The Pantheon of Gaetano Cima in Guasila. Interdisciplinary studies for its structural conservation

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1. INTRODUCTION

This paper presents an interdisciplinary study carried out on the Sanctuary of the Beata Vergine Assunta (Figure 1) placed in Guasila, a monument designed by the Arch. Gaetano Cima (1839-1849) and object of several restoration works since its construction aimed at solving numerous problems such as infiltrations of water that have produced over time various phenomena of structural and material degradation. Recently, its state of conservation is gotten worse, requiring an integrated investigation aimed at understanding the causes of decay. For this reason, the Guasila council requested the collaboration of the DICAAR (Department of Civil Engineering, Environmental and Architecture) of the University of Cagliari, which specifically involved the

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disciplinary areas of construction and architecture technology, topography and survey, architectural restoration, geomaterial and applied geophysics. Therefore, the joined study has been finalised to assess the state of conservation and the static efficiency of the basilic as well as to definition possible lines for future interventions. The research *Architectural and structural survey of the Santuario della B.V. Assunta in Guasila* has been financed by the Guasila council, Scientific coordinators: Prof. Fausto Mistretta and Paolo Sanjust. The study has been published in the short monography “Il santuario della Beata Vergine Assunta in Guasila. Storia, analisi e prospettive future per la conservazione”, edited by CG Creazioni grafiche in 2017.

2. METHODOLOGY (P. S., F. M.)

The interdisciplinary protocol of research has been led by the D.M. LL.PP. 17.01.2018 “Technical Standards for Construction” (NTC), which set the fundamental steps in the procedure of safety assessment for historic structures and definition of possible intervention. Thus, the study consisted firstly in the historic investigation, through an accurate research in the local documentary archives focused to reconstruct the history of the Sanctuary and its restoration works. Thanks to this examination it has been possible not only
to understand techniques and constructive technologies adopted during the construction site, but also to experimentally evaluate the vulnerability of the structures, enabling the understanding of the structural behavior in relation to the various restoration phases. At the same time, a geometric-structural survey and the mechanical characterization of materials have been carried out in order to understand the geometry, the materials and consequently the building techniques of the fabric. More in detail, architectural surveys (1:50) - conducted by the DICAAR, Unity of Geomatic of the DICAAR; Scientific Coordinator: Prof. G. Vacca - were performed through laser scanning techniques, to assess the overall geometry of the structure and any possible problem of deformations and anomalies. This survey supported the understanding of the cracks pattern, the quality of connections between vertical and horizontal elements, the efficiency of architraves above openings, the inspection of any structural element, the presence of elements, also non-structural, with high vulnerability, the typology of the masonry and its construction characteristics. Then, endoscopic surveys - performed by the DICAAR, Unity of Structure, Scientific Coordinator: Prof. F. Mistretta - on the masonry allowed the detection of cavities and voids, the morphology and typology of the masonry and the state of conservation of materials. The construction materials and their state of conservation have been also analysed with the combination of non-destructive and partially destructive controls - performed by the DICAAR, LabMAST - Mediterranean Laboratory for Historical materials and architectures, Scientific Coordinator: Prof. S.M. Grillo - to characterize the physic-chemical and mechanical properties of mortars, plaster (type of binder, type of aggregate, binder/aggregate ratio) and natural stones. Other investigations concerned the foundations through geognostic and geotechnical surveys for the geotechnical characterization of the site by defining a geological model of the subsoil. These have been carried out by taking core samplings and three excavations for inspections, geophysical surveys, conducted by means of a georadar to verify the possible presence of pre-existing masonry structures under the present building. Finally, based on previous knowledge acquired during the aforementioned phases, an advanced structural analysis with a finite element model was carried out to assess the presence of any structural finding.

3. HISTORY THROUGH THE ARCHIVAL SOURCES (P. S., E. P.)

The Sanctuary, placed at the highest altitude of the historical centre, dominates the village and the countryside of Guasila with its hemispherical dome (Figure 2). It was designed in 1839 by the architect Gaetano Cima, officially opened
in 1852 and built on the ruins of a Baroque church after its demolition. Signs of the previous building can be seen in the bell tower, unique testimony now on the right side of the current building.

