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THE CHURCH OF SANTA MARIA DELLE GRAZIE AL CALCINAIO: FROM DIAGNOSTIC STUDIES TO ARCHITECTURAL AND STRUCTURAL REHABILITATION PROJECT.

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Abstract

This paper illustrates the results of the cognitive process for the defining structural consolidation interventions, seismic risk reduction and architectural rehabilitation of the church of "Santa Maria delle Grazie al Calcinaio", Cortona (Arezzo, Italy). The church represents a splendid example of Renaissance architecture in which the architect Francesco di Giorgio Martini rigorously applied the architectural principles of proportion and perspective. The use of local stone (sandstone) is evident inside in the frames that decorate the facades.
Today the building has several problems. The most important is the advanced state of decay of the external stone cladding. However, over time the structure has highlighted structural instability that have already required interventions in the past and that have given rise to the need for a static analysis and an evaluation of seismic vulnerability. To this end, a cognitive phase was carried out in accordance to the NTC2018 and the Guidelines for the assessment and reduction of the seismic risk of cultural heritage, which included: historical-critical analysis, digital survey, structural and material diagnostic campaign, HBIM modelling, definition of the structural model and dynamic behaviour. All these studies have made it possible to highlight all the criticalities of the building and to plan interventions aimed at reducing structural vulnerabilities and for securing the stone ashlars and strongly protruding cornices in order to minimize the risk of falling fragments and protect the safety of users.

Keywords: Cultural heritage, HBIM, Seismic vulnerability, Calcinaio, Cortona.

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1 INTRODUCTION

The church of “Santa Maria delle Grazie al Calcinaio” stands on the south-east side of the hill of the city of Cortona (Arezzo, Italy), and with the facade it looks towards the Tuscan Valdichiana (Figure 1).

The building’s design is by the architect Francesco di Giorgio Martini and the works began in 1485 and ended in the mid-1500s. The building is located in an area where skins were tanned in vats with quicklime since the 1400s. Its construction is linked to the cult of an icon of the Madonna and Child, painted on the wall of a vat, which began in 1484 to work miracles. The building was entrusted to various ecclesiastical communities and after a period of abandonment and restoration, it was reopened in 1730 and proclaimed a Marian shrine in 1985.

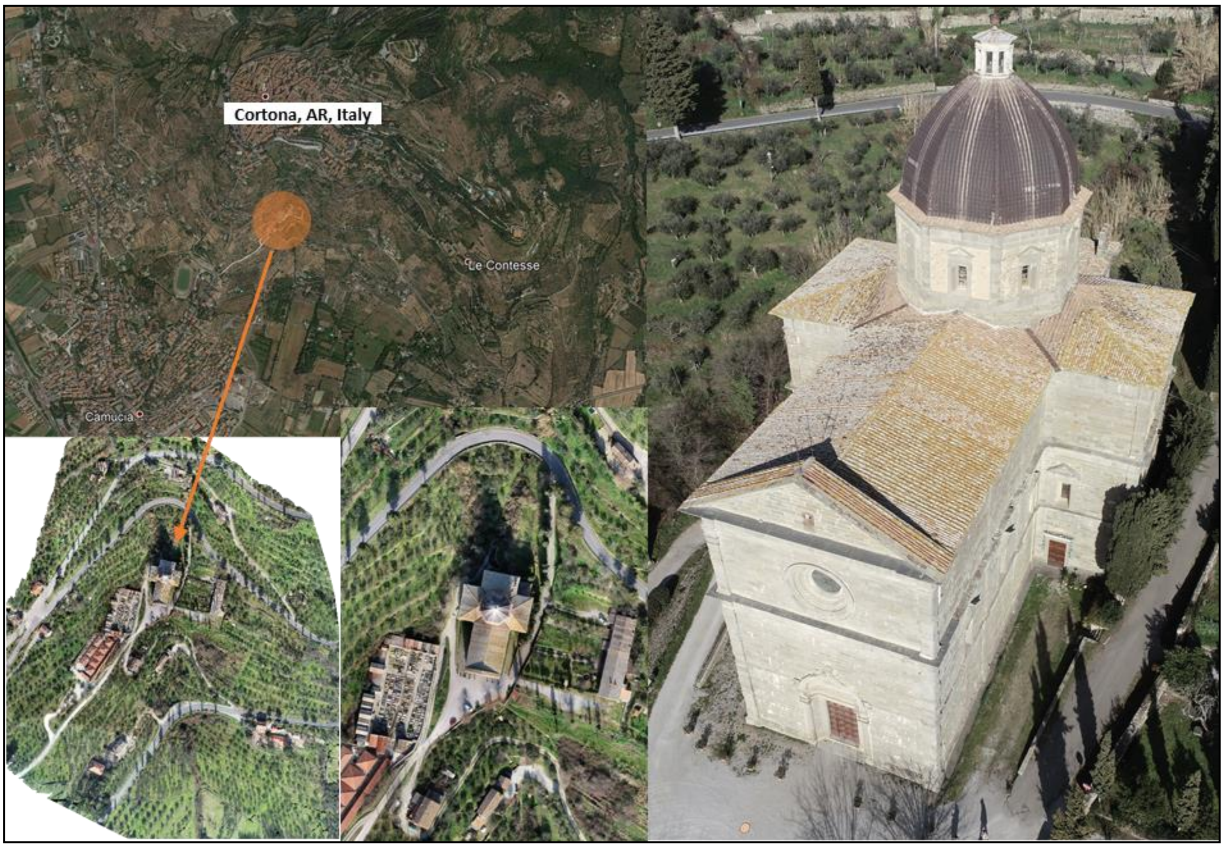

Figure 1: The Church of Santa Maria delle Grazie al Calcinaio, Cortona, (AR)

In 2019-2020, the Soprintendenza Archeologia Belle Arti e Paesaggio di Siena, Grosseto e Arezzo commissioned Studio Micheloni Srl, with a tender, to carry out a study for the knowledge and protection of the complex. This paper presents the result of the studies about the analysis of the vulnerabilities and the state of conservation of the building and the design of specific intervention methodologies. The diagnostic studies start from a detailed geometric survey with advanced laser scanner and photogrammetric technics.

The results of geometric survey and of material analysis merged into an integrated HBIM model, who contained all the data necessary for carrying out the static and seismic vulnerability checks both on the main structures and on the decorative surfaces.

Starting from the cognitive studies and the checks of static stability and seismic vulnerability, have been identified the criticalities that required an intervention in order to guarantee a uniform level of safety.

2 THE PROCESS FOR STRUCTURAL AND MATERIAL KNOWLEDGE

An accurate phase of knowledge of a building allows to reach in a conscious way the definition of technical interventions that aim to protect the building in respect of its history, its architectural value and its function, without altering the construction characteristics from the point of view typological, but above all preserving the established structural functioning.

However, to prevent irreparable losses, a campaign of destructive and weakly destructive investigations would be too invasive and incompatible with conservation and protection requirements. The aim was therefore to plan a campaign of non-destructive investigations that would give sufficient certainty of the results, to be calibrated and validated locally by little destructive investigations.

