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EVALUATION OF INTEGRATION BETWEEN A BIM PLATFORM AND A TOOL FOR STRUCTURAL ANALYSIS

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ABSTRACT

Today, the process of building an enterprise is based on printed and disconnected documents. There is a global tendency that a project is designed by many companies and different teams, however computer tools used in present time are the same from decades ago. Due to the chang in paradigm, the methodology known as building information modeling (BIM) is little by little finding space in the area of Architecture, Engineering, and Construction (AEC). Moved by the process of transition, this research aims to study and evaluate the integration between a BIM modeling platform and a tool for structural analysis. In order to achieve the expected result, it was used a structural project of a real enterprise, first using traditional methodologies, or in other words, based on 2D indepenendent documents. The project was modeled in 3D with an integrated database according to BIM, with the support of the software *Autodesk Revit Structure* 2012. The model was then exported to the software for structural analysis *Autodesk Robot* 2012. Strategies for integration are tested and the best practices are described in detail. The results found suggest the use of the methodology in structural analysis is promising, and its implementation must be seriously considered in Brazil.

Keywords: Building information modeling; information modeling in construction; BIM tools; 3D parametric modeling; Structural analysis.

1. INTRODUCTION

Building Information Modeling (BIM) is a set of policies, processes, and technologies that generate a methodology used to manage an enterprise and to store all information in digital format through the life cycle of a building (Succar, 2009). One of the advantages of the use of software compatible with BIM methodology is the capacity of integration with many different review tools, or in other words, of financial review, energetic efficiency review, structural analysis, and many more.

Nowadays, the means of communication of an enterprise during its life cycle are still fragmented and based on printed paper documentation. Documents produced with errors or omission of project information usually generate additional costs, delays, rework, and eventual lawsuits among the many parts of the project team (Eastman *et al.*, 2010).

The success of BIM methodology requires the integration of the various phases of the life cycle of an enterprise. The work presented in this article focuses on the integration between the phases of structural design and structural analysis. More specifically, this article aims to observe the integration of the software *Revit Structure* 2012 and the structural analysis software *Robot* 2012, both from *Autodesk*.

The article is organized according to the following scheme: section 2 presents a review of literature where the main concepts involved in BIM methodology are mentioned. Section 3 presents the enterprise used in the simulations, as well as the results of the integration between the two softwares mentioned. Final considerations and conclusions are presented in section 4.

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2. REVIEW OF LITERATURE

In the area of civil construction, there is a tradition to do things always in the same fashion as it has been done for decades. This affects directly the evolution of the construction process, where changes and innovations occur in a slow pace (Gradvohl *et al.*, 2011). Since some decades ago, the use of computers and technology associated to them have helped in civil construction, but their use is still considered incipient (Linderoth, 2010). These technologies were called CAD (computer aided design) systems and became the main format in 2D designing for architecture, engineering, and construction projects. Besides the CAD tools, the use of computers permitted the generation of CAE (computer aided engineering) tools. These tools came to assist in different necessary analysis required by an enterprise, such as: structural, mechanical, budget reviews, among many others.

Throughout the years, the complexity of the projects increased, as well as the number of team involved in the construction of an enterprise, thus requiring significant changes in the way to work. Therefore, even when using optimized means of production, with proceedings and standards defined and followed by all teams involved in the project, it was possible to notice some ineffectiveness in the 2D CAD systems. Such reduced achievement build up to generate pressure in order to meet the schedule, duplicity of information, reworking, excess in production, parallel tasks, loss of confidence in information and in planning, lack of a rigorous project, loss of effectiveness of the project, and failure in management and in communication (Arayici *et al.*, 2011). All that makes work more difficult and tiresome, which represents a perfect environment to human errors.

One of the main issues associated to the present methodology, based on 2D documents, is the challenge and the amount of time spent to access a specific information in a project, such as a structural detail, as well as to estimate the costs or the analysis of energy effectiveness. The change in the necessities, and the evolution of the CAD and CAE systems led to the development of the building information modeling (BIM) systems.