The church is considered the first example of neoclassical architecture in the panorama of Sardinian architecture. It has a central plan and it is preceded by a pronaos with tympanum supported by six Doric columns and two lateral pillars. It is also overcome by a large dome decorated with tempera. Its construction site was opened in 1842 and proceeded with many difficulties because of the poor expertise of the craftsman as shown by the archival documents.

Numerous errors were conducted during the building site, especially for realising frames, columns, roofs and masonry structures. In 1849, once the dome was finished and before the paintings were realized, the rector of the church, Dr. Melas wrote to complain about water seepages from the roofs. A year later, the painter started to decorate the dome signalling numerous irregularities in the plastered surface and construction defects. After more than ten years, on February 15, 1852, the church was finally consecrated.

As reported into the archival documents, the first report of “scratches” on the

Figure 2. Historic photo of the Guasila countryside with the view of the Sanctuary.
Dall'analisi dei documenti di archivio, la prima segnalazione di “lesioni” sull'edificio non si sa di che tipo, di quale entità, e dove fossero localizzate – risale al 1897; il Vivanel, Direttore dell’Ufficio regionale Antichità e Belle arti, sollecitato dalla Prefettura ad esaminare un progetto redatto da un certo ingegner Loni, predispone una relazione nella quale si elencano lavori relativi a rifacimenti di intonaci, interni ed esterni, sostituzione di embrici nella cupola, realizzazione di cornici, e si raccomanda l’uso del cemento, al posto della malta ordinaria, per la “profilatura delle lesioni”. Nel corso del ‘900 poi i progetti e gli interventi si susseguono quasi senza interruzioni, senza che si riesca effettivamente ad incidere sulle cause del degrado, e forse neanche ad individuarle con esattezza, così che due problemi si ripetono con continuità nel corso dei decenni: le lesioni sulle strutture in elevazione e le infiltrazioni d’acqua dalle coperture. Riguardo alle prime, che interessano di volta in volta le murature portanti, gli archi, le volte e la cupola, si susseguono progetti e realizzazioni di vario tipo. Nel 1948 l’architetto Crudeli prevede per la prima volta di individuare le cause del degrado quando segnala la necessità di effettuare delle verifiche sul sottosuolo e sulle fondazioni, in corrispondenza del forte distilvio nel settore nordest. Seguono il progetto del Genio Civile di Cagliari del 1954 interviene con il consolidamento delle murature con l’applicazione di catene di ferro, il risarcimento di lesioni con barre di ferro e betoncina e la ricostruzione di murature lesionate. Negli anni ’70 la chiesa viene addirittura dichiarata inagibile dal Genio Civile e chiusa al pubblico. Nel 1985 a causa di “pioggie torrenziali” crolla un tratto di dieci metri del muro di contenzimento sul lato est, e la chiesa viene nuovamente chiusa al pubblico perché “si sono formate delle lesioni sulla muratura della chiesa e alcuni punti della fondazione non appaiono stabili per il dilavamento del terreno circostante” (Ordinanza del Sindaco del 12 aprile 1985); ma è solo nel 1998 che si provvede a realizzare un nuovo muro di contenimento in calcestruzzo armato (Progetto dell’ing. Zara – Ordinanza del Sindaco del 12 aprile 1998).
fall continuously with serious prejudice to public safety. In the second half of ‘80s, a more radical restoration on the roof, signed by the arch. Secci and Morand was designed: the structure of the dome was restored by laying an insulating layer and waterproofing and by replacing the mantle of “squared tiles”, in addition to interventions on the system of rainwater disposal and fixtures of the lantern to facilitate the circulation of air in the dome itself.

The aforementioned projects, directed by the architect Spigno and realized in 1991-93, still provided the use of special plaster for restoration, and the waterproofing of the roofs and new gutters. Nevertheless, despite this long series of interventions, the monument is still object of the same problems of decay: presence of humidity, water infiltrations from the roofs and widespread lesions on the dome, arches and architraves.

4. TECHNIQUES, MATERIALS AND STRUCTURES

4.1. TECHNIQUES (P. S.)

The geometric knowledge of the church has been made possible through the laser scanner and GPS technique supported by the laser scanner terrestrial Focus 3D and using the photogrammetry. The point cloud obtained from the
scans has been georeferenced in the ETRF2000 reference system (with geoid dimensions), through the use of Ground Control Point placed outside the Church and detected with a GNSS survey in RTK mode, reconstruction a 3D model of the fabric (Figure 3). From this model, detailed graphic drawings and renderings were made to understand the dimensions, forms, anomalies and possible deformations of the structure investigated with particular attention to the vaulted structures, widely affected by the phenomena of decay. From these surveys, it has been possible to verify the regular geometry of all the masonry, except for the roof of the dome, slightly embarked probably as a result of the last restorations.

