# 3D AND HBIM MODELS: DIGITAL TOOLS FOR THE DIAGNOSTIC STUDY OF THE STAIR TURRET OF THE SOUTH-EAST CORNER OF THE MAIN TOWER OF STRASBOURG CATHEDRAL

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## ABSTRACT:

During the construction of Strasbourg Cathedral, men aspired to see it radiate eternally. However, like any monument, it experiences structural weakening due to the effects of time, but also to the many external aggressions that damage the materials. Regular interventions therefore make it possible to preserve this building over time. It is in this context of conservation that the cathedral lives to the rhythm of a major restoration campaign since 2014. The objective of this project was to carry out a modeling and a BIM model of the stair turret in the south-east corner of the main tower built entirely of sandstone. This work was part of the preparatory phase of the restoration work on the south-east stair turret of the high tower scheduled for 2024-2025. The objective was to carry out a diagnosis of the turret (35 m high, 168 steps) with the help of a 3D and BIM model. This study could be understood as the beginning of a more global work of 3D representation extendable to the entire monument. In addition, in the spirit of gathering information and building knowledge base, it could be interesting to develop a complete BIM model of the entire building later.

## 1. INTRODUCTION

### 1.1 Purpose of the study

The Cathedral of Notre-Dame de Strasbourg is one of the most mythical monuments in eastern France if not the most mythical. It has been the symbol of the city of Strasbourg, known for its cathedral, for more than five hundred years now. It was in the year 1015 that the first foundation work was carried out on the remains of an old cathedral, and finally in the year 1439 that the construction of the cathedral of Strasbourg ended, more than four hundred years of work with different periods well marked. Indeed, the cathedral has gone through several styles, including the roman style from the beginning of its construction until the end of the twelfth century where a major project of reconstruction and modernization of the eastern parts of the cathedral were undertaken. The construction ended in 1439, marked by the construction of the spire culminating at a height of 142 meters, giving Strasbourg Cathedral the title of the tallest building in the world for more than two centuries. Today, the cathedral is the second tallest cathedral in France after Rouen, and the fifth in the world. From 1439 to the present day, the cathedral would undergo many changes with renovations and additions of elements. It was also dedicated to Catholic worship, but also Protestant from 1527 to 1681 and survived three major conflicts, the Franco-Prussian War of 1870, the First and Second World Wars of 1914-18 and 1939-45 respectively. These conflicts have changed the nationality of the cathedral five times!

Even today, the Foundation Œuvre Notre-Dame has been dedicated to the maintenance, conservation, and restoration of the cathedral for more than 800 years. Indeed, the bishop of Strasbourg and the cathedral chapter founded the Œuvre Notre-Dame in the early thirteenth century to manage donations, legacies and organize the reconstruction of the Roman cathedral.

Since its construction, the cathedral was the property of religion and in particular until 1527 when the foundation was considered as Supreme Lodge of the Holy Roman Empire thus having an important power in the empire. It was in 1789 that the cathedral became the property of the State and in 1793 that the assets of the foundation were nationalized. Thus, since the end of the eighteenth century and early nineteenth century, the administration of the foundation is entrusted to the city of Strasbourg.

Today, the foundation continues the mission it was given at its creation, which is to say, the maintenance, conservation, and restoration of the cathedral. For this, stonemasons, sculptors, masons, curators, archivists, blacksmiths, and many others work together to perpetuate what is the symbol of the city today. Strasbourg Cathedral underwent major renovations during its lifetime and still benefits from it today.

On the agenda, it is the south-east stair turret of the high tower that will soon be concerned by a renovation. A study will be deployed by the new chief architect of historic monuments as soon as he is appointed in 2024 to find out if this turret needs a renovation intervention. Indeed, the question has been raised for several years now, but has never been studied thoroughly since other more important renovation works have been undertaken. Thus, a pre-study of this south-east turret tries to identify the different pathologies in order to be able to assess whether renovation work is necessary or not. A work upstream of that of the next chief architect of historical monuments.

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## 1.2 The South-East Turret

### 1.2.1 Structure

The southeast turret (Figure 1) is one of the four turrets of the high tower of Strasbourg Cathedral. It is the most authentic of the four with a majority of original stones built entirely in sandstone like the rest of the building. It is located on the platform 66 meters above the ground and measures 34.50 meters high so with its highest point culminating at more than 100 meters above the ground.

