Chapter 4: Conservation Approaches, Applications, Case Studies

Chapter 4.1

THE DIFFICULT CHOICE OF MATERIALS FOR THE RECONSTRUCTION OF THE CATHEDRAL OF NOTO

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Abstract: In 1996, the Cathedral of Noto (Sicily), suddenly collapsed partially, after being damaged by the 1990 earthquake, which hit the eastern part of Sicily. As the continuous propagation of cracks and damages in the pillars (made with external leaves in limestone and filled internally with rubble) due to the weak materials used and the poor construction adopted was considered as the main cause of the collapse, it was decided to rebuilt the collapsed and part of the damaged pillars adopting the traditional techniques and the same materials used in the past, with improvements of the pillars technique of construction. A difficult task was the choice of the stones for the reconstruction, first of all the choice of a suitable quarry and then the control of the stone properties at each delivery.

Key words: limestone; Noto cathedral; experimental investigation.

1. INTRODUCTION

The Cathedral of Noto (Sicily, Italy) dedicated to S.Nicolò was built after an earthquake which hit the eastern part of Sicily in 1693. On March 13, 1996, the Cathedral of Noto suddenly collapsed partially, after being damaged by the 1990 earthquake. The four left pillars of the central nave, the vault, the domes of the right lateral nave, the transept roof and vaults and three quarters of the central dome were lost. Following destruction a choice was made to reconstruct the collapsed part with local traditional materials. The Cathedral had been built in different phases beginning in 1764. In 1780, the dome collapsed and the church was reopened in 1818. In 1848, the dome collapsed again due to an earthquake, it was rebuilt, and the church reopened again in

S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, 185–200.

1862 although the dome was not completely finished until 1872. In 1950, the Cathedral was restored with new plasters and paintings, and the timber roof was substituted by a concrete structure. The work continued until 1959.

An extensive investigation was carried out by D.I.S. Politecnico di Milano laboratory, responsible L. Binda, on the materials and structures, in order to: (i) find the causes of the collapse, (ii) characterise the materials, (iii) identify the structural damages on the remaining parts of the church, (iv) choose the materials for repair and reconstruction.

The extensive experimental and numerical investigation carried out after the removal of the ruins, showed that the collapse started from the pillars (one or more), due to the damages they had already accumulated before the earthquake. The pillars showed a state of damage due to compression with vertical cracks covered. The poor construction technique and the use of the weak limestone were probably the cause of the damages to the pillar of the Catherdral, even if a clear crack pattern was reported to have appeared only after the 1990 earthquake.

A unanimous decision was made by the authorities and the Noto citizens to reconstruct the collapsed parts of the Cathedral, as they were before the collapse, with the same type of materials used in the past, improving the structural elements, which were indicated by the investigation as being the weakest. A difficult task was the choice of the stones for the reconstruction. First of all it was necessary to find the right quarry, since several quarries were closed in order to protect the environment. The choice was made by testing physically and mechanically the stones which were coming from different quarries. Once the quarry was chosen continuous experimental studies were made on the cut stones statistically sampled in order to control their quality. A rather difficult task was the quality control on site. Rather complicated was also the preparation of the stones in order to reduce the influence of their rather high absorption on the mortar hardening and on the bond between stones and mortar.

The methodology used for the investigation and the results will be reported and discussed and some guidelines will be suggested for the future intervention, also in case of small reconstructions in seismic areas, after an earthquake damage.

2. CHARACTERIZATION OF THE ORIGINAL STONE

The losses caused by the collapse were the following: 4 pillars of the right part of the central nave and one of the 4 pillars supporting the main dome and the transept, the complete roof and vault of the central nave, three quarters 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 (Figures 1, 2). The right pillars were named A, B, C, D, E; the left ones were named A′, B′, C′, D′, E′ starting from the internal part of the façade (Figure 1).

The investigation carried out by the authors, together with the designers of the reconstruction, showed that the collapse certainly developed starting from one or more of the right pillars of the central nave. Being the support for the dome, these pillars consisted of a multiple leaf structure in which the external leaf made with regular stones confined a central rubble masonry core 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 carbonate 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 height of the blocks varies from 24 to 26 cm and the thickness, which is very small

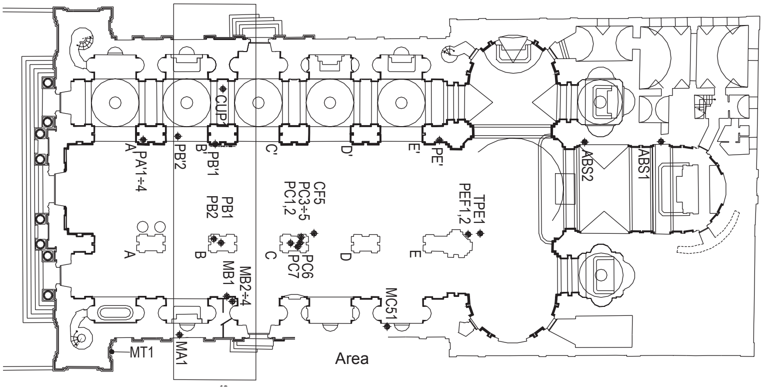


Figure 1. The Noto Cathedral: plan of the remaining parts and samples locations.

