geometric information from Revit footings to Robot is not possible. However, Robot allows the transfer of the reinforcement of each of these elements to Revit. As a result, in order to be able to detail the reinforcement of the selected footing, its geometry was defined in Robot according to the footing created in Revit. Then, the necessary reinforcement was calculated for safety verification.

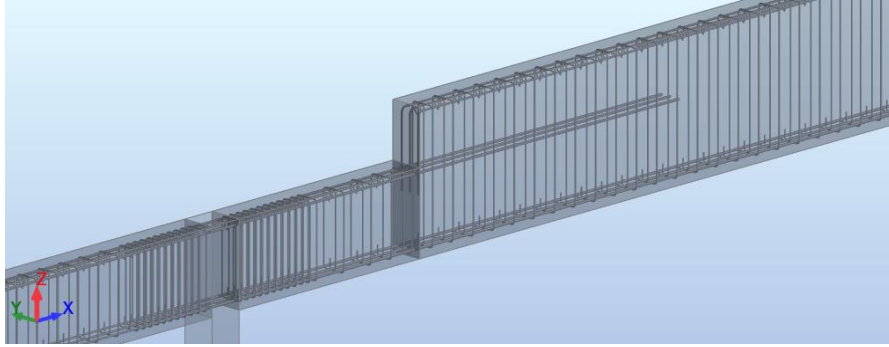


Figure 8 - Detail of beam reinforcement on Robot after manual adjustments.

4 Transferring from Robot to Revit

One of the fundamental concepts of the BIM methodology is to centralize all information in a single model. Therefore, also within the scope of the analysis of the level of interoperability between program, the information created in Robot on the reinforcement of each element is transferred to Revit, verifying the consistency of the data transferred.

After updating the initial structure model, modeled in Revit, with the imported reinforcement information from the Robot, the program alerts to a set of errors detected resulting from the transfer. Those inaccuracies are related to incorrect location of rebar in relation to the elements that are associated. Also, the interaction between the two programs reveals inconsistency in relation to the geometry of the reinforcement hooks, since Revit does not identify the lengths indicated in the Robot.

In the first beam analyzed, the reinforcements exceeded in length the size of the beam. This occurrence may reside in the fact that the lengths of the spans of the modeled beam presents different dimensions in Robot and Revit. This happens because when the transfer from Revit to Robot is made, the analytical axes of the support columns maintain their position in the model, but the relative position of their geometric section in relation to this axis changes, making the analytical axis coincide with the geometric axis. Thus, there is a variation in the length of the free spans of the beams in the Robot in relation to reality (as modeled in Revit). In the case of the beam with different sections, the errors reside in repeated rebars and wrong spacing. In order to solve these problems, Robot was used in the first case, where the span lengths were changed to be consistent with the provisions of Revit. This adjustment does not cause changes to the model, serving only for the purpose of detailing the reinforcement. In the case of the second beam it was used the Revit Extensions application. Analyzing the two previous cases, it was observed that the errors of transfer of reinforcement between programs are more severe when the beam detailed in the Robot is composed of more than one parametric element.

Regarding the columns, the transfer of the rectangular column occurred more satisfactorily than the "L" section. The section of the rectangular column suffered changes in terms of dimensions in the Robot, which were correctly transferred to Revit. Their reinforcements were also correctly transferred, and in this case a good interoperability was observed. The transfer of the "L" section column occurred in a less satisfactory way. The reinforcement dimensioned in this column is positioned outside its geometry due to a 180° rotation in relation to the Robot. In Revit, this error was easily solved by repositioning the column reinforcement set, through a rotation along the vertical axis. There was also the need to shorten the length of the waiting bars since the column located above and aligned vertically, does not have the same dimensions of section. Figure 9 represents the bad positioning of the rebar set on the left, and the corrected one on the right.

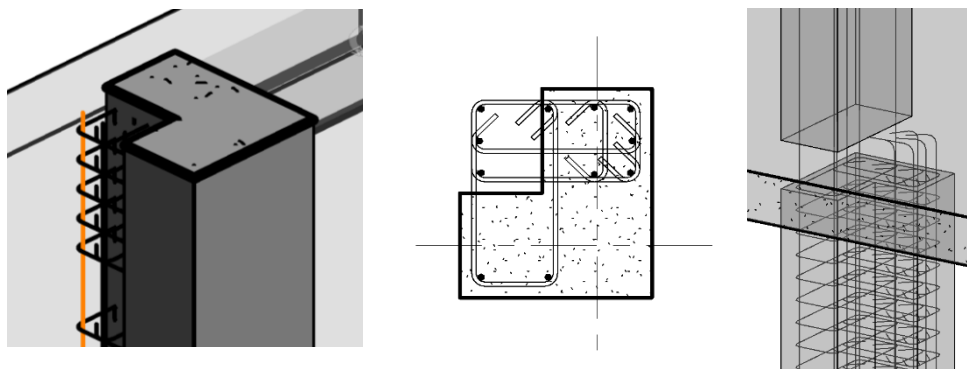


Figure 9 - Initial and final position of the rebar set in the "L" column

As mentioned, the reinforcement dimensioned for the slabs, in Robot, is not transferred to Revit. Therefore, the reinforcement of the slab was modeled in Revit, from the solution dimensioned in the calculation program. For this purpose, using the Robot, a CAD file was recorded, in *dxf* format, with the detailed drawings of the reinforcement. This procedure proved to be very useful, because the drawings include all the reinforcement, required in the calculation. The drawings are placed under the floor plan to support the modeling of the reinforcement of the main slabs and reinforcement areas, making this process very fast.

