BIM Methodology applied to Structural Analysis of the Built Heritage

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Abstract. Built heritage is one of the key elements through which the identity and culture of a society manifests itself. The so-called Building Information Model (BIM) is a methodology that has gained wide notoriety in fulfilling the role of portraying the physical characteristics and storing information of historic monuments. One of the most useful applications of the BIM methodology is structural analysis, which can be performed based on the graphic representation of the building itself. Structural analysis makes it possible to obtain parameters that are of great value for the study, maintenance, monitoring, and eventual repair of structures. The present work had the objective of comparing two parallel models of the "Nossa Senhora de Fátima" church, known as "Igrejinha", in Brasília, and the results of their respective structural analyses. The first model was developed based on the structural documents of the building, and the second one, based on accurate survey methods usually employed in historic BIM modeling - terrestrial laser scanning and aerophotogrammetry. The methodology adopted was based on automatically obtaining the analysis results from the architectural representation of the building and its corresponding analytical abstraction. The physical comparison of the models showed a high dimensional similarity. The resulting values of the structural analysis showed, however, significant variations for certain internal forces, demonstrating the influence of the modeling process and the discretization of the structure on the calculation results.

Keywords: BIM, Structural Analysis, Heritage, Point Cloud, Igrejinha.

1 Introduction

Architectural heritage corresponds to everything that was built with the aim of creating and limiting space, and that has in itself a cultural and anthropological value related to human activities [1]. The conservation and preservation of architectural heritage has been a long-standing challenge. Buildings, regardless of their structure and composition, are subject both to the natural action of the weather - such as incidence of solar radiation, rain, climatic variations - and to harmful anthropogenic actions - such as wars and vandalism [2].

The adoption of processes of knowledge, maintenance, management, and enhancement of architectural heritage is essential for the conservation of its original characteristics and for the preservation of its value acquired over generations [3]. All these steps are based on documentation, records and inventories of the studied building. The constant updating of this documentation is often time consuming and costly. Furthermore, traditional documentation methods are insufficient in more complex preservation and maintenance processes [4].

As an alternative tool for studying, recording, and maintaining historic buildings, the Building Information Modeling (BIM) methodology has gained wide notoriety internationally [5]. BIM is a modeling methodology that integrates parametric elements endowed with information with three-dimensional visual representations, providing data integration, interdisciplinarity, graphic representation, and construction management never previously envisioned in the construction industry [6]. Currently, BIM is most often employed in the design stage, but it is an equally powerful tool for the other stages of the life cycle of a building [7].

The Historical Building Information Modeling (HBIM) is the application of the BIM methodology specifically for heritage preservation. HBIM constitutes a management repository of a cultural asset, allowing the insertion and updating of information directly into its three-dimensional model. Associated with specific technologies, it also provides precise geometric modeling of the building, capturing details that would be imperceptible in other circumstances [4].

The preservation and maintenance of architectural heritage involves ensuring the safety and functionality of the building, which are directly related to the integrity and health of its structure. Structures, especially those of historic buildings, are subject to long periods of load-bearing, temperature variations, accumulation of deformations and several other unfavorable situations [9][10]. The structure, besides associated pathologies, can be relevant for its integration with the architecture of the monument, constituting an integral part of the visual identity of the historical heritage [11].

A powerful tool for the study and verification of structures is computational structural analysis. When correctly parameterized in the architectural model, the structure can be exported to a specific software that enables computational processing in order to predict its behavior under certain conditions. In the context of built heritage, structural analysis can be employed with the purpose of checking the resistant capacity and integrity of a structure [12], aid in the maintenance and operation of the building [10] or as a tool to study the structural conception of a building [11].

This paper will study specifically one of the most renowned examples of built heritage of Brasilia, which is characterized by remarkable harmony between the architectural designs and their respective structural systems. Based on a case study, different processes of surveying existing buildings for their modeling in BIM, the interoperability between architectural and structural computer models and the possibilities of structural analysis and processing will be discussed, highlighting the specific characteristics of the selected historic building.

The next sections are structured as follows: item 2 presents the literature review of the topics covered; item 3, the methodology used; item 4, the results of the modeling and structural analysis; item 5, the conclusions.

2 Literature Review

2.1 Structural Analysis as a BIM Use

The Building Information Modeling (BIM) methodology emerged as an alternative to traditional models of project design and construction documentation. Sometimes mistakenly seen only as a three-dimensional representation of the building, BIM corresponds to a process that extends to the entire life cycle of the building and aims to streamline the process of conception, design, construction, and management. With respect to modeling, BIM adopts parametric objects endowed with information for the graphical representation of building elements [6].

