Methodology applied to the removal of the ruins and to the survey of the remains after the collapse of the Noto Cathedral in Sicily

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Abstract

The Cathedral of Noto, built in the eighteenth century, and damaged by an earthquake occurred in 1990 collapsed partially the evening of March 13, 1996. The removal of the collapsed parts had to be carried out following a methodology which did not have any existing guideline. After the provisional structures were built for the safety of the site, the survey of the site was carried out by traditional geodetic techniques and by an aereal photogrammetry of the ruins. Every recoverable block and piece of material was cleaned, catalogued and removed carefully following a stratigraphic methodology. All the materials are preserved in a special site, protected from rain and damages and will be reused in the reconstruction of the Cathedral. The design for reconstruction will then be based a good knowledge of the remains. The special methodology followed and the survey of the remains will be presented.
1 Introduction

After the partial sudden collapse of the Noto Cathedral on March 13, 1996 fortunately without any casualty (Figure 1), the Noto community astonished by the loss of one of its most famous buildings, decided to rebuilt the Cathedral as it was. The Cathedral was damaged as many other buildings in Noto and in other cities of Sicily by the earthquake which occurred on December 13, 1990. For a certain time it was closed to the public until some provisional structures were built while waiting for the necessary repairs [Balsamo [1]]. The Cathedral was built in different phases from 1764 over a previous smaller church opened in 1703 to the public and demolished in 1769/70 as the new Cathedral was growing. The Cathedral was opened in 1776. In 1780 the dome collapsed and the church was riopened in 1818. In 1848 the dome collapsed again under an earthquake and then it was rebuilt and the church reopened again in 1862 but the dome was not completely finished until 1872. In 1950 the Cathedral was restored with new renderings and paintings and the timber roof substituted with a concrete structure; the work continued until 1959 (Iacono [2], Tobriner [3], Pisani [4]).

The losses caused by the collapse were the following: 4 piers of the right part of the central nave and one of the 4 piers sustaining the main dome and the transept, the complete roof and vault of the central nave, three quarter of the drum and dome with the lantern, the roof and vault of the right part of the transept and part of the small domes of the right nave.

The necessary works for removal of the ruins had to be carefully studied and designed in order to guarantee the safety and the preservation of all the remaining parts. This duty is one of the most difficult after a collapse; in fact the interpretation of the collapse mechanism and the preservation of the remains depend upon the methodology applied for the removal (Binda [5]). The works started on March 1996 and were carried out in two different phases. During the first phase the following operations were performed: (i) demolition and/or

Figure 1: General view of the situation after collapse
removal of the unstable parts, (ii) construction of supporting provisional structures for the remaining parts and protection works for the site safety, (iii) protection of the ruins and of the partially collapsed walls from the rain, (iv) installation of a monitoring system for the remaining structures, (v) photographic, topographic and photogrammetric survey of the state of the structure after the collapse, (vi) removal and storage of the materials after cataloguing what could be reused.

The second phase consisted in the following operations: (i) survey of the constructive and technological features of materials and structures, (ii) geometrical and photogrammetric survey of the remains, (iii) historic survey through documents, memories and archives, (iv) survey on materials and structures, (v) geognostic investigation on soil and foundation.

A special methodology had to be studied during the first phase in order to reduce the loss of the collapsed materials and to respect the remains which were supposed to be possibly reused in the reconstruction.

The works lasted from January 21, 1997 to February 7, 1998. The volume of the removed ruins was 3,610 m$^3$. The surface covered by the ruins was 1026 m$^2$ (totally 7,000 m$^2$ disposed in 7 layers). The every day examined, chosen and stored volume was 21 m$^3$. 5855 pieces of stones and other elements were numbered and stored. The total cost was 387,493 ECU.

The aims of the work were the following: (i) to acquire data useful to understand the collapse mechanism and the causes of the collapse through the description of the type and the position of the collapsed elements; answers to these questions were given by the experts of the Committee nominated by the Prosecutor of the Procura della Repubblica of Syracuse, (ii) to have more knowledge on the constructive technique of the original church, (iii) to verify the possibility of utilizing the recovered materials.

2 Provisional operations for the site safety

After the site was delimited and all the services had been prepared, the following preliminary operations were carried out:

- a provisional structure was realized with steel elements and wood tables along the internal perimeter of the building in order to have a protection from the eventual unstable stones and pieces falling down (Figure 2);
- the unstable masonry elements were then removed after accurate photographic documentation, avoiding overlapping to the already collapsed material;
- realization of ties and steel truss rods connecting the transept walls at the spring of the 4 arches supporting the dome (Figure 3);
- waterproofing with sprayed gunite of the fractured surfaces of the top of the remaining walls;
- preparation of a side storage area near the church for the recovered materials.
3 Topographical and photogrammetrical survey

Before any removal, a topographical survey of the situation after the collapse was necessary; this in order to leave a documentation of the actual situation and to start the study of the collapse mechanisms.

