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Some experiences about the retrofitting of tower masonry structures

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Abstract

The paper deals with some intervention methodologies for tower structures belonging to the architectural Italian heritage, aimed to the reduction of the collapse risk under normal and exceptional loads. Then the special investigation for evaluation of the structural safety of the bell tower of Palermo Cathedral and the following collapse risk mitigation are described.

First through the paper the history of the tower is presented then in situ and laboratory tests are described. The interventions adopted after the investigation are discussed and finally the dynamic tests for the validation of the analytical model used in the assessment of the seismic vulnerability are showed.

1 The rehabilitation of tower monumental structures

Constructions belonging to the monumental heritage need special maintenance interventions. As a matter of fact ageing and exceptional loads during the life time produce in many cases the damage of the structure with very dangerous situations for its stability. Among the structures having a high architectural value, the ancient masonry towers produce a great interest, especially in Italy (the Pisa tower is the most famous example) [1].

A great collapse risk is associated to the tall masonry towers. The risk depends on the nature itself of the tower. Really towers represented a symbol that had to be as high as possible and every increase in the height, decided often during the building for the not satisfied desire "of reaching the sky", meant a reduction of the safety whose degree was lift to the builder.

The reduction of the safety because of the height is clear: the increase of the base stresses and a more sensitivity to lightning are produced. Further, tower doesn't allow the possibility of redistribution of stresses among different critical sections, therefore the collapse of one section is sufficient for the total collapse.

Many Italian towers disappeared as it is proved by the history, further some of them collapsed and were rebuilt after the collapse. As an example, two important towers underwent a structural collapse under dead loads in Italy in the past century: the St. Mark bell tower in Venice in the 1902 and the Civic Tower in Pavia in the 1989. The collapses were different: in the first case two days needed from the first alarm and 20 minutes from the first fall of bricks, in the second case few seconds were enough for the disappearing of the construction.

The history of the two mentioned towers proves the low level of safety (strongly reduced by the ageing) that often characterises these kind of structures. Further their end justifies the increasing interest in the evaluation of the collapse risk level and the research in its reducing to an acceptable value by means of proper devices.

The high vulnerability of the ancient masonry tower structures with respect to the normal loads suddenly suggests the low capacity that these kind of structures may have with respect to the seismic loads. Certainly the brittle behaviour of the masonry associated to the generally little dimensions of the base, where the stresses are bigger, doesn't help to remove this statement. As an example in Fig.1 the collapse of the bell tower of the Foligno town hall during one of the Umbria-Marche earthquakes on September-October 1997 is depicted.

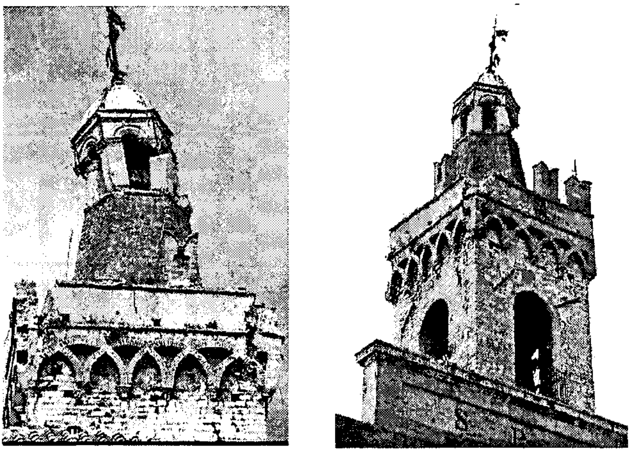

Figure 1: Two views of the bell tower of the town hall at Foligno, collapsing during the Umbria-Marche earthquake in the 1997

Tall towers have however a low fundamental frequency that may be favourable for the real horizontal loads acting during seismic events.

Many rehabilitation projects have been carried out for ancient masonry towers whose "efficiency" has been discussed for a long time. Really, for monumental structures the choice of the structural intervention to be made is very difficult. Several general criteria should first be followed, related to economy, durability, availability of know-how, reducing the pathological cause. At the same time, some more technical criteria should also be taken into account, such as enhancement of strength, maximising available ductility, physical and chemical compatibility of new and existing materials. However, in addition to these general and technical criteria another class of requirements has to be taken into account related to the particular value of the structure. For this reason the rehabilitation often seems almost impossible.

The commonest intervention is constituted by mortar injections for the reconstitution of the masonry continuity. Really masonry is often cracked because of the very high stresses or the lost of the original mechanical property of the joining mortar that does not ensure a proper distribution of the stresses themselves.