According to Ramaji; Memari [13], structural analysis is one of the most commonly employed types of BIM use among those involving engineering analysis. In this context, the analytical structural model is generated from the architectural model in BIM, also called the physical or geometric model, without the need to build it from scratch. Such practice, in addition to reducing the time allocated to structural modeling, significantly increases the accuracy of the analytical model. Structural analysis is the second most cost-effective BIM use among engineering analyses, preceded only by energy performance analysis. Interoperability is key when employing structural analyses classified as BIM. For these to reach their full potential, a high level of interoperability is required between architectural modeling and structure processing software.

In the case of existing buildings, it can play different roles: verification of the resistant capacity of a structure [12], aid in the maintenance and operation of the building (planning of structural interventions, determination of the relationship between internal efforts and observed pathologies, identification of critical regions of the structure [14][15][10]) or tool for studying the structural design of a building [11].

2.2 HBIM

The term HBIM (Historical Building Information Modelling) was first proposed by Murphy, Mcgovern and Pavia [16]. The authors presented HBIM as a reverse engineering exercise, in which constituent elements of a monument are mapped (laser scanning and photogrammetry techniques are recommended) and then interpreted as parametric objects in the BIM model.

The main requirement in using BIM for the representation and survey of historic architecture is the quality of the model and its reliability with respect to geometry. A second requirement involves adding a comprehensive database of historical notes on each component, including materials and interventions performed over time. If models are able to meet these requirements while avoiding laborious computational processes, in the coming years HBIM will play a key role in the restoration, representation and communication of built cultural heritage [17].

Terrestrial laser scanning. Terrestrial laser scanning (TLS) is one of the most effective data collection methods for accurate as built modeling of a building. TLS is capable of automatically registering millions of three-dimensional points on the mapped object in near real time. It measures distances and angles from the sensor to the scanned object with an accuracy that can range from millimeters to centimeters [4]. TLS can operate by three different principles: triangulation, time-of-flight, and phase comparison. All three types generate a three-dimensional point cloud of the analyzed object as a product, but the range and accuracy of each method varies. TLS is an accurate, efficient, and user-friendly solution to acquire three-dimensional (3D) data for as-built modeling, with its main disadvantage being the relatively high cost of obtaining and operating this technology [4].

Photogrammetry. Photogrammetry is the process of determining precise measurements and three-dimensional data from photographs. Photogrammetric techniques use images taken from different locations to record the three-dimensional geometry of an object or building. This methodology has become popular for modeling existing buildings, especially with regard to historic built heritage. Low-cost digital cameras, powerful computer processing and increased availability of commercial and open-source photogrammetric software are driving many new applications for this technology [4]. It is also noteworthy the possibility of obtaining information indirectly, without the need for displacement by the professional [18]. The output data from photogrammetric surveys are similar to those obtained by laser scanning and include orthographic images, point clouds, triangulated surface models, and textured surface models [4].

2.3 Nossa Senhora de Fátima Church

The Nossa Senhora de Fátima church (known by its affectionate nickname of “Igrejinha”, or “little church” in Portuguese) was chosen as a case study for this work. Igrejinha is located in Brasília, between superblocks 307 and 308 South, and is an individually protected property as determined by IPHAN, Brazil´s Institute for Historical and Artistic Heritage. The architectural project was conceived by Oscar Niemeyer and the structural project was entrusted to engineer Joaquim Cardozo. The structure and architectural form of the Igreja Nossa Senhora de Fátima, although based on traditional construction elements (columns, beams and slabs in reinforced concrete), result in a creative geometry, unusually-shaped and endowed with movement. In general terms, the structure of the Igrejinha consists of two structural walls, three external pillars and the roof.

The roof is triangular and curved, with variable thickness along its length (10 cm in the central curved section and 25 cm to 30 cm at the ends) [19]. It consists of four slabs and five inverted beams, which are not visible to the observer on the ground plane. The five beams start from the same point, at the meeting with the main pillar, and extend to the other edge of the roof. Like the slab, they have variable heights, 90 cm in their central section and 25 cm at the ends - in these, beams and slabs converge to the same height [11]. The three columns have a variable trapezoidal cross section, determined by a curve in the direction of their height. Other supporting elements are the two structural walls, covered by tiles. The integration of structural components as part of the plastic conception of the architectural project is remarkable [19].

