Investigation on materials and structures for the reconstruction of the partially collapsed Cathedral of Noto (Sicily)

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Abstract

The Cathedral of Noto partially collapsed on March 13th, 1996, after being damaged by the 1990 earthquake. Following the removal of the ruins and the geometrical survey of the remains, an experimental investigation was carried out on site and in laboratory. The aims were: to understand the causes of the collapse and to know if some damages to the structure existed prior to the 1990 earthquake, to clearly state whether the remaining piers could be saved or had to be reconstructed and to test the possibility of repair by injection of the remaining structural elements.

The experimental survey was carried out by the Laboratory of the DIS, Politecnico of Milan, in collaboration with the designers and the experts working on the reconstruction.
The investigation procedure will be described and its results presented and discussed in view of the reconstruction.

1 Introduction

On March 13th, 1996 at 10.30 P.M. part of the beautiful massive Cathedral of Noto (Figure 1) collapsed, without causing any casualty to the people, leaving everybody astonished for the loss of an important part of a city considered a jewel of the Baroc style. Warning of the danger were given by the cracks appeared on the piers and vaults of the Cathedral after the 1990 earthquake which had caused damages to several cities of Sicily.

Sicily has seen many earthquakes in its history. One of the most destructive occurred in 1693; Catania and Siracusa were badly damaged and the ancient Noto destroyed. So it was decided to build a new town of Noto not far from the sea in a place which was considered safer from the earthquake. The architecture of Noto is so precious, an example of a uniform Baroc style, that the entire town is under the protection of UNESCO.

The Cathedral was built with a longitudinal plan, three naves and a transept, terminated by an apse. The facade has one tower on each side and the four piers of the transept sustain a dome with a diameter of ...m. The collapse involved all the piers of the right side of the central nave, the central barrel vault and the concrete beam roof, the domes of the right nave and three quarter of the central dome. The Noto community together with the National authorities have decided that the missed parts of the Cathedral have to be reconstructed so that the building should return to its beautiful appearance of before the collapse.

The investigation carried out by the authors after the removal of the ruins had the aim of detecting the state of damage of the remaining parts in order to know what can be preserved and repaired and what has to be demolished and rebuilt.

R. De Benedictis and S. Tringali the designers of the reconstruction were assisted by L. Binda, G. Gavarini and other experts for the experimental investigation, the structural analysis and the choice of the materials and the constructive techniques for the reconstruction. S. Tobriner from the University of Berkeley carried out the historic survey (Tobriner [1]) and experts from the Catania University have performed the geognostic investigation. The on site and laboratory experimental tests on materials and structures were conducted by the Laboratory of the Structural Engineering Department (DIS) of the Politecnico of Milan under the supervision of L. Binda and G. Baronio. All the operations were
previously longly discussed among the authors and the other experts in order to choose significant positions for sampling and testing, and to harmonize the different tests. In the following the procedure adopted for the experimental investigation and its results will be described.

2 Damage description

The Cathedral was damaged by the 1990 earthquake; a series of cracks were visible mainly interesting the piers of the central nave and some of the little domes over the lateral naves. Provisional structures were set up in 1992 to help the most damaged piers. A collapse was not expected at that time, neither was suspected a continuous worsening of the situation; no further intervention took place. Only after the identification of the causes of the collapse of the civic tower of Pavia in 1989 it was possible to understand that certain damaged situations, connected to a serious state of stress of the material can proceed toward failure in a rather long time (Binda [2], Binda [3]).

After the removal of the huge amount of ruins (3,610 m$^3$) and the execution of the necessary provisional structures (De Benedictis [4]), the actual damages consequence of the collapse could be checked and described. Figure 2 shows only a partial view of the destruction, Figures 3 and 4 clearly show the missing parts: the right piers of the central nave, the vault and the roof, a large part of the central dome, the domes of the right nave and other local destruction. The feeling of a person watching for the first time at the ruins is really a sense of frustration.

Figure 2: View of the entrance of the Cathedral after removal of the ruins

Figure 3: Prospect of the left side of the nave
3 Aims of the investigation

The on site and laboratory research carried out by the authors concerned: (i) a study, based on the results of surveys and tests, of the state of damage of materials and structures and of their possibility of being reutilized, (ii) the choice of the materials for the reconstruction of the piers and of the missing parts and for repair and reinforcing, (iii) the verification of the chemical, physical and mechanical compatibility of the new materials with the existing ones.

The aims of this research were the following: (i) to give assistance to the designers in understanding the behaviour of the structure left on site after the collapse, (ii) to detect the possibilities of preserving the functions of the structural and non structural elements left apparently undamaged or slightly damaged (i.e. the left piers), (iii) to suggest on the basis of the tests results on existing and new materials the techniques for repair of the damaged parts, (iv) to define and choose the best materials for the reconstruction.

The time given to the Politecnico for the experimental research requested by the Prefettura of Syracuse was 60 days.

