Relations between static-structural aspects, construction phases and building materials of San Saturnino Basilica (Cagliari, Italy)

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Abstract: The construction site was used several times: in a first phase, in the republican era of Roman domination it hosted, probably, a temple whose height could reach 25 meters. In a second phase, during the Roman Empire, it was used as a burial area.; then around IV-V century AD a first Christian Basilica made of a naved building with an apse was built there, at the center of a large monastery. Subsequently in a third phase in VI century AD a Byzantine Martyrium, with a Greek cross-shaped plan, was built: the central part of it, supporting a dome is still standing. Finally after 1089 the church was given to Marsilian monks who deeply renovated it and changed its shape converting the plan to a Latin cross.
A macroscopic material analysis shows the presence of various rocks, whose use appears to be inhomogeneous during all construction phases. Sedimentary rocks (limestones, sandstones, calcarenites etc belonging to local geological formations) are generally used for masonry structures. Marbles, mostly coming from abroad and previously used in Roman buildings have been adopted for architectural elements (columns, capitals, and so on). At a lower extent there are masonry blocks in Oligo-Miocenic volcanic rocks and seldom stone materials which are not originally from Sardinia. Both mineralogical and petrographic tests (e.g. XRF, XRD) and the most important physical properties (porosity, density, water absorption coefficients, compressive, flexural and tensile strength, etc.) show that many of the more representative samples of rock materials (like limestones, calcarenits) are often highly decayed, with a corresponding reduction of their mechanical strength.
A structural analysis is particularly useful for helping in clarifying the historical evolution of the building, checking reconstruction hypotheses and assessing the true residual strength of the more important parts. As an example, a FEM analysis of the Byzantine domed part is going to be presented in a forthcoming paper.

Keywords: Stones, Byzantine architecture, Reconstruction, Physical properties.

Introduction and aims

The study of San Saturnino church (Fig. 1), located in Cagliari, requires the definition of a specific research methodology. The peculiarity of this building is that it is the oldest Byzantine architecture in Sardinia. It represents the model from which an evolutionary line was developed. However, as a prototype of Byzantine architecture, it is indeed unique: no other previous example exist in the Sardinian island. It is possible, of course, to establish comparisons with the Apostoleion church in Constantinopolis, but also in this case the two architectures are not directly comparable since the Constantinopolitan church has disappeared and the only available description come from documentary and iconographic sources. Its history begins between the fifth and sixth centuries AD, and is characterized by long periods of decay and lack of historical sources. Among the few reliable data is its donation in 1089 to the order of Vittorini monks, originally based in Marseille. This change of property brought changes which can be linked to proto-Romanesque models. In 1363 the church was entrusted to the Knights of St. George de Alfama and in 1444 it became part of the assets of the Archbishop of Cagliari. It is not known if these two last steps have indeed altered the church structure, while it certainly occurred during the Vittorini monks period. The first historically recorded restoration dates back to about 1484 and was performed by Giacomo Rovira and Archbishop Pietro Pilares. When this renewal occurred and what it consisted of is not clear today; above all there is no way to deduce which was the spirit that motivated them.

Fig. 1 – Church of San Saturnino, the main prospect.

For sure in 1631 when Juan Francisco Carmona designed the plant and an overview (Fig. 2) of the building, the church appears to be complete in all its parts, but already in 1667 the north and south arms had already been destroyed and the building was apparently abandoned at the mercy of materials reusing hunters. The recovery of the building began in 1714 when it was entrusted to the guild of physicians and apothecaries. The documented history of the building in modern times starts in the XIX century with some photographic plates which show the church in an abandoned state, and reused perhaps, as a warehouse for storage purposes.

Despite many mistakes and stretching the building revival began in the first years of the XX century under the guide of Superintendent Antonio Taramelli whose intervention aimed mainly to the consolidation of the structure and the, often unjustified, removal of decorations which were applied after the Romanesque period.

A second historic moment of great importance occurred after World War II, during which the building was hit by a bomb. It required major structural interventions for reconstructing and consolidating the existing remains. The superintendent who directed these works was Raffaello Delogu. These interventions were followed by decades where the building remained closed to the public until about 1980, when as a result of a restoration campaign conducted by ing. Gabriele Tola, the building was reopened to the public. Today the building is closed again and routine maintenance are mainly targeted to the archaeological surroundings, while the structural needs of the church are somehow mostly neglected.