3 Methodology

Two parallel models of the structural system of the Church of Our Lady of Fatima were built. The first was based on the collection of records from the original structural design, the second, on a point cloud elaborated by the association of terrestrial laser scanning with drone aerophotogrammetry. The two models were then compared, both with respect to their physical characteristics and dimensional differences and with respect to the results of the structural analysis. The structural system was processed with the aid of analysis software, associated with the architectural modeling software.

It was defined that, as much as possible, the whole construction effort of the structural system would be concentrated on the architectural modeling software. This already establishes an automatic relation of the physical structural elements created with their analytical interpretation. The so-called analytical model can also be adjusted manually by the users, if they judge that the software interpretation does not fit the particularities of the structure studied. All discretization of the analytical model was reserved for the structural analysis software, so that its automatic readings of analytical structures from different physical models could be compared.

The need for automatic interpretation of the structure by the analysis software directly influences the physical modeling of its constituent elements. First, these must have an analytical correspondent, otherwise they will not be considered in the calculation. In addition, they must be readily recognized by the analysis software, without redefinitions of shapes or cross sections. Such redefinition can result in considerable rework, depending on the magnitude of the building, and goes against the elimination of redundancies provided by BIM methodology. These factors limit the possibilities of the features used, such as the creation of custom families.

Only native tools of the modeling and analysis software were used. The use of plug-ins or additional programs can facilitate the process of automatic interpretation of the structure, but this work sought to evaluate the programs' own ability to represent and analyze complex geometries, characteristic of historic monuments. Based on a study of the physical characteristics and use of the church, as well as to simplify the comparison between the models, it was established that the acting load for the calculation of internal forces was only the structure's own weight. The software selected were Revit and Robot Structural Analysis, both from Autodesk, due to the high interoperability between them.

4 Results

In order to standardize the nomenclatures of the following discussions, all structural elements of the Nossa Senhora de Fátima church will be named as shown in Figure 1. The letter C refers to "column", W to “wall”, SL to "slab" and B to "beam".

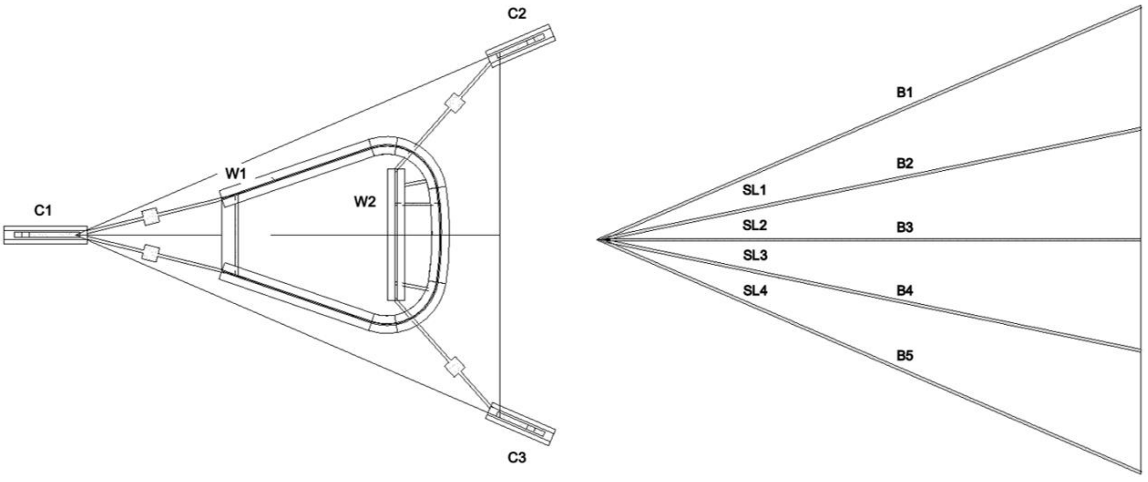

Figure 1. Nomenclature of the structural elements.

Project Model. The exact curvatures could not be obtained because Revit only admits planar projections of analytical floors and because the export process to Robot, as adopted in this work, is only successful when all structural elements present cross sections common to both software. Sections with complex geometry created through families in Revit are not automatically recognized by Robot. This work sought to concentrate the modeling efforts on the architectural software, which made the simplification of cross sections necessary. The methodology for representing the curves was the same in the case of columns, beams, and slabs. All were subdivided into smaller segments, rectilinear and of uniform cross section, so that the final geometry approximated the projected curvature. The physical and analytical representations of the model in Revit can be seen in Figure 2.