4 On site investigation

Knowing that the collapse took place starting from the right piers it was necessary to decide whether the left piers still standing but badly damaged should be preserved and which technique for the reconstruction of the collapsed piers should be adopted.

The on site investigation consisted in the following operations: (i) excavation in strategic sites, near the piers and the walls in order to identify the type and the depth of the foundations, (ii) demolition, layer by layer of the base of one collapsed piers, in order to study their technique of construction and the materials used, (iii) removal of the external stones to study the section typology of piers and walls, (iv) sampling of mortars and stones in the most representative areas, in order to study the material composition in laboratory, (v) survey of the remaining piers to know their state of damage, (vi) single and double flat-jack
tests to define the state of stress in compressed areas and the stress-strain behaviour of the masonries, (vii) injection of the remains of two collapsed piers and of a small part the lateral walls with different types of grouts, (viii) ND evaluation of the state of damage of the piers through sonic and radar tests and detection of the effectiveness of injections by sonic tests.

The investigation (i) (Figure 5) has shown that the foundations of piers and walls were sufficiently well constructed; rubble walls but with enough load carrying capacity for the weight of the above structures. The soil was a sort of natural compact silt and clay thick layer from where also the aggregates of the mortars were taken.

The removal (ii) by layers of the components of the collapsed piers allowed to understand the poor technique of construction used for them. Layers of large round river stones with thick mortar joints, where the mortar appeared very weak and dusty were found in the core of the structure, surrounded by an external leaf made with regular blocks of calcarenite at the base of the piers and of travertine in the upper part (Figure 6). This poor technique of construction and material were probably cause of early damages to the piers of the Cathedral, even if a clear damage appeared only after the 1990 earthquake. The walls were built similarly; nevertheless the internal part was made with smaller sharp stones alternated with a slightly stronger mortar, in some way a better masonry (Figure 7). Some stones were sampled from piers and walls and mortar samples were taken from horizontal, vertical joints and from the interior of
the masonry (Figures 3 and 4). The samples were sent to the DIS Laboratory and tested in order to find the material characteristics. Since the still standing left piers seemed to have been damage during the collapse, it was decided to investigate the situation under the rendering applied probably in the sixties during a previous restoration. When the rendering was removed a surprise appeared on the pier surface. Large vertical cracks had been filled with gypsum and lime, the same material used for the render (Figure 8).

A single flat-jack test was carried out on the pier E' in order to know the state of stress in it simply due to the dead load of the pier itself and a value of 0.85 N/mm² was found at a height of 3.00m. Taking into account the missed weight of arches, vaults and dome in the collapse, it is easy to hypothesize that the piers must have been under a non negligible state of stress. Double flat-jack tests were also carried out on piers E' and A' and on the external walls of the Cathedral (see Figure 7). The results are reported in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Max stress applied (N/mm²)</th>
<th>Stress interval (N/mm²)</th>
<th>Eₛ (N/mm²)</th>
<th>Δₑₑ/Δₑᵥ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNJ1d</td>
<td>1.88</td>
<td>0.1-0.5</td>
<td>1760</td>
<td>0.06</td>
</tr>
<tr>
<td>CNJ2d</td>
<td>0.76</td>
<td>0.1-0.5</td>
<td>1525</td>
<td>0.09</td>
</tr>
<tr>
<td>CNJ4d</td>
<td>1.20</td>
<td>0.1-0.5</td>
<td>1215</td>
<td>(0.89)</td>
</tr>
<tr>
<td>CNJ5d</td>
<td>1.18</td>
<td>0.1-0.5</td>
<td>1205</td>
<td>0.09</td>
</tr>
<tr>
<td>CNJ6d</td>
<td>0.88</td>
<td>0.1-0.5</td>
<td>370</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1: Test results of double flat-jack
Test CNJ2D was done on the internal part of pier A' in order to check the behaviour of the weakest part of the loadbearing piers. Figure 9a shows the difference between the external leaf (CNJ1D) and the core (CNJ2D) which had a much higher deformability and lower strength. CNJ4D, CNJ5D and CNJ6D were performed on a masonry which apparently was similar to the core of the piers but built with better materials: Therefore the results given in Figure 9b show a better behaviour compared to the interior of the pier (CNJ2D) even if CNJ6D was clearly made in a weaker part of the walls.

A research was also carried out to check the possibility of repairing the damaged structures by injection of various grouts. Four grouts were used for laboratory tests and on site C, N, M, P respectively lime + pozzolana, hydraulic lime, hydraulic commercial binder, microfine. After injection some sonic tests were carried out on the piers and an example of the results is given in Figure 10 showing some improvement of the injected parts. After one month some part of the piers were dismantled and small recovered specimens of the injected material tested in laboratory.

### 5 Laboratory testing

On the materials sampled on site physical, chemical, petrographic-mineralogical and mechanical tests were carried out in Milan at the DIS
Laboratory. The aim was to characterize the materials of a typical (CC') transversal section of the Cathedral (Figure 11).