The base of the turret has a triangular plan while the spiral staircase it contains has a hexagonal plan. The staircase is composed of 14 revolutions of 12 steps each, giving a total of 168 sandstone steps.

From the 9th revolution, the base constituting the wall facings marries the hexagonal shape of the staircase.

Thus, from the 10th to 14th revolution, the geometry remains similar.

It appears independent of the octagonal main tower. However, it is connected to the latter, from bottom to top:

- By two small decorative "flying buttresses",
- By iron anchors.
- On the small floor by a stone footbridge at the vault of Ulrich d'Ensingen,
- At the base of the spire by a stone walkway.

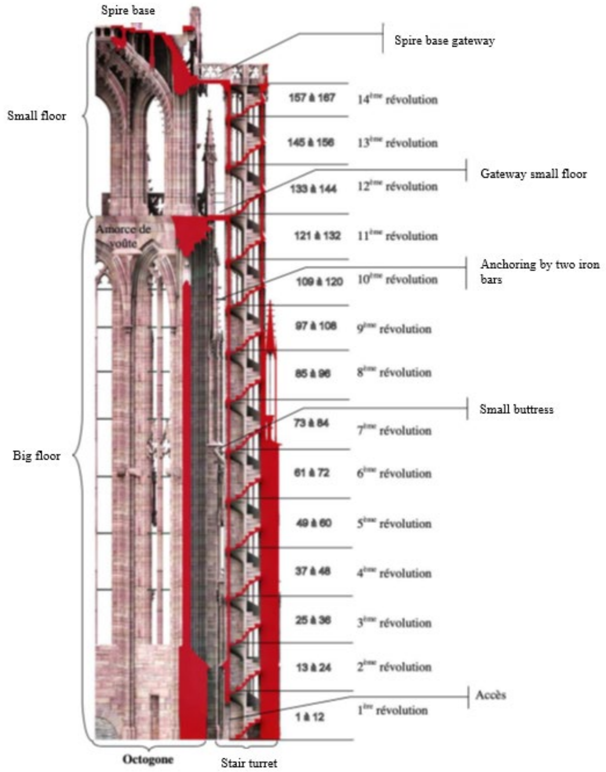


**Figure 1:** Cross-sectional view of the turret (Doc. Foundation Oeuvre Notre-Dame).

The different stages of the cathedral's construction have been the subject of numerous writings (OND, 2023). The turrets, including the southeast turret, are part of the construction of the great tower (Figure 2). It was around 1399 that the architect Ulrich d'Ensinger drew up the plan for a high tower enhanced by an openwork spire. The octagon is composed of eight monumental bays, punctuated by protruding buttresses. It is flanked by four spiral stair turrets, which are completely independent of the tower, except for two small walkways located at the level of the small floor. Ulrich d'Ensinger died in 1419 before completing his work and it was the master builder Johann Hültz of Cologne who completed the spire in 1439 following a new plan.

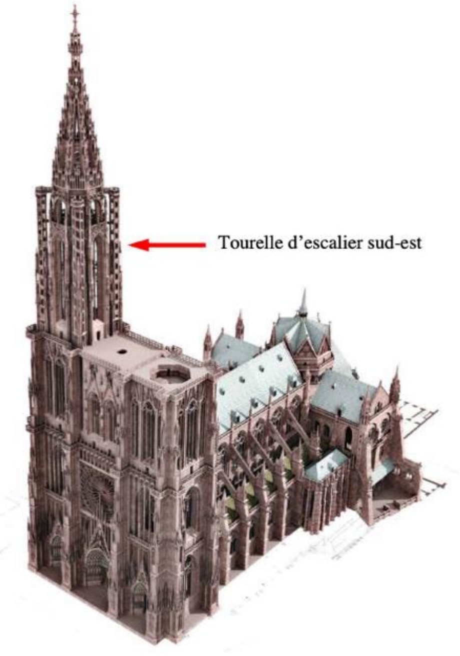


**Figure 2:** The Southeast Turret (Doc. Foundation Oeuvre Notre-Dame).

### 1.2.2 History of renovations

Like any historic building, Strasbourg Cathedral, and in particular the have undergone renovations. Nevertheless, it is the southeast turret that has undergone the least renovations unlike the other three that have been completely renovated. It was at the beginning of the nineteenth century that two revolutions were completely renovated. Indeed, steps 55 to 64 and steps 151 to 168 have been completely replaced by new ones. To do this, it was necessary to remove and rest all the steps that were above the steps that had to be replaced in order to be able to remove them. The size and type of sandstone used made it possible to determine the date of step replacement. At the beginning of the twentieth century, the southeast turret was the least degraded of the four. However, the steps were very worn because the high tower was then open to visitors, and it was the southeast turret that was used as access by tourists. A resoling was undertaken but was finally filed later because it seemed to be at the origin of the disintegration of the steps. In 1976, fireworks fired from the platform of the cathedral damaged (cracking) the studied turret. Some steps will then be replaced.