This work represents the first step of a wider research which aims at a static-structural analysis of San Saturnino church according to a multi-disciplinary approach which involves studying at the same time structural loads and physical and mechanical properties of geo-materials. At this stage according to the data obtained by macroscopic analysis of the monument and to preliminary investigations performed on several construction materials, a first schematic picture of San Saturnino Basilica was sketched, allowing to identify the most critical areas from the structural point of view. The interpretation of data from petro-physical characterization is currently in progress, and it will supplement the already performed in situ investigations.

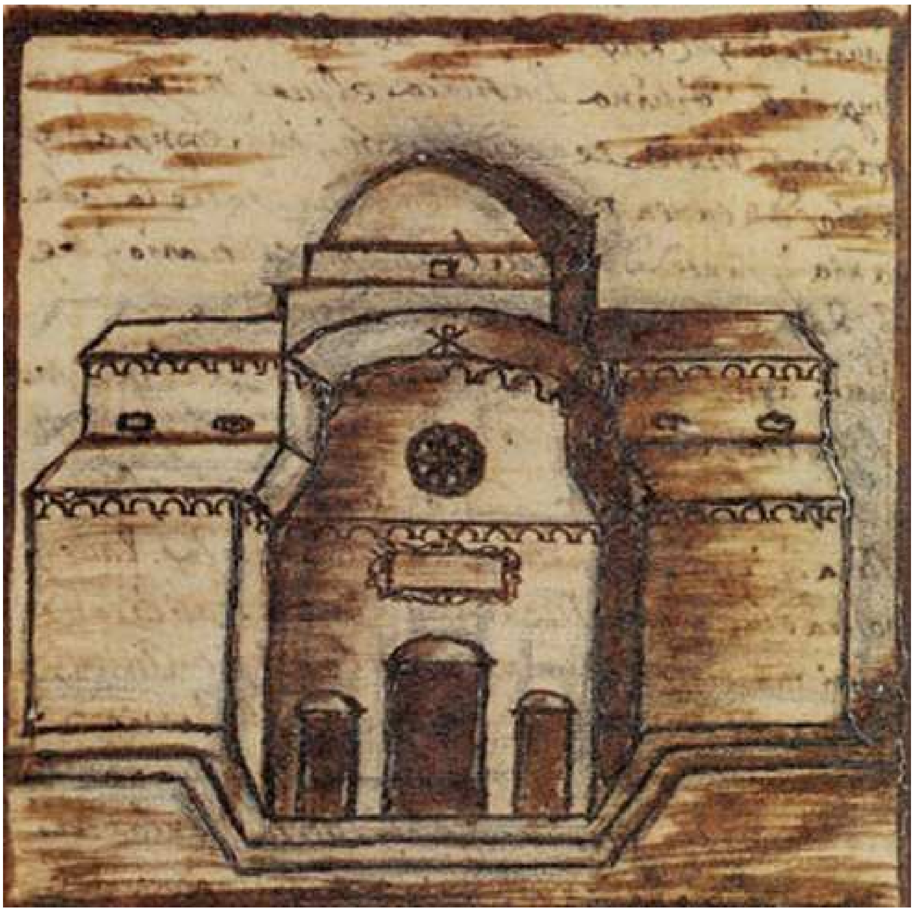

Fig. 2 – Drawing of the church of San Saturnino in the paper manuscript of Juan Francisco Carmona dated 1631 and kept at the University Library in Cagliari.

Methodological approaches

Analysis of historical-architectural-structural aspects on monuments

The research methodology used for the study of San Saturnino church in Cagliari can be divided into three phases.

The first phase involved literature searching and historiography studying on both the building and the archaeological site where it stands. In case of differences in interpretation between authors we proceeded by verifying the documentary sources. The study continued with archival research at the premises of MIBAC where we proceeded to acquiring the entire iconographic section (over 700 images) which were kept at stock photograph, providing documentary evidence of the evolution of the church and the site from the late XIX century to the present. The iconographic documentation was compared with paper records produced by the XX century to the present day, which are kept in the archives of MIBAC. Metric surveys and drawings were also referred to, in MIBAC archives. The comparative study of images and documents has allowed to sketch a diachronic evolution of the site without excluding the peculiar historical events where the set of events forced a synchronic reading.