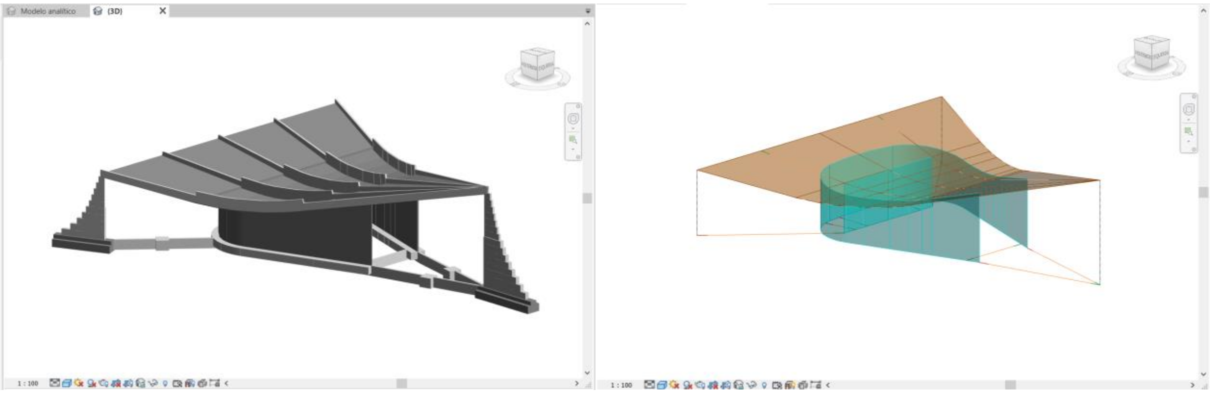

Figure 2. Design-based physical and analytical models.

Once the structure was processed by Robot, some warnings were presented by the software after the process of creating the finite element mesh. It was observed that adding levels of complexity to the structure - such as a high number of distinct cross sections and curved elements, no matter how many precautions are taken, makes it difficult for the analysis software to interpret the model automatically. The warnings, however, do not prevent the calculation of efforts by the software. The results obtained are illustrated in Figure 3.

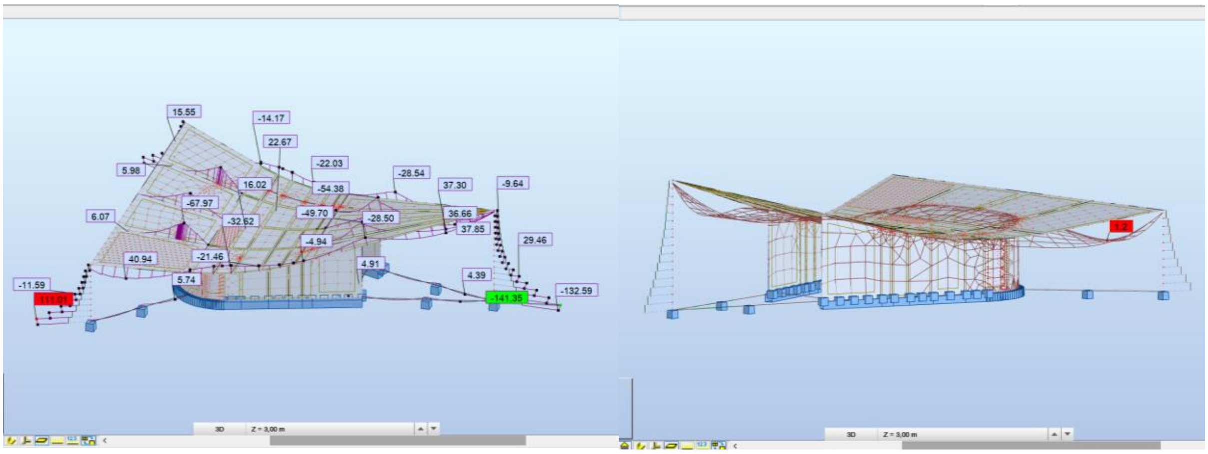

Figure 3. Structural parameters obtained from Robot for the project model.

Point Cloud Model. Two different methods were employed for composing the final point cloud: ground laser scanning and drone aerial photogrammetry. The terrestrial laser scan is not able to provide, for example, the thickness of the roof slab or any information about the three central inverted beams, which cannot be viewed from the ground plane. The aerophotogrammetry point cloud, on the other hand, does not contain data on elements that cannot be visualized in an elevated view, such as the delineation of the interior rooms or the outline of the underside of the roof slab. The association of the two techniques can be seen in Figure 4.

