Features of information modeling of cultural heritage objects

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Abstract. This paper focuses on features of heritage objects information modeling and its integration with structural analysis under various types of impacts. We discuss different results of structural analysis based on finite element model (FEM) of the New Hermitage portico. Thanks to laser scanning technology it was possible to collect all the geometric features of this object and generate an adequate mathematical model based on the obtained data. The methodology of finite element model creation based on laser scanning and BIM technologies is proposed. Some interesting results of laser scanning survey and numerical modelling have been discussed. Deviations of the portico's structural elements have been identified based on the use of laser scanning, BIM and FEA. It has been found out that the displacement of the upper parts of the columns relative to the lower ones in the direction of the facade wall is 4 cm. An intermediate HBIM of the portico (LOD 100) has been created inside Revit. Finite element model with default element size of 300 mm has been created using ANSYS. Directions for further research have been also determined.

Key words: laser scanning, hermitage, finite element, structural analysis, atlant, HBIM.

1 Introduction

The assessment of the historic heritage structural behavior is an important engineering and architectural issue, because of the economic and cultural relevance of such buildings [1-3]. Computer modeling is one of the most effective tools for understanding the causes and consequences of various structural elements deformations. However, to obtain reliable results, a model of the object under study with a high degree of accordance must be created. The finite element method (FEM) is a widely accepted numerical method for solving such problems in science and engineering [4-6]. The adaptive virtue of this method offers an effective way to solve complex problems in structural analysis, heat transfer, fluid mechanics and electromagnetic fields among other applications [7-9]. In turn, structural analysis is commonly used in the design and construction of new buildings. Structural analysis is the determination of the effects of loads on physical structures and their components. The results of the analysis are used to verify a structure's fitness for use [10]. The main approach of this method is to use certain mathematical models to represent the geometry of a body as a large number of small elements called finite elements (for example, triangular elements). This approach is also used when analyzing existing structures and identifying the causes and consequences of their deformations. At the same time the complex geometry of historical objects causes many problems in structural analysis and simulation of their behavior under various types of impacts. Thanks to the development of new survey technologies it is now possible to obtain all geometric features of historical objects using laser scanning and photogrammetry [11-12]. Laser scanning is an essential technology that allows creating high-density point clouds that represents the exact geometry of scanned object. At the same time the technology of building information modeling has become widespread. The application of BIM...
technology in the field of historical buildings is called HBIM (Historic Building Information Model). HBIM is a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements are accurately mapped onto a point cloud or image based survey. HBIM is proposed as a new system of modelling historic structures and a range of software programs are then used to combine the image and scan data [13, 14].

Additionally, the integration between HBIM technology and Finite Element Analysis (FEA) is gaining particular interest in recent years for structural analysis of built heritage, since the increasing computational capabilities allow manipulating large datasets. FEA is an exciting engineering solution that digitally predicts and simulates material behavior under defined conditions [15]. Using build material information and accurate 3D-models of a part or assembly, FEA enables predicting structural or performance problems before they occur in the real world [2, 16]. The main advantage of using laser scanning and BIM technologies is to obtain a three-dimensional digital model of the object, which allows determining the stress values with greater accuracy during structural analysis as well as predicting the future behavior of the structure [17-20].

A methodology for creating a Historic Building Information Model based on laser scanning point clouds is proposed in this paper. The results of structural analysis of historical buildings elements are also discussed. This work illustrates the first preliminary step in a comprehensive study of the current state of the Atlant’s sculptures in the New Hermitage in Saint-Petersburg, which is one of the main symbols of the city. Ten monolithic sculptures carved from serdobolsky granite by Russian stonemasons under the direction of the sculptor A. I. Terebenev were installed on the granite pedestals of the portico of the New Hermitage in 1848.

It should be pointed out that granite sculptures of Atlantes were installed between the columns of the portico in such a way that sculptures supported the granite posts and the portico's run beams by their heads and arms. It was not assumed by the initial project that the sculptures would play the role of the bearing element of the portico. Meanwhile, the slightest deformation of the portico structure causes sculptures to be also involved in the deformation process; therefore, the sculptures experience additional stresses with a force concentration in the upper and lower parts. Since the level of loading of the building and the portico is different, the more loaded main part of the building structurally connected with the portico by the same foundation and the 1st floor drags the portico structure, causing its towards the building of the New Hermitage [21].

The authors of the article have successful experience in implementing of scan-to-BIM technologies, which allowed them to obtain interesting results for such a complex object as a portico of the Hermitage [22-26]. At this stage, relying on interoperability between HBIM and FEA, we will try to figure out what processes caused the deformations of the Atlantes of the New Hermitage in St. Petersburg. This article is a preliminary stage of detailed study of the New Hermitage. The main objectives of this research are the following: creation of finite element model based on an intermediate HBIM (LOD 100) [27] of the portico of the New Hermitage inside Revit and identification the deviations of the portico's structural elements.

2 Materials and methods
The proposed methodology is shown on figure 1. It consists of 7 steps. First of all, for accurate HBIM creation laser scanning survey is needed. Then it is necessary to process raw data in form of laser scanning point clouds and convert it to relevant common formats. Then the HBIM creation begins from combining the results of two separated actions: (I) parametric families creation and (II) creation of Atlant sculpture. After generation of accurate HBIM it is now possible to create automatically finite element model from it. The last step is to configure the boundary conditions and loads, and then perform structural analysis.