The knowledge path can be traced back to the following activities, in accordance with current legislation (Italian NTC 2018 chap. 8 on existing structures and guidelines for the assessment and reduction of seismic risk for cultural heritage) [1,2] and with the same criteria of the discipline of architectural restoration:

- building identification: first schematic survey and identification of any elements to be safeguarded;
- the geometric survey of the building in its present state, including any cracking and deformation;
- the identification of the historical evolution from the hypothetical original configuration to the current state;
- the identification the elements if the resistant organism, with particular attention paid to the techniques of carrying out the works, the construction details and the connections between the elements;
- the identification of materials, their degradation, their mechanical properties.

The cognitive framework has allowed to increase the level of knowledge of the existing building and to arrive at the definition of a model that describes the structural behaviour to evaluate the intrinsic vulnerabilities and criticalities. Starting from these evaluations, the consolidation measures have been defined to ensure the preservation of the property in full respect of historical and artistic characteristics.

2.1 The historical background

The cult building was created to guard and honor an image of the Madonna with child to which miracles were attributed around the mid-fifteenth century. This mural painting was located just outside the walls of Cortona, near a tub where the shoemakers tanned the hides, due to the use of lime in the tanning process the place has been called Calcinaio since then. With the increase in devotion, the Arte de' Calzolai decided to erect a temple where this sacred image could be venerated. Although the initiative was not received with unanimous consent by the population, at the behest of Pope Sixtus IV, the ambitious project was started and in June 1484 Luca Signorelli called Francesco di Giorgio Martini to carry out the project. The following year, in 1485, construction work began on the church which was certainly completed by 1525 [3].

The building stands out on the side of the hill presumably around to the primitive location of the Marian painting, which is found today in the High Altar.

The stream that flowed near the sacred image was regularized and channeled into a winding tunnel that today passes under the building next to the high altar and then runs along the entire length of the nave and flows back to the outside just beyond the facade. The bed of the river follows the natural slope of the hill, the building was built according to the watercourse which has important symbolic meanings for the Christian religion [4].

Construction work began in 1485 based on a project by Francesco di Giorgio Martini multi-faceted personality, like many others of his time, he was an artist, sculptor, architect and engineer. As an architect and military engineer, he built numerous fortresses and castles in many towns of Italy. He worked in many cities of Italy and was a friend of the most renowned artists and intellectuals of the time, one of them was Leonardo Da Vinci [3].

The church of Santa Maria delle Grazie al Calcinaio fits perfectly into the historical period in which it was conceived and built and represents an example of Renaissance architecture of the highest level.

The study and relief from life of ancient buildings and the centrality of man are the cardinal concepts on which the architectural language of the Renaissance is based, which saw the ideas of Humanism bring to maturity where the centrality of man is the point hinge [5].

The building had a troubled conservation history from the first years of its construction; it was built thanks to donations from the people, the municipality and the Guild of Shoemakers but since it was a religious place it was necessary for an ecclesiastical institution to supervise it. The latter gave priority to the construction of a convent near the church before the church itself. Because of this situation there were continuous disagreements and delays in the works as the clerics were more interested in building a convent next door than in completing the construction of the sanctuary [4].

The construction of the dome was completed many years after that of the rest of the factory, the stone decorations inside the building thus remained exposed to the elements for decades causing the degradation of the stone decorations inside the building due to the leaching of the water and wind erosion. The building passed into the management of various religious orders over the centuries, but maintenance and conservation was practically nil.

For some decades the church had been used as a seminary and had been left in a state of complete abandonment; the windows had been walled up and the building had been used partly as a granary and partly as a stable for animals.

After numerous pressures and with the advent of a new Bishop, the church became canonical in 1815; it was immediately evident that numerous restoration works would be necessary to return to office; from 1822 numerous renovations were made.

Important structural consolidation interventions to the dome were made in 1887 through the insertion of tie rods and chains.

Starting from the fifties of the twentieth century, restoration work was carried out on the external face under the direction of the Superintendence; some architectural parts, portions of cornices and tympanums were replaced on the outside while the walls were repainted in white inside.

2.2 The integrated digital survey

The knowledge of architectural and structural geometry of the building was achieved through an integrated digital survey. The new methodologies of digital survey allow the acquisition of a large number of data of existing elements by postponing a part of the interpretative-subjective phase to a later time.

The methodology used involves the integration of 3D models realized with LST 3D methodology (Terrestrial Laser Scanner) for the interiors and photogrammetric survey models made by drone for the exteriors. In addition, the combination of aerial and terrestrial photogrammetry allowed the elaboration of high-resolution orthophotos to acquire detailed information about state of conservation of the decorative system of the facades.

The survey operations required two weeks of field work in February 2020 and were planned to define the quantity and location of the scans and the drone's flight area. The laser scanner used is a Trimble TX8 with a "time of flight" measurement principle, a measurement range of

340 m and acquires large quantities of points in a short time (1 million/sec). Scans were performed in all internal areas including the attics and the access staircase to the dome and in the external areas. The scan parameters have been set to have a resolution of 22.6 mm at 30 m indoors and 11.3 mm at 30 m outdoors.

In particular, metal targets have been positioned outside, on the ground, which are useful for recording the cloud from a laser scanner with that from a drone. Similar targets were used to link scans for more complex structures to detect, such as spiral staircases leading to the attic. The instrument is equipped with integrated cameras for acquiring the RGB data which is applied to the point cloud. The survey operations produced a total of 180 scans.

The aero-photogrammetry was carried out using a DJI Phantom 4 RTK drone and a DJI Matrice 300 RTK. The aircraft are equipped in the first case with an integrated camera with a 1” CMOS 20 megapixel sensor with 24mm equivalent lens, in the second case with a DJI P1 camera with a 45 megapixel full-frame sensor and 35mm lens. In the UAV environment, the GPS RTK (Real Time Kinematic) system allows satellite positioning in real time, thanks to GPS, GLONASS and Galileo signals, where a single reference station provides real-time connections with centimeter-level accuracy. Thanks to this system, therefore, the high precision of the survey operation was guaranteed.

An automatic flight performed on two different days and with different atmospheric conditions was planned to evaluate the best possible contrast and lighting conditions. The survey phase ended with the creation of photos in manual mode from a drone and from the ground at close distances from the elevations. This operation was useful for the preparation of detailed orthophotos describing the state of conservation of the stone face. The images were taken with a Sony Alpha 6500 mirrorless camera, with sensor APS-C type Exmor® CMOS sensor (23.5 x 15.6 mm) and 24.2 megapixels.

Figure 2: The point cloud from LST survey and fotogrammetric survey

The photogrammetric survey obtained a GSD (Ground Sample Distance) of less than 3 cm.

