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Failures due to long-term behaviour of heavy structures: the Pavia Civic Tower and the Noto Cathedral

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Abstract

The failure of monumental buildings is fortunately an exceptional event; nevertheless, when their safety assessment is required, any risk factor that may affect the integrity of the buildings has to be taken into account. Ancient buildings often show diffused crack patterns, which may be due to different causes in relation to their original function, to their construction technique and to their load history. In many cases it is simply the dead load, usually very high in massive monumental buildings, which plays a major role into the formation and propagation of the crack pattern. Some case histories are presented with more attention to the main collapses: the Civic Tower of Pavia and the Cathedral of Noto.

1 Introduction

The failure of some monumental buildings apparently happened a few years after a relatively low intensity shock took place. This seems to suggest that some phenomenon developing in time has probably to be involved in the causes of the failure, combined in a complex synergetic way with other factors.

The phenomena of early and retarded deformations of historic masonry structures will be described referring particularly to two representative cases: the Pavia Civic Tower collapsed in 1989 and the Cathedral of Noto collapsed in 1996.

The state of damage detected through on site investigation on two other towers, the bell-tower of the Cathedral of Monza and the bell-tower of the Cathedral of Cremona will also be described together with the damage state of the pillars of some Sicilian churches. The investigation shows that the damage

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state of these structures or structural elements can be precociously detected by the recognition of the typical crack patterns, even based on simple visual investigation.

Collapses may be prevented by detecting the symptoms of structural decay, particularly the crack patterns, through on site survey, monitoring the structure movements for periods of time long enough, choosing appropriate analytical models and appropriate techniques for repair and strengthening the structures at recognized risk of failure.

2 The collapse of the Civic Tower of Pavia and the investigation on its causes

The Civic Tower of Pavia, a 11th century Tower apparently made of brickwork masonry, suddenly collapsed on 17 March 1989 (Fig. 1). Several hypotheses were made about the causes of that sudden failure from soil settlements to the presence of a bomb, from vibrations due to the traffic to the passage of super sonic jets. For a thorough understanding of the real causes of the collapse, an experimental investigation was carried out on site and in the laboratory on the large amount of material coming from the remains of the Tower.

Figure 1: The Civic Tower of Pavia after collapse

Approximately 100 large blocks of masonry were recovered for testing from the 7000 m^3 of ruins. The following procedure was adopted to determine the reasons of the collapse [1]:

- search of documents on the history of the Tower;
- reconstruction of the geometry of the Tower;
- geognostic tests to define the consistency and mechanical properties of the soil;
- chemical, physical and mineralogical/petrographycal analyses of the mortars, bricks and stones forming the masonry;
- compressive tests on masonry prisms obtained from the ruins;
- numerical stress analysis of the Tower, assuming elastic behaviour.

On the one hand, settlements and chemical-physical damage were ruled out as causes of the collapse. On the other hand the following information were found:

- the Tower was built in three to four different phases, starting from 1060; the belfry, built with granite blocks, was added between 1583 and 1598;
- the 2.8 m. thick load-bearing walls were made of two thin external faces in regular brickwork and an internal sort of concrete made with layers of broken bricks and stone pebbles alternated with thick mortar joints (Fig. 2); a staircase built within the wall thickness raised from the south-west corner around the four sides of the Tower up to the belfry;
- the total estimated weight of the Tower was 120,000 kN, while the weight of the belfry alone was 30,000 kN.

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- the lower part of the Tower was subjected to high stress values under its own weight: maximum values of 1.7 to 2.0 N/mm^2 in compression were found by a FE elastic model, against experimental strength values, obtained on 400 x 600 x 700 mm prisms, ranging between 1.8 and 3.5 N/mm^2.

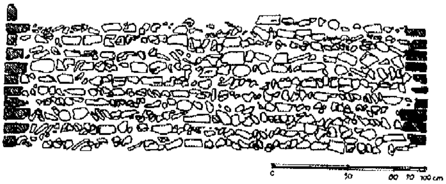

Figure 2: Cross section of the 2800 mm three leaf masonry constituting the Civic Tower of Pavia.

The causes of the collapse were difficult to single out, having been ruled out those that looked like the most obvious ones. The only clear situation was the high value of compressive stress due to the dead load of the tower. Nevertheless, the time dependency of the material behaviour still had to be shown. Different kinds of uniaxial compressive tests were carried out including monotonic tests, fatigue tests to simulate the effects of the wind [2], tests applying unloading reloading cycles, creep and pseudo-creep tests [3]. The experimental campaign revealed the long term behaviour of the material under constant high level stresses due to the dead load in the case of the tower. Fatigue due to temperature variation and cycling loads as wind in the course of the centuries could also constitute a synergetic effect to bring the material to the collapse. Typical thin diffused vertical cracks on the loadbearing walls were shown from pictures of the tower taken in the sixties by archaeologists.