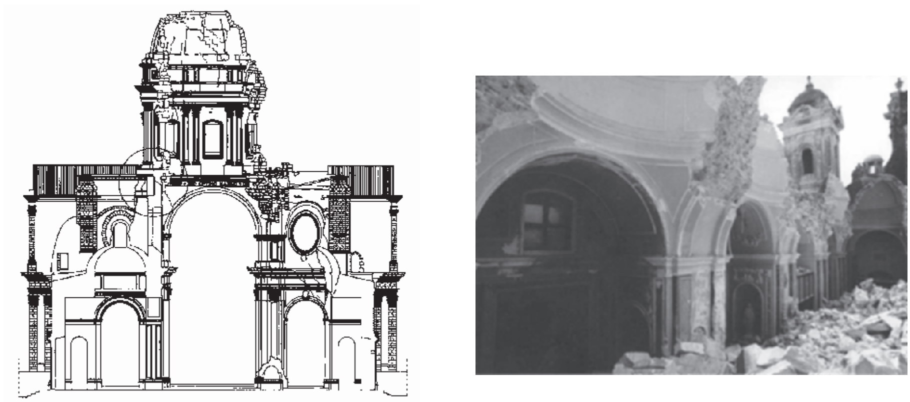

(a) (b)

Figure 2. (a) The transversal section and (b) the collapsed Noto Cathedral.

compared to the pillar dimensions, varies from 25 to 30 cm. No effective connection was realized between this external leaf and the core (Figures 3, 4). The external part of the base is made with regular blocks of limestone (calcarenite) which have a greater thickness and a better strength than the travertine (see next sections).

The inner part of the pillars represents 55% of the entire section, while it represents 58% in the piers supporting the dome. This part, with irregular by-cut stones up to the half of the total height, was made with large round river pebbles (Figure 3). Nevertheless, every 50 cm a course, made with small stones and mortar, was inserted in order to obtain certain horizontality (Figure 4). Scaffolding holes were left everywhere, some crossing the whole section. The mortar made with lime and a high fraction of very small calcareous aggregates appeared to be very weak. 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 pillars without any difficulty and with the stones completely clean of mortar.

The left pillars, still covered with a thick plaster, showed vertical cracks at the bottom (Figure 5a), but the concern that the damage could be inside and perhaps even present before the 1990 earthquake, suggested that the plaster made in the fifties should be removed and a series of large vertical cracks were found, some of which were filled with the gypsum mortar used for the

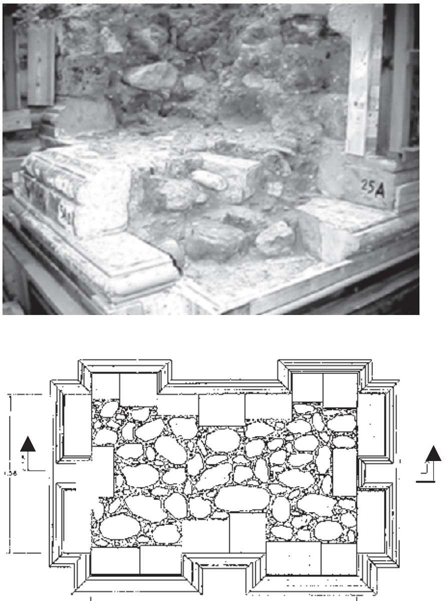


Figure 3. Detail and horizontal reconstruction of a pier section.

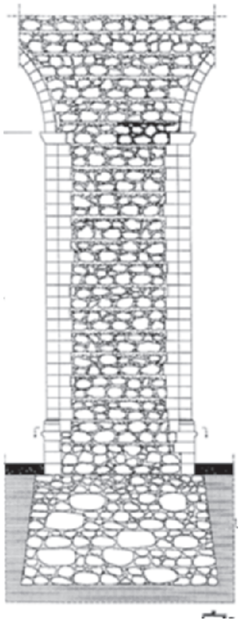
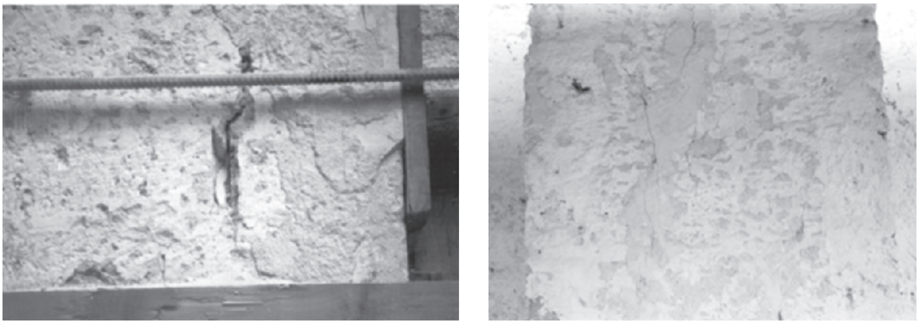


Figure 4. Reconstruction of a vertical section.