The second phase was characterized by a direct approach to the monument. Six inspections were performed, which were aimed at finding those pieces of information derived from the first phase of research and later by compiling a defectology list. In preparing such list no predefined severity levels have been selected: all exhibitions of decay were reported. However only the most serious events, which are related to a mechanism of local or global collapse, have been presented here. Some key values for checking the safety conditions of the structure were acquired instrumentally. For example, the slopes of alveolar columns were measured since these are suitable indicators of the condition of the entire central body. It was found that the slope of the aisle oriented south is affected by a failure backdrop. The measurements were made using a digital inclinometer Leica. The whole structure and the individual exhibitions of physical decay have been documented photographically by a high resolution camera. The orientation compass was used in order to provide the correct location within the building, and four points GPS were beaten with Garmin GPS mapping to twelve channels, in addition to the detection of the elevation above sea level. These data allow to geo-reference the building into a GIS system.

In the third phase, we proceeded to identify the logical relationships that exist between the occurrence of decay and restoration experienced by the building, depending on the different approach of the time when such interventions were carried out. In particular, it takes into account the operating conditions in the aftermath of World War II. The end result is a macroscopic analysis which is based on the current structural damage (defectology list) linked to the history of the building. Some items were left out that in the short to medium range cannot produce further deterioration, while attention has been focused on structural damage whose curve evolution is not flat and can degenerate into worse conditions, producing an increase of damage which is not manifest now. At the end, some intervention hypothesis have been proposed that, taking into account the existing regulatory framework, allow to record the response of the building through a monitoring instrument which follows targeted interventions and helps in preserving the historic structure.

Analytical methods on geo-materials

In order to make a correct analysis of the materials used in the construction of San Saturnino basilica, and carry out a macroscopic analysis of the processes of physical and chemical degradation occurring in situ, minero- petrographic analyses and physical-mechanical laboratory tests have been made (and are currently still in progress). These allow to determine some important physical properties (density, porosity, water absorption, compressive and tensile strength, etc.) for evaluating the static-structural characteristics of the monument. Laboratory tests are performed on very small samples taken from the monument, and for comparison purposes, even on samples taken from rock outcrops from which the geo-materials come. This allows to better assess the different degree of alteration between samples of the monument and field outcrops.

In the specific case of the church of San Saturnino, about 50 samples were taken from ancient stones and mortars of various origins and function within the structure of the basilica. More precisely these materials were sampled:

- limestones "pietra cantone" and limestones "pietra forte"; sandstones and conglomerates of the "panchina tirreniana", all belonging to the well-known formation of Cagliari, which have been widely used in the construction of San Saturnino church;
- marbles and limestones whose source is not Sardinia and are probably belonging to the Roman period and were reused in the Romanesque period;
- volcanic rocks (from the Oligo-Miocene volcanic cycle of Sardinia: 32-11 Ma) used at a much lesser extent as random ashlar both inside and outside of the structure.

Given the diversity of characteristics of these rocks the study of petro-physical properties assumes a key role in the evaluation and analysis of the structural damage problem (in particular, with reference to active failure phenomena due to physical decay processes).

These activities may be summarized with the following sequence of operational phases of work.

1. Macroscopic analysis of the aspects of stone surface (e.g., micro-morphology) determined through photogrammetry observations, etc.;
2. Sampling of: a) micro-samples of stones and mortars, collected indoor and outdoor, and macroscopic study to acquire data on physical-chemical processes on surface of building materials; b) additional micro-sampling of altered materials (newly-formed minerals and soluble salts), occurring as alterations on stones and mortars. Then the samples were geo-referenced and digitalized by a laser scan survey.
3. Laboratory analysis on geo-materials, aimed at acquiring data on physical features and chemical composition of both materials and their decay products.
4. Study of alteration processes to allow to identify a) nature and texture of decay materials, b) causes of the alteration, c) physical-chemical agents which are responsible of such decay.

The investigations focus on the acquisition of physical-chemical data for preliminary project and plan for a correct diagnostic protocol of restoration.