### 1.2.3 Health status of the turret

It was a question of listing all the pathologies that affect the turret, as well as all the changes that may have been made on this turret (Figure 3). The state of health is subject to:

- Deformation of the central core (a);
- Subsidence of steps (b);
- Vertical cracking of the steps to the right of the core;
- Cracking and / or bursting of the core (c);
- Disintegration of steps (d).

After listing each of the pathologies present on the south-east turret, we were able to see that the most worrying and important

pathologies were the deformation of the core as well as the collapse of the steps between the 9th and 11th revolution.
Thus, this structural modeling study on these two pathologies focuses between the 9th and 11th revolution.

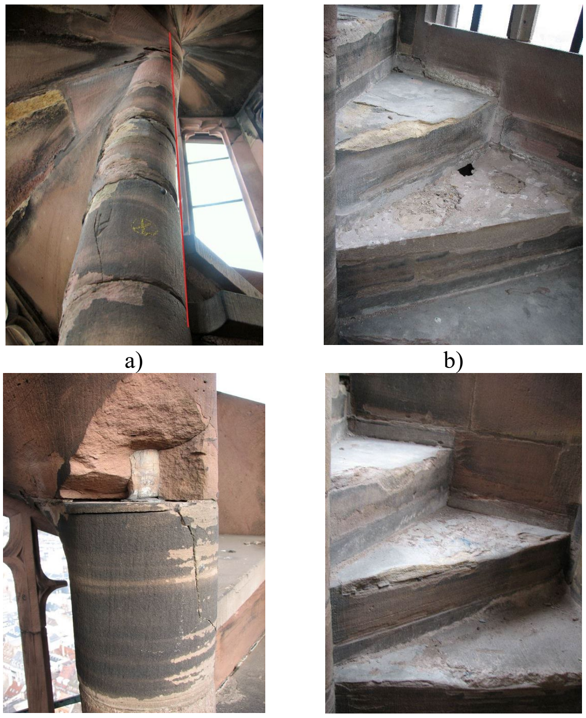

a) b)
c) d)

**Figure 3:** Pathologies of southeast turret.

First, a BIM model of the turret was defined. This approach was not so much a structural approach as rather an architectural one. Indeed, this BIM model will allow to obtain a 3D vision of the turret, initially composed of steps, but which can be filled later with the staircase. However, the objective was not only to have a 3D model, but a BIM model, which will allow to form a library to identify all the elements of the turret and in particular, as part of our work, the steps and their core to which it was possible to attribute properties. This library would have been supplemented by other elements constituting the turret.
In a second step, the objective was to be able to determine a mechanical model of the step for calculations of the strength of the materials.
Finally, the objective was to determine the main causes of deformations and the most sensitive areas of the turret. The complex geometry of the turret and the many factors aggravating the situation make it impossible to approach the problem with conventional civil engineering assumptions and methods (Fang et al., 20121) (Qin et al., 20121). This was why our approach consisted in establishing a stress mapping on the most damaged elements of the turret using finite element calculation software. These tools will allow, from an analysis of the construction materials (sandstone) and a mesh of the external surface of the turret steps to understand the distribution of forces inside the material. Modeling the behavior of this structure could then make it possible to make assumptions about the future behavior of the structure, with or without rehabilitation work.

## 2. MODELLING

### 2.1 Theoretical BIM model

On the basis of the plans of revolutions, a revolution is composed of 12 steps and carried out with only two types of steps: a first type of step that will be called odd step and a second type of step that will be called even step because of their number. Each of these steps is repeated 6 times to obtain an entire revolution of 12 steps. First, we established the 3D model in *Autodesk Revit* software before we could use the true BIM features.
The exact geometry of the steps could be defined from the various planes and sketches, but with dimensions that are not exact. The models were first established with approximate dimensions. Nevertheless, to be able to resize these families, it is necessary that these families (Figure 4) were configurable and resizable according to the in-situ measurements.

