Mechanical damage due to long term behaviour of multiple leaf pillars in Sicilian Churches

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ABSTRACT: After the partial collapse of the Cathedral of Noto in Sicily, damaged by the 1990 earthquake which hit the oriental part of the Italian island an extensive investigation carried out on site and in the laboratory allowed to detect a pre-existing damage of the pillars due to long term behaviour of the material under compressive stresses. The investigation extended to other churches and buildings showed other cases of progressive damage, which can in an unknown time take the structures to sudden collapse. As a premise the research carried out in the field after the collapse of the Pavia Civic tower and the results are briefly presented the followed by the description of the case histories.

1 INTRODUCTION

The dramatic collapse of the central nave and part of the dome of the Noto Cathedral, damaged by the 1990 earthquake, took place only six years late, in 1996. The accurate on site and laboratory investigation confirmed that the earthquake was only worsening the situation of the materials and structure already highly damaged. The removal of the plaster (made in the sixties) from the remaining pillars of the central nave revealed the pre-existence of a diffused distribution of vertical cracks and spalling of the corners in the external leaf made with limestone (calcarenite) regular blocks. In fact these cracks had been filled with the gypsum mortars used for plastering. Furthermore the internal rubble masonry of the pillars was found to be very weak and in a high state of damage.

The materials used and the construction technique of these loadbearing elements were both typical of the area; in fact the presence of several quarries of calcarenite (also called Noto stone) in the eastern part of Sicily made this material very popular for the construction of churches, noble palaces and other monuments. Also the mortar aggregates were very frequently obtained from the same stones and quarries. In the particular case of the pillars of the Cathedral a further weakness was found in the materials used for the collapsed pillars: the mortars were composed by hydrated lime and silt weak aggregates, the internal core was made with rather irregular courses of round river stones and thick mortar joints, the lack of connection between the external leaf made with regular stones and the internal core. These characteristics did certainly contribute to create weak loadbearing elements which resulted in the long range as highly stressed elements which evolved toward increasing damage in the long range.

Several other churches and monuments are now under investigation to detect the extension of the phenomenon. Among them two churches had been found in real danger after on site and laboratory investigation. SS. Crocifisso in Noto and SS. Annunziata Church in Ispica. As said above the materials and technique of construction are similar to the ones of the Noto Cathedral.

After a brief discussion on the long term behaviour of masonry structures, the different cases will be described with some information on the material and structure characteristics. Without any doubt all the cases suffered from long term damage and the similarity of the damage to the
one of Noto is stressed out together with the necessity of starting a research in order to understand better the phenomena. The long term behaviour of the material under compressive stresses as it was the case of other monuments as the Civic Tower of Pavia collapsed in 1989 is considered for the moment as the principal cause of the damage. In the presented cases the damage caused by moment and shear under horizontal dynamic loads due to the earthquake is also to be considered as a synergetic cause together with the dead loads.

2. LONG TERM BEHAVIOUR OF HEAVY MASONRY STRUCTURES

Apparent viscosity beyond the elastic range for masonry under heavy compressive loads has been extensively investigated only recently (Lenczner, 1965), (Lenczner, 1969), (Shrive and England, 1981), (Shrive et al., 1997), (Binda et al., 1991). The experimental research carried out on the materials of the Civic Tower of Pavia, suddenly collapsed in 1989 (Binda et al., 1992), stimulated subsequent studies.

In fact, in that occasion a quite interesting finding was the identification of the time-dependent behaviour of the masonry, also typical of soft rocks, as the cause of the collapse.

2.1 Description of the phenomenon

The phenomenon is of great interest, especially with respect to ancient buildings such as towers or massive masonry structures, which have been bearing constant heavy vertical loads for centuries. It has been shown that the behaviour of masonry under the action of persistent loads can evolve in a relatively long time until collapse; this can happen under lower stress values than those corresponding to the nominal material strength obtained by a standard monotonic compression test. The phenomenon can start at 45-50% of the nominal strength value.