As an example the last set of tests carried out on the material from the Tower ruins is described below. Six prisms of dimensions 300x300x510 mm were tested in compression for creep behaviour in controlled conditions of 20^{0}C and 50% RH, using hydraulic machines able to keep constant a maximum load of 1000 kN [4].

All the test results are reported in Fig. 3a, b; in Fig. 4 the strain vs. time diagrams of one of the prisms tested are shown.

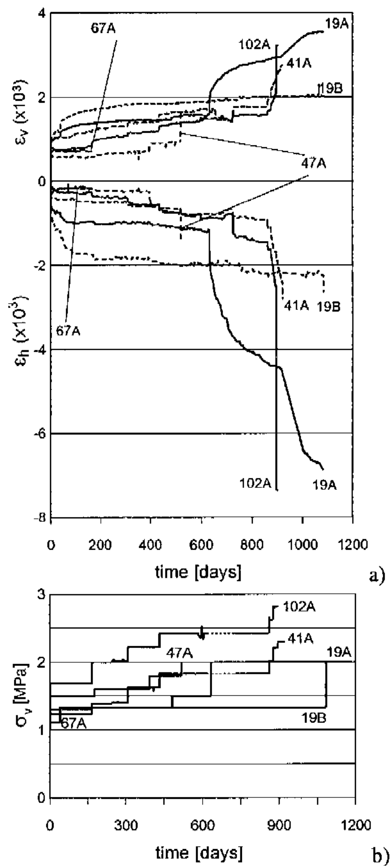

Figure 3: Long term tests on the masonry of the tower of Pavia: average strain components a) and nominal stress b) vs. time for all the prisms tested.

Having assumed positive the vertical deformation corresponding to the shortening of the prism, the horizontal

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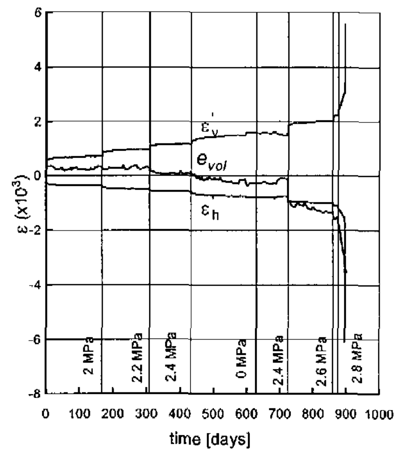

Figure 4: Deviatoric and volumetric strain components vs. time on prism 102-30A.

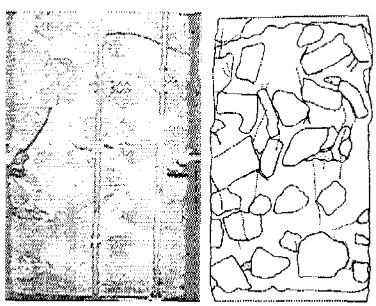

Figure 5: Prism 102-30A: face A at the beginning of the test and face B at the end of the test.

Figure 6: Interior of the Cathedral of Noto before the removal of the ruins.

expansions due to fracturing and crack opening are of course negative, The volumetric strain seems nearly constant during the first phases of the test, then it starts to decrease markedly until collapse is reached; a negative volumetric deformation indicates that the effect of the horizontal strains are prevailing on that of the vertical one, therefore an apparent overall dilation is taking place. The creep behaviour is evident since the beginning from the deviatoric strain plots.

In Fig. 5 two faces of the same prism at the beginning and at the end of the test are shown. The highly irregular texture of the wall is evident, with a great part of the masonry being occupied by mortar. The crack pattern is characterised by the presence of vertical and sub-vertical cracks.

3 The partial collapse of the Noto Cathedral

On March 1996 the collapse of the Cathedral of Noto (Sicily), a town considered a jewel of the baroque style and therefore under the protection of UNESCO, involved 4 piers of the right hand side of the central nave, 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 the dome with the lantern, the roof and vault of the right hand side of the transept and part of the small domes of the right hand side nave (Fig. 6).