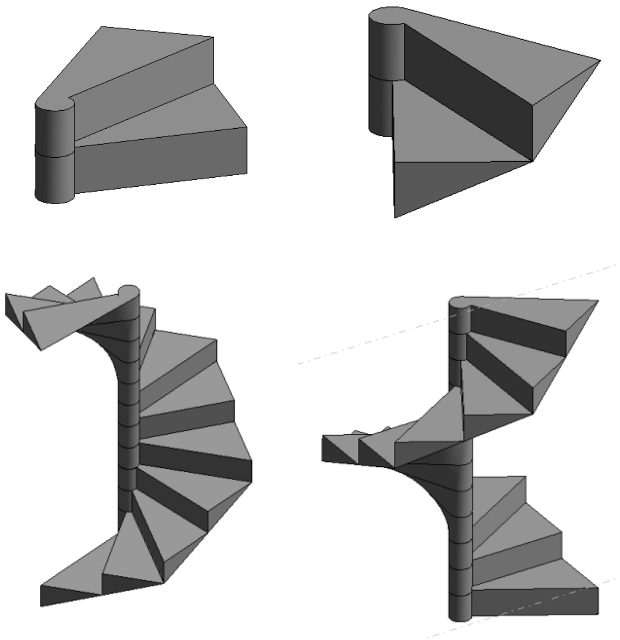
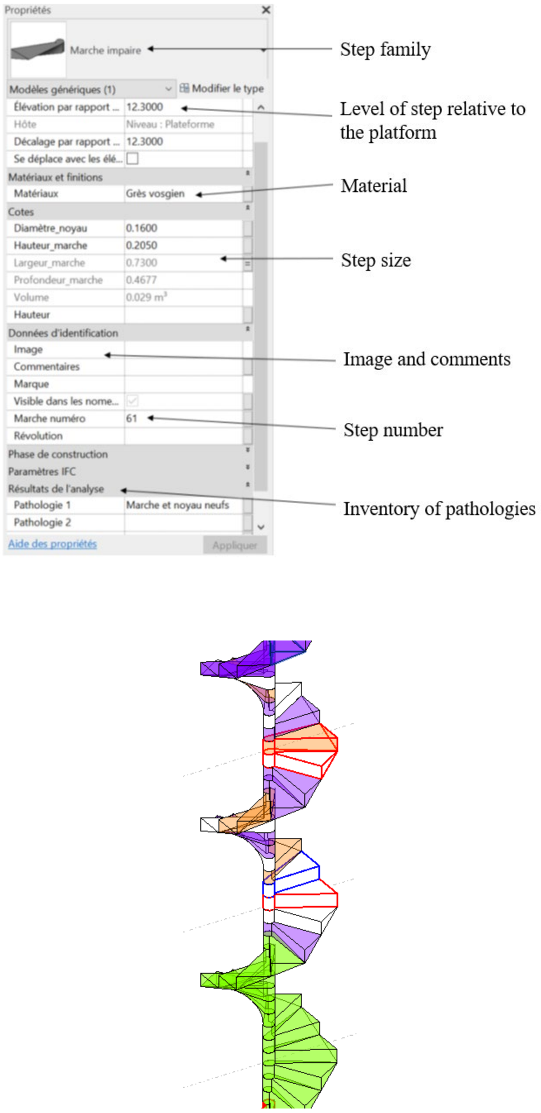


**Figure 4:** BIM families of steps and architecture of a revolution.

The importance of BIM and the objective of this part was to be able to assign properties to each of the 168 steps of the turret by associating them with their own identity. In the context of the project, this made it possible to have a better nomenclature of each market and to identify them more precisely.
It was necessary to create a nomenclature which will be used to fill in all the information (Figure 5-a) needed to identify the different steps.
This information is as follows:
- Step number
- Height of the step
- Width of the step
- Core diameter
- Step volume
- Pathologies
- The material
- The level in relation to the platform
- Comments

For a more visual result, it was possible to add filters that will allow to better identify steps with certain characteristics, including particular pathologies (Figure 5-b).