(a) (b)

Figure 5. a) Large crack found in a pillar and b) Example of a crack filled with gypsum mortar in the sixties

plaster (Figure 5b). This finding was the proof that the damage was already present before the last earthquake. The pre-existing crack pattern showed clearly damage from compressive stresses, indicating long term damage dating probably even before the rendering. This damage would have probably progressed even without the earthquake, which only accelerated the collapse[1].

Four main types of stones were used in the construction of the Cathedral:

1. limestone (Noto stone, a calcarenite), as regularly cut blocks in the external leaf of pillars and built-in columns, but only for the base, and also used for the internal leaves as sharply cut pebbles,
2. "travertine", as the limestone, but in much larger quantities,
3. "*giuggiolena*", a sort of compact "travertine" for arches and dome voussoirs and
4. round (boulder) river stones used in the internal part of the pillars.

For each type of stone some blocks were sampled in order to carry out chemical, petrographic, physical, and mechanical tests[1]:

1. The Noto limestone (a calcarenite) comes from a calcareous rock with fine grains, finely porous, and of light yellow colour. Observed with polarized light in a thin section, the stone has the characteristics of a fine grain limestone with small pores rich in foraminifer calcareous fossils. Furthermore small black and ochraceous masses were present.
2. The "travertine" is a carbonate rock of light yellowish color with high percentage of voids probably from the same quarries as the calcarenite. In thin section, the carbonate nature is confirmed; numerous irregular voids appear and the material is mainly calcite with very fine grain size which are clean or impregnated with a fine brown material probably clay.
3. The "giuggiolena" is composed by carbonatic rock fragments with fine grain, friable and of brownish colour. In thin section the rock appears to be made by rather round elements with dimension around 0.1 mm; the calcitic cement is scarce and the material is very porous.

Table 1. Physical test on calcarenite and "Giuggiolena" specimen

SPECIMEN		Bulk density dry (kg/m^3)	Bulk density satured (kg/m^3)	Absorption coeff. (total immers. 24h) (%)	IRS (kg/m^2.min)
Calcarenite	CNP-C51.1	1726	1969	14	5.55
	CNP-C51.2	1746	1989	14	6.78
	CNP-C51.3	1689	1947	15	5.81
"*Giuggiolena*"	G.1	1585	1858	17	2.44
	G.2	1598	1881	18	2.50
	G.3	1536	1834	19	2.46

From each stone, 3 to 5 cylinders of 50 mm diameter and 100 mm height were cored for the physical and mechanical tests. It was impossible to have larger dimensions, perhaps more representative of the material, due to the small dimension of the cut stones. Chemical analyses were also carried out in order to find the eventual presence of sulfates.

The physical tests were only carried out on the calcarenite and on the "*giuggiolena*"; in fact, the "*travertine"* voids were filled with mortar or clay and therefore the results were not reliable. It can easily be seen that the stone absorbs a very high quantity of water when saturated, and that the IRS coefficient is very high. This fact usually means low strength and low durability.

Compression and indirect tensile (splitting) tests were carried out on dry and saturated specimens. The results and discussion are reported in the following. Due to the peculiar use of the results and to the dimension of the specimens, the tests did not refer to a specific code of standard[2].

Uni-axial compression tests: no material was put between the specimen and the machine platen due to the dimension of the specimens which already assures pure compression in the central part. For the vertical displacements two LVDT's were applied between the plates and three extensometers (DD1) were directly applied to the specimen. For the lateral displacements a ring clip gauge was used. A hydraulic press with a load cell of 30 to 50 KN was used for the tests, and the tests were carried out in displacement-control at a speed of 4 μm/s. The specimens were tested under two different conditions: dried to constant mass and saturated up to constant mass.

For the detection of the tensile strength, the authors have chosen the splitting test which is easy to perform on cylinders and gives reliable results. The test was carried out according to the Italian code specification (UNI 6135, 1972). Also in this case, the specimens were tested dry and saturated.