Figure 4. Point Cloud-based physical model.

Compared to the design prescriptions, few differences in dimensions were identified in the actual building. The actual longitudinal length was 29.12 m, and the width was 25.05 m (29 x 25 m in the design). The planned heights of 8 m and 5 m for the ends of the roof slab actually corresponded to the heights of the columns, and the slab thickness was added to determine the total height.

Once the physical correspondence between the two modeling methods was ascertained, the results of the structural analysis were compared. Beforehand, an equally high level of similarity is expected. Table 1 condenses representative values of the structural analysis and computational processing effort for both models. The abbreviation F corresponds to normal forces, M to bending moment, S to shear force, and x, y, and z are the respective axes indicating the direction of the efforts. The x-axis is the horizontal axis longitudinal to the church structure, the y-axis, transverse; the z-axis corresponds to the vertical axis.

Table 1. Comparison between design and point cloud model's structural analysis results. Source: Author.

Parameter	Project	Point Cloud	Difference
Export Time	23 s	30 s	30%
Processing time	9 s	12 s	33%
Number of warnings generated	5	8	60%
Fz - C1	232,41 kN	251,20 kN	8%
Fz - C2	135,54 kN	154,32 kN	14%
Fz - C3	135,82 kN	153,30 kN	13%
My - C1 (base)	328,44 kNm	356,80 kNm	9%
My - C2 (base)	-99,86 kNm	-108,86 kNm	9%
My - C3 (base)	-99,74 kNm	-107,22 kNm	7%
Mx - C1 (base)	0,01 kNm	-0,07 kNm	800%
Mx - C2 (base)	42,12 kNm	46,51 kNm	10%
Mx - C3 (base)	-42,09 kNm	-45,73 kNm	9%
My max - Covering Slabs	61,10 kNm	86,56 kNm	42%
My min - Covering Slabs	-18,90 kNm	-31,48 kNm	67%
Mx max - Covering Slabs	63,93 kNm	76,50 kNm	20%
Mx min - Covering Slabs	-33,50 kNm	-50,65 kNm	51%
My Max - B1, B5	40,94 kNm	47,68 kN	16%
My Min - B1, B5	-30,08 kNm	-33,94 kN	13%
My Max - B2 - B4	37,87 kNm	32,62 kNm	14%
My Min - B2 - B4	-67,97 kNm	-124,76 kNm	84%
Sz Max - B1 - B5	36,26 kN	117,00 kN	223%
Sz Min - B1 - B5	-36,18 kN	-71,95 kN	99%
Max. Displacement	1,20 cm	1,00 cm	17%

The divergence of internal efforts values calculated for the two models proved to be significant. Two modeling processes identical in their procedure and with little variation in the final building geometry resulted in variations of 20% to 67% in the magnitude of the bending moments acting on the roof slabs, of 84% in the critical negative moment of beams B2 to B4, and of 99% and 223% for the critical shear forces in the roof beams. It was observed that there is a direct correspondence of fluctuation points in the values of efforts and errors identified in the mesh. The largest variation, 800%, was not considered relevant, due to the bending moment around the x-axis at the base of column C1 being practically null in both cases.

On the other hand, other efforts presented admissible variations, of the order of magnitude of 10%, such as the column support reactions and the other critical bending moments of the roof beams. Although the magnitude of the values differed, the global behavior of the structure was similar in both cases, with deformed mesh representations and congruent diagram formats.

5 Conclusions

Taking into account the similarity of the physical models, the study concludes that the characteristics of the modeling process in the architectural software have a relevant influence on the final result provided by the analysis software, especially when errors and warnings are verified during the structure processing. The correspondence of inconsistent points in the finite element mesh with the manifestation of distinct effort values is strong evidence that the automatic discretization by the analysis software interferes in the calculations. The result should, therefore, be critically analyzed by the user. Despite the significant variation of certain internal forces, the global behavior of the building remained the same, with similar representations of displacements and diagram formats.

Therefore, if the intention of the analysis is the identification of critical regions of the structure and the understanding of its characteristics and operation in general, the methodology adopted in this work proved to be adequate. If, however, it is desired to obtain acting efforts, calculate displacements and evaluate the resistant capacity of structural elements in a precise manner, it is recommended that additional procedures be applied. These can range from a simple improvement of the finite element mesh automatically generated by the calculation software to elaborate procedures, such as load tests. It should be emphasized that, in this work, only the native tools of the selected software were used, and possibilities of improving the structural model in the Robot Structural Analysis itself were not explored.