In some cases reinforced injections are used in order to enhance the capacity of the masonry with respect of tensile strength. For example the Bargello tower in Florence was improved by means of diagonal reinforced injections displaced along the height of the tower (see Fig.2).

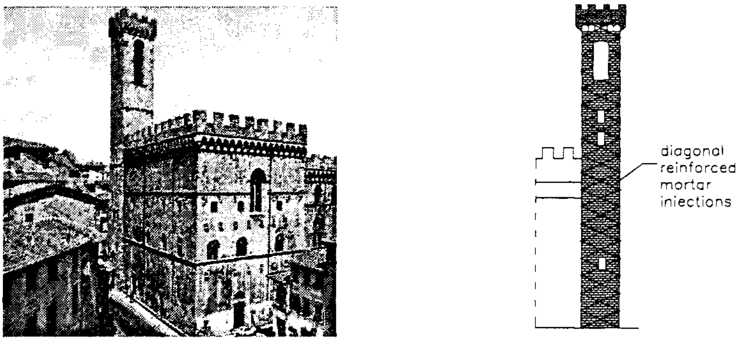

Figure 2: Rehabilitation of the Bargello tower at Florence

In other cases the mortar injections are coupled to other kind of improvement devices. For example the S. Martino in Rio Civic Bell tower (Fig.3-a), damaged during the earthquake of october 15th 1996 that interested the area around Modena and Reggio Emilia, was retrofitted by means of special mortar injections, aimed at re-establishing the continuity of the cracked masonry; then the insertion of 16 post-stressed steel bars into the walls (connecting the bell cell to the foundations) was taken in place in order to increase the bending resistance [3].

Also the bell tower of San Giorgio church at Trignano (Fig.3-b), damaged during the above mentioned earthquake, was repaired by using steel vertical post-stressed bars, but in this case the bars were placed in series with Shape Memory Alloys (SMA) devices (Fig. 4), which are able to recover totally the deformation and dissipate energy at the same time. In this case the dissipation features of the structure were highly improved.

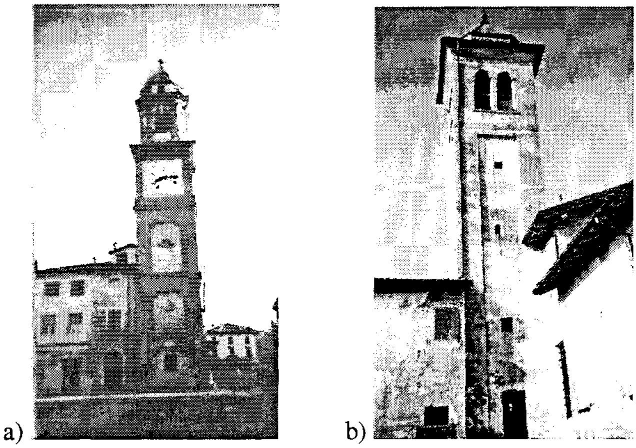

Figure 3: a) Civic bell tower at S Martino in Rio; b) Bell tower of S. Giorgio church at Trignano

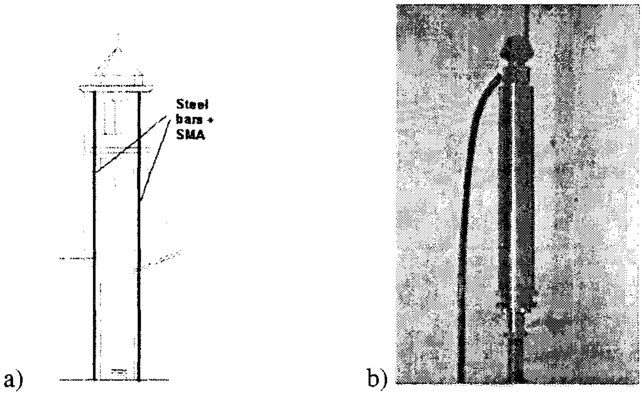

Figure 4: a) Layout of improvement devices in S Giorgio church; b) SMA device

In the next paragraph the procedure followed in the rehabilitation of a tower belonging to Italian monumental heritage (the bell tower of the Palermo Cathedral) will be in detail discussed.

2 The bell tower of Palermo Cathedral

2.1 The history and the actual geometric features

The rehabilitation of an ancient structure has to take into account the history of the structure itself as a preliminary investigation. As a matter of fact in this case every exceptional event that has regarded the structure (exceptional loads as earthquakes, damages, structural interventions, etc) may be known.