The available experimental data collected up to now tend to show an evident increase of lateral deformations developed in time caused by the development of the typical vertical cracks due to compressive stresses. This dilation phenomenon, an apparent increase in volume, can lead to collapse due to crack propagation.

The collapse of Tower of Pavia, was not an isolated case; through the literature, other similar cases appear, some of which are famous like that of the Bell Tower of San Marco in Venice, the Bell Tower of St. Magdalena in Goch (Germany) or, more recently, that of the Cathedral of Noto (Italy).

Several case histories show that significant crack patterns, clearly due to vertical compression caused mainly by the dead load, often appear on the walls of ancient towers or on church pillars, indicating structural damage (Fig. 1). Towers, as well as particularly slender or heavily loaded elements like columns, pillars, etc., turn out to be overloaded by heavy persistent compressive stresses. Moreover, significant concentrations of stresses can take place in some portions of the material due to non-uniform stress distributions.

Sometimes around major cracks there may be a net of vertical flaws, cutting the bricks, or stones, and proceeding through the mortar joints (Fig. 2). Unfortunately, they are in most cases considered superficial and not particularly worthy of care (Binda et al., 1998).

The effects can also be coupled with synergetic stresses caused by cyclic wind action and temperature variation induced stresses. Additional minor shocks, like storms, low intensity earthquakes, etc., may contribute to increase the damage. Of course the study of these phenomena is fundamental from the point of view of safeguarding of the architectural heritage and of assessing the safety of ancient masonry structures. The traditional stress-strain analysis is not prepared to take account of this particular aspect, which has been only recently revealed crucial to ancient buildings. L. Binda and others have recently made an attempt to model the behaviour of towers under these phenomena (Papa and Taliercio, 2000), (Papa et al. 2000) (Papa et al., 2001).

2.2 Experimental results.

The time dependent behaviour of the masonry has been shown experimentally by recent researches carried out by the authors (Binda et al., 1991), (Binda et al., 1992), and other
scientists (Lenczner, 1965), (Lenczner, 1969), (Shrive and England, 1981), (Shrive et al., 1997). In particular, the experimental data concern both long term creep tests and accelerate tests under subsequent step of constant load tests (Binda, 1993).

Constant load step tests turned out to be a suitable procedure for analysing (Anzani et al., 1999, 2000 and 2001), (Anzani et al., 2000), (Anzani et al., 2001) creep behaviour, having the advantage of being carried out more easily than long term tests. Primary, secondary and tertiary creep phases, in fact, were clearly detected also during this type of tests (Fig. 3).

From an experimental point of view the following aspects have been particularly highlighted:
- the material dilation under severe compressive stresses with high values of the horizontal strain developing before failure;
- the development of creep strains depending on the stress level, with secondary creep showing even at the 40% of the estimated material peak stress;
- a slow crack propagation and failure developing in a relatively long time. This aspect suggests that the evolution of vertical cracks, which might appear on the external walls of a building should be carefully analysed. In fact, the possibility of continuous damage with the consequence of a future sudden collapse cannot be a priori ruled out;
- the combination of cyclic actions with the effect of a heavy dead load turns out to be a particularly critical situation, which is able to induce material damage
- the eventual continuous damages produced to the compressed parts of the structure by cycling moments caused by the horizontal loads during subsequent earthquakes need also a high attention and new research.

3 PROGRESSIVE DAMAGE UNDER COMPRESSION AS CAUSE OF THE COLLAPSE OF THE NOTO CATHEDRAL

After the partial sudden collapse of the Noto Cathedral on March 13, 1996 fortunately without any casualty (Fig. 4), 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, 1996). 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 reopened 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 (Pisani, 1953), (Iacono, 1996), (Tobriner, 1998).