In order to implement the BIM methodology in the working environment, it is necessary to use a platform that merge the information of the project together with a 3D model. This step would allow the relationship between project information and a 3D model integrated and complemented with data from different parts of the project, planning, and execution, as well as the operation and maintenance. Therefore, the 3D model is parameterized, which means, besides the geometric parameters, the objects have complementary attributes, follow rules, and have a relationship among each other. Because of that, in this article the result of modeling is called parametrized 3D model. From this type of model, it is possible to generate many types of analysis and reports. All project documentation is generated automatically from a database created from the parametrize 3D model. This fact guarantees a consistency of documents and of the information present in these documents.

The main goal of the BIM methodology is the integration between the different subjects and phases of the project, with the support of the new working computing tools available in the market. The evolution of computing tools occurs once the market, when using them, demonstrates new necessities. The need of a higher interoperability (the capacity of a computing system to communicate with another system) between computer tools is one of the main factors that generate a challenge in a wider use of BIM.

The BIM methodology is possible with the development of network technology and graphic processing, combined with the evolution of CAD/CAE tools. Throughout the projects, which are everyday more and more complex, this technology is becoming inadmissible to support the present necessities of architecture and engineering companies, changing their working methodologies in construction projects and in the whole life cycle of the enterprise. The BIM tools are known as the new generation of CAD tools (Crespo *et* Ruschel, 2007).

The main characteristic of these tools is the capacity to keep all information of a project located in a central database, through a parametric 3D model.

The computing 3D model must be the single repository place and source of all information of the project. Drawings, amount of material, and other documents must be extracted from the information about the project, instead of using different separated sources of information. This eliminates the majority of inconsistences generated by the set of drawings and documents (Sacks *et al.*, 2010) associated with the traditional methodology.

When using the proposed methodology, it is possible to perform the tasks related to modeling and engineering analysis in a more automatized format. For example, in piping, when connecting pipes of different calibers, the computing tool automatically sets all geometric adaptors needed and inserts all necessary connection components (Sacks *et al.*, 2003). Besides that, a BIM platform has checking tools and automatic identification of errors, alerting the user regarding nonconformities, such as, interference between components, elements without proper connection, among many others (Sacks *et al.*, 2003).

The computing tools must allow that the individuals involved in the enterprise work together, and then, are also able to share information during the complete life cycle of

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the project (Andrade and Ruschel, 2010). It is also possible to incorporate in the modeling platform the rules so the shared work is controlled, updating the process, and increasing effectiveness during a certain phase of the project and construction. Due to all these functions, the complexity of computing tools is getting higher and higher (Lee *et al.*, 2010). While a draftsman or engineer is not fully confident in the tools of in the methods used by the tools, the professional will not use them (Coenders, 2009).

It is important to note that many times the tools used by a company are not compatible with the tools of other companies involved in the enterprise. This requires customization and adaptation from the involved computing tools and the conversion of electronic documents to another format, which can cause loss of data.

3. STRUCTURAL ANALYSIS OF A 3D PARAMETRIC MODEL

3.1. Objective

Knowing that the area of AEC (Architecture, Engineering, and Construction) is in the process of transition between the traditional methodology and the BIM methodology, this study focuses on studying and evaluating the integration between a BOM modeling platform and a tool of structural analysis available in the market. This procedure was done by analyzing the modeling of a chemical analysis laboratory, which project was completely detailed in 2D and its construction is about to start. The project was redone using 3D BIM tools from *Autodesk*. The modeling was done on the software *Revit 2012*, exported to the structural analysis software *Robot 2012*.

3.2. Description of the enterprise

With the aim to evaluate some aspects of the BIM methodology and some of its computing tools involved in this process, a civil engineering project was chosen to exemplify the use of BIM under a project set under traditional methodology. This enterprise uses technologies based in 2D drawings and documents in text files. This is the format that most projects are designed today in Brazil and around the world. When replicating the project using 3D parametrized technology, it is possible to compare the two methodologies.

The enterprise observed has a total area of 2,500 m^2 and it will be a two-stores chemical analysis laboratory. On the ground floor, there will be the reception hall, many rooms, such as materials deposit, sample receiving room, reagents deposit, chemical analysis room, X-ray room, and many other technical rooms. Besides that, it has an administrative area, a training center, a meeting room, a snack bar, dressing area, and restrooms. To support all these technical rooms, on the second floor, also called technical floor, there are all sorts of equipment, such as pumps, many cabinets for conditioners, exhausts, fans, heating boxes, and humidifiers. The technical floor also has water tanks, boiler, electricity room and a room for IT and Communication.