The following methods were used for the characterization of geo-materials from the San Saturnino Basilica:

- optical microscopy, providing data on mineral phase composition and textural parameters belonging to rocks and mortars;

- thermal-gravimetric analysis (DTA, TG, DTG), for the characterization of composition and characteristic of binder of mortars;
- X-Ray Diffraction Analysis (XRD), for qualitative and quantitative data on mineral composition (crystalline phases) of solid samples powered;
- scanning Electron Microscope (SEM) analysis, for textural parameters of samples (e.g., lamellar, compact, porous morphologies), as well as quantitative chemical analysis on micro-surfaces by the technique known as EDAX microprobe;
- X-Ray Fluorescence (XRF), for quantitative chemical data on the bulk sample, for major (wt%) and minor (ppm) chemical elements;
- inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a more sensitive (10 ppb) and precise technique than the XRF. Major, minor and trace elements - from Lithium to Uranium - of solid and liquid materials can be determined.
- helium and water picnometry (together water absorption) and Hg porosimetry for physical characterization, and to determine the physical properties (solid and real densities, bulk density, open and closed porosity to water and helium, saturation index, mechanical strength, etc.) of rock or mortar specimens are made according to the following methods: water and helium picnometry, water absorption, hydrostatic balance, hydraulic press machine.

OBJECT: Basilica of Saint Saturnine
TOWN: Cagliari
PROVINCE : Cagliari
AREA: Sardegna
G.P.S BEATING POINT COORDINATES

G.P.S. 1: **N** 39°12'51"**E** 009°07'22.3"
G.P.S. 2: **N** 39°12'50.5"**E** 009°07'22.2"
G.P.S. 3: **N** 39°12'50.4"**E** 009°07'24.7"
G.P.S. 4: **N** 39°12'49.7"**E** 009°07'24.6"

Share on the sea level

G.P.S. 1: m 20
G.P.S. 2: m 21
G.P.S. 3: m 15
G.P.S. 4: m 12

DATE: 05/03/2014
OPERATOR: Alessandro Ruggieri
TECHNICAL INSTRUMENTATION: Laica Disto D 3 – G.P.S. Cartographic Garmin 12 Channel - Camera Nikon D 200
CLIMATIC CONDITIONS: Temperature 14°C Relative Humidity 78%
NUMBER OF INSPECTIONS: 5

Fig. 3 – Overview of the church of San Saturnino defectology list and geo-referencing.

The remark of structural damage

Areas affected by exhibitions of degradation due to structural damage: aisle facing south, aisle facing north, domed central structure (Figs. 3, 4, 5).

The analysis of cracks and generally the defectology list indicates a condition of damage caused by heterogeneous agents in a very long period of time. The focus is on two specific areas identified in the heads of the side aisles of the east-facing arm. The south-facing aisle (Figs. 6, 7) has a clear slope towards the outside of the structure. This condition is accompanied by the presence of numerous cracks originating from the node. The clamping between the apse and the masonry of the head of the aisle and continuing downwards with vertical and diagonal trends from the roof of the nave (Fig. 8) up to reoccur in the blocks of the foundation where it assumes a diagonal trend with open external flaps. When crossing the wall of the cylinder head the crack involves the element lintel which is cracked both at the intrados and at the extrados.

The north-facing aisle, as mentioned, is the result of the reconstruction which took place after the bombings of World War II (Fig. 9). However it should be noticed the structural damage whose condition might short endanger the structural safety of the aisle. The head of the nave rests on a reinforced concrete beam which has as support points two small plinths made for two thirds above-ground (Fig. 10). The girder was reinforced with a single profiled type IPE steel beam and presents the almost total expulsion of the concrete cover (Fig. 11). The same IPE beam is oxidized with obvious exfoliation and detachment of plaques. The reduction of the resistant section represented by the web has caused the deformation of the web itself by crushing. The plinth support, placed below the perimeter wall, presents a deep vertical slot with a beginning of angular detachment which can be due to a strong compression action, together with the likely carbonation of reinforcing rods.

The central domed structure exhibits, at present, no degenerative structural underway. However, it should read the current condition as the result of multiple restorations that have contributed to the current condition of substantial balance. Starting from the four pillars with alveolate columns the widespread presence of cracking with a beginning of vertical separation in the pillars marked with numbers 1, 3, 4 can be observed. Pillar number 3 does not have any signs of detachment while number 1 presents the basic slots angled at 45°. The arch that rests on pillars 1 and 3 shows the loss of the mortar in the vicinity of the dressed stone at a time and the subsequent extraction of the same end. This anomaly is evident both inside and outside the building. Slippage of the dressed stone at once suggests the presence of a tension zone, which produced the dismissal taking place between pillars 1 and 3. As an evidence of this condition, perhaps even spread to the pillars 2 and 4, there are four passive iron rods that bind among them the pillars. By inspection it is not possible to infer the condition of stress which they are subjected. Imaging studies would provide useful pieces of information about the actual work done.