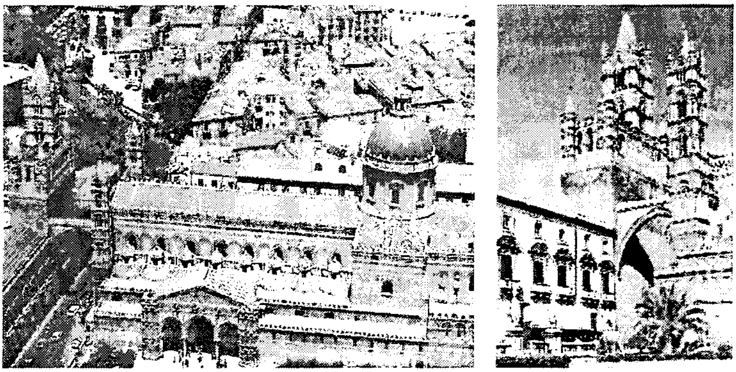

Figure 5: Two views of Palermo cathedral and its bell tower

As a result of the history composition the features of the structure may be pointed: the age and provenience of the materials may be defined, the evolution of the damaging processes can be known, further by the structural behaviour observations the weakness of the structure itself may be estimated.

Probably the first execution of the bell tower (Fig. 5) is dated III century B.C. during the Punic Roman age and it was inserted in the walls of the ancient urban nucleus of Palermo. So initially the tower had a defence function and was constituted by a full volume without any definition of internal spaces. The area, where actually the Cathedral is, was first occupied by a basilica that was destroyed by the Vandals in the IV century A.C.. In the VI century, on the rest of the basilica, a new church was built by the archbishop Vittorio. The new church, entitled to Virgin Mary, was jointed to the actual bell tower by means of one great arch. So in this period the tower had the double function of defence garrison and bell tower and it became a symbol of the religious power on the temporal one.

In 1169 the new church was strongly damaged by the earthquake. The damage of the tower was minimum so only few repair interventions needed. After the earthquake, in 1185, the archbishop Gualtiero Offamilio made possible the rebuilding of the church that became the actual Cathedral. The tower was assumed as a fundamental part of the new project. The Cathedral facade and the tower were connected each other by means of two great arches so the tower itself had three functions: defence of the church, bell tower, and contrast against the thrusts of the navy.

In the XIV century the Cathedral and the tower were reformed for the desire of having a symbol more and more great. The most important reform was the raising of the bell tower that produced in 1350 the partial collapse of it and the arches. Subsequently the tower was restored thanks to the intervention of the Pope in Rome. The signs of the collapse are still in evidence, as a matter of fact, on the North-East side, a line inclined toward the Cathedral divides the masonry realised before the collapse and after the collapse (Fig.6).

During the XV century the new archbishop palace was built, adjacent to the tower. So several interventions regarded the tower in order to create the passages between the Cathedral and the archbishop palace. Real tunnels were made in the basement of the tower to create the above mentioned passages making weak the basement of the tower itself.

In the XIX century the upper part of the bell tower was radically transformed by Ferdinando Fuga in agreement to the project of Architect Palazzotto. The works were concluded in 1844. The tower reached the actual height of 55 mt from the base. Today the bell tower can be distinguished in two parts: the basement that belonged to the town walls, until 26 mt, and upper part that contains the bells placed at different levels, until 55 mt.

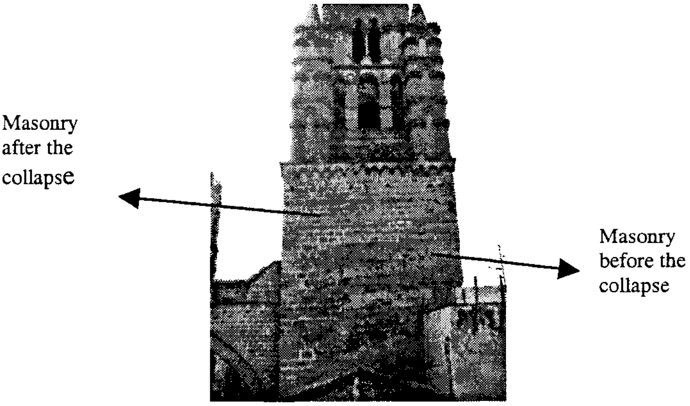

Figure 6: The North-East side of the bell tower of Palermo cathedral constituted by two different kind of masonry, before and after the collapse of 1350

The top of the tower, having the shape of an octagonal pyramid, is constituted by eight reinforced concrete thin walls whose thickness is 5 cm, covered on the external side by means of little calcarenite ashlars. From the height of 50.10 to 35.30 mt the tower is constituted by four angular columns connected at different levels with chains along each side of the tower. A reinforced concrete floor can be found at 42.10 mt where the main bell was anchored. From 35.30 mt to 26 mt (where the basement begins), the structure is featured by two walls displaced along two opposite sides of the tower itself by means of that the vertical loads are transferred to the basement.