This section describes step by step the application of the developed method on the example of the new Hermitage building portico. The proposed method begins with a laser scanning survey, the purpose of which is the laser scanning point cloud for HBIM creation and measurement of all the features of the portico of the New Hermitage. This step is crucial because of the complexity of its
geometry and the inability to measure it using traditional methods. To get a high-quality result, all field work must be planned in advance. For this reason, a plan for the scan locations was developed, in addition, at this stage it was necessary to coordinate the work with the staff of the Hermitage and ensure the availability of a lifting mechanism. The Atlant's figures are about 5 meters high and are located at a fairly close distance to the columns. The layout of the scan stations around sculpture looks as shown in figure 2. To get a complete view of the geometry features, scanning was performed from 72 scanning stations using Leica BLK 360 (figure 3).

![Pipeline of developed methodology.](image1)

**Figure 1.** Pipeline of developed methodology.

![Layout of the scan stations around the sculpture.](image2)

**Figure 2.** Layout of the scan stations around the sculpture.
In the next step, the raw data was pre-processed. This process involved several operations: first, to get the registered point cloud of an object, the unsorted point clouds were brought to a common coordinate system. Second, to simplify post-processing, point cloud was resampled with the use of subsample algorithms in CloudCompare. The number of points was reduced by 100 times. Third, the points describing individual elements (windows, doors, columns, sculptures, and so on) were segmented and exported to single files for subsequent creation of parametric families and solid geometry. Since at this stage we were more interested in the causes of deformations, we decided to limit ourselves to constructing the exact geometry of the supporting elements of the portico and their correct spatial location relative to each other. In turn, it was also decided to significantly simplify the geometry of Atlante sculptures to improve the performance of Revit.

Taking into account the fact that the parameters of real load-bearing beams cannot be determined at this stage due to the fact that the real structure is not accessible to the laser beam, in this study, visible portico structures are accepted as load-bearing elements. Also, due to the geometric complexity of the Atlante sculptures, as well as the lack of accurate data on the structure of the sculpture mounts, only the bearing elements of the portico are used for FEA, the movement of which is presumably the cause of deformations of the Atlantes themselves.

At the last stage, materials and their physical properties were assigned to the structural elements, boundary conditions were set, and then stress and deformation calculations were performed.

3 Results
After 72 separated laser scanning survey, the corresponding point clouds of laser scanning were registered in the common coordinate system. The total number of points in common cloud after registration was approximately 10 billion points (figure 4).
After performing all the preliminary manipulations with the cloud and creating single objects, an intermediate HBIM of the portico was created inside Revit (figure 5). Thus, the level of detail in this case corresponded to LOD 100 [27].

![Figure 5. An intermediate HBIM of the portico (LOD 100) inside Revit.](image)

After the generation of finite element model the boundary conditions and loads were set, the structural analysis was performed. Then HBIM was exported to ANSYS, where a finite element model (FEM) was built with the default element size of 300 mm (figure 6).

![Figure 6. Finite element model (FEM).](image)

Based on the results of the calculations (figures 7-8), it can be concluded that the portico structure experiences movement (roll) along the line of the facade wall and the highest values of internal stresses are located in those places where the Atlantes are attached to the beam.
After analyzing the actual state of the portico structure, we were able to determine the deviation of the structural elements from the intended design positions with centimeter accuracy. Thus, it turned out that at the time of the survey, the top of the columns was shifted towards the wall by 3.5 cm. At the same time, no significant column displacements were detected in other directions. If the statues are really hard-Pack ed at the top and bottom, then with the horizontal displacement of the columns, they should experience the same displacement (3.5 cm) of the head relative to the base. However, to get reliable results, it is necessary to scan the entire building, including the basement, roof and surrounding areas, and repeat the calculation to identify the causes of deformations of the Atlantes.

4 Discussions
A methodology of finite element model creation based on laser scanning and BIM technologies is described. Some interesting results of laser scanning survey and numerical modelling based on methodology proposed have been discussed. Deviations of the portico's structural elements were identified based on the use of laser scanning, HBIM and FEA. It was found that the displacement of the upper parts of the columns relative to the lower ones in the direction of the facade wall is 4 cm. An intermediate HBIM of the portico (LOD 100) was created inside Revit. Finite element model with default element size of 300 mm was created using ANSYS.
However, despite the large number of stations for laser scanning and a pre-planned work program, we still could not avoid a large number of blind spots in the processed point cloud. This problem is mostly related to the complexity of the geometry of the sculptures themselves and the narrow gaps between the sculptures and the pylons behind them. In future studies, it is necessary to capture blind spots (forearms, back) using a hand-held scanner or photogrammetry. And also special attention should be paid to the precision scanning of Atlant’s capstones that connect the hands and head with the girders. These areas are extremely important, as presumably due to the deformation of the portico structures, they transfer the effort to the sculptures. And this factor is especially important at the stage of obtaining a correct grid of finite elements (FEM) and therefore reliable calculation results.

To improve the accuracy of laser scanning data registration, as well as taking into account the fact that the object of research has a complex geometry, it is necessary to provide for the creation of a geodetic network around the building in future works. An equally important factor is the correct choice of equipment. Since after registration, it was found out that due to the heterogeneous geometry of the sculptures, measurements of the most distant elements from the scanning station were made with a greater error than measurements of the same objects from a closer distance. Therefore, in order to reduce noise during subsequent operations, it is recommended to use a scanner with higher accuracy (Riegl, Faro). It is also recommended to create an information model of the entire building of the new Hermitage – LOD350 (or 400, 500), to survey the surrounding territories, to clarify the engineering and geological conditions of the site in order to analyze the entire building and obtain reliable results. In order to achieve more accurate results in the future, it is necessary to study the archival documentation to clarify the internal structures of girders and their connection nodes. The materials and type of foundation as well as the conditions for fixing sculptures from above and below must also be specified.

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