The registration procedure of the laser scanner stations was performed using the Trimble Realworks software. Like other registration software, it allows you to rototranslate the scans and connect them automatically by analyzing homologous planes between adjacent scans or manually by identifying common reference points. The resulting cloud is oriented in a local reference system. The images from the drone survey were processed using photogrammetric software producing a point cloud of the surveyed area and the roofs.

The georeferencing of the laser scanner cloud is obtained by roto-translation on the drone point cloud and using the reference targets. The result is a cloud of approximately 700 million points oriented in a WGS 84 / UTM zone 32N geographic reference system and which reported an average residual error of less than 10 mm. The point cloud which, processed using software, has returned all the information regarding geometries and distances of the visible elements of the exterior and interior of the building, which can be navigated in 3D, interrogated and used as a basis for 2D and 3D reconstructions (Figure 2). The elaboration of the orthophotos of the facades required specific elaborations. The same SfM (Structure from motion) algorithms used to process the aerial photogrammetric survey have made it possible to process the photos from the ground and those from the drone together. The combination of the two types of photographic shots made it possible to eliminate occlusions and obtain complete orthoimages. Through various stages of processing (sparse cloud, dense cloud, mesh and texture), five 3D models relating to the facades of the Church were obtained.

High-resolution orthoimages were extracted from these models. In fact, the resolution of the images made it possible to precisely identify the types of deterioration even in areas of the elevation that are not visible from the ground.

2.3 The diagnostic campaign

The historical material collected, the surveys and the inspections carried out allowed the achievement of a first level of knowledge of the building. However, this objective is not totally exhaustive for the purposes of defining the structural behavior of the building, therefore in line with the aforementioned regulations, it was necessary to prepare a campaign of diagnostic tests. Documentary knowledge and visual knowledge have made it possible to identify the areas to be investigated by choosing the most significant or most critical points of the structural organism.

The diagnostic operations will focus in particular on the following points:

- The vertical walls, stone masonry
- The vaulted systems and brick and stone arches
- The brick dome
- The wooden structures of the roof.

The in situ investigation techniques are mainly of a little or non-destructive nature:

- Thermographic photos
- Endoscopic investigations on the walls and vaults after drilling;
- PNG tests on mortar;
- Collection of samples of stone material, bricks and mortars for mineralogical, petrographic and mechanical analyses.
- Exploratory tests with removal of plaster to verify the masonry setting of the dome and the connections;
- Visual investigations on the conservation of the wooden elements of the roof.
- Cataloguing of the wooden elements of the roof with the DRESL (Diagnosis of wooden structural elements) method, developed in collaboration with Italian National Research CouncilInstitute of BioEconomy – IBE.

The use of single and double flat jacks on masonry was limited to a couple of trials.

While the geognostic investigations were carried out for the geotechnical characterization of the land and geoelectric investigations to investigate the structure of the subsoil also in relation to the presence of the watercourse and the foundations of the building.

The localization of the investigations was carried out by identifying the critical and most significant elements from a structural point of view, avoiding the execution of investigations in the most valuable areas.

A specific analysis was performed on the wooden elements for the cataloguing and dating based on dendrochronological master chronologies [11]

The complete framework of surveys carried out has made it possible to reach a high level of knowledge which can be identified according to Italian standards as level LC3, with a safety factor FC = 1,0.

3 THE BIM METODOLOGY FOR THE DIAGNOSTIC AND SEISMIC VULNERABILITY

With a view to integrating all the information useful for the project phase (architectural, structural, systems engineering, etc.) into a single model, the diagnostic phase and numerical processing for structural verification were managed using the BIM methodology (Building Information Modeling).

In the case of the church of Santa Maria delle Grazie in Calcinaio, a BIM model was created aimed not only at the extraction of the 2D geometric survey drawings, but also to the importation into a software for structural analysis. In this way the "re-modeling" phase of the building within the structural calculation software was eliminated with considerable savings in terms of time and costs to the advantage of the intervention design phase.

The BIM model itself was used as the "first container" of the data collected during the studies and surveys carried out with the possibility of being updated whenever an intervention is carried out on the building about the structures or decorative devices [6,7].

3.1 From the real building to the three-dimensional model

The BIM methodology allows, starting from the data coming from the surveys, to convert the information of the point cloud into a 3D model of the built object. In a BIM model each element is a parametric geometric object and the parameters can be of two types:

- **dimensional parameters** that regulate the shape, size and orientation in space of the object, making it capable of adapting to different contexts.
- **informative parameters** already in the survey restitution phase it is possible to proceed with the combination of non-geometric information to each element.

The degree of geometrical and informative development of each object is defined by the LOD (Level of Development) [8].

In the case of the model of the "Calcinaio" church a LOD 300 has been achieved, whereby the quantity, size, shape, position and orientation of the element as designed can be measured directly from the model without referring to information not modeled, and non-graphical information can also be attached to the model element.

The complete point cloud was imported into the modeling environment of the Autodesk Revit software and the architectural and structural modeling phase was prepared. The point cloud maintains its geographic coordinates therefore it follows that the 3D model will acquire its georeference.

The use of system families allowed the modeling of elements such as walls, slabs, roofs and beams.

However, historic buildings have structures with unique and irregular shapes and therefore make the geometric parameterization particularly complex. The use of adaptive families and customized families has allowed the overcoming of geometric difficulties and the creation of families adaptable to various contexts. In this case it concerned particular types of windows, frames, pillars and vaults.