The calcarenite used for the external leaf of the pillars is characterized by a fairly good strength when tested dry up to constant mass (18.0 average N/mm^2 in compression, 2.2 N/mm^2 in tension for cylinders of 50 mm diameter and 100 mm height) and by a much lower strength when tested saturated up to constant mass (11.6 N/mm^2 in compression and 1.3 N/mm^2 in tension), as showed in Figure 6. This means a reduction of 35.5% in the compressive strength and of 39% in the tensile one. The "*travertine*" used in the core of the pillars and in the external leaf above the base has a much lower strength than the calcarenite (5.2 N/mm^2 in compression as an average value measured on dry prisms of 100x100x200 mm dimension). The different mechanical characteristics of the two stones were also detected by sonic tests in laboratory and on site[3]. The other type of stone, very light, called "*giuggiolena*" was used for the construction of the arches and dome. This stone also shows a different behaviour when tested dry or saturated: 5.3 N/mm^2 in compression and 1.0 N/mm^2 in tension, when dry, 5.05 N/mm^2 in compression and 0.8 N/mm^2 in tension, when saturated.

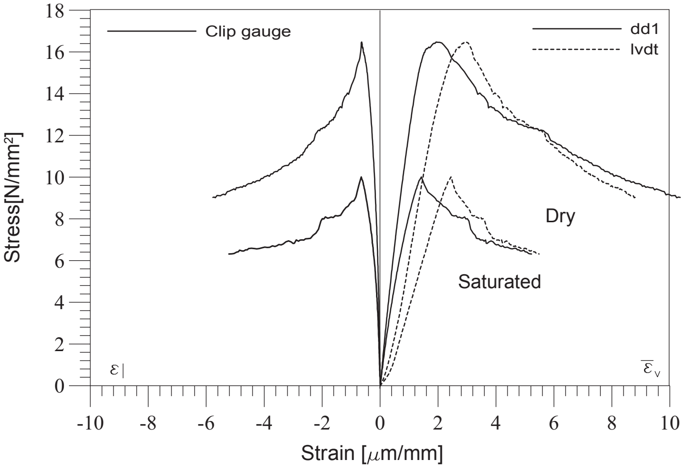


Figure 6. Stress-strain plots of compression tests on saturated and dry calcarenite specimens.

3. CHOICE OF THE NEW STONE

The extensive experimental and numerical investigation carried out after the removal of the ruins showed that the collapse started from the pillars (one or more), due to the damages they had already accumulated before the earthquake. The pillar showed a state of damage with vertical compression cracks covered by the plaster.

A unanimous decision was made by the authorities and by the Noto citizens to reconstruct the collapsed parts of the Cathedral as they were before the collapse, with the same materials used in the past, improving the structural elements which were indicated after the investigation as being the weakest. It was decided to rebuild not only the collapsed pillars of the central nave, but also to demolish and rebuild the survived ones. This was a possible alternative, taking into account the necessity of symmetry in the structure due to the fact that Noto is situated in an active seismic area.

3.1 Search for the quarries

Following experimental investigation, it was concluded that the new stones should be taken from the original or similar quarries. It was necessary to find the right quarry, since several quarries were closed in order to respect the environment. In order to choose a limestone adequate for the reconstruction, samples were taken from different quarries. Even if it was impossible to use the same limestone as the original one, care had to be taken in order to use new stone with similar characteristics to the ones used for the construction of the Cathedral for several reasons. The new stones should have: a) chemical, physical and mechanical compatibility with the original materials, b) good mechanical and physical characteristics and c) minimum salt content for a better durability.

Six quarries situated in the area of Noto were visited by the authors and by the designers (Figure 7). The stones sampled from the quarries were sent to the DIS-Laboratory in Milan for characterization. As to the quarries, the stones were named E, N, D, Dg, S, B, I (D and Dg come from the same quarry). Cylinders were cored from the stones, of 50 mm diameter and 100 mm height. The dimensions are not always representative of the stone structure, but they were chosen for uniformity allowing comparing the results of the tests to those of the original stones. Physical and mechanical tests were carried out after mineralogical identification of the material[1,4].

Figure 7. Limestone quarries.

3.2 Test on the sampled new stones

Physical tests: apparent bulk density in dry and saturated state is very important because the limestone behaves differently in the two states and this property certainly influences the mechanical strength and the long-term behaviour of the stone. The absorption is very important for durability and the initial rate of suction defines the retentivity of the mortar in order to obtain a good bond between mortar and stone.

The results of the tests are reported in Table 2. It has been confirmed that the density shows a high increase in the saturated state for all the stones. The lowest absorption belongs to the stone I followed by Dg, D, S and B. The best rate of suction (for the bond with mortar) belongs to D, Dg and B.

Mechanical tests: uniaxial compression and splitting tests were carried out on the seven types of stone. The procedures were the same as for the original stones. These results were compared in order to choose the appropriate quarries and were also compared to the ones obtained from the tests carried out on the stones recovered from the collapsed pillars of the Cathedral[4,5].