Considering the extrapolation of the adopted methodology to other historic buildings, some points should be raised. Firstly, the difficulty of modeling structural elements of complex geometry that are readily interpreted by the analysis software may prevent an accurate representation of the structure of buildings of greater proportions than the "Igrejinha", a case in which manual segmentation of curved elements was feasible. Therefore, the need to study ways to create analytical models directly from physical elements with unusual geometry is reinforced. Secondly, many historic monuments do not have any record of their structural systems. The global behavior of the structure modeled by the point clouds was considered appropriate, validating the use of the exposed methodology for cases in which the building is surveyed without design information and high precision of the stress values is not required. The integration of structural representations with the architectural model in a precise manner is a subject still under development, but of great interest and value for building preservation. Other engineering analyses and BIM uses can also be incorporated, enriching the model as a whole.

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References

[1] T. G. Abdelhamid, "Digital Techniques for Cultural Heritage and Artifacts Recording". *Resourceedings*, v. 2, n. 2, 72 p., 2019

[2] A. Conti *et al*, "HBIM for the preservation of a historic infrastructure: the Carlo III bridge of the Carolino Aqueduct". Applied Geomatics, n. ii, 2020.

[3] A. Osello; G. Lucibello; F. Morgagni, "HBIM and virtual tools: A new chance to preserve architectural heritage". Buildings, v. 8, n. 1, pp. 1–12, 2018.

[4] C. Dore and M. Murphy, "Current state of the art historic building information modelling". International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, v. 42, pp. 185–192, 2017.

[5] A. R. M. Cuperschmid *et al*, "Casa de Vidro: BIM e Gestão do Patrimônio Histórico Arquitetônico". Cadernos do PROARQ (UFRJ), pp. 177–198, 2018.

[6] C. Eastman *et al*, "Manual de Bim: Um Guia prático de Modelagem da informação da Construção para Arquitetos, Engenheiros, Gerentes, Construtores e Incorporadores". Bookman, 2014.

[7] CIC GROUP, "BIM Project Execution Plan Guide". CIC Group - The Pennsylvania State University, v. 53, 160 p., 2010.

[8] D. P. Pocobelli *et al*, "BIM for heritage science: a review". Heritage Science, v. 6, n. 1, pp. 23–26, 2018.

[9] C. Dore *et al*, "Structural simulations and conservation analysis-historic building information model (HBIM)". ISPRS Archives, v. 40, n. 5W4, pp. 351–357, 2015.

[10] D. Oreni et al, "Survey turned into HBIM: The restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila)". ISPRS Archives, v. 2, n. 5, pp. 267–273, 2014.

[11] L. da S. P. Inojosa, "O Sistema Estrutural na Obra de Oscar Niemeyer". Universidade de Brasília, master's thesis, 159 p., 2010.

[12] C. Araujo *et al*, "Verificação de segurança e dimensionamento de reforço em fibra de carbono em estrutura de concreto armado". Projectus, v. 5, pp. 36–53, 2020.

[13] I. J. Ramaji and A. M. Memari, "Interpretation of structural analytical models from the coordination view in building information models". Automation in Construction, v. 90, pp. 117–133, 2018.

[14] T. T. Ribeiro *et al*, "Análise de estruturas de concreto usando BIM para manutenção". CILAMCE, 2020.

[15] E. Abbate; S. Invernizzi; A. Spanò, "HBIM parametric modelling from clouds to perform structural analyses based on finite elements: a case study on a parabolic concrete vault". Applied Geomatics, 2020.

[16] M. Murphy; E. Mcgovern; S. Pavia, "Historic building information modelling (HBIM)". Structural Survey, v. 27, pp. 311–327, 2009.

[17] R. Quattrini *et al*, "From TLS to HBIM. High quality semantically-aware 3d modeling of complex architecture". ISPRS Archives, v. 40, n. 5W4, pp. 367–374, 2015.

[18] B. Barbosa and K. Vieira, "H-BIM no controle e avaliação do Patrimônio Histórico: Revisão Bibliográfica". v. 25, pp. 13–24, 2021.

[19] S. R. Arakaki; E. B. de C. Azambuja; J. M. M. Sánchez, "Forma arquitetônica e função estrutural da Igreja Nossa Senhora de Fátima em Brasília". Paranoá: cadernos de arquitetura e urbanismo, n. 15, pp. 63–70, 2015.