2.2 The in situ tests for the physical and mechanical characterisation of the materials

The historical analysis of the tower allowed the partially knowledge of the vulnerability factors of the structure. The visual survey evidenced then a generalised damage of the materials, above all the masonry then the chains and the reinforced concrete parts (the top and the floor at 42.10 mt). It was noted the absence, in many points, of the mortar joints, so a distributed transfer of the stresses was not possible. In this condition many ashlars were cracked. The upon mentioned chains were in many cases not effective with high risk for the angular columns. Then the oscillations of the main bell caused a diffused cracks on the masonry around the height of 42 mt so its activity was stopped. This was the clearest prove of the vulnerability of the tower to horizontal loads.

By means of in situ tests further data were collected about the mechanical, chemical and physical characterisation of the materials. In addition a lot of samples of the materials that constituted the masonry were taken for laboratory testes. Under this condition a complete frame of the state of the tower was defined and the intervention project was possible.

On the walls of the tower 22 horizontal and 13 vertical perforations were done by means of an hole drilling machine (Fig.7-a) for the extraction of cylindrical samples of the masonry, further 3 manual surveys were executed. Several samples of mortar were chosen among the extracted material after the perforations for the chemical analysis. Then stone specimens were obtained from the extracted materials for their mechanical characterisation. The internal structure of the walls was observed through the holes and the rate of empty spaces, the type of resistant materials with respect to the external ones and the conditions of the internal joining mortar were defined. A sample of an extracted cylinder is shown in Fig.7-b where a difference between the features of the internal and external masonry can be seen: the first is constituted by high strength calcarenite stones of great dimensions while the second by an aggregate impossible to extract in the cylinder form for its little strength. The same fact was observed for every perforation.

The state of the internal masonry was further observed by endoscopic camera. In Fig.8-a the absence of joining mortar between two ashlars causing a not correct transferring of the stresses noted by endoscopic camera is showed.

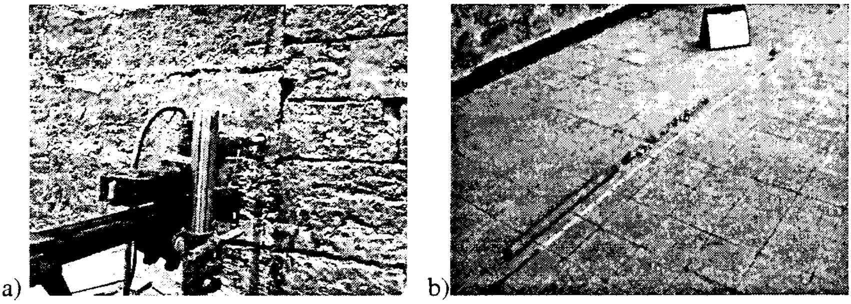

Figure 7: a) Hole drilling machine; b) extracted cylinder

The mechanical features of the calcarenite stones were evaluated referring to cylindrical and cubic specimens. Moreover the tensile strength was evaluated by means of the indirect tensile test (Brazilian test). The mortar was chemically analysed and compared with similar composition mortars with known mechanical features. The level of the acting stresses in the masonry was evaluated in situ by means of the flat jack test (Fig.8-b).

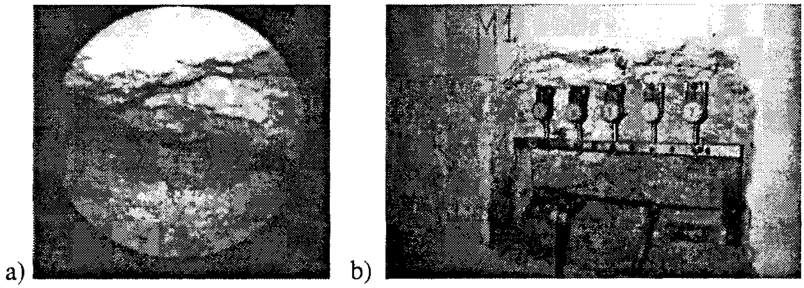

Figure 8: a) Endoscopic camera view; b) Flat jack test

Values of the stresses compatible with the materials used were obtained.