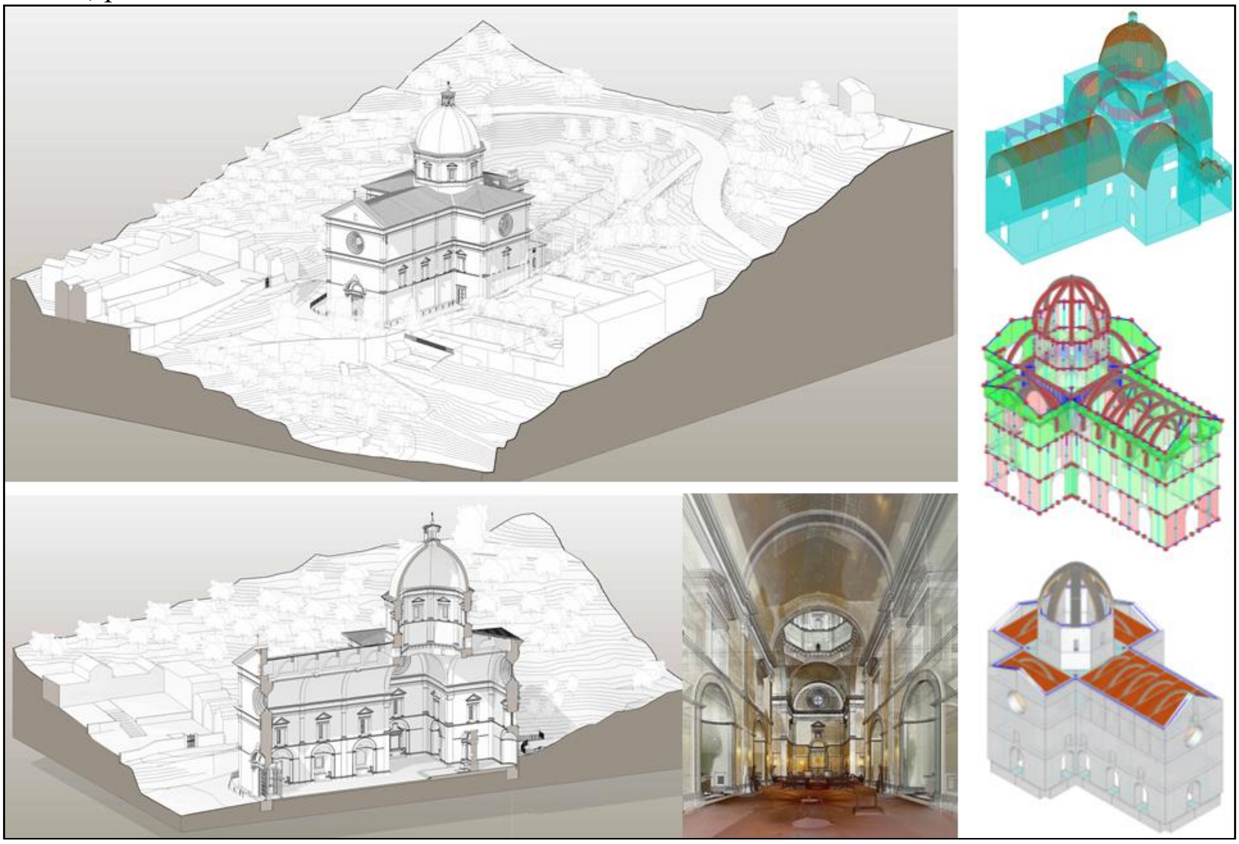

Figure 3: On the left, the complete BIM model; on the right the extracted structural model.

The export of the model without the decorative elements allowed the creation of a model with surface elements and a model with solid elements to be processed with FEM solvers, generating a linear and bidirectional data exchange.

The calculation models were therefore closely interconnected with the geomatic survey models and constituted a real digital-twin of the real building (Figure 3).

3.2 The BIM database

The management of a historic building through "informative models" essentially leads to the creation of a database.

The structure of an information model is therefore completely similar to that of any database: each element is associated with a unique code, it can be assigned a name in accordance with a classification system, a position based on georeferencing, as well as pdf files concerning technical specifications, detailed sheets on the state of conservation of the elements or reports relating to diagnostic investigations carried out may be attached.

The types of information inserted in the church model are of two types:

- data relating to the diagnostic campaign;
- data relating to the state of conservation of the stone facing.

The inclusion of surveys in the model was done by creating custom or adaptive parametric families.

The geometry of the objects representing the investigations was studied according to the characteristics of the investigation using symbols that visually refer to the type of investigation. The information entered within specific parameters relates to the date of execution, the description, the tool used and the results, as well as other data relating, for example, to the classification of the masonry (Figure 4).

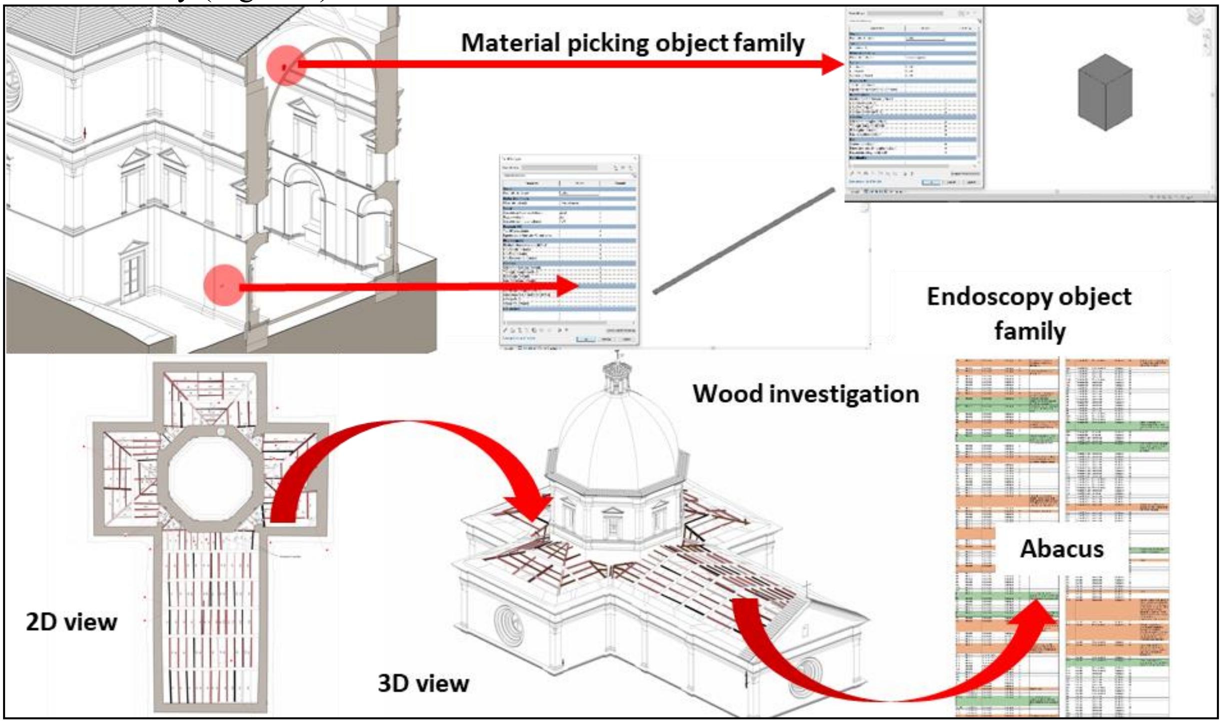

Figure 4: Some examples about implementation of the model with the diagnostic information.