Different from usual projects, the quotes of this project are provided based on sea level. When designing a conventional, isolated building, it is set a 00.00m quote for the terrain, however as this is an industrial enterprise inside a location with many other installations connected to the laboratory, in order to have a better integration between the other projects of all units of the site, sea level is used as reference. In industries such as this one, this reference is important, once many pipes and tubes are connected to different installations of the industrial site. As the quotes are established based on sea level, the projects of each installation will have the same referential, facilitating the integration of common ducts between the industrial facilities. In this project, the ground floor is in the quote 801.05m, the technical floor is placed on the quote 805.29m and part of it is in the 806.25m quote. In Image 1 and Image 2 generated from a 3D non-parametrized viewer, it is possible to see the rendering of the building simulating the result after construction.

Image 1 - Simulation of the South Facade.

Image 2 - Image of the West Facade.

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The beams and the pillars of the building are made of precast concrete (except the beams of the ground floor, which are of reinforced concrete, casted on site), the slabs are made in steel deck, and the support of the roof is composed by metal profiles. The stairs and the roof straps are also casted on site.

3.3. Integration Revit - Robot

In this work, the 3D parametric model is called physical model. The terminology physical model is used to refer to the model that is closed to the geometrics of the structure, in detail, and therefore, has three dimensions. For example, the physical model of a beam has height, width, and depth. The software *Revit* enables the creation of the physical model once it works in an 3D environment, but the software *Robot* is not capable to generate a structural analysis directly from the physical model. Therefore, the physical model is designed by the draftsman, and from it, *Revit* generates a model for structural analysis, which in this study is called analytical model. The analytical model can then be exported to a structural analysis software, in the present research, the selected software was *Robot*. This software has better compatibility resources with *Revit*, once both belong to *Autodesk* (2010a; 2010b).

The analytical model is an approximation of the physical model, which makes possible the use of structural analysis theory to calculate internal tension and efforts (i.e., shear forces, bending moments etc.), as well as displacements and deformations. This approximation is done by elements with only one dimension in a geometrical format of bars, which are part of the models of beams and columns, the connection of elements, called knots. When modeling a structure using *Revit Structure*, one has to have in mind that this is the way the software interprets this element of modeling. As this step is done automatically, sometimes it is necessary to perform some alterations manually in order to produce an analytical model coherent to the physical one.

In order to understand how an analytical model is created from a physical model by the *Revit Structure* software, it was decided to model a simple portico, as seen on Image 3. For this physical model, *Revit* automatically creates the bars of the analytical model in the center of the pillars and on the top of the beams, as seen on Image 4 (a). This model is called "model 1".

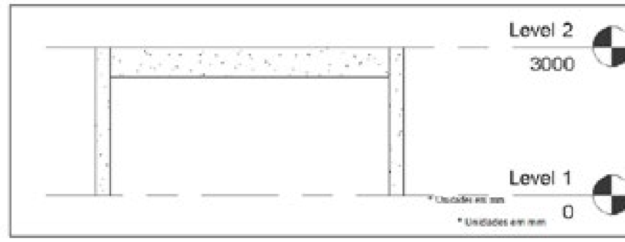

Image 3 - Physical model of a portico.

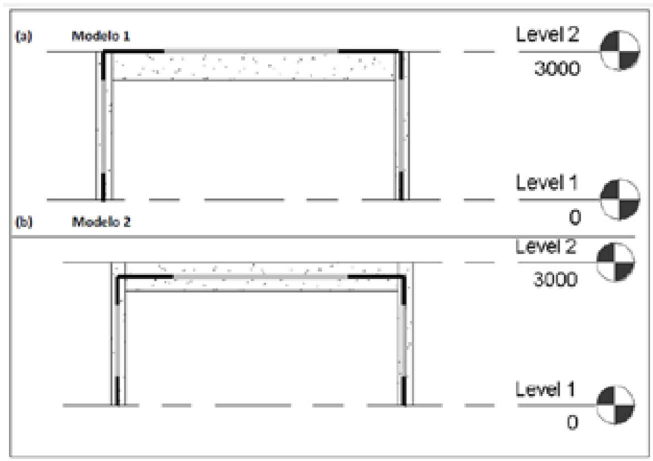

Image 4 - (a) *Revit* standard analytical model; (b) Modified analytical model.