The transfer of the foundation elements, from Robot to Revit, only includes the reinforcements dimensioned in the calculation program. After transposition, as occurred in the "L" section columns, the reinforcement is transferred with all the associated information, but rotated in relation to its actual position, as imposed in the Robot. The resolution of the incorrect orientation of the reinforcement requires the imposition of a rotation, of the element reinforcement set, through the Revit object handling tools. As in the other categories of structural elements, Revit automatically imposes hooks on the longitudinal bars. The information previously indicated in the Robot for their length is lost in the transfer process. It is concluded that this type of information should always be reviewed and adjusted in all elements.

4.1 Detailed drawings

Finished the BIM model of structures, including the reinforcements of each element, a set of drawings was made, as required in the design of structures (Figure 10). The automation allowed by the BIM-based tool used ensures the correction of the different detailed drawings, in real time, when changes or adjustments are made to the BIM model, which must always correspond to the most updated version. It was concluded that, despite the speed of their design compared to traditional methods, the program is not yet prepared to obtain the representation of the drawings, to the level required in common practice, where the drawings are prepared through current graphic applications of layout.

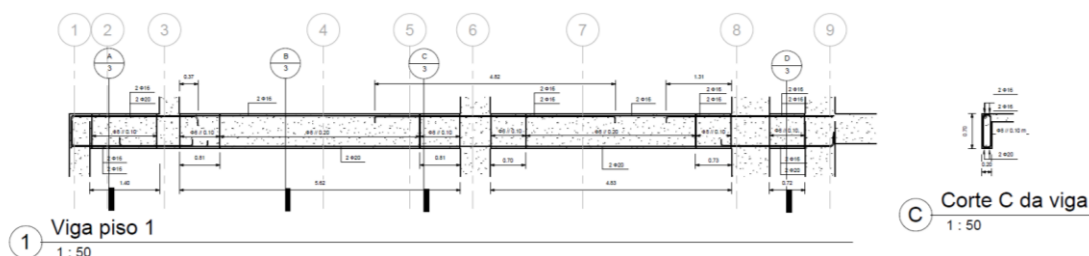


Figure 10 - Drawing of beam detail

The presentation of the drawings, obtained in Revit, is still somewhat limited, mainly in terms of annotations regarding the reinforcement. The program allows, however, some adjustment to the mode of representation. This adjustment is done in a punctual way and by using similar functionalities to commercial

tracing systems. In some cases, it is possible to approximate the shape of the desired representation. However, in order to privilege the automation of the process, it is more appropriate to develop families of labels in this area, which can serve as applicable templates, meeting the needs of users, in order to ensure the same quality of current graphic documentation.

5 Conclusions

The present study demonstrates the applicability of the BIM methodology in the development of the design of structures, using the functional and interoperability capacities of the required tools. Throughout the elaboration of the project, related to a case study, the main obstacles in terms of modeling and interoperability were identified. After analyzing the sequence steps to be followed in a design office, the advantages and disadvantages of the procedure applied were found.

- A BIM tool was used to create the two components, architecture and structure, of the BIM model. The tool supports collaboration between specialties, allowing the verification of interferences between the two disciplines. In the transfer process of the analytical model, from Revit to Robot, the level of interoperability between both proved to be adequate to obtain good results, including when changes were made to the geometry of the section of the columns, in the calculation program, and the consequent update in the modeling program. It should also be noted the ease of extracting maps of quantities in Revit.
- The reinforcement detailing is a process that can be performed in both Robot and Revit. In Robot, the different structural elements were initially detailed using the automatic reinforcement calculation tool, allowing the realization of some adjustments to the reinforcement. The software presents, however, some limitation, related to inconsistencies in the detailing following the adopted standards (Eurocodes). Information regarding reinforcement was transferred from Robot to Revit, which occurred with some errors, namely, in the continuous beams with duplication of reinforcement and in the slabs, where the reinforcement was not transferred. The Revit reinforcement capacities and the Extensions functionality was used to correct this kind of occurrences.
- It is also worth mentioning the fast way of creating drawings, and any change in the model is automatically updated in the drawing sheets. However, in terms of reinforcement annotations, the program still does not meet the necessary quality criteria.

It was concluded that the main limitations resulting from the development of this project occurred at the level of interoperability, essentially in the transfer of reinforcement information from Robot to Revit. Therefore, it is necessary for the user to master all the tools, to know their potentialities and limitations, in order to optimize their use and the time spent in solving each error. This study contributes to the knowledge of the application of a methodology in the design of structures. Its use should be encouraged in the engineering office, accelerating the implementation of BIM, and the its development and improvement, leading to the reduction of limitations, and enhancing all its advantages.

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