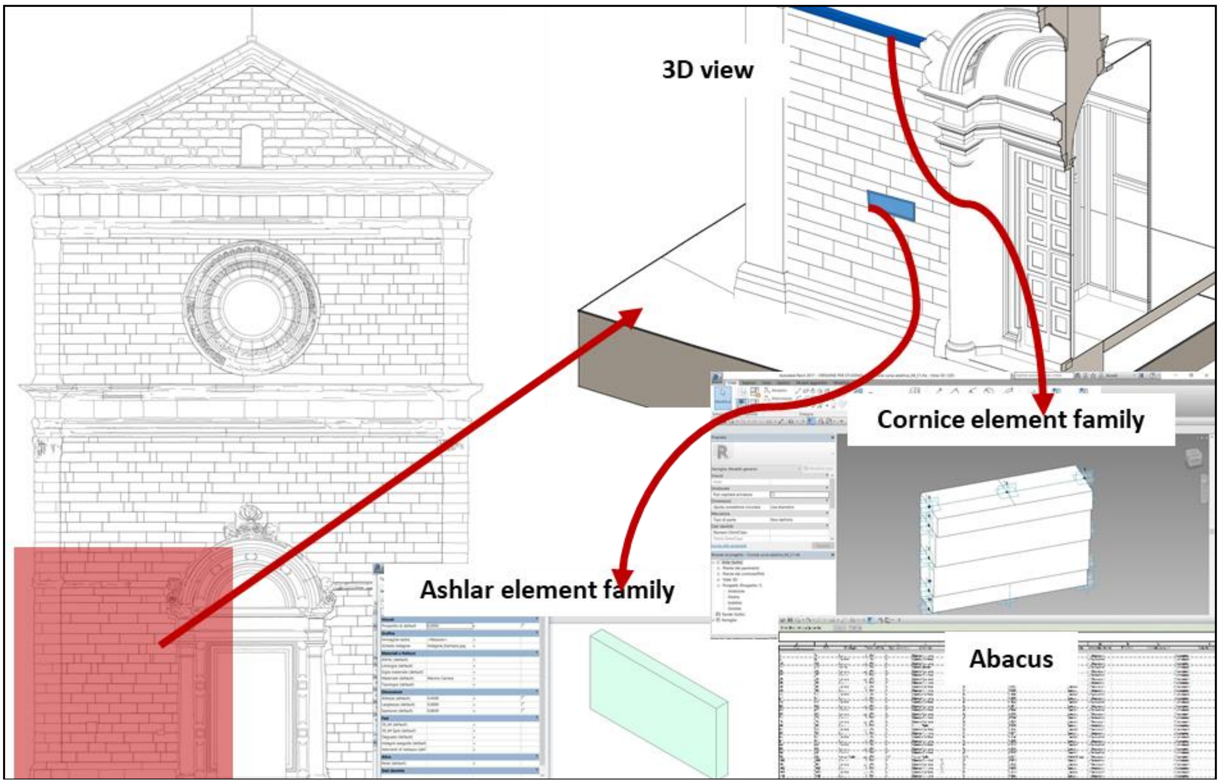

Figure 5: An example about implementation of the model with the stone information.

A particular case is represented by the database of the classification of wooden structures for which the information has been associated directly to the object-beam. The colour filters set in the model views allow you to have a global view of the state of conservation of the beam system (Figure 4).

As regards the decorative elements, a sample of the façade was set up to experiment with an information database relating to the state of conservation of each element. The slab or frame parametric object has been associated with information relating to material, finish, degradation, etc.. (Figure 5).

In general, all the objects of the model, from the wall to the investigations, have been provided with an ID which identifies them and which can be displayed within an abacus which allows the model to be queried.

The one-to-one interaction between 3D views and schedules allows for rapid database management and implementation.

3.3 The structural calculation model

From the BIM model was extract the structural model of the whole building and it is imported in the structural calculation software Aedes PCM (Figure 6).

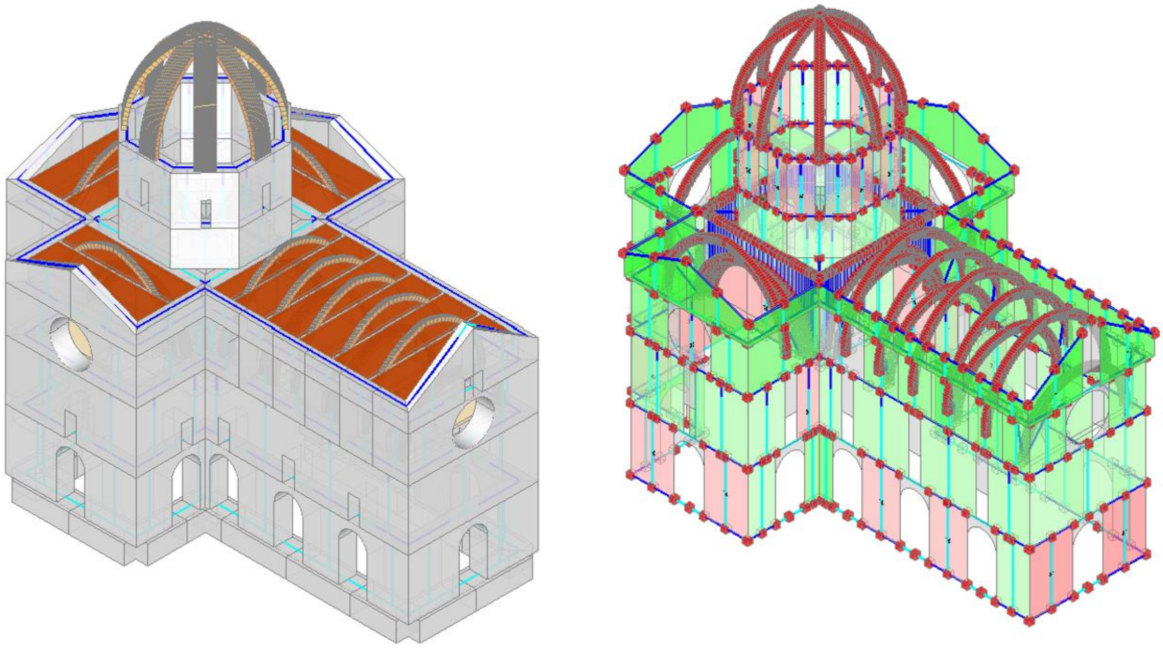

Figure 6: Structural calculation model

Through this structural model, that represent a digital twin of the real building, it was possible to carry out the vulnerability checks of the building.

In detail both the global risk indicators of the building and of the individual local mechanisms of masonry overturning were calculated.

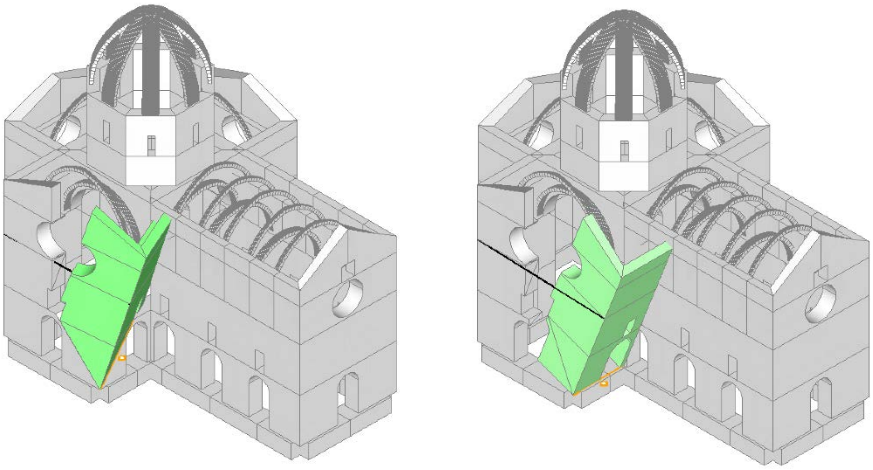

Figure 7: Example of local mechanism of masonry collapse for the transept

A detailed analysis was performed for the dome with three different models:

- The global model of the building with the dome.
- The simplified model of a single arch discretizing a segment of the dome.
- A FEM model with shell element .