The chemical and mineralogical analyses were carried out following a procedure set up in (Baronio [5]) on the mortars sampled from all the piers and walls at different height. The mortars contain a high percentage of CaCO₃ showing that they are based on hydrated lime with a high content of soluble silica and fine aggregate size distribution. Table 2 gives the results on the mortar of pier A' together with the crack repair composition. Figure 12 gives an example of grain size distribution of aggregates. The soil was also examined and it appears of being composed by more than the 87% of calcium carbonate, by 8% of different silicates and for the remaining 5% by alcali, allumine, iron, gypsum, etc. The grain size distribution of the soil shows that it is composed for the 8% by clay, the 72% by silt and the 20% by sand, a very fine material.

Mechanical tests on the calcarenite ("Noto stone") show that the strength of this material can vary very much from the dry to the water saturated state (nearly the 50%) with an average strength of 17.98 N/mm² in compression and of 5.16N/mm² in tension under the splitting test. The travertine has instead a compressive strength of 5.16N/mm² and a tensile strength of 1.00N/mm² being much weaker than the calcarenite as it was also shown on site by the sonic tests on the piers.

Injectability tests proposed by L.Binda and G. Baronio (Binda [6] were carried out in laboratory on materials sampled from the internal part of the piers and walls (Figure 13). Compressive and splitting tests on the injected cylinders in laboratory gave respectively a compressive strength of 1.75 N/mm² and a tensile strength ranging from 0.10 to 0.40 N/mm² depending on the effectiveness of injection. The injected material sampled from the piers was also tested but the

Table 2: Chemical analysis and bulk density of mortar of pier A'

<table>
<thead>
<tr>
<th></th>
<th>PIER A'</th>
<th></th>
<th>PIER A'</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
<td>Al</td>
<td>Fe₂O₃</td>
<td>CaO</td>
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<td></td>
<td>4.27</td>
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<tr>
<td></td>
<td>Al₂O₃</td>
<td>MgO</td>
<td>Na₂O</td>
<td>K₂O</td>
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<td></td>
<td>0.41</td>
<td>0.47</td>
<td>0.98</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>41.13</td>
<td>40.50</td>
<td>4.20</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Cl</td>
<td>0.025</td>
<td>0.028</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bulk d.</td>
<td>1,313 kg/m³</td>
<td>1,489 kg/m³</td>
<td></td>
</tr>
</tbody>
</table>
dimension of the specimens were smaller than the ones of the cylinders. Compressive and tensile strength of these specimens were ranging respectively from 0.9 to 5.0 N/mm² and from 0.3 to 0.4 N/mm².

6 Suggestions for the design of reconstruction

The results of the investigation allowed the designers to take decisions on the reconstruction of the Church based on a deep knowledge of the construction. Even if the theories and the present attitude are tendentially favorable to the conservation of the existing historic buildings, two questions had to be answered in the case of the Cathedral before taking any decision: (i) how much damage had suffered the loadbearing parts still standing, (ii) in the case of high damage should those parts together with the collapsed ones be rebuilt with the original technique and materials.

The answers from the consultants to the designers were as follows.
- The external loadbearing walls, the arches and domes (lateral and central) which were made with a rather good technique (being in any case the mortar very poor) can be preserved and/or repaired or rebuilt where missing, as they were, using the same technique and materials. Grout injections with carefully chosen grouts can also be used for strengthening.
- The left hand piers cannot be preserved due to the high state of damage caused by the weak technique of construction and the weak materials; therefore they have to be demolished and rebuilt together with the collapsed ones using better materials and technique of construction, i.e. hydraulic mortars obtained with hydrated lime and pozzolana, calcarenite stones avoiding travertine and good connections between the external leaf of the pier and the core.
- The soil and foundation seem to be acceptable everywhere; the only exception can be made for the foundation of the central nave piers which can eventually follow a new conception.
7 Conclusions

The accurate and detailed survey carried out by a multidisciplinary team was very helpful for the designers who had to take many difficult decisions. The crack pattern survey revealed large vertical cracks already present and filled with poor material in the sixties when the timber roof of the Cathedral was replaced by a concrete roof. These damages indicate, together with the laboratory results that the material used for the construction was very weak and damaged by long term effects; the collapse perhaps could have taken place in a longer time without the earthquake. On site and laboratory tests on the materials allowed to demonstrate that the choice of the composition used for the existing mortar with very fine aggregates was probably the first cause of the damages together with the use of large round stones and of travertine. The survey of the internal texture of the piers and walls was also important to identify the morphology of the section. The information was also useful to understand even before testing that some masonries (the piers) are not injectable; a confirmation was also given by laboratory and on site injection tests. The application of NDT as sonic and radar allowed to experience the advantages and the limits of those techniques as qualitative investigation means.

8 Acknowledgements

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9 References

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