Propriétés

Marche impaire

Modèles génériques (1) | Modifier le type

| | |
|---|---|
| Élévation par rapport ... | 12.3000 |
| Hôte | Niveau : Plateforme |
| Décalage par rapport ... | 12.3000 |
| Se déplace avec les élé... | ☐ |
| **Matériaux et finitions** | |
| Matériaux | Grès vosgien |
| **Cotes** | |
| Diamètre_noyau | 0.1600 |
| Hauteur_marche | 0.2050 |
| Largeur_marche | 0.7300 |
| Profondeur_marche | 0.4677 |
| Volume | $0.029\ m^3$ |
| Hauteur | |
| **Données d'identification** | |
| Image | |
| Commentaires | |
| Marque | |
| Visible dans les nome... | ☑ |
| Marche numéro | 61 |
| Révolution | |
| **Phase de construction** | |
| **Paramètres IFC** | |
| **Résultats de l'analyse** | |
| Pathologie 1 | Marche et noyau neufs |
| Pathologie 2 | |

**Figure 5:** a- Nomenclature; b- Example of colorized representation by pathology.

## 2.2 Principles of 3D as-built modeling

### 2.2.1 Principle

Before starting the survey phase, we researched the different techniques of 3D surface acquisition in order to choose the one that seemed most appropriate to us.

To guarantee a complete data acquisition and accurate as possible, several methods can be combined (Morena et al., 2021). This was the case in similar work carried out on the spire of the Cathedral of Milan (Fassi et al., 2010) or the Esplanade du Peyrou in Montpellier (Fuchs et al., 2016).

Three methods were detailed:

- Topographic survey: the topographic survey (which includes total station, GPS or leveling) is a measurement method at one point that can be tedious if the number of points to be acquired is large. The total station acquisition can be used in addition to the lasergrammetric survey to georeference the point cloud.
- Photogrammetric acquisition: this method is based on several shots (photographs, aerial or terrestrial images) of the same area with different shots. The principle of stereoscopy is then applied.
- Lasergrammetric acquisition (Landes et al., 2011): this data acquisition method makes it possible to measure point clouds in three dimensions. The terrestrial laser scanner performs a laser beam scan of the surrounding elements. This technique is particularly interesting since it makes it possible to collect millions of points in a very short time. Data acquisition can be done indoors, in small spaces, as well as outdoors. Spheres allow the connection of point clouds between them. Cameras are also built into the scanner to colorize the point cloud in true color.

### 2.2.2 Processing phases and modelling

Data acquisitions were made by use of a FARO Focus X330 scanner (Faro, 2023), point clouds were consolidated and georeferenced using spheres and checkerboards targets.

From the consolidated, georeferenced and cleaned point cloud, the modeling of the turret could be carried out.

For this, the *3DReshaper* software since it offers interesting modeling tools was preferred.

In view of the large number of details, it seemed wise to use mesh modelling to model the turret. *3DReshaper* offers two types of mesh (3DReshaper, 2016):

- Regular sampling: This method creates a closed mesh based on an average distance between points, automatically filled according to cloud properties. A grid is then projected onto the point cloud and selects the most representative point in each box. A 3D mesh is then generated. This choice of mesh is not always the most appropriate because the level of detail is not the same throughout the mesh.
- Two-step meshing: This method first creates a coarse mesh to obtain the overall shape of the model. Then, this coarse mesh is distorted according to the point cloud in order to add all the details.

To keep as much detail as possible in the final mesh, the two-step mesh method was finally used.

### 2.2.3 Highlighting results

To better visualize the results, *CloudCompare* and *3ds Max* software were used.

Using this software, it is possible to provide a comparison of the derived mesh model and the theoretical BIM model designed in *REVIT* software.

Since the *REVIT* software does not allow to import a very dense mesh (unless significantly reducing the number of meshes, which implies a loss of detail), we chose to use the *3ds Max* software to extract views from the two superimposed models. We chose this software because it is part of the Autodesk suite (the link with the *REVIT* model is simplified) and allows to easily import heavy meshes, such as our mesh model from *3DReshaper*. Finally, this software offers high quality renderings, which can be interesting to best visualize the deformations.

To go further in the analysis of the results, we could also test the different colorizations (Figure 6) of point cloud. (Barber, 2016). Reflectance vision is evoked to study cracks in a structure. The reflectance measurement makes it possible to highlight cracks according to a color scale.

This type of colorization would therefore be a perspective to study.