The relative position of the elements that compose the analytical model can be easily adjusted in this case, once it was a simple structure. To do so, it is necessary to modify some proprieties of the analytical model. After some changes in the height of the Z axis on the top of the center of the physical model, the resulting analytical model is shown on Image 4(b). this new model is called "model 2" to compare to "model 1". Model 2 is the analytical model that is traditionally used in this example in conventional structural analysis. This model is the first model exported to *Robot* using a *Revit* option that automatically generates offsets to correct the position of the analytic beam to the center of the physical model inside *Robot*.

Inside the environment of the structural analysis software *Robot*, there was a small simulation of structural analysis using the *Robot* software. In order to proceed, it was applied a uniform load of 10 kN/m (in the direction of gravity acceleration) on the superior beam, and a wind pressure of 8 kN/m on the right column. The structure is supported by a crimp on the base of the left column and by a simple support on the base of the right column. The three compared are seen on Image 5.

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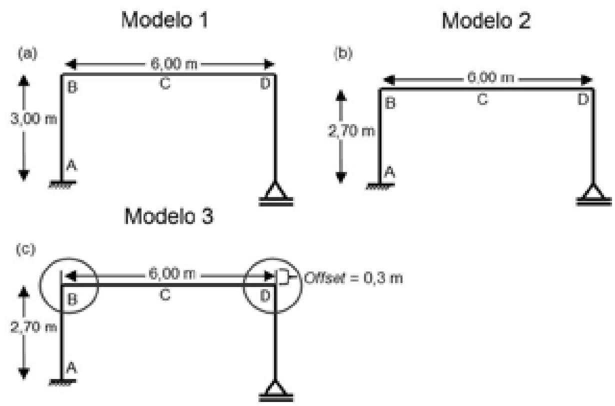

Image 5 - (a) Model 1; (b) Model 2; (c) Model 3.

Chart 3 provides the results of the bending moments in sections A, B, C, and D (indicated in Image 5) acquired for the three models, where M.1 is equivalent to "model 1", M.2 is equivalent to "model 2", and M.3 is equivalent to "model 3". Table 2 shows the percentage of the difference between the results. It is possible to observe there is a considerable difference in the connections between the structural elements and in the crimp.

Chart 1 - Comparison between the standard *Revit* analytical model and the modified one.

	M. 1 (kN.m)	M. 2 (kN.m)	M.3 (kN.m)
A	34.80	29.01	35.80
B	-37.20	-29.31	-29.00
C (My max)	28.24	15.76	16.10
D	36.00	29.16	28.80

Chart 2 - Difference between results.

	Difference		
	M.1 – M.2	M.1 - M.3	M.2 - M.3
A	17%	3%	19%
B	21%	22%	1%
C (My max)	44%	43%	2%
D	19%	20%	1%

By the results it is possible to visualize that "model 1" is the most distant from the others. The reason is, when observing the analytic axis on the top of the beam, the height of the pillars is 30 cm above than "model 2" half of the height of the section of the beam), which is enough to generate higher moments, once there is a horizontal load. The "model 3", which is the "model 1" added by the offset, has results closer to the "model 2", which is model traditionally used in structural analysis. When inserting the offset, the moments of the beam are reduced and the results are near to the model 2. However, it was observed that on the top of the pillars there are bending moments with relatively high results that were not existent in "model 2". This fact occurs because in robot, when adding the offset, the height of the pillars is kept to the top of the beam, but it is only transferred to the beam at the moment it is at 2.7m from the pillar. These horizontal loads that work in the 30cm of the pillar above the beam also generate alterations in the bending moments of the crimp (point A).

Hence, the "model 2", which was adjusted manually, is a good option to use in the structural analysis of the simple portico, however when the structure is too complex, which means, with many floors with little uneven structural surfaces and beams with variable sections, the project may require adjustments that can lead to issues in the interpretation of the structural analysis software. When there are beams of sections with different heights, when selecting the analytical axis in the center of the beam, the axis of each beam is placed in different levels, not matching the knots of the pillars. This can cause problems during the structural analysis, impeding that *Robot* concludes the operation. Therefore, for this study, this solution was not adopted. The solution adopted in this research was the "model 3", i.e. the automatic generation of offsets. This solution presents results similar to the "model 2", which is closer to the traditionally used model.