In the dome, by visual inspection, no cracks were evident but this is the result of many restorations. In documentary sources dating back to the 50s numerous cracks are observed with a vertical trend and running along the beds of mortar determining the separation and subsequent extraction of the segments. In this sense, it is operated with infiltration of cement mortar and numerous localized damages. The dome in the 50s was reinforced with circular bars within the drum hoops, but in the 80s was close to failure due to horizontal thrust caused by its self-weight. The comparison between the condition of pillars, arches and dome indicate that there has been a kinematic collapse, which was effectively stopped by the positioning of the tie rods located between the pillars and the hoops of the dome. Their effectiveness is deductible from the total lack of cracks in the dome concentric, dents or buckling. Further evidence of a safe condition comes from the almost total lack of off-the-lead of the pillars and alveolar columns (the values are given in the annex graph).

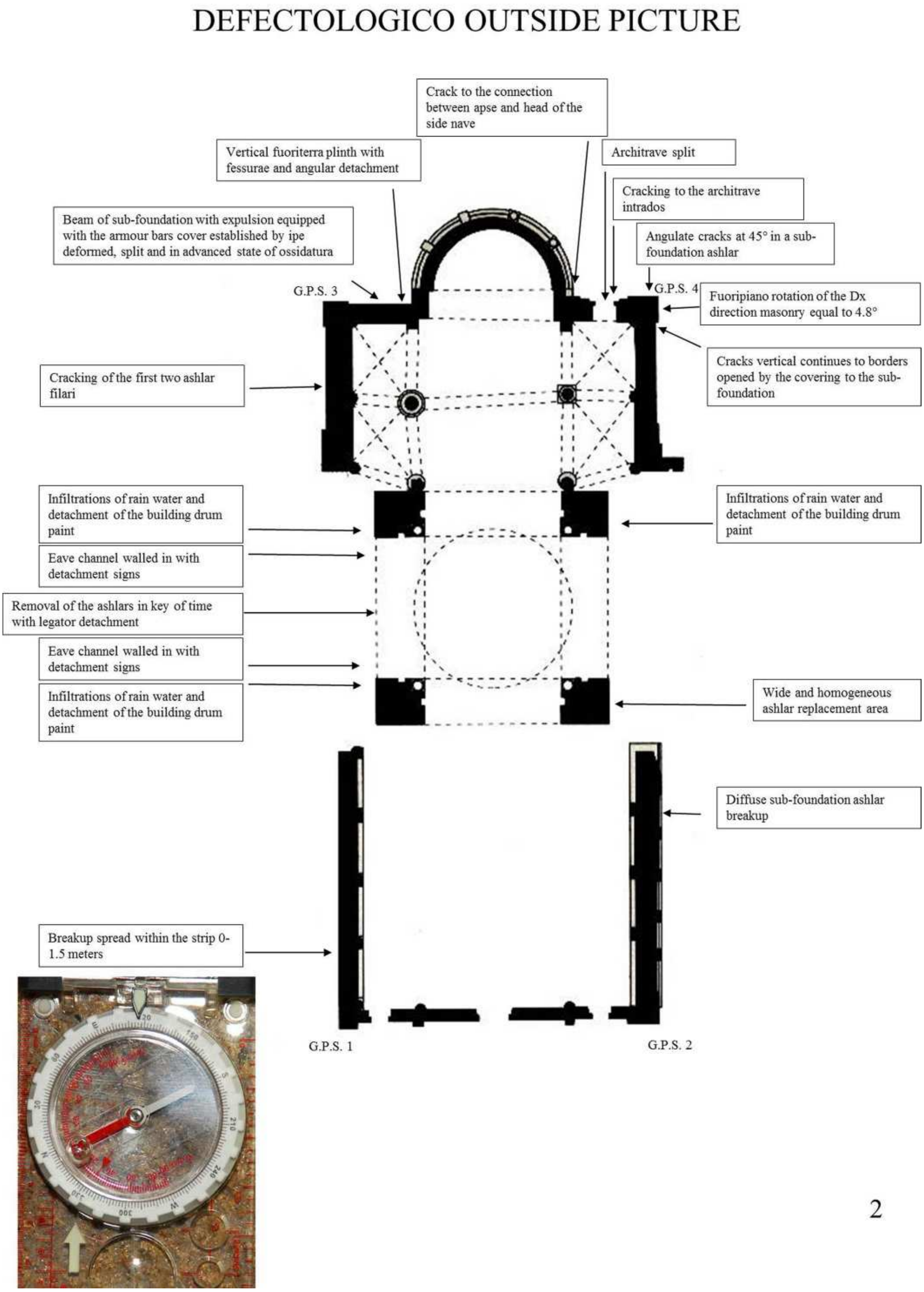

Fig. 4 – Defectology list of San Saturnino church; survey of the exterior of the building.

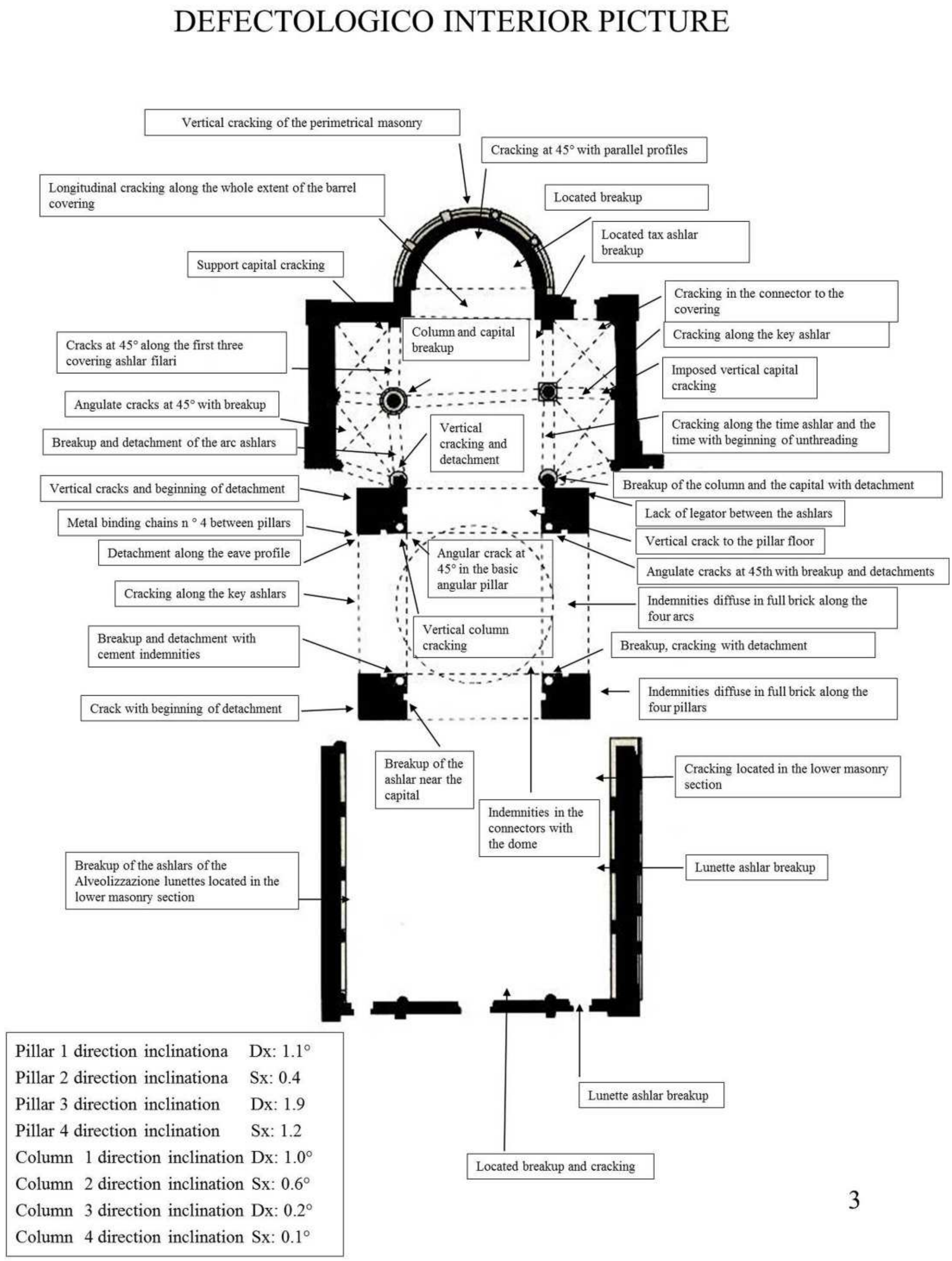

Fig. 5 – "defectology sketch" of San Saturnino church; the interior of the building pad.