Table 2. Results of physical tests

SPECIMEN	Bulk density dry (kg/m^3)	Bulk density satured (kg/m^3)	Absorption coeff. (total immers. 24h) (%)	IRS (kg/m^2·min)
E	1679	1956	16	2.70
N	1744	2026	16	3.16
D	1864	2103	13	1.68
Dg	1853	2079	12	1.53
S	1770	2033	15	2.37
B	1818	2060	14	1.53
I	2070	2221	7	1.97

The mechanical properties: Compressive and tensile strength, F_c and F_t, respectively, Young's secant modulus, E_{sec} and Poisson's coefficient, $\Delta\varepsilon_l/\Delta\varepsilon_v$ are reported in Table 3. The secant modulus was calculated in an interval between 30% and 60% of the peak stress: in this interval the behaviour of the material could be considered as linear. The test was carried out on specimens dry and saturated to constant mass and the specimen dimensions were: 50 mm diameter and 100 mm height.

Table 3. Compressive and indirect tensile test results

SPECIMENS (50x100 mm)	Dry				Saturated			
	F_c [N/mm^2]	E_{sec} (30-60%) [N/mm^2]	$\Delta\varepsilon l/\Delta\varepsilon v$ (30-60%)	F_t [N/mm^2]	F_c [N/mm^2]	E_{sec} (30-60%) [N/mm^2]	$\Delta\varepsilon l/\Delta\varepsilon v$ (30-60%)	F_t [N/mm^2]
D	23.8	7487	0.25	1.7	10.9	4707	-	1.1
Dg	21.1	6530	0.18	2.0	10.0	4187	0.30	1.1
S	17.0	5617	0.15	1.5	7.8	3450	0.29	1.0
N	15.7	6137	0.19	1.3	11.6	5327	0.30	1.2
E	12.3	5627	0.23	1.4	10.2	4230	0.34	1.2
B	20.7	8690	0.17	2.0	11.6	6197	0.43	1.2
I	14.6	8720	0.09	2.4	10.5	4863	0.07	1.4

3.3 Choice of the quarry

In order to verify the performance of the stones and choose the right quarry, the values of bulk density, absorption by total immersion, Young's modulus and tensile strength were reported against the compressive strength of dry and saturated specimens (Figure 8(a,b,c,d)). Even though the number of specimens was low and statistically not representative, it was possible to find some linear correlation.

It is also possible to conclude from Tables 2 and 3 that the two stones of the quarry D and the one of the quarry B gave similar values and seem to have the best behaviour; furthermore the stone B tends to have a higher Young's modulus that can indicate also a better hardness.

The capillary rise test on the stone D and B gave respectively capillary rise coefficient values of 0.0105 and 0.0114 ($kg/m^2min^{1/2}$), which are very similar. In order to better distinguish the durability of the two stones Amsler tribometer tests were carried out (according to the code R.D. 16/11/1939) which allow to calculate the surface loss under a turning carborundum brush. The stone D with a loss of 27.91 mm after 1,000 m running showed to be softer than the stone B which lost only 17.51 mm.

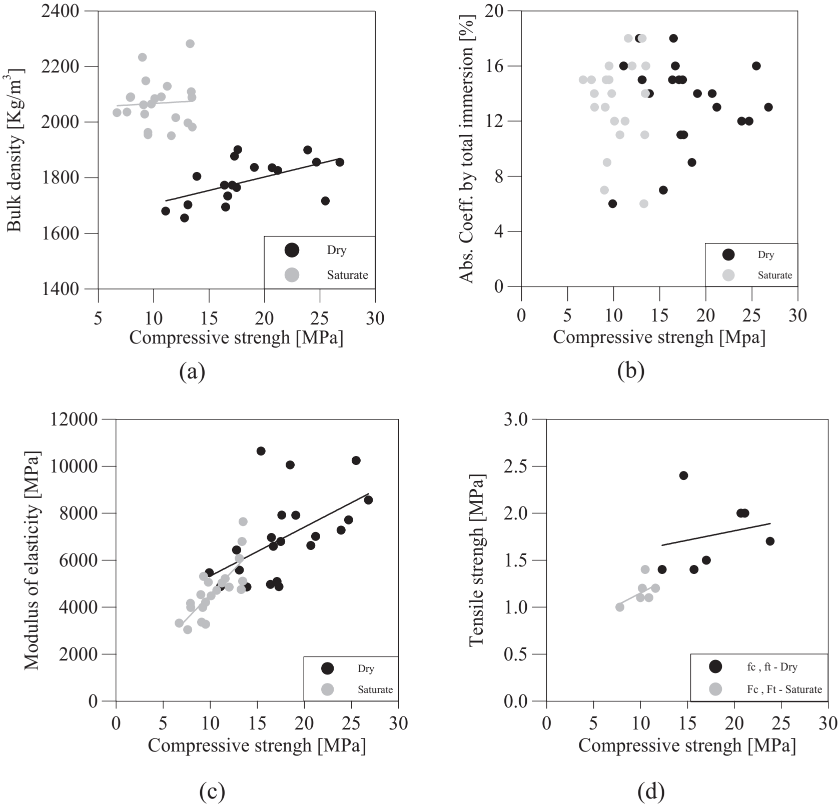
Therefore the two types of stones coming from the quarries D and B were chosen as suitable for the reconstruction.