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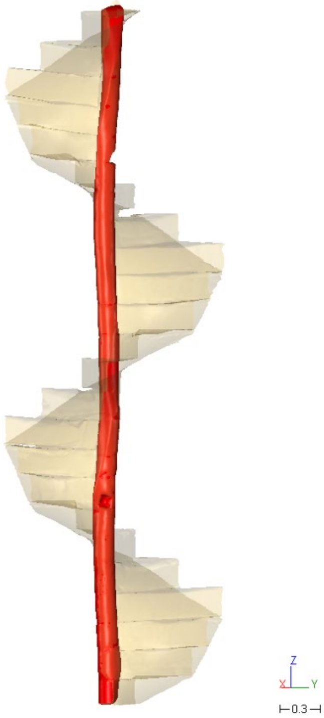


**Figure 6:** colorized deformation of core and steps.

## 2.3 Application to the South-East turret

### 2.3.1 TLS survey

For the acquisition of the turret staircase for TLS Faro Focus X330, the parameters of the profile "Interior, less than 10 m", and thus set the resolution to 1/8 and the quality in 3x were used.

To scan the exterior of the turret on the other hand, the resolution was set to 1/2 and the quality in 3x.

To do this, we started by positioning numbered checkerboard targets on the inner walls of the stairwell. These checkerboard targets allow the consolidation of point clouds between them to form, after processing, a single point cloud. We also positioned spheres, visible from the outside, in order to record them later with a total station to georeference the point cloud in a global system. These spheres were also used for point cloud consolidation. Thus, we have ensured that at least three common targets (checkerboard and/or spheres) were visible on two successive scanner stations. The point density chosen for the scanning was quite high since we wanted a high precision so that the centers of the checkerboard targets and the various details of the structure, such as cracks, would be visible.

We have listed in the following table the significant information of this survey (Figure 7).

| | |
|---|---|
| Number of TLS station | 45 |
| Scanning speed | 244.000 points per second |
| Step (distance between two scanned points) | 1,23 cm at 10 m |
| Number of points in the overall project | 125.077.551 points |
| Number of checkerboards | 36 |
| Number of spheres | 10 |
| Scanning time | 1 min. 30 (only for points) |
| Data format | .fls |

**Figure 7:** characteristics of TLS survey.

For the processing of point clouds, we used *Faro Scene* software. Automatic processing made it possible to automatically point out certain checkerboard targets and spheres and to create auto-clusters, groups of point clouds consolidated together. To complement the automatic recognition, a manual pointing of checkerboard targets and unrecognized spheres as well as common planes to two successive point clouds was necessary. For the consolidation to be carried out correctly, at least three common objects between two point clouds (checkerboard targets, spheres or planes) were mandatory. Thus, 67 plans were created in total so that the consolidation could be done correctly on the entire southeast turret.

Once the consolidation was completed, a single point cloud of the entire turret was obtained. The last step was to import the .csv file with sphere coordinates in order to georeference the whole object in the local system.

### 2.3.2 As-built modeling

Before the as-built modeling phase (Sanghyun et al., 2015) could be started, the point cloud had to be cleaned up in *Faro Scene* software.

The goal was to clean up the entire point cloud. Indeed, it was necessary to remove unwanted objects for modeling such as spheres and their tripod. In addition, it was necessary to clean surfaces that contain false dots such as glass surfaces. This type of surface is highly reflective and therefore disturbs the measurements made by the laser scanner during the survey. During processing, false dots or noise may appear, created by the reflections of the laser on these surfaces. In our situation, the majority of windows were covered with plexiglass. It was therefore necessary to focus on each of the windows covered with plexiglass to eliminate the false dots. This step was tedious and time-consuming.

After manually cleaning the point cloud, a tool can be applied to reduce noise. Noise refers to the "blurring" of the point cloud, i.e., points that are too far from the actual surface of the object. These are random imperfections in the data. It was important to remove these points because excess noise can lead to problems in modeling. This is because the software does not differentiate between good points and noise, and therefore creates surfaces from all points. Depending on the number of false dots, the modeled surfaces can be very different from reality. Also, too much noise makes a point cloud bigger, resulting in larger files and longer transfers.

Once the cloud was cleaned of all these artifacts, a point cloud of over 400 million of points in total was generated.

### 2.3.3 Mesh modelling

From the cleaned point cloud, we can start the surface modeling by mesh on the *3Dreshaper* software.