Fig. 6 – Prospectus apse, particularly the apse and the head of the Aisle facing South.

Fig. 7 – Cracks along the Aisle facing South.

Fig.8 – Cracks along the Aisle facing south.

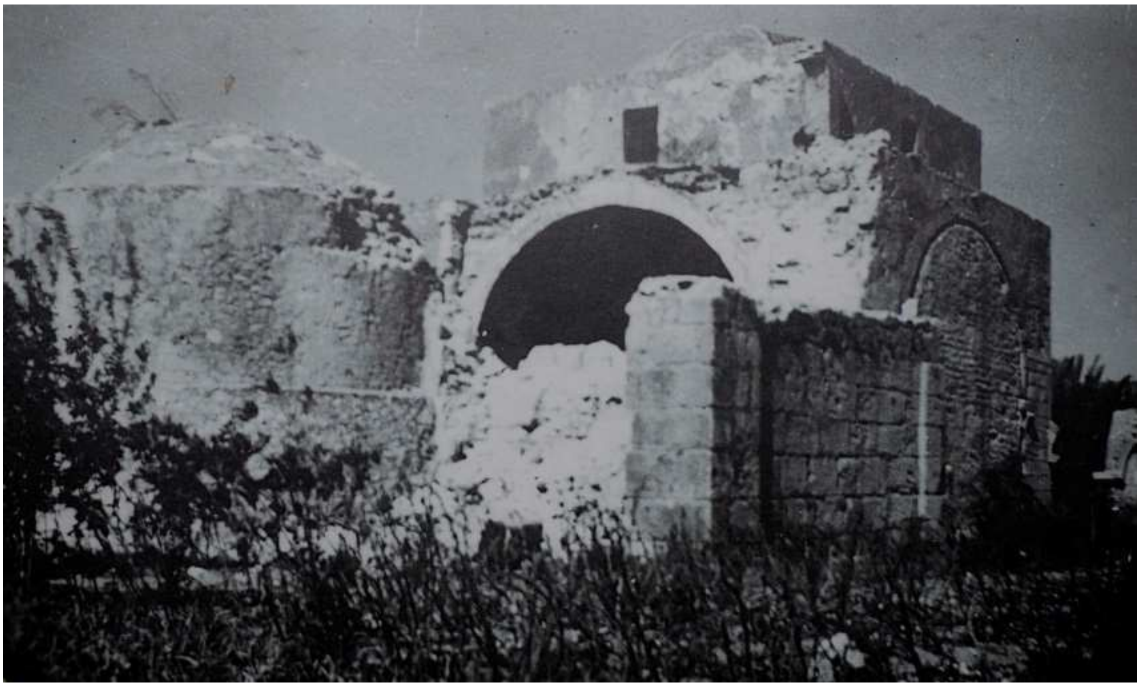

Fig. 9 – Church of San Saturnino after the bombings of World War II, image property of the Superintendence for Architectural, Landscape, Historical, Anthropological Heritage of Cagliari and Oristano.