As concerns the surfaces, these instead appear marked by a series of cracks that have been investigated according to a survey of the crack pattern, with the aim of classifying the typology and the associated mechanism: all the lesions in the masonry are originated by mechanisms of failure of the architraves; in the vault, instead, lesions can be divided into two types: cracks placed in the keystone, which generally occur due to the differential failure of the abutments without causing danger situations; cracks placed at the base of the arch caused by the geometry of the vaults themselves, which are not

Figure 4. Results of the thermographic investigations.
attributable to a failure of the masonry. After these findings, a series of diagnostic surveys has been conducted in order to investigate more precisely the security and the conservation of the structures, their materials, techniques and technologies. In particular: the endoscopic investigation which allowed us to explore the core of the masonry, impossible to know only with laser scanners, their morphology and typology as well as the state of conservation of materials; the thermography, conducted in passive conditions and finally geognostic wells, deep around -1.60 meters from floor. From the integration of all these studies, it has been possible to assert that the church is built, as recommended by the arch. Cima, with two building techniques: a first one, used in all the load-bearing structures such as foundations, columns, flats, jambs in large squared blocks; a second one, used into the second level walls (vaulted spaces) in irregular ashlars. Also, the thermographic investigations have allowed us to identify a third construction technique related to the dome, which from the first third of its development is built in bricks, while in the lower part (the remaining two thirds) is made of squared ashlars hypothetically sandstone as the rest of the church (Figure 4). Finally, thanks to the geognostic wells, it has been possible to identify not only the gravel-bearing material on the subsoil of the surrounding square, but also the typology of the buttresses on the east side, built with header bond.

4.2. MATERIALS (E. P.)

At the same time, natural and artificial building materials have been systematically investigated considering both those used for the first construction and those used during the restoration works. This study has allowed us to understand the nature of materials, to hypothesize the origins and the quarry sites and to identify the different typologies of weathering. The characterization of mortars and plasters required particular attention in order to define their minero-petrographic nature: composition, shape, size, grain size of aggregates, type of binder, and to assess the level of decay. The number of samples collected, enough to represent the heterogeneity of the materials, is the result of a preliminary analytical survey carried out in different parts of structure with the support of a crane used during the endoscopic survey. Different types of bedding mortars, plaster and various painting layers made with different techniques at different times were sampled. In general, the mixtures have shown a mediocre accuracy as it can be seen in the low
presence of fractures, voids and scarce cohesion of the mortars. Moreover, the material analysis has revealed that six of these were samples from restoration works. Only three samples, hypothetically historical mortars have shown a thin aggregate and a lower aggregate/binder ratio. The typology of decay can be summarised in strong decohesion, presence of patinas that are caused by the high presence of water infiltrations from the walls and roofs. Further four geognostic surveys were conducted in four different points of the square outside the church going to investigate the nature of the subsoil. This has resulted from inconsistent to consistent, and increasing in depth, from thickened to hard and compact. It can be considered settled material with eluvial-colluvial and/or terraced alluvial olocenic deposits in place (at about -6.0m) part of the Marmilla Formation essentially marly siltose, alternated to - from rough to fine - arenaceous levels (oligo-myocenic succession of Campidano Sulcis). Moreover, two soil samples were taken during the execution of geognostic surveys for studying the grain size, the classification of land (UNI 10006), the Atterberg limits and the weight of natural volume. From these last investigations, it can be asserted that the materials have a degree of plasticity of the soil \( I_p = \) low plasticity. Lastly, within the church, georadar prospections, conducted to verify the presence of pre-existing masonry structures, have not reported significant results.