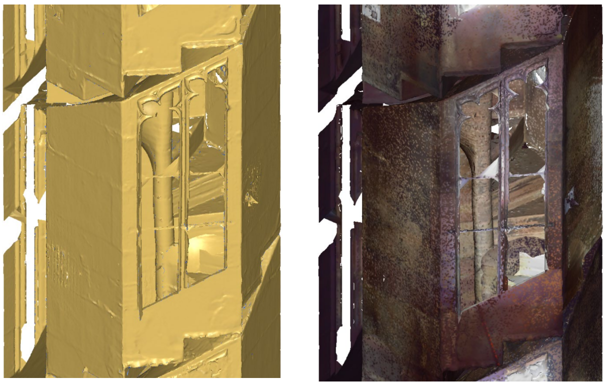


**Figure 8:** Extract of the resulting mesh model, without and with texture.

**Figure 9:** Complete modeling of turret interior and detail.

The surface modeling phase by mesh was done automatically but so that the 3D model is as representative as possible of reality some adjustments were necessary. As mentioned earlier, to perform an accurate surface modeling the mesh in two steps method was favored: creation of a coarse mesh and then refinement. First of all, a coarse closed mesh was generated. The "average distance between points" parameter was automatically adjusted according to the properties of the point cloud.

Once the coarse 3D mesh was generated, all the expected fine details were not visible, but the overall shape was correctly represented. In the second phase of mesh process, it was necessary to supplement the initial point cloud with complementary interpolated points.

In the literature (3DReshaper, 2016), it is recommended to use the point cloud only if it is cleaned and not noised. Otherwise, it is preferable to use the interpolation method. Since our point cloud was properly cleaned, we chose to use the point cloud to refine the mesh (Figure 8 and 9).

Once the mesh was created, the core and steps were isolated by segmenting the mesh. Then the mesh was adjusted. Indeed, the mesh model still has many defects. One of the main shortcomings to be rectified was the unification of normals.

The second phase of treatment consists of removing noise and plugging holes. This once again long and tedious step was carried out mainly by hand because the automation of plugging holes tends to fill the spaces actually present on the turret model. This treatment also made it possible to highlight defects in the mesh that had not been identified before, in particular the presence of "double layer" in certain places, i.e., the presence of two superimposed mesh surfaces. We then take advantage of this step to correct them. Thus, the manual processing of the mesh forced to dwell on each step and therefore to correct them one by one (Figure 10).

**Figure 10:** Resulting of mesh models.

## 3. RESULTS

### 3.1 Comparison with the theoretical model

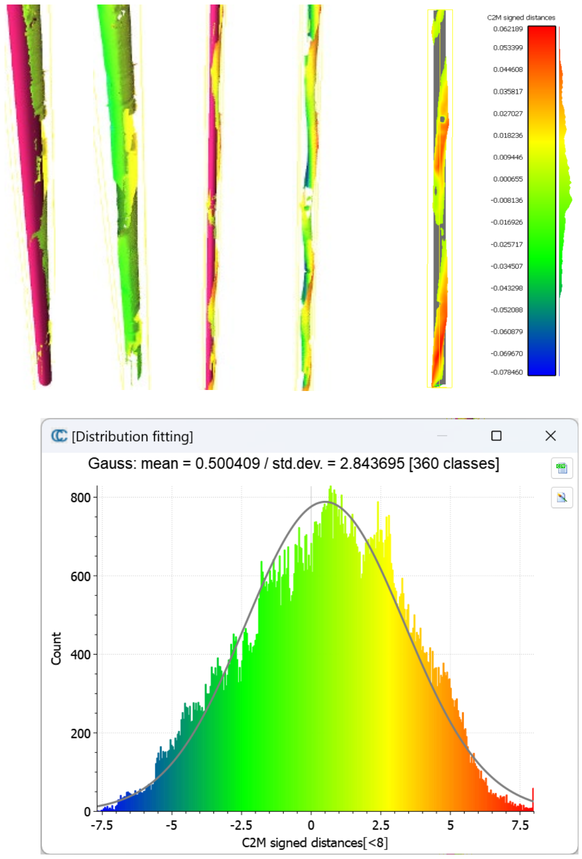
The objective of this section was to compare the actual state turret model with the theoretical BIM model in order to identify the differences between the two models.

For the realization of the qualitative comparison, therefore visual, a first superimposing of the models was realized on *3ds Max*.

The kernel of the two models could be then isolated. First of all, it was to notice that even if the bases of the core merged, a strong shift (6 cm) could be observed between the two models at their vertex.