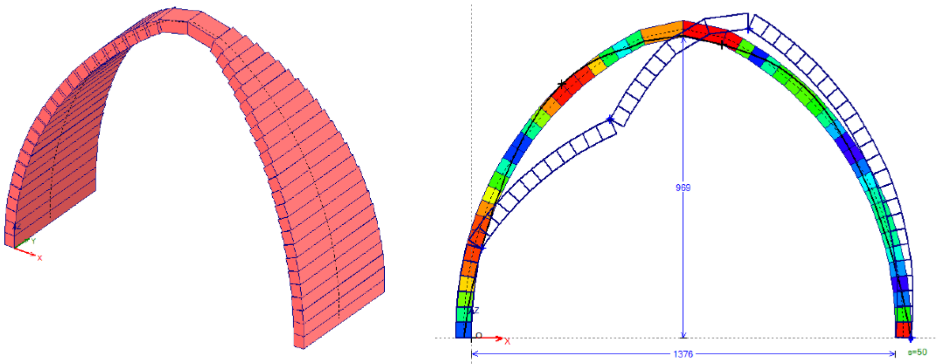

Figure 8: simplified model of a single arch discretizing a segment of the dome with its collapse mechanism

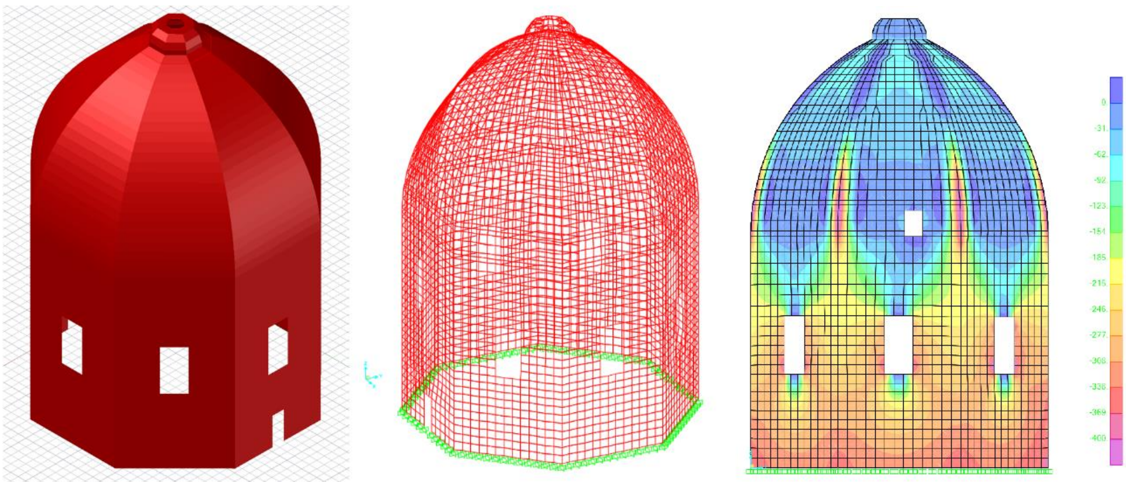

Figure 9: FEM model of the dome with the vertical loads stresses

The checks on the dome therefore is the result of the envelope of the studies carried out with global models and with local models aimed to identify both risk indexes.

4 RESULTS ANALYSIS AND PROJECT OF INTERVENTION

From a visual analysis from below and from the analysis of the photoplans obtained by photogrammetry from the ground and from a drone, various degradation phenomena have been identified that are still active today. After an initial analysis it was clear that the state of degradation of the projecting stone parts is very advanced and can represent a risk for people; pending a complete restoration of the entire exterior of the building, however, it was necessary to plan safety operations at the access doors to the church so as to allow the faithful and tourists to access the structure safely. Therefore, surveys and mappings of the deterioration were carried out which acted as a guide for the identification of the operations to be carried out.

The church of Santa Maria delle Grazie al Calcinaio has a stone facing entirely composed of sandstone here the phenomena of exfoliation and detachment [9] are very widespread and in some areas in a very advanced stage of degradation. The surface, in fact, is discontinuous in many points due to the presence of numerous gaps created by the loss of one or more stone layer.

The characteristic deterioration phenomenon of sandstones, exfoliation is mainly caused by water which causes part of the clayey matrix to swell and wash away between the sub-parallel layers that form the stone [10]. The tensions created between the swollen layers are aggravated by the cycles of freezing and thawing and cause the fall of fragments, even of considerable size.

Sometimes there is the total loss of three-dimensional stone elements, such as stone ashlars at the first cornice and the tympanum at one of the access doors to the transept.

Making the stone facing safe is a preventive measure while awaiting the restoration work. Once the scaffolding has been built, it will be possible to carry out in-depth analyzes of the surfaces in order to define the methodological choices for the restoration and integration of the gaps.

Moreover, the results of the static analysis and an evaluation of seismic vulnerability have highlighted a problem on the west transept and on the dome, which require structural interventions. So, an executive project was performed in accordance to the Italian NTC2018 and the Guidelines for the assessment and reduction of the seismic risk of cultural heritage [1,2].

The aim of the project was to implement the necessary consolidations to ensure the structural safety while respecting the historicity of the church.

4.1 The structural project

The structural design concerns the resolution of the vulnerabilities identified through cognitive studies and structural checks on the building.

In detail the structural consolidation project involved the following interventions:

- Reinforcement on the dome with carbon fiber textiles confinement
- Reinforcement on the west transept with a steel bar and a shock transmitter system
- Reinforcement of the wooden elements of the roof

For the dome was identified a minimally invasive but at the same time effective intervention to solve problems of seismic vulnerability. Two carbon fiber textiles confinement hopes are designed at the top of the dome and near the lower level of the dome, according with the structural simulations performed.

For the west transept, the existing crack and the local overturning mechanism are reinforced with a steel bar which comes into operation only in case of a seismic event, thanks to a shock transmitter which allows thermal expansion, while it freezes if stressed by a seismic impulsive force.

For the wooden elements reinforcement was identified a consolidation strategy using carbon fibre reinforcements. The aim was to consolidate the existing beams in place without replacing them. In fact, the replacement of the beams would have resulted in the loss of historical elements and difficulties in handling bulky beams in a position that is difficult to access.