3.4. Interpretation of the analytic model of the provided original project

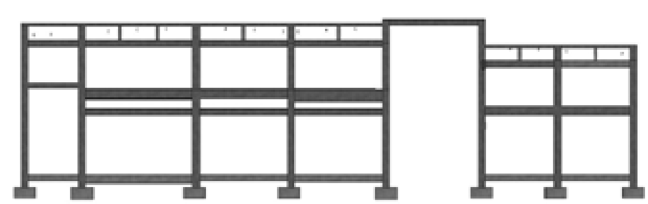

Image 6 - West facade of the case study.

Image 6 shows a structure of one of the facades of the building to be studied, demonstrating some structural characteristics of the chemistry laboratory, which is the object of study of the research. It can be observed that below the beams of the second pavement there is a second sequence of beams that are the window frames. On the rooftop, there is a system of beams and small pillars supported by the lower beams. These characteristics made the integration between *Revit* and *Robot* even more complex. Besides modeling becomes more complex in Revit, the automatic generation of the analytical model done by Robot can present some errors. Hence, before the analytical model generated can be analyzed by Robot, there are some adjustments to be done.

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As seen in the example of the simple portico, all analytical axis that are on top of the beam, which most of the times is also the top of the slab when it is visible, or in other words, when there is a change of pavements that is coincident to the top of the pillars. In this structure, besides the double beams, there are inverted beams and uneven slabs. In the beginning, there was an idea to divide all pillars in order that all beams would connect to a knot of the pillar. However, the option to subdivide the pillars already created in *Revit* is not available. In order to do so, it would be necessary to recreate many new levels, which would subdivide the structure in a series of pavements and recreate the pillars in every sub-pavement. This idea was discharged when it was realized that, when the extremity of a beam coincides with the top of a pillar, Robot automatically creates a new knot in this section of the pillar. This can generate other issues during the generation of knots in the structural analysis software. When there are many beams merging in a single pillar and the analytical axis of the beams do not match, many knots are generated in the proximity where should have only a single knot.

In the case of the laboratory under investigation, there is one system of beams of profile I that works as support to the slab which the top is located in the level 808.15 m. The slab has 12cm width, and because of that, the beams must be places 12cm below. When these metal beams are inserted, their analytical axis are automatically set at the level of 808.15 m, to match the top of the slab and not the top of the profile. This is necessary so the extremities match the analytic axis of the side beam that is placed in this pavement. But this is not what happens when some of these beams meet a pillar. In these cases, their axis is still on the top of the profile, which means, 12cm below the level, where the knot is present and where the side beams are connected. Image 7 illustrates the case. The consequence is that there is a new knot is created automatically, exactly 12cm below, during the export of the model to *Robot*.

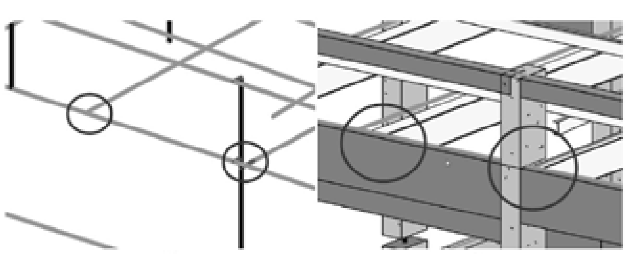

Image 7 - (a) Highlighted connections in analytic model; (b) Connections in the physical model.

A pillar in Revit is normally modeled in segments divided by the pavements. See on Image 8(a) and on Image 8(b) that, in this case, there is one element of a column below the level, and one element of a column above the pavement level, where the analytic axes are represented by elements that are connected by a knot. When there are close knots, the *Robot* software produces an error in which it demonstrates loss of reference in the end of the lower bar and in the beginning of the upper bar. This forces that the bars are superimposed, as exemplified on Image 9. In this image is possible to observe that a beam was added 100mm below the pavement “Level 2”, when exporting to Robot, a new knot will be created exactly over this point. This generates an error where the elements of the column are superimposed exactly 100mm one to the other. On Image 10, it is visible that one of the cases in which this error occurs in the modeled project in *Robot*. The solution adopted for these cases was to leave the pillar as a single element, from foundation to the top. It was seen that this procedure does not affect the precision of the structural analysis.