Evolution and consequences of structural damage

With reference to the aisle facing south, the detected elements provide a circumstantial framework, which is homogeneous and convergent, corresponding to the occurrence of a kinematic localized collapse. It produced an off-plane rotation of the south- facing masonry. Along the first row of vines a cylindrical hinge takes place that leads to the rotation, not only of the perimeter wall facing south, but because of the effectiveness of the node this angular displacement involves also the masonry head facing east, which, finding in the structural node represented by scarfing the nave an effective constraint, produces the elevation of the entire head of the aisle in what is called a rollover-type complex. Further evidence of the onset of a kinematic collapse is found in the shell from the same aisle with the cracking of ashlar junction between the vault and the perimeter wall. Cracking of some blocks and extraction of the same can be clearly observed. Vertical cracks resulting from compression of the capitals sets and localized detachment from eccentric compression in a column are also seen. Detachment and loss of the mortar between blocks caused the dismissal. The most obvious cause of this condition is identifiable in a yielding backdrop that involves the entire south side of the nave and the front thereof. The failure was caused by the excavation perimeter, which runs along the entire perimeter of the structure. Archaeological research at the site resulted in a lowering of the share of foot traffic outside in some places which exceeds two meters below level zero. Moreover, this excavation was performed arriving close to the perimeter walls, virtually eliminating the counterforce that these exerted against the perimeter walls. The situation is also complicated by the nature of the walls that have been made with the technique and reveal a lot more points diatones shortages and the lack of homogeneity of the materials used in the cavity. In these conditions, and in the absence of elements of confinement, the dividing wall outside deviates from the septum of ceiling. Such removal in the absence of viscosity can lead to the collapse of the only external face, but often this involves the hanging ceiling which has not a sufficient mass and yields to an horizontal thrust. Indeed, the resulting vector determined by the weight acting vertically and the thrust vector acting horizontally produce a force oriented at 45° right in the direction followed by the walls at the time of the collapse. Among the factors that have worsened the situation there were the constant changes in the groundwater level and the history of the building, which suffered its strong horizontal thrust in the off plan direction. In 1943, a bomb exploded at the eastern arm of the church destroying it; the shock wave severely damaged the south aisle, while the north was destroyed completely. With reference to the north-facing aisle, the outer perimeter wall of the nave has along the first two rows of blocks a crack pattern characterized by a repetition of vertical slits, which indicates an eccentric compression probably due to a differential subsidence of the foundation ground. This condition could trigger, similarly to what already happens in the nave mirror, the phenomenon of a cylindrical hinge. The imminent failure of the beam and the plinths that serve as the foundation for the head of the aisle would produce the collapse of the same. In this case it is likely a reversal of a simple type, since the reconstruction of the affected area has determined a condition for which the corner constraints with the masonry of the apse are not such as to cause the "dragging" of the tangent masonry. This assumption is made even more remote from the solid structure that supports the under wall Apse.

Fig. 10 – Plinth above ground in aisle facing north.

Fig. 11 – Ejecting the concrete cover in the beam on the foundation of the aisle facing north.

Possible interventions to improve structures and concluding remarks

In order to maintain the current structural condition of the building there are two desirable interventions. The first aimed at monitoring the cracks in order to evaluate their speed of propagation. The second, closely related to the first, aimed at a structural consolidation that in the case of the south-facing aisle determines a condition of counterforce to the eccentric rotation. This condition can be achieved in different ways: burying, for instance, the excavation that runs along the end of the aisle in question. Such intervention would not be invasive to the structure, but would preclude the use of a part of the excavations. Alternatively one could underpin the area affected by subsidence with drilling having an angle of penetration close to 45° from the outside of the building, with subsequent injection of binder within the holes. This intervention, if executed properly, is of minimum impact and ensures the strength of the bond even in the case of alterations of the groundwater level. A third hypothesis could be that of injecting expanding resins of different densities. This solution would have an aesthetic advantage tied to the minimum diameter of the hole required for the application and the considerable advantage of "lift" section of masonry treated. By contrast, a non-perfect control of the mixture and of the relative expansion phase, could create pressures which are not controlled in the soil resulting in leakage of resin in the excavation area. In the case of the north-facing aisle the solution would be to reduce the impact of footings and beam underpinning eliminating corrosion because of carbonation and the subsequent expulsion of the concrete cover. With reference to the central domed portion, it would be advisable to check the behaviour of the tie rods, both those that connect the four pillars and the metal band which surrounds the base of the dome at the extrados. Especially the latter tie would be indicative of an evolution of static equilibrium. Remembering that is has been positioned in the mid 50's and that in 1984 it was inefficient for the occurred tensile rupture. As it always happens when interventions involve buildings which are well-protected for historical and artistic reasons, there are many questions to ask, i.e. technical, legislative and aesthetic ones. Sometimes the fear of producing irreparable damage can generate a dangerous inertia. It is the task of the historian to remember that all the works, which have survived to the present day have been tampering, but have come to us. All interventions have error rates, but only the non-intervention would be the absolute error.

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Note: The bibliography below was used in the initial phase (prior to analysis in situ) during the analysis of the literature and archival documents for further historical-archaeological-architectural related monument. For these reasons, the following references have not been reported in the body of the paper.

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