4.3. STRUCTURES (F. M.)

The aim of the structural surveys has been to establish the degree of efficiency achievable by the elevation structures at the moment of the inspection, with an assessment of the causes of the cracks as well as a prediction of their behaviour in the continuation of the exercise life, reaching, therefore, a judgment on the structural performance state of the building. Known the geometric characteristics and the type of the wall elements, the study has been focused on the understanding of the deforming and tensional state of the structures with the development of a numerical model. Stresses and deformations were calculated using the ‘finite element method’ (FEM) where the masonry is considered as a continuous discrete isotope with finite elements whose mechanical characteristics are homogenized with respect to the single wall panel. The church has been modelled with 23064 flat elements, with 4 knots and 20 beams with 2 knots. Plates are two-dimensional elements able of simulating both the membrane behaviour (plate) and the bending behaviour (plate), the beams represent the behaviour of the pillars (Figures 5-6). In addition, to the gravitational loads are considered the carried permanent loads, such as the roofs and the lantern at the top, accidental loads as per
standard, snow loads, wind loads and seismic loads. The evaluation of seismic action was carried out with a modal analysis with response spectrum (linear dynamic analysis). The stress test has been carried out according to the Mohr-coulomb rupture criterion, which is based on the hypothesis that the material crisis occurs in order to reach a critical value of the tangential tensions. The structural analysis, together with the verification of the type of foundations and the laying ground, has allowed to exclude that the building is affected by structural defects and backdrops that induce excessive reliance on the construction materials. The static and dynamic stresses are inducing to the masonry structures, tensional conditions well below the permissible limits, with the system bottom that is effective for the containment of actions.

Figure 5. 3D 'finite element model' (FEM).

Figure 6. Displacement under live load.
5. CONCLUSIONS

In conclusion, this interdisciplinary and integrated study of the monument has allowed us to outline a clear state of conservation. After the detailed reconstruction of the life of the building, starting from its construction till its last restoration works, geometric, structural and geognostic studies, have permitted us to assert that the monument is not affected by structural faults that could be so dangerous for its safety. The only element of concern is the ‘retaining wall’ built on the north-east side of the church which has showed clear signs of collapse (again accentuated by faulty rainwater disposal). The diffused cracks, displayed mainly near arches and vaults, can therefore be ascribed to the typical static behaviour of the jack arches, and can be solved with operations of reinforcement to apply to the internal side of arches. All the other lesions are superficial, mainly due to the material decay that is mainly caused by the continuous infiltrations of rainwater, which scoured the Church for over 100 years.

6. REFERENCES


Una previsione del comportamento delle stesse nel prosieguo della vita di esercizio, raggiungendo, così, un giudizio sullo stato contemporaneo e prestazionale dell’edificio.

È stata dunque effettuata una campagna di indagini conoscitive riguardanti in particolare geometria, particolari costruttivi e materiali degli elementi utilizzati allo scopo di individuare i rapporti e i legami fra le varie parti che costituiscono il manufatto. Note le caratteristiche geometriche e la tipologia degli elementi murari, al fine di studiare lo stato deformativo e tensionale dell’opera, è stato sviluppato un modello numerico ad elementi finiti dell’intera struttura. Le sollecitazioni e le deformazioni sono state calcolate con il metodo agli elementi finiti (FEM) dove la muratura è considerata come un continuo isotropo disegregato con elementi finiti le cui caratteristiche meccaniche sono oggettivizzate rispetto al singolo pannello murario. La chiesa è stata modellata con 23064 elementi piani di tipo plate a 4 nodi e 20 beam a 2 nodi. I plate sono elementi bidimensionali in grado di simulare sia il comportamento membranare (lastra) che flessionale (piastra), i beam rappresentano il comportamento dei pilastri (figure 5-6). Oltre ai carichi gravitazionali si sono considerati i carichi permanenti portati, come le coperture e la lanterna in sommità, i carichi accidentali come da normativa, i carichi da neve, i carichi da vento e sismici. La valutazione dell’azione sismica è stata eseguita con un’analisi modale con spettro di risposta (analisi dinamica lineare). La verifica dello stato di sforzo è stata eseguita secondo il criterio di rottura di Mohr-Coulomb che si basa sull’ipotesi che la crisi del materiale si verifichi per il raggiungimento di un valore critico delle tensioni tangenziali. L’analisi strutturale, unita alla verifica della tipologia di fondazioni e del terreno di posa, ha consentito di escludere che l’opera sia interessata da difetti costruttivi e fondali che inducano cimenti eccessivi sui materiali costruttivi. Le sollecitazioni statiche e dinamiche stanno inducendo quindi nelle strutture murarie, stati tensionali ampiamente al disotto dei limiti ammissibili, con il sistema fondale che risulta efficace per il contenimento delle azioni.

5. CONCLUSIONI