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 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 of 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 vegetable 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/mm$^2$. The height of the blocks varies from 24 to 26cm and the thickness, very small compared to the pier dimensions is varying from 25 to 30 cm. No really effective connection was realised between this external leaf and the core (Fig. 5). 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 limestone (calcarenite) which have a greater thickness and a better strength (more than 17 N/mm$^2$ in compression calculated for cylinders of diameter 80mm and 160mm height).

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 (Fig. 6). 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.

The left piers, still covered with a thick plaster, 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. As the plaster made in the sixties was removed a series of vertical large cracks were found, some of which filled with the gypsum mortar used for the plaster (Fig. 7 and 8). This finding was the prove that the damage was already present in the sixties. The pre-existing crack pattern was clearly a damage from compressive stresses, hence a long range damage dating probably even long time before the rendering. This damage would probably progress even without the earthquake, which only accelerated the collapse.

It was therefore decided to rebuild not only the collapsed pillars of the central nave but also to demolish and rebuild the remaining ones; this was the possible conservative alternative taking into account the necessity of symmetry in the structure due to the position of Noto in a active seismic area.

The successive study of the Noto limestone and the research for the most appropriate mortar and of the joint thickness to be used in the new pillars allowed to have much more interesting information on the behaviour of the Noto stone.

It was difficult to find quarries were the stone was similar to the one used in the past. These stones were submitted to compressive, tensile and shear tests in the condition dry and saturated, showing in this last condition a the reduction of approximately the 50% in strength. Compressive tests based on steps of load kept constant for 180 min, showed that the stone develops a secondary creep behaviour already at low stress level (50% of the peak stress) and collapse happens for tertiary creep; this behaviour can be seen in Fig. 10 where the vertical $\varepsilon_v$ and transversal $\varepsilon_h$ strains are reported against the time.

Some compression tests were also carried out on stone couplets made with 200mm side cubes in order to choose the right thickness of the joints for the reconstruction of the Cathedral pillars. Fig. 11 shows the behaviour during compression carried out under displacement control for
different mortar joints thickness. It is clear from the results that when the stones have possibility of contact either direct as in the case of dry joint or indirect (as in the case of the 5mm joint thickness and aggregate size 0-2mm), the masonry strength is reduced. It should be noted that the compressive strength tests carried out on cylinders of the same stone with dimensions 80mm in diameter and 160mm height, gave an average value of 28 N/mm$^2$.

4 OTHER CASES OF PROGRESSIVE DAMAGE TO THE STRUCTURES

After the collapse of the Noto Cathedral careful investigations are being carried out on similar churches, all built approximately in the same period after the 1693 earthquake that struck the oriental part of Sicily. In fact the ancient Noto, which was destroyed by that earthquake, was
abandoned and rebuilt on a hill near the sea in no more than 50 years. The same was for other cities in the eastern part of Sicily; one of them is Ispica situated in the most southern part of the island. In the following, two cases of damage similar to the Noto Cathedral are analysed; they were discovered by removing the plaster from the pillars of the central nave in both cases. This was suggested by the experience carried out on the Cathedral of Noto where the existing damage of the pillars was found to be hidden by the plaster. In fact as in that case, the presence of diffused thin cracks had never been considered as dangerous before the investigation.

4.1 The SS. Crocifisso Church

The Crocifisso Church, placed in the highest part of Noto, was built using the local calcarenite, the same as the Cathedral and finished in 1715 a relatively short time after the earthquake using poor workmanship. Nevertheless the facade and the interior show harmonious proportions, with rather slender pillars. In Fig 12 the Church vertical section is shown. In the left side the precious Landolina Chapel of the Virgin is present. A sequence of structural small domes covers the lateral naves; the aisle, instead, shows a continuous barrel timber vault and a large dome. Above the barrel vault, a timber truss is present.

4.1.1 Damage after the earthquake

The Church was damage by the 1990 earthquake, especially the transept and the domes of the lateral naves and the vaults, which were then supported by provisional structures. The pillars, all covered with plaster and stuccoes apparently, did not show any damage. A simple calculation of the state of stress due to uniformly distributed stress for dead load gave 0.72 to 0.81 N/mm². The maximum compression value caused by horizontal forces + dead load was 1.20 to 1.59 N/mm².