A brief description of the construction phases can be useful to better understand the reasons of the collapse. The construction of the Cathedral began after 1693, according to the design of Gagliardi, a well known architect in Sicily. The cupola first collapsed after 1760, apparently because of "an insufficient support" [5]; after the reconstruction,

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entrusted to another architect, Stefano Ittar in 1789, a subsequent collapse occurred in 1848, under the earthquake of that year. Some time later, while the third cupola was under construction, the roadbed of the streets of Noto was lowered, apparently without significant consequences to the Cathedral [5].

It is interesting to follow the different steps of the construction of the Cathedral, according to the historians [5]. At first the external walls, the façade and towers were built, while inside the pre-existing church was still functioning. The central nave, the vault and the lateral domes were built at the end, after the demolition of the inner church. This can explain why the materials and even the construction techniques were partially different from the ones used in the first part of the construction. In fact, the pillars of the central nave were built with weaker materials and a less refined technique, that included the use of round river stones in the inner leaf and the large use of travertine rather than a more compact limestone in the outer leaf [6].

The original roof of the Cathedral rested on longitudinal rafters, 8 meters long, supported by traversal stone arches staggered with respect to the piers, their thrust being supported by external buttresses. Around 1950, the timber roof was substituted with a plane reinforced-concrete floor, cutting the upper part of the arches and rising the lateral walls. Lastly, at the end of the eighties, the masonry of the front and of the right hand side bell tower was strengthened with reinforced grout injections.

In December 13th 1990 the most significant recent earthquake occurred in the region, producing evident damages to the building, though apparently not such that a collapse could have been expected. A series of cracks were visible mainly on the piers of the central nave and on some of the little domes over the lateral naves. Provisional structures were set up in 1992 to the most damaged piers, which revealed to be not really efficient.

On March 1996 the collapse took place (Figs. 6-8); it seems very likely that it was initiated by the yielding of one pillar and then propagated to the other pillars involving the vault, the lateral domes and the central dome and transept. The hypothesis might be formulated that the effect of propagation was very extensive due to the presence of the reinforced concrete floor connecting different structural elements, although this cannot

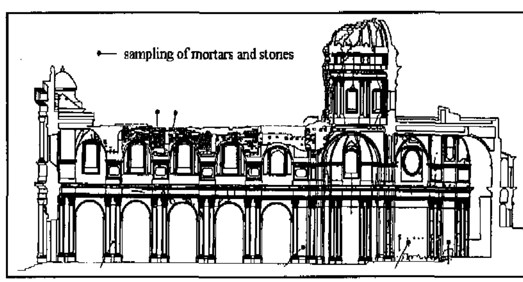

Figure 7: Cathedral of Noto: longitudinal section of the central nave looking north.

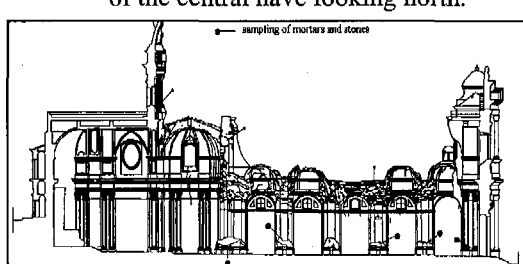

Figure 8: Cathedral of Noto: longitudinal section of the central nave looking south.

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be really proved [6], [7].

After the removal of the huge amount of debris (3610 m^3) and the erection of the necessary temporary structures, an on site investigation was carried out, aimed to the safety assessment of the left hand side piers, not involved in the collapse, and to the choice of the constructive technique to be adopted in the reconstruction.

The investigation allowed to see that the pillars were already damaged in the fifties by large vertical cracks due to high compression stresses. In fact, the pre-existing cracks had been filled with gypsum mortar used for the plastering [6], [8]. This finding improved very much the knowledge on the causes of the collapse. The presence of the cracks shows that the damage had started long time before the seismic event of 1990 and that the earthquake only accelerated a collapse, which would in any case have occurred later if no repair would have been made.

4 Damage of towers and pillars

Several case histories show that significant crack patterns, clearly due to vertical compression caused mainly by the dead load and/or by synergetic effect of wind, temperature variation, dynamic actions during earthquakes, often appear on the walls of ancient towers or on church pillars, indicating structural damage (Fig. 9). 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.