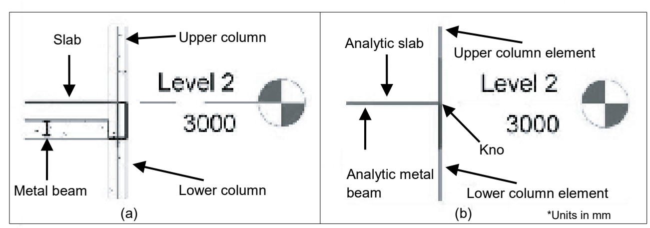

Image 8 - (a) Physical model between two pavements; (b) Analytic model in the same location.

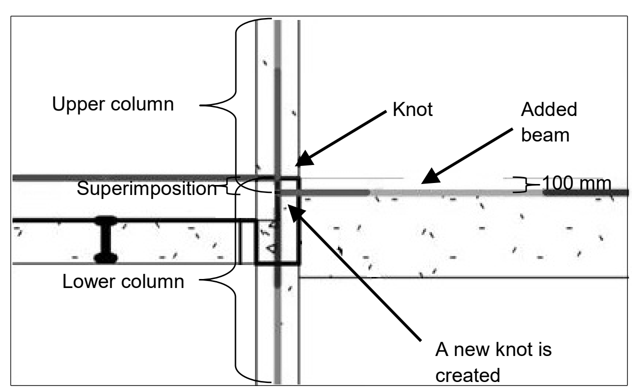

Image 9 - Interpretation *Robot* does when adding a beam some millimeters below a knot.

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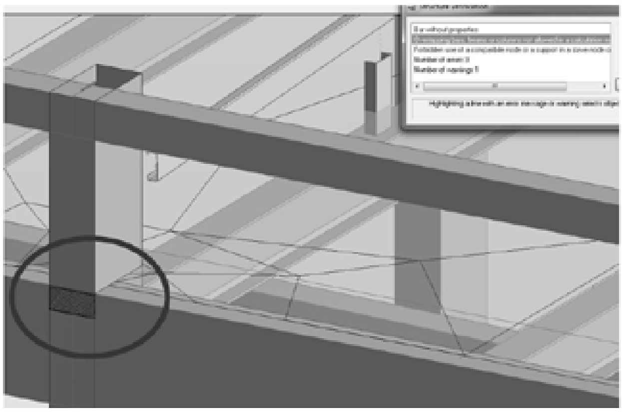

Image 10 - Superimposition of elements that represent the columns.

3.5. Rigid Links

The attribute Rigid Links, when active on beams or columns, generates a weightless rigid element with the objective to connect the analytic axis of the beam to the axis of the pillar when necessary. Image 11 shows a case of the use of the rigid link.

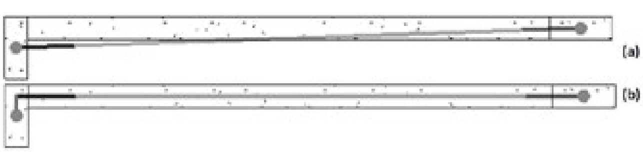

Image 11 - (a) Necessity of a rigid link to fix the analytic axis of the beam; (b) Correction of the axis after insertion of the rigid link.

Initially in this study, the necessity of the rigid elements of *Revit* were recurrent during the modeling of the project provided. Then, this option was activated in all analytic beams in order that the axes of the beams were placed correctly into *Revit*, and connected to all pillars. When exporting the model to *Robot*, it was seen that many beams had errors in superimposition in the extremities due to these rigid connections. Image 12(a) shows from a bird's eye view a part of the structure in question. In this image, the beams are with the rigid link option off. This makes the position of the analytic axis of the horizontal beams are adjusted automatically so that the beams are connected with the center of the pillars, which places them in the wrong position. See on Image 12(a), the analytic axis of the horizontal beam off the center as indicated by the arrows.