4. CHARACTERIZATION OF THE STONES AT EACH DELIVERY

Following the study carried out both on site and in laboratory and the decision to also demolish and reconstruct the remaining left pillars, the design for the new elements was to be decided. The design should respect the geometry of the original pillars, and the technique of construction would provide a section with a certain amount of filling, but with much better connections. The choice of good mortars was important since the limestone used is a very soft material and sensible to the moisture content. Furthermore, the mortars had to be compatible with the stones and be free from sulphates.

Once the materials had been chosen, a constant quality control from the site was required by the designers. A difficult task was the quality control on site. Rather complicated was also the preparation of the stones in order to reduce the influence of their high absorption on the mortar hardening and on the bond between stones and mortar.

Minimum values for the compressive and tensile strength were specified for the contractor involved in the reconstruction, respectively, as 16.5 N/mm^2 dry, 9.5 N/mm^2 saturated in compression and 1.45 N/mm^2 dry, 0.95 N/mm^2 saturated in tension on cylinders cored from the stone blocks with dimensions:



(a) (b)

(c) (d)

Figure 8. Tentative correlations between compressive strength (a) and, respectively bulk density, absorption coefficient for total immersion (b), Young's modulus (c) and tensile strength (d) for dry and saturated specimens.

80 mm diameter and 160 mm height. These new dimensions were chosen due to the fact that the blocks could be cut with dimensions of 200x200x400 mm.

Unfortunately, after the design was approved, due to the difficulty of finding good quarries, the contractor could only provide the type D stone for the foundations and the type B for the base of the new pillars. For the remaining parts of the pillars two types of stones called NTB and BS were found; but their strength was rather low (even below the minimum values, particularly in tension). Nevertheless, the designers accepted this material, taking into account that the minimum values incorporated large safety factors.

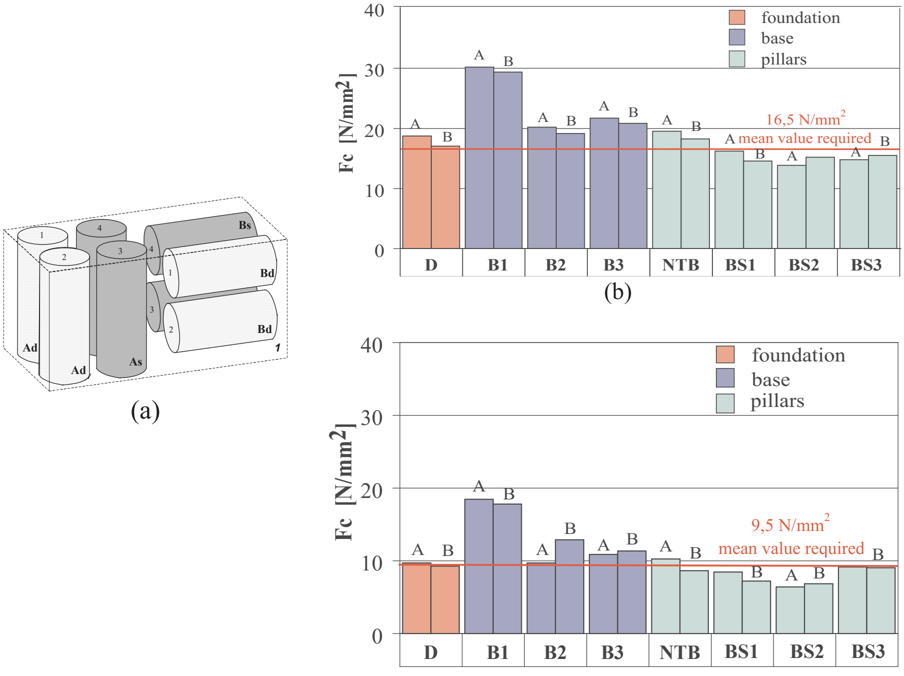
4.1 Experimental results

In laboratory, a continuous control of the stone quality was made every time a new supply came from the quarry to the site[6]. A similar control was made on the mortar sampled on site during the visit of L. Binda and/or G. Baronio who were consultants for the Prefect of Syracuse[3], responsible for the work of reconstruction made with the public support of the Province of Syracuse.