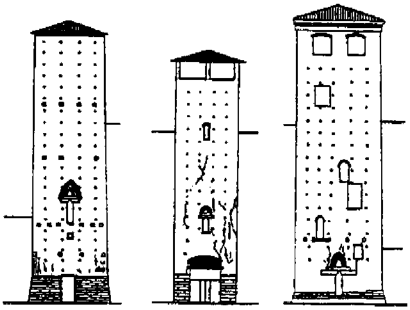

Figure 9: a) Torre Galluzzi, b) Torre Alberici, c) Casa-torre Uguzzoni in Bologna (Italy)

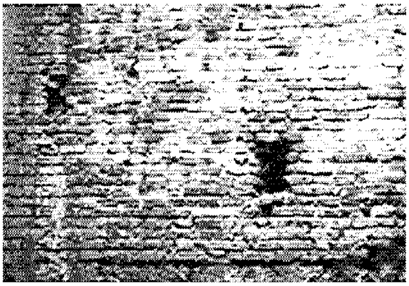

Figure 10: Detail of the crack pattern of Torre Galluzzi.

Depending on the degree of brittleness of the masonry, which in turn depends on the constructive technique, the material used, the geometry of the structural element, an excess of compression may result into major cracks clearly visible, or into a net of vertical flaws, cutting the bricks, or the stones, and continuing along the mortar joints (Fig. 10). In all cases, the crack pattern needs to be considered worthy of care and not neglected [9].

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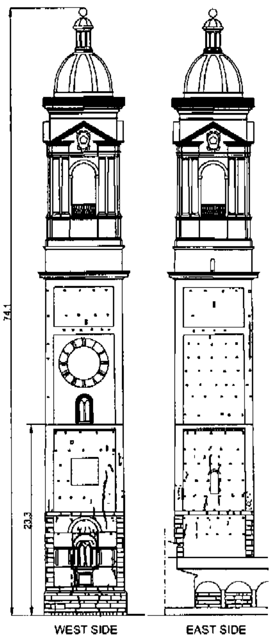

Figure 11: Crack pattern survey of the Bell Tower of Monza.

The Bell Tower of the Cathedral of Monza is a XVI century building made of solid brick masonry, at present subjected to a repair intervention. Its walls were showing large vertical cracks crossing the whole transversal section of the walls on the West and East sides (Fig. 11), which were continuously opening at a constant rate [10]. These cracks were certainly present before 1927, when started to be roughly monitored. Wide cracks were also present in the corners of the tower at a height of 30 m, together with a damaged zone at a height of 11 to 25 m with a multitude of very thin and diffused vertical cracks.

A similar crack pattern is visible on the Torrazzo, a medieval brickwork Tower adjacent to the Cathedral of Cremona [11]. The precise date of construction is not known but it is assumed around the 13th century. It belongs to a group of monuments, including also the Cathedral, the Baptistery, the Town Hall Palace, the Militia Loggia, which forms one of the most beautiful Italian squares.
The external load-bearing walls of the Tower, which is about 112 m tall, have been showing several cracks for many years [11]; since the crack pattern has experienced an evolution, a time dependent behaviour of the material may possibly be assumed to interpret the phenomenon.

Based on a simple geometrical and crack pattern survey more about 60 were investigated. A comparison with the Pavia Civic Tower state of stress before collapse, allowed to detect that at least 9% of the towers be at risk [9].

After the collapse occurred to the Noto Cathedral, other churches damaged by the 1990 earthquake were investigated. Among them the SS. Crocifisso Church in Noto itself [12]. In view of a strengthening and repair intervention, an investigation program was planned. The program included coring, boroscopy, flat jack tests and sonic tests on the masonry structures, the characterisation of mortar and stone and an investigation on the foundations. During the first phases of the survey, after local removal of the plaster, an alarming state of damage was observed on the pillars that showed a series of vertical cracks cutting the stones and continuing through the mortar joints (Fig. 12). The presence of a grey patina on the stones underneath the plaster indicated that it was not original. A lack of adherence to the masonry was noticed, given an inadequate mechanical preparation of the support; in the area of the deep cracks, the plaster looked particularly thin and completely detached.

The pillars, as in the case of the Cathedral, are built with an external leaf made of regular blocks of stone of Noto and an internal filling made of rubble masonry. The technique of construction is similar to the one of the Cathedral

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pillars, but the internal rubble appears of better quality.

After assessment of the damage, the removal of the plaster from all the pillars up to a height of 3 m was planned, in order to carefully surveying their crack pattern, plotted as an example in Fig. 13. As can be seen in the picture, the cracks are diffused over the whole face, and concentrated in the corners. In some cases, the fissures have been filled with mortar and the corners reconstructed. This fact suggests that the crack pattern was present before the plaster was applied [12]. The design of the strengthening intervention was urgently up-dated and the pillars were confined by cross-shaped stainless steel reinforcements laid at every two courses.