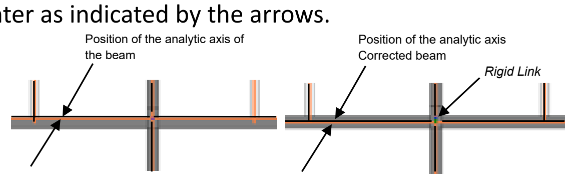

Image 12 - (a) Beam with decentralized analytic axis; (b) Corrected analytic axis.

To fix the problem, the option rigid links was activated, as seen on Image 12(b). However, despite apparently the model is correct, the model that is imported by Robot leaves the rigid elements superimposed and in conflict with transversal beams. This error is repeated in many structural beams, impeding that the structural analysis in *Robot* to be performed in satisfactory means. Then, it was decided to keep the beams with the option *Revit Links* off, thus keeping the analytic model apparently wrong into *Revit*. To fix the analytic model exported to *Robot*, the option *Execute Model Correction in Robot must be on*. Then, the *Revit Links* are automatically inserted by *Robot*, producing a valid model for structural analysis.

3.6. Exporting new families created in *Revit*

The laboratory under study has some columns which transversal sections do not exist into the library of object of the *Revit Structure*. Because of that, it was necessary to modify a family of columns and to create new columns according to Image 13.

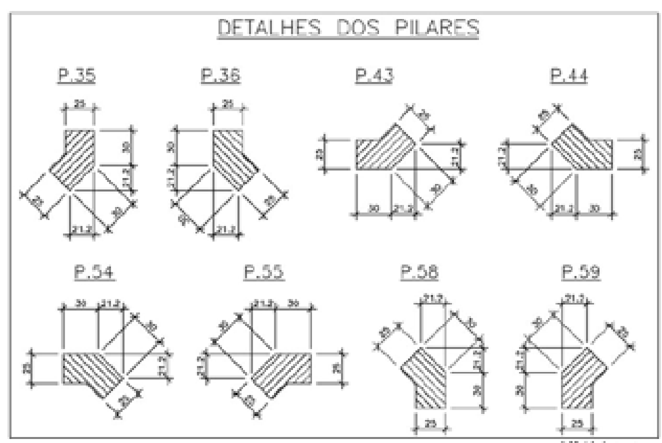

Image 13 - Atypical pillars of the original project.

The characteristics of this new family created in *Revit* could not be exported directly to *Robot*, or in other words, all the information that depended on the section, such as dimensions, moment of inertia, and radius of spinning need to be inserted manually on *Robot*. Thus, the family created on *Revit Structure* needs to be created again on *Robot*, which reduces the level of integration between these two computing tools.

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3.7. Mesh of finite elements

After exporting the model from *Revit Structure* to *Robot* with all settings described in this chapter, when generating the mesh of finite elements in *Robot* did not achieve the expected result. Most of the connections of the slab with columns or beams, the discretization of the elements was not considered satisfactory. Image 15 and 15 show the mesh in two slabs of the modeled project.

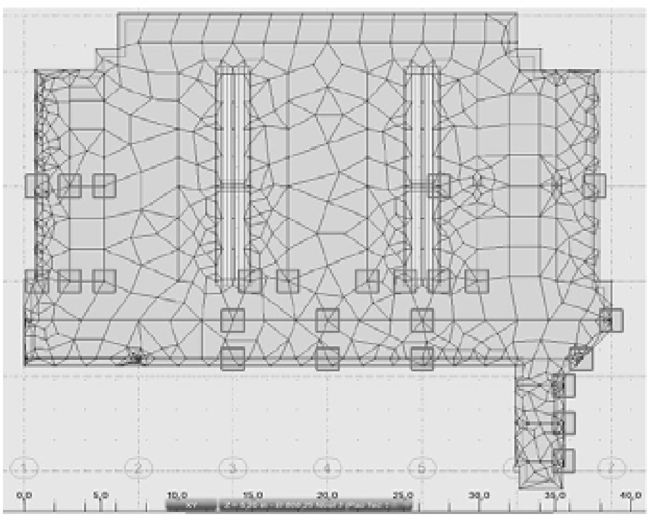

Image 14 - Slab of the level 806.25 m (technical floor).