The cylinders were cored from each block in two directions A (rift plane) and B (perpendicular to rift plane) in order to characterize the eventual anisotropy of (Figs.9a and 10a). In Figures 9(b,c) the results of the compressive tests and in Figures 10(b,c) the results of the tensile strength carried out on stone cylinders in the state dry and saturated during subsequent testing campaigns are presented, compared to the strength limits required by the contractors; they show the variability in strength of the different types of stones and how the quality of the stones tended to decrease at each delivery.

The difference between the two directions A and B is not so evident, indicating low anisotropy. Subsequent deliveries of stone blocks show a decrease of compressive strength values below the requested one, while the indirect tensile strength varies according to the stone type. Large difference in strength shown by dry and saturated specimens was also clear. Saturation of the stones always induces a reduction in compressive strength of about 40%.

The values obtained for the original limestone seemed to be more homogeneous around an average value of 17.89 N/mm^2. If the designers wanted to



(a)

(b)

(c)

Figure 9. (a) Scheme of the stone specimen coring; (b) compressive strength in two directions of dry cylinder type D, B, NTB, BS at various times (numbers after letters indicate different supplies) and (c) compressive strength in two directions of saturated cylinder type D, B, NTB, BS at various times.

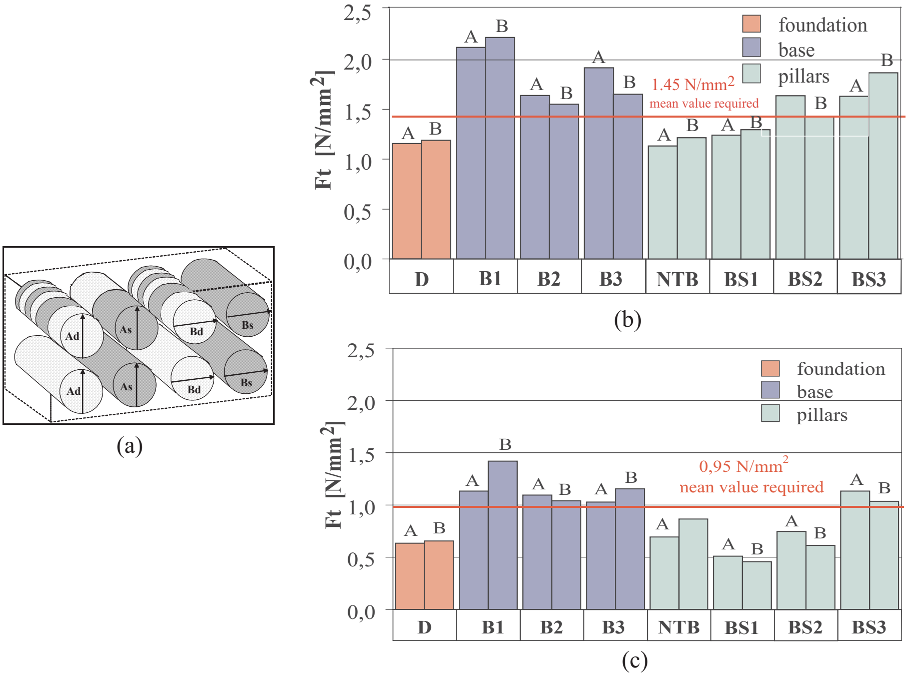


Figure 10. (a) Scheme of the stone specimen coring. (b) tensile strength in two directions of dry cylinder type D, B, NTB, BS at various deliveries (numbers after letters indicate different supplies) and (c) tensile strength in two directions of saturated cylinder type D, B, NTB, BS at various deliveries.

use a stone with similar strength as the original one then the S stone should be used. As a slightly higher strength was needed, stones B or Dg were employed. It is in any case better to use a quarry, which gives stones with less scattering in strength.

Figure 11 shows the elastic modulus against the compressive strength of the stones from quarry B, achieved by two different strain measurement devices. There is a good correlation between the values, in particular with the measurements made with the instrument LVDT positioned between plates, while measurements made with DD1 directly applied on the specimens are more scattered. The lower strength values are referred to saturated specimens and the higher to the dry specimens. This behaviour is quite similar for all the analysed stones as shown in Figure 12.

The consultant requested to saturate the stones on site. This request was based on the observed high absorption of the stones which could influence the behaviour of the mortar used for the joints. The presence of swelling clay inclusions in the stones (due to the characteristics of the quarry) caused the fracture of some percentage of stones during the immersion in water (Figure 13). This phenomenon suggested using the operation also as a quality control useful to eliminate the defective stones.