4.1.2 Investigation and crack pattern survey

In view of a strengthening and repair intervention, an investigation program was planned. The program included investigations on the foundation and on the masonry structures, as coring, boroscopy, flat jacks, sonic tests and mortar and stone characterisation.

During the first phases of the diagnosis an alarming state of damage was found in the pillars, by locally removing the plaster. The plaster, in fact, was hiding a complex of vertical cracks passing through the stones and continuing along the mortar joints (Fig. 13).

The plaster was not the original one of the Church, as demonstrate the presence of a dirty patina on the stones under the plaster itself. Furthermore after the removal it was possible to detect that it was not adherent to the masonry, in absence of an adequate mechanical preparation of the support.

The plaster was particularly thin (Fig. 14) and completely detached in the area in which deep cracks were distributed.

The pillars as in the case of the Cathedral were built with an external leaf made of Noto stone regular blocks and internal filling with rubble masonry; the technique of construction is similar to the one of the Cathedral pillars, but the internal rubble seems to be better built. After the recognition of the damages, the removal of the plaster from all the pillars up to 3 m of height,
was planned in order to survey the crack pattern.

Fig. 15 shows an example of the crack pattern of the pillars. As it possible to observe, the cracks are diffused and interesting the whole prospect, with a concentration in the corners.

In some cases, the fissures were filled by mortar and the corners reconstructed (Fig. 16). This fact suggests that the crack pattern was present before the plaster was applied.

The strengthening design was urgently change and the pillars, were urgently confined by stainless steel cross shaped reinforcements confining the pillars at every two courses.

4.2 SS. Annunziata at Ispica

The second Church analysed, has 3 naves, with continuous external walls and pillars between the aisle and the lateral naves (Fig. 17). A timber barrel vault covers the aisle. The dome, at the intersection between the transept and the aisle, is supported by 4 massive pillars.

The texture of the external stone leaf of the bearing walls seems rather regular, with large cut blocks and thin mortar joints. The pillars were all covered with a thick (40 to 60mm) plaster made with lime mortar.

4.2.1 History

The Church was founded in the 1703, 10 years after the earthquake that devastated the Noto region. The original design, probably of R. Gagliardi, was simplified due to economic difficulties of the orders.

During the centuries, the Church was damaged several times, and after each event repaired and partially rebuilt. In particular, after the 1727 earthquake some of the main arcade pillars showed considerable out of plumb. The arcade was urgently supported, in view of its rebuilding, never happened for economical reasons, even if the design was already prepared. In the 1869 the facade collapsed probably due to its bad conditions or for unwise repair works. The facade

Figure 14: A very thin plaster (4 to 5mm thick) made with lime-gypsum mortar covers the base of the pillars, hiding the cracks

Figure 15: SS. Crocifisso Church. Crack pattern of the base of the pillars

Figure 16: SS. Crocifisso Church. Damages found under the plaster

Figure 17: Plan of the SS. Annunziata Church.
was then rebuilt, but decreasing the Church length. In the 1976, a mixed r.c. and tile roof was placed.

4.2.2 Damage after the earthquake and crack pattern survey

As in the case of the Crocifisso Church at Noto, the plaster was hiding most of the cracks. Only some thin vertical cracks appeared from the exterior, which showed to be alarming after the plaster removing. Fig. 18 shows well the situation before and after removal of the plaster. The cracks are very diffused in the pillars and interest the whole stone depth. A provisional confining structure was built around the pillars before removing completely the plaster in the most damaged areas. The Figs. 19 and 20 show the extent of the damage in some pillars as it appears after the removal of the plaster. Also in this case the damage was certainly present before the execution of the thick plaster, perhaps twenty or more years ago since most of the cracks were filled with the plaster and some detached corners also remade with the same mortar. It is now clear that the responsible engineers or architect did not take into account the clear signs of damage as dangerous nor they did think that this damage could proceed under constant loads in long term.