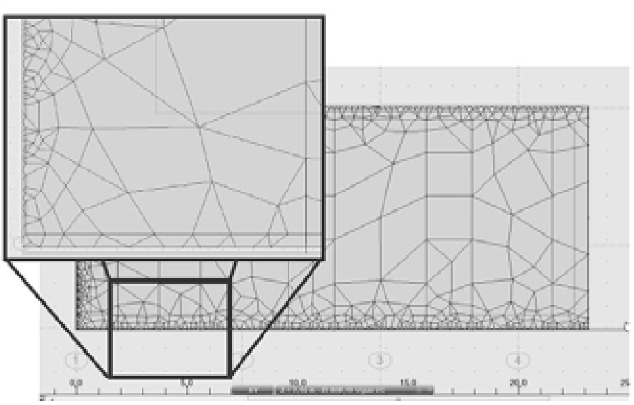

Image 15 - Slab of the level 808.15 m with details from the edges.

For the slabs to be discretized with more regular elements and with similar dimensions, it is necessary that the beams near the edges are well aligned with the edge of the slab. When there are rectangular pillars, the analytic axis of the beams can be bent, as discussed previously. The rigid links can fix this issue. However, besides the issues the rigid links can cause during exporting to Robot, it is necessary only in the beams located in the borders of the slabs, and cause this failure in discretization. Then it is possible to generate better meshes for the cases in which the issue is the connection of the beam with the border of the slab. Image 16 shows the improvement of the discretization of the slab of level 808.15 m.

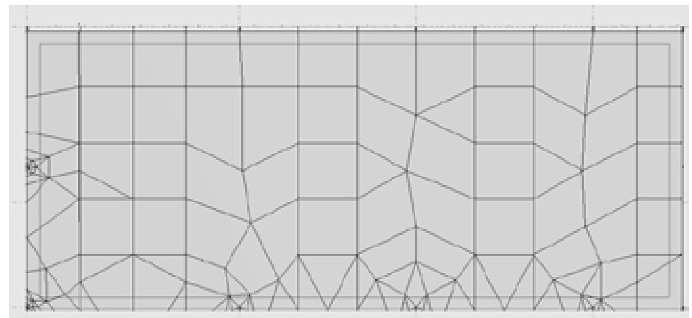

Image 16 - Slab of level 808.15 m after the adjustments of the edges.

4. CONCLUSION

In the present study, it was evaluated the integration between the BIM platform *Revit* (2012) and the structural analysis tool *Robot* (2012). It was evident that the integration between these two softwares is possible, however as more complex the structure is, more challenges in the integration were observed. In the studies performed with simple porticos, the integration was effective, practical, and did not present errors during the structural analysis. In the model of the project used, some errors were generated by *Robot*, which impeded that the structural analysis was performed during the first trials. It was necessary some manual adaptations and approximations related to the ideal analytic model so these errors did not appear during the structural analysis. For example, it was concluded that in complex structures, the positioning of the analytic axis in the centroid of the bar, which is only possible by using offsets. In the studies performed, it was clear that the modeling using offset can present bending moments slightly higher on the top and on the base of the pillars when compared to a model without offsets. However, the moments of the bends with offset were near to the conventional model used traditionally in structural analysis. Besides these differences in the pillars, the use of offsets is a solution that presents the best approximations to the integration of complex structures coming from *Revit* and exported to *Robot*. It was also concluded that is best to use the option "*Use drawing model offsets as analytical*" during the export from *Revit* to *Robot*. Using this option, the offsets are inserted automatically on the beams. This makes the integration between the softwares more effective and facilitates the work of the draftsman.

It was also shown that the practice of not subdividing the pillars by pavement does not interfere in the results of the structural analysis. These subdivisions were performed ac-

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cording to the proceedings of modeling indicated by *Autodesk*. It was necessary to leave the pillars intact in the points where there were problems with superimposed pillars.

Another function from *Revit* that can also generate problems of superimposed elements is the use of the rigid links. It is concluded that is more effective to generate the rigid links automatically on *Robot* during export. The rigid links of *Revit* are only necessary in the beams placed in the limits of the slabs. They are necessary so the analytic axis of the beams in the edges of the slabs are perfectly aligned with the limits of the element of the plate of each slab. Then it is possible to achieve better results in generating the plate mesh.

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