The deformation was all the stronger at revolutions 9 and 10 where the gaps were of the order of several centimeters, up to almost 8 cm.

In a second step, it could be carried out on *CloudCompare* a quantitative comparison of the two models. Thus, the two models were superimposed in the same way at their base before calculating the deviations. Then attention was paid to revolutions 9 and 10. In *CloudCompare*, there were solid blue and red areas, i.e., the extreme colors of the scale associated with the deviations. As detected earlier during the visual comparison, the deviations were therefore greater in these areas (Figures 11).



Gauss: mean = 0.500409 / std.dev. = 2.843695 [360 classes]

**Figure 11:** Comparison with the theoretical model of different parts of the central core.

### 3.2 Other results of structural calculations

The study also focused on the structural mechanics of the turret. The turret is composed of sandstone from various quarries around Strasbourg. The nature and properties of the rock are very variable from one block to another depending on where they come from. This was influenced by the different building policies as the cathedral was built and maintained as well as the repairs that were carried out. To establish the calculation model, the determining mechanical properties will be the density of the sandstone, the Young's modulus, and the Poisson coefficient.

Each step of the turret subjects the core to certain efforts. A study of the interaction of the steps with each other and with the stairwell made it possible to estimate the forces transmitted (Huang, 2020).

The main contact between a step and its previous one is concentrated in the core of the staircase. In addition, the majority of steps, because of degradation, no longer have a contact surface with each other outside the core. This observation imposed the hypothesis that the steps rest on two supports: at the level of the core, on the lower step and at the level of the staircase. The steps thus have the behavior of supported beams. They transmit to the core a vertical cutting force as well as a bending moment to the core. These constraints were approximated by calculation.

The study proposed the following results:

- Turret mass: the modeling of the steps and the study of the materials allowed an approximation of the volume of this complex geometry and to make an estimate of the mass of the elements and by summation of the total mass of the turret.
- Revolution model: the balance sheet of the modelling hypotheses was well represented by the one-revolution model. The study geometry, the optimal mesh, and the boundary conditions representative of the actual mechanical conditions of the turret were observable.
- Model comprising only the core: a model of a revolution in independent blocks for each step was carried out, with a blocking of displacements at the ends. A lateral displacement was remarkable towards the upper middle of the element. This similarity with real conditions is a development track for future models. The deformation took the form of a twist rather than a simple bending, this can be explained by the circular nature of the section and was all the closer to the actual conditions.

## 4. CONCLUSION AND OUTLOOK

### 4.1 Theoretical model

This study made it possible to carry out different models to provide elements for understanding the behavior of the south-east turret of the cathedral. A BIM model could be established to identify each of the 168 steps constituting the turret. As a result, the model made it possible to give a specific identity to each step and thus to associate the different properties recorded or calculated.

These properties can be further extended according to the needs of the study and the finesse of knowledge of the object. In particular, it would be possible to review the material, which has different technical characteristics depending on the period and place of extraction.

Our initial model contained only one type of material, which is Vosges sandstone. This work would require, upstream, to precisely know the material of each step. This could also lead to the dating of the steps with the property to add in the nomenclature the date of extraction of the sandstone, for example.

Other properties can still be adjusted such as the dimensions of the step. Indeed, in the initial theoretical model the steps were all identical and have the same dimensions.

The dimensions could be adjusted thanks to the geometric as-built model established by the in-situ measuring means.

### 4.2 Geometric model

The geometric model was based on a TLS survey with a significant constraint which was the difficulty of access to the site and the low setback margins available in this spiral stair turret. Some points could be improved to obtain a more reliable model. The consolidation of the point clouds had to be based on a large number of tie points, here checkerboard targets, to allow automatic processing. The initial point cloud has holes corresponding to areas too close to the laser scanner while data acquisition. The number of scans must be adjusted to the geometry of the object.

The use of a mobile scanner in addition made it possible to fill the various holes while maintaining a correct geometry.

The complete turret was very substantial to model. Focusing on the most relevant study areas (revolutions 8 to 11) as well as the core saved processing time.

However, the outer walls may be useful for future structural studies.

The pooling of theoretical modeling and geometric modeling work made it possible to carry out a description and a technical diagnosis of the steps, in particular thanks to the more in-depth study of deformations and cracks using our model.

Work is planned as early as 2024 to renovate the areas of the turret that have been deemed the most critical according to 3D modeling.

## ACKNOWLEDGEMENTS

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