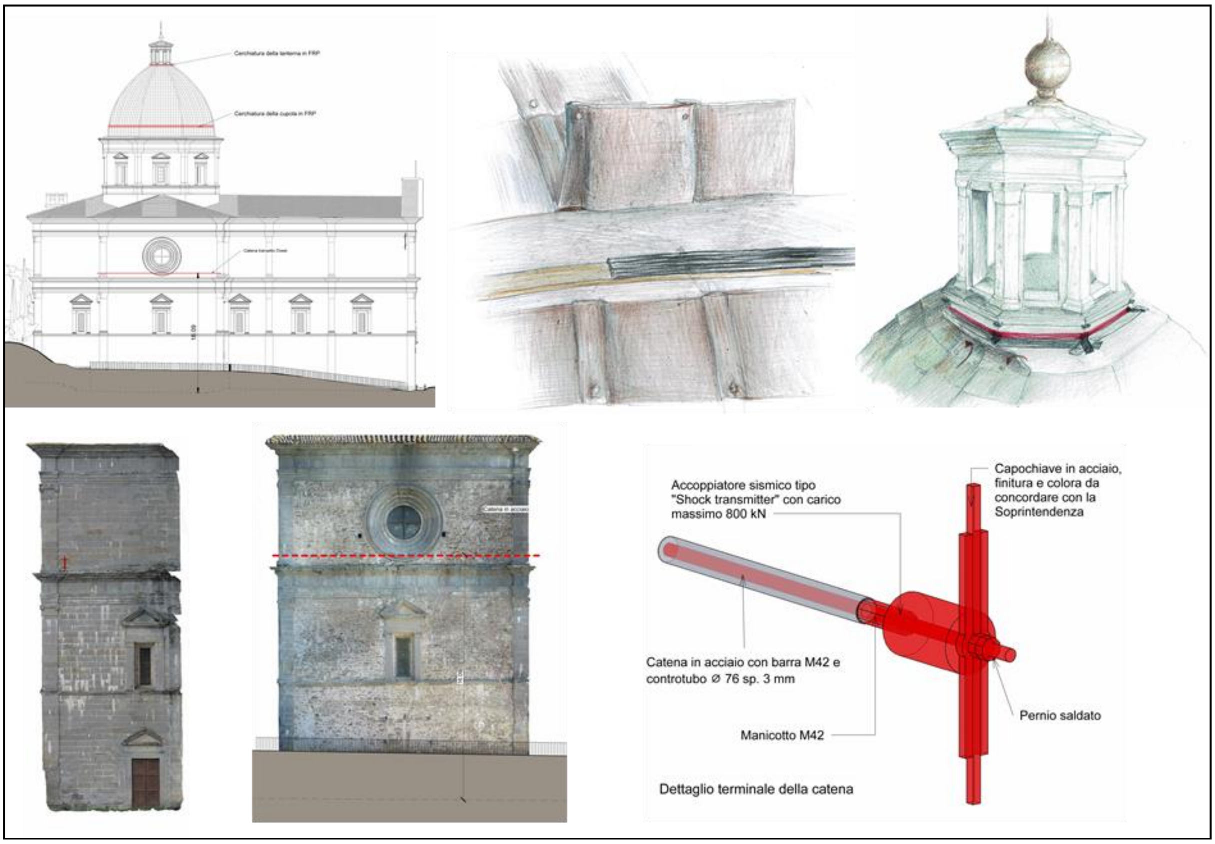

Figure 10: The structural consolidation project:

4.2 The project for the securing of stone facing

Given the seriousness of the degradation phenomena and the importance of the work, it is necessary to approach the safety intervention with the technical/scientific and deontological criteria already outlined to avoid losing entire portions of the model which would add serious gaps to those already existing. The removal of unstable portions and elements must be carried out with criteria and method, evaluating the necessary operations on a case-by-case basis.

The safety project involves various processes depending on the type of degradation;

- in areas affected by decohesion phenomena, the surfaces must be pre-consolidated by applying ethyl silicate-based products, a highly recommended and used material because it is chemically compatible with sandstone;
- in the presence of serious cracks and fractures, grouting with hydraulic mortars will be carried out. The phenomena of detachment and exfoliation must be made safe, where it will be possible to do so, through the construction of bridges in epoxy resin and injections with hydraulic mortars;
- we envisaged the application on the horizontal surface of the cornice and along the external slopes of the openings of strips of carbon fibers and epoxy resin, laid so as to form a reticular system according to the morphology of the surface itself. The orthogonal strips in carbon fiber and resin will be anchored to the wall facing by making a break and inserting 10 cm long CFRP connectors;

- at the end of the installation of the fibers above, a shoe grouting must be carried out along the entire area of the upper surface of the stringcourse. From a conservative point of view, this operation is essential as it creates a layer of sacrifice which, by virtue of the slight difference in height, favors the flow of water and protection from the sun's rays, contributing significantly to protecting the original surface and the consolidation system. On an aesthetic level, it camouflages the visual impact of the presence of the carbon fiber mesh;
- the stone elements of the stringcourse which, due to its morphology, cannot be consolidated with the carbon fiber fabric will be anchored by inserting CFRP pins (or connectors) anchored with epoxy resin. These operations must be carried out in correspondence of the elements considered to be at risk of falling.