The operations were carried out in two phases:

a) subdivision of the area occupied by the collapsed materials in 114 square subareas of dimension 300x300cm. The edge coordinates of each subarea were surveyed and referred to a coordinate system internal to the Cathedral;

b) topographical three-dimensional survey of the ruins and calculation of their volume (Figure 4).

4 Data collection, photographic survey and storage

This operation was very important for the reconstruction of the Cathedral. Each
possible recoverable piece had to be catalogued and stored in such a way that it could be in the future reused where it was originally. The methodology adopted was the following:

- all the materials and pieces were previously cleaned in order to be recognized by a photographic survey especially the stone blocks which had to be all numbered and stored in a provisional area;
- each block and piece of fallen material which could be considered as recoverable and significant for the reconstruction was given a progressive number. A special form was filled for each containing the number, the description and the structural element to which it was supposed to belong. A special abacus was prepared containing the characteristics of all the structural and decorative elements of the building;
- a picture of each subarea was taken from the top with a special device before any removal. All the pictures were codified with a system set up for the site and examined by the responsible R. De Benedictis and S. Tringali. The removal of the ruins was only authorized if each picture clearly reported the date, the number on each recoverable element, the edge number of the square subarea, did not contain strange object (tools, etc.) and could easily allow for the determination of the camera position.

5 Removal of the ruins

After being catalogued and photographed the a first layer of material was removed from each subarea and following successive layers from the top. The destination was different according to the future use of the material and following the procedure here reported:

- all the recognized elements (or with any probability of future recognition) easily transportable were taken away to a special protected storage area (stone blocks, concrete elements, steel elements, etc.);
- elements of large dimensions heavy and difficult to be carried away (centerings, concrete beams, provisional structural elements, etc.) were stored on the floor;
- delicate small dimension elements (furnitures, steel elements, timber frames, stucco and glass fragmentts, lamps, etc.) were stored in the church presbitery;
- unrecoverable elements as soil, sand, etc. stored temporarily on the storage area before being transported to the refuse disposal site.

Then the successive layer of ruins was removed as described above applying the same criteria (survey, choice, numbering,
Particularly costly was the cleaning operation of each piece (Figure 5) which was done by hand in order to avoid any damage. In fact a thick layer of dust, pieces of mortar and small fragments was usually covering every piece of stone and decoration. At the beginning every operation was particularly difficult for the contractor, who was working at the removal for the first time. Nevertheless the concern for saving as much as possible and the deep respect for the monument were of great help in overcoming the difficulties. So after a first period of trials and rather slow productivity, the further experience helped in becoming more and more fast.

6 Survey of the remaining structures

During and after the removal it was possible to survey and analyse the constructive characteristics of all the structural elements. Figures 6, 7, 8, 9 show the plan, the section and the internal prospects of the central nave of the Cathedral as the ruins were removed. The design for repair and reconstruction should respect as much as possible these remains. As an example a synthetic description of some elements which represent the loadbearing parts of the Cathedral will be given in the following.
6.1 Piers

The collapse certainly developed starting from one or more of the right piers of the central nave. As in the case of the ones sustaining the dome, these piers consisted in a multiple leaf structure in which an external leaf made with regular stones confined a central core in masonry made with calcareous stones of different dimension and shape. The external leaf, except for the base of the piers, was made with regularly cut blocks from the "local travertine" also called calcareous tuff. This material came from sedimentary carbonatic deposition in the presence of turbulent waters and it is rich in voids of various shape and dimensions which previously contained vegetarian and organic parts later on dissolved. The compressive strength of this material is very low and can vary from 4 to 6 or more N/mm². The height of the blocks varies from 24 to 26 cm and the thickness, very small compared to the pier dimensions is varying from 25 to 30 cm. No really effective connection was realized between this external leaf and the core. (Figure 10). The stones of the pier strips supporting the arches have no connection either to the internal masonry or to the other parts of the external leaf.