5 REMARKS ON THE INTERPRETATION OF THE DAMAGE.

The examples shown above confirm that the long term damage under compression due to the dead load of heavy structures occurs in several cases. The most exposed type of structure and structural elements to this damage are massive and slender tower and bell-towers and slender and heavy pillars of Cathedrals and large churches. The damage can easily develop when the material used for the construction is rather weak (weak bricks and mortars with irregular joints, soft stones) or the technique of construction is such that the internal core of the masonry can settle and deform more than the external leaf. In all these cases the damage can start early after the construction or after some partial reconstruction or even repair and continue very slowly for decades, until a sudden collapse happens. Nevertheless the failure might in some cases be avoided even if simple investigation as crack pattern survey is carried out. The failure is caused by the dilatancy of the material, i.e. by vertical crack propagation and consequent transversal dilation. This phenomenon can be stopped or delayed by horizontal confinement of the structure carried out with tie rods (Modena et al., 2001) and/or by confinement of the pillar and column carried out with stainless steel or FRP wires and/or joint reinforcements.

In seismic areas the horizontal forces produced by the earthquake induce shear and flexural actions on the vertical bearing elements as piers and columns. The compressive stresses developed by the flexural action can be either a synergetic cause of damage together with the stresses developed by the dead loads or even perhaps be the initial cause of crack opening in vertical direction and the damage can continue in time overlapping to the one caused by the vertical loads.

Two cases can support this hypothesis: the first one concerns some piers of the Church of St. Nicolò l’Arena in Catania damaged also in 1990, the second one the columns of the church of Montesanto in Umbria, partially collapsed after the 1997 earthquake. Here only some figures will be shown which can support the hypothesis. In the case of St. Nicolò the dome and the

Figure 18: The appearance of a crack on the plaster and underneath it

Figure 19: Diffused vertical cracks on different pillars
vaults were damaged and the appearance of vertical cracks on the original pillars were detected. It is not clear whether those cracks were already visible and were simply propagating during the earthquake, but certainly they show effects due to vertical and shear stresses (Fig. 21).

Fig. 22 shows instead the damage caused to the Montesanto Church columns by compression due to flexural action connected with the earthquake loads. How the earthquake effects can cause accumulate damages in time has to be studied in the future.

6. CONCLUSIONS

The long term effects due to creep behaviour of historic masonries has been demonstrated through on site investigation and experimental research. It is now proved that this phenomenon causes accumulation of damage due to the development of increasing deformation under constant stresses.

Secondary creep can develop in the masonry at 40 to 50% of the peak stress in compression and continue in time until tertiary creep is reached. At that moment the sudden collapse of the structure can occur.

After the experimental campaign performed on masonry specimens for ancient buildings, a mathematical model to simulate the creep behaviour has been proposed (Papa and Taliercio, 2000) based on an appropriate constitutive law taking into account primary, secondary and tertiary creep introduced in a commercial code (ABAQUS) for structural analysis.

The synergetic effects of cycling loads as wind load and temperature variations can accelerate the damage.

The damage can also be accelerated by the effects of moment and shear actions caused by an earthquake. Even if the event does not cause itself the collapse the situation can worsen and the failure occur years after the earthquake (Noto Cathedral).

The presence and extent of the damage can be surveyed through on site slightly destructive and non destructive investigation and preventive measures or repair can be carried out. Sometime the simple survey of the crack pattern can give the first necessary information.

Nevertheless it should be remembered that cladding or simply plasters and renders carried out even years ago can hide the cracks so in some cases the partial removal of these material is necessary to observe the situation underneath them.

Research is needed in the future to understand how soft stones and weak mortars can be continuously damaged by subsequent earthquakes even if they are not apparently very much destructive.
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