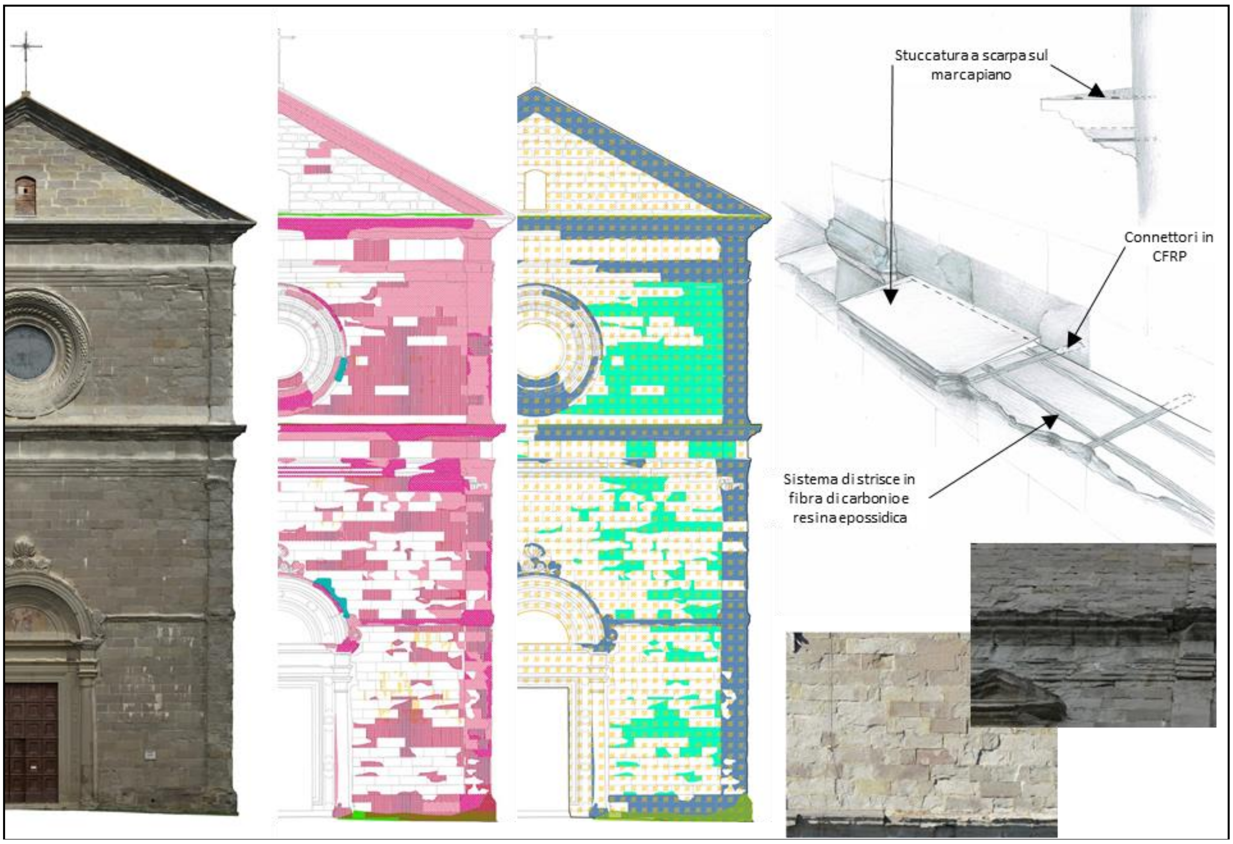

Figure 11: The decay analysis and the project for the securing of stone facing of the main façade.

The structural reinforcement project with composite material in carbon fiber and epoxy resin was preferred because by making a harm/benefit reasoning it emerged that; to put in place protective nets against falling rubble it is necessary to make holes for anchoring, furthermore some more unstable stone portions should be anchored with temporary steel brackets having to create new lodgings on the stone surface. These intervention methods allow, once the restoration site is ready, to be able to remove all the elements but at the same time create damage and gaps in an already very fragile and degraded surface (Figure 11).

The method for the repairing and strengthening of the stone cantilevers involves the stitching of carbon FRP stripes at superior faces of the stones. To perform the design of reinforcements, it was very important to determinate the exact geometry of the stone ledge and the characteristics of the materials. With these information, the structural calculations and the design were performed to determinate the exact layout and the quantity of FRP strips and the level of safety of the structure. Moreover, the using of FRP strips have many advantages due to the structural resistance and corrosion absence.

The use of these reinforcement techniques on sandstone structures has already been tested in the past on similar churches in Mediterranean areas. [12]

With the aim of making the safety intervention not a source of new damage but a starting point for the future restoration intervention, it is considered appropriate to use a resin composite material (which protects and allows the tensile strength) and carbon fiber fabric.

5 CONCLUSIONS

The paper address the main phases relating to the study and planning of the interventions for securing and consolidating the Church "Santa Maria delle Grazie al Calcinaio".

The workflow started from the definition of the cognitive framework which, through modern methodologies, made it possible to identify the critical issues and vulnerabilities of the building.

These methodologies were used for the execution of a very precise geometric and structural survey and through the creation of a BIM model the possibility of digitization and archiving was tested by applying it to a particular case study of cultural heritage.

Therefore, the management of the entire design and knowledge process was performed through the creation of a digital model that describes the current state of the building with a good level of detail and the creation of a BIM model that archives all the information of the project and diagnostic phase in a simple and easily accessible way.

The result of the diagnostic phase took the form of intervention design choices aimed at reducing structural vulnerabilities and securing the decorative apparatus preparatory to the final restoration.

This structural check and the project of the consolidation are driven by a digital twin model derived from the main BIM model of the building.

Moreover, the use of innovative materials and solution permits to guarantee the safety of the heritage building with minimal invasiveness and in compliance with the restoration principles.

In conclusion, a well-structured workflow was outlined, which ensured in-depth knowledge of the building in line with the requirements of current regulations and which made it possible to achieve the expected results.

REFERENCES

[1] NTC (2018), “Aggiornamento delle «Norme tecniche per le costruzioni». G.U. No. 42 del 20 Febbraio D.M. Ministero Infrastrutture e Trasporti 17 gennaio 2018, Roma (in Italian). NTC (2008) Norme tecniche per le costruzioni. D.M. Ministero Infrastrutture e Trasporti 14 gennaio 2008”, G.U.R.I. 4 febbraio 2008, Rome, (in Italian).

[2] MIBACT (2011), “Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme tecniche per le costruzioni (d.m. 14 gennaio 2008)” (in Italian).

[3] G. Mancini, Notizie sulla chiesa del Calcinaio e sui diritti che vi ha il comune di Cortona, Tipografia Bimbi, Cortona.

[4] P. Matracchi, La chiesa di Santa Maria delle Grazie al Calcinaio presso Cortona e l’opera di Francesco di Giorgio, Calosci, Cortona, Gennaio 1992.

[5] F. Di Giorgio Martini edite by C. Salluzzo, Francesco di Giorgio Martini. *Trattato di architettura civile e militare*, *con dissertazione e note per servire alla storia militare italiana*. Tipografia Chirio e Mina, Torino, 1841.

[6] Coli M., Ciuffreda A. L., Micheloni M. 2019, An informative content 3d model for the hall holding the Resurrection of Christ by Piero della Francesca mural painting at Sansepolcro, Italy. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W11, 435-442, 10.5194/isprs-archives-XLII-2-W11-435-2019.

[7] Malinverni, E. S., Mariano, F., Di Stefano, F., Petetta, L., and Onori, F.: Modelling in HBIM to document materials decay by a thematic mapping to manage the cultural heritage: the case of "Chiesa della Pietà" in Fermo, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W11, 777-784, https://doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019.

[8] The LOD gives the degree of reliability of both the information integrated into the model: level of detail of the geometry and level of information, cfr. Bim Forum, Level Of Development (LOD), Specification Part I & Commentary For Building Information Models and Data, December 2021.

[9] ICOMOS-ISCS : Illustrated glossary on stone deterioration patterns, International Scientific Committee for Stone (ISCS), MONUMENTS AND SITES XV, Electronic Version, 2010

[10] P. Matracchi, C.A. Garzonio, F. Radicioni et all., The Church of Santa Maria della Grazie al Calcinaio by Francesco di Giorgio Martini. New studies on characterization of the facing wall decay in a striking architecture of the Italian renaissance, 1st international and 5th National Conference on Sustainable Architecture and City, Torchia, March 2020.

[11] M. Bernabei, M. Brunetti, N. Macchioni, M. Micheloni, M. Nocetti, Surveying and Dating the Wooden Roof Structure of St Francis of Assisi Church in Valletta, Malta. March 2020. International Journal of Architectural Heritage 15(7):1-9

[12] M. Micheloni, Fiber Reinforced Polymers Textiles for strengthening of historical buildings and the examples for the use in Italian and Maltese heritage. SBE16 Malta, 2016 - Europe and the Mediterranean Towards a Sustainable Built Environment. pp. 149-157 ISBN 978-99957-0-935-8