Later, similar damage symptoms were found in the Church of SS. Annunziata in Ispica (Fig. 14) and S. Nicolò l'Arena in Catania (Fig. 15), the Cathedral of Siracusa (Fig. 16) and the Church of S. Andrea in Campi (Umbria).

Figure 12: Church of SS. Crocefisso: crack appearance (a) before and (b) after removal of the plaster from a pillar

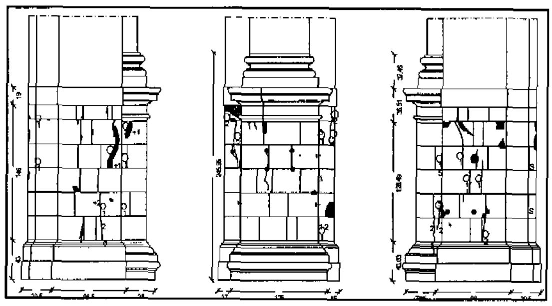

Figure 13: Church of SS. Crocefisso: crack patterns on the base of the pillars.

5 Conclusions

The cases histories presented

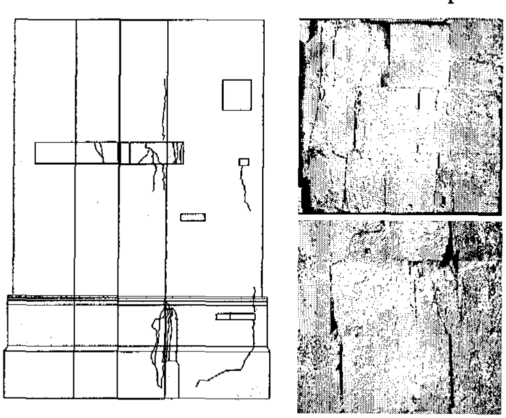

Figure 14: SS. Annunziata Church. Crack pattern of a pillar

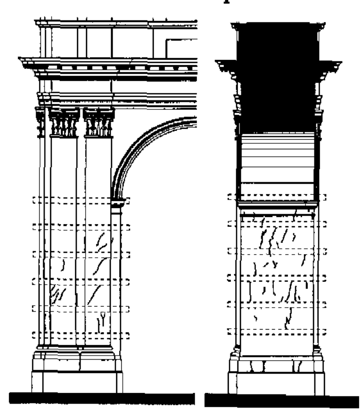

Figure 15: Crack pattern of a pillar at S. Nicolò.

Figure 16: Siracuse Cathedral. Crack pattern of a pillar

indicate that not only towers, but also particularly slender or heavily loaded elements like columns, pillars, etc., turn out to be greatly influenced by creep deformations, due to their geometry and to the heavy persistent compressive stress to which they are subjected. Moreover, the stress distribution within the load-bearing area of these structural elements and buildings is generally non-uniform, due to their non-homogeneous cross section often made by multiple leaf masonry. A combination of these factors, together with the fatigue effect due to cyclic actions induced by temperature variation, wind and earthquakes action, can well be responsible of very serious structural damage and in some cases even of failure.

Although the collapse of massive buildings (towers, cathedral pillars) happens apparently suddenly, nevertheless crack propagation proved to develop in a relatively long time. To this respect, the rate of propagation of vertical cracks and the rate of dilation (thickness increase) of load-bearing walls of ancient buildings can be interpreted as significant indicators of the structural conditions of an ancient structure. An important damage index could be the amount by which they exceed certain significant limit values.

Sometimes, before planning large investments for monitoring and/or designing a repair intervention, a pre-screening may be carried out to estimated the degree of damage. To this purpose, a basic visual survey may be followed so as to indicate the possible need for a more detailed investigation and/or of periodically repeated surveys, following the steps here described [9]:

- geometrical survey including measures of the wall thickness;
- reconstruction of the building evolution and of its load and earthquake history;
- visual survey of the crack pattern;
- interpretation of the crack pattern and recognition of its causes: tilting, effect of dead load, others;
- rough calculation of the maximum stress value, based on geometrical data and values of the density of the material, assuming homogeneous material and uniformly distributed load.

After this survey a decision can be taken on a more accurate investigation based on static and dynamic monitoring, non destructive and slightly destructive on site techniques and laboratory characterisation of the materials. In the most risky cases (SS Annunziata in Ispica, St. Nicolò L'Arena in Catania) provisional

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supporting structures can become necessary before any investigation or repair decision.

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