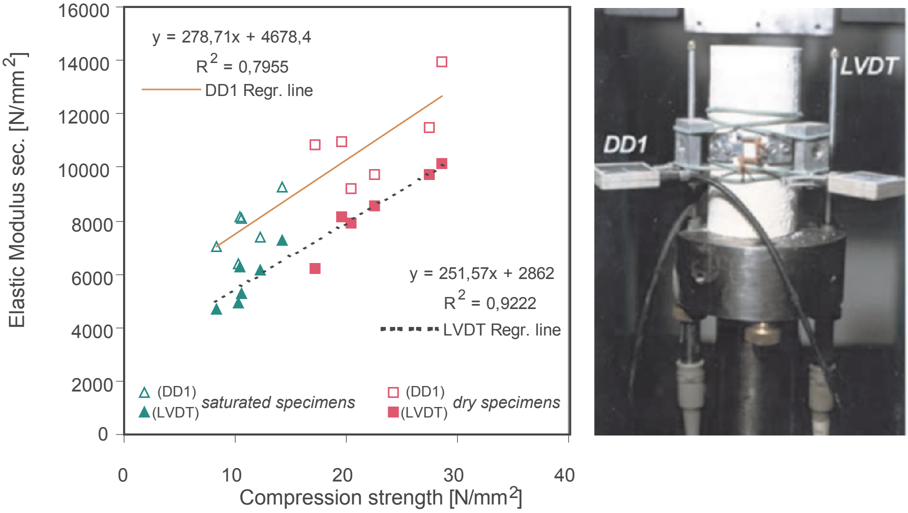


Figure 11. Correlation among the compressive strength values and the elastic secant modulus for the calcarenite B with different measurement devices.

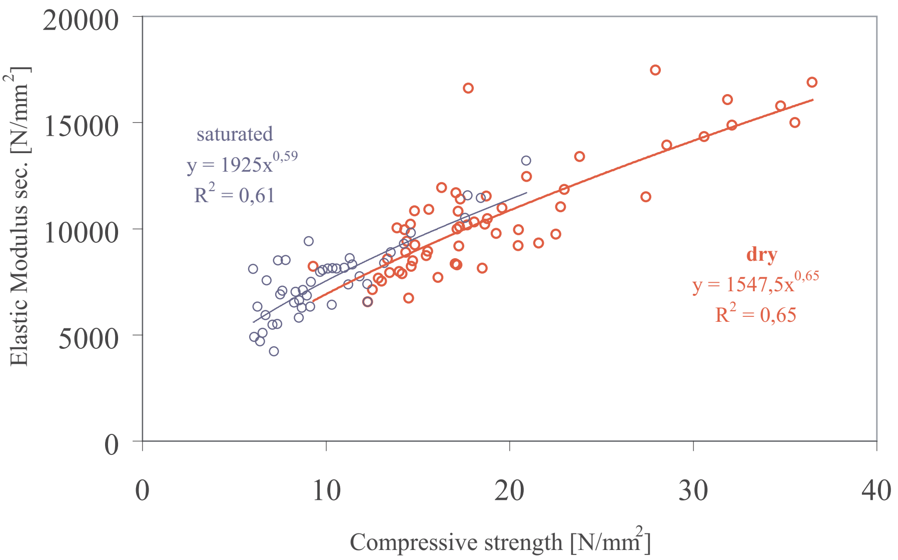


Figure 12. Compressive strength against elastic secant modulus of all the different types of characterised stones distinguished between saturated and dry specimens.

5. CONCLUSIONS

The high level of difficulty of choosing and controlling the materials for the reconstruction of partially collapsed historic buildings has been shown.

Figure 13. Creaked blocks in quarry.

It was decided to rebuild not only the collapsed pillars of the central nave, but also to demolish and rebuild the lowest part of the survived ones. This was a possible alternative, taking into account the necessity of symmetry in the structure due to the fact that Noto is situated in an active seismic area.

The efforts made and the frustrations encountered during reconstruction show the difficulties in applying the approach to the following steps: i) finding a better technique for the reconstruction of the collapsed pillars due to the original use of materials that were too weak, ii) choosing the quarries and the most appropriate type of stones, to replicate the original ones, iii) choosing the most appropriate and compatible mortars following the decision that the traditional ones could not be remade, iv) studying the right thickness of the joints and the most appropriate grain size distribution of the mortar aggregates, v) controlling the supply of materials and the workmanship.

A rather difficult task, together with many others, was the quality control on site. Complicated was also the preparation of the stones in order to reduce the influence of their high absorption on the mortar hardening and on the bond between stones and mortar.

Determining the stone properties at each delivery was important in order to control the quality of material. In fact, it was possible to detect the variation in strength due to different quarry. This action allowed in fact keeping under control the minimum values also, even if they were accepted by the designer.

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