The external part of the base is made with regular blocks of calcarenite which have a greater thickness and a better strength (more than 17 N/mm²). The inner part of the piers represents the 55% of the entire section, while in the piers sustaining the dome is the 58%. This part is a masonry made with irregular stones and, up to the half of the total height, with large round river pebbles. The courses of these stones are rather irregular without any transversal connection or
small stones to fill the voids and with thick mortar joints. Nevertheless every 50cm (every two courses of the external leaf a course made with small stones and mortar was inserted in order to obtain a certain horizontality (Figure 10). Scaffolding holes were left everywhere, some crossing the whole section.

The mortar appeared to be very weak made with lime and a high fraction of very small calcareous aggregates. Also the bond between the mortar and the stones was very weak; in fact it was possible to sample stones and pebbles from the interior of the piers without any difficulty and with the stones being completely clean (Figure 11).

The left piers, still covered with a thick rendering, seemed to have minor damages, but the doubt that the damage could be inside and perhaps even present before the 1990 earthquake, suggested to subject these piers to a more accurate survey in the future.

6.2 Concrete roof

The real date is not known nor documented, but in the second half of this century unfortunately the timber roof of the central nave and of the apse was substituted by a concrete structure. This intervention caused also the destruction of the upper part of the extrados of the arches sustaining the old roof. In the meantime the lateral walls were raised in order to avoid that the new structure could cut the vault now collapsed.

The roof of the presbytery is still a concrete truss structure made with prefabricated elements with a thickness of 48cm. bearing hollow clay elements and with a concrete cover 12cm thick. Also the collapsed roof was made with prefabricated concrete elements (Figure 12). Light clay elements were put between two beams.

The roof structure was finished with a 20cm thick concrete cover.

6.3 The drum and the dome

The drum of the dome was made with a double leaf masonry constructed with regularly tooled stone blocks. The external leaf was made with a local calcarenite called "Noto stone" with perfectly shaped stones and vertical and
Horizontal joints only 3mm thick and with sculptured decorations (Figure 13).

The internal leaf was made with the so called "giuggiolena" stone, a local rather light biocalcarenite (1,600 Kg/m³). These stones were also tooled and the decorations made with gypsum. The mortar joints (vertical and horizontal) have a thickness between 10 to 25mm.

The dome was the third in the history of the Cathedral. It was completely built with voussoirs of "giuggiolena" stone, one leaf thick. Its geometry was obtained by rotation of a stilted arch (Figure 14). The geometrical figure which better matches the dome profile is a polycentric with three centers for the extrados and a polycentric with two centers for the intrados. The courses are all together 21 with a decreasing depth from the bottom to the top from 680mm to 440mm and a constant height of 425mm. All the sides of the stones are tooled.

At the external part of the dome eight couple of modest ribs, circa 80mm thick, made with appropriately tooled voussoirs can be seen. The joints have a thickness ranging from 15 to 20mm. The rendering of the external part is made with an hydraulic mortar which maintained a very good adhesion to the stones. Only the upper ring which served as support to the lantern was made with white facing stones with very thin joints and no rendering.

No metallic ties were found in the dome and in the drum.

The drum of the heavy lantern so as the closing ring of the dome were made with white stone voussoirs with very thin mortar joints. The little dome at the top was made with "giuggiolena" stone rendered with a mortar made with lime and crushed bricks similar to the dome rendering. The column system was strengthened with a steel frame tied to the upper dome.
7 Conclusions and needs for further investigation

The importance of a programmed removal of the ruins is shown by the positive results of the operation.

- Particularly efficient were the measures taken for the security of the site and of the persons, the provisional structures and protection.
- The first observation carried out thanks to the monitoring system applied to the remaining structure allowed to detect that a relaxation of the piers took place with an apparently unusual increase of the crack.
- The clearly poor technique of construction of the collapsed piers also suggested to extend the survey of the internal section of the masonry to the remaining piers but also to the loadbearing built in piers of the external walls.
- The removal done layer by layer allowed to reconstruct with good reliability the mechanism of failure of the Cathedral which is confirmed to have started at one of the right piers. Nevertheless it was not possible at the first investigation to clearly define if the mechanism was due only to the earthquake or, to some other cause. Therefore it was decided to examine in details the situation of the remaining left piers and also to check the possibility of consolidation.
- The damages could certainly be attributed to the very poor technique of construction and to the use of very poor materials. Travertine and mortars seemed to be the weakest ones, therefore their identification was needed. Also the mechanical behaviour of the masonry was needed and on site tests seemed to be the most interesting.
- A survey extended to the arches and domes on materials and construction technique was also necessary in order to choose materials and techniques compatible with the existing ones, for the reconstruction and repair.
- A need for a geognostic survey on soils and foundations was also clear required, in fact the possibility of maintaining the existing foundations or building a supporting structure depended on the results of the survey.

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9 References