The results of the investigation are more extensively reported in [4].

2.3 The interventions

As a consequence of the investigation a lot of data were collected that assumed a basic function in the comprehension of the degeneration processes and for the project of the interventions aimed to the stopping of the degeneration processes themselves and the reduction of the collapse risk.

The primary facts evidenced during the investigation on the tower are: 1) the age; 2) the earthquake undergone in 1185; 3) the collapse under dead loads in 1350. Then the visual investigation has evidenced the discontinuity of the masonry for the missing of the joining mortar in large zones. In this condition a reduction of the capacity of the masonry has been produced as a consequence of the reduction of the resistant sections. An other important factor is the deep difference between the masonry that constitutes the walls externally and the one that constitutes the walls internally. The difference was great for the basement while it was reduced for the bell cell.

The collapse happened in 1350, and the damage processes of the materials proposed the possibility of a new collapse. In order to reduced this possibility, properly horizontal holes were made at two levels of the basement of the tower in direction of the smaller side. The holes had the function to allow the injection of mortar inside the wall in order to full as far as possible the empty internal volumes of masonry. Further the creation of resistant horizontal elements having the function to reduce the probability of collapse mechanisms of the structure with the formation of inclined sliding plane (as it is typical for the collapse of geotecnichal materials) was permitted.

The main bell was disconnected from the reinforced floor at 42.10 mt and a metallic structure was made and connected to the floor at a lower level with dissipation devices. In this way a certain degree of isolation was obtained between the tower and the inertia forces produces by the oscillating main bell. The steel chains were made effective and externally the joining mortar was reconstituted with the double function of re-establishing the continuity of the masonry and to avoid the infiltration of the meteoric water inside the masonry where a breaking up action may be produced.

2.4 Dynamic tests and evaluation of the structural safety

The prediction of the structural response under exceptional load and the establishing of the effectiveness of every part of the structure were performed by a proper analytical model. The defining and validation of the model was executed by using the data of the in situ and laboratory tests above described. Furthermore, several dynamic tests were performed. These tests allowed the observation of the actual structural response and the recognition of anomalous structural behaviour connected to every factors not explicitly knowable by means of the investigation before described [5].

The dynamic response of the structure to the environmental noise (urban traffic, wind, etc.) and other usual excitations (for instance the bell moving) was recorded. Seismometers located in different points of the tower were used to this goal (Fig.9-a). The simple observation of the response gave the first information about the stiffness of structure and the constrain degree of the tower with the arches that connect it to the Cathedral. Then the response was analysed by means of proper identification algorithms and the analytical model of the tower was obtained (Fig. 9-b)[6,7,8]. The seismic analysis was performed and the weakest zones of tower were localised [9].

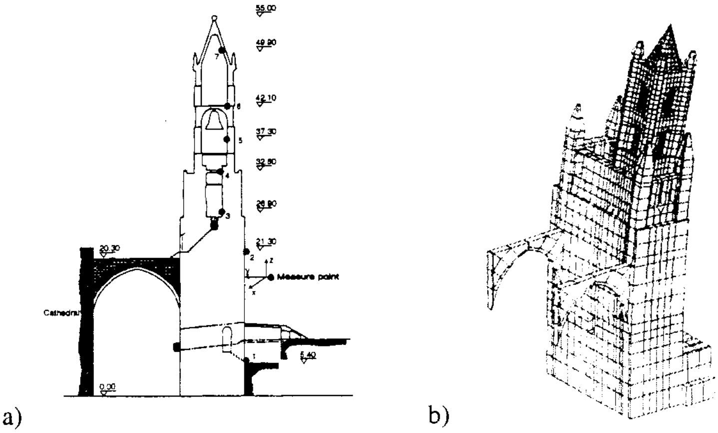

Figure 9: a) section of the tower with measure points; b) model of the tower - first modal shape (1.70 hz)

3 Concluding remarks

The rehabilitation of monumental structures is not simple depending on the serving of their architectural value. Nevertheless the rehabilitation is possible and it requires specific preliminary investigations. Among the monumental buildings, masonry towers have a special structure that need a specific control in order to reduce the collapse risk.

As in the case of the bell tower of Palermo Cathedral a methodical reconstitution of the original structural materials is an effective intervention for reducing the collapse risk and above all for the maintenance of its historical value even if special devices can be used as it has been done for other cases.

As a support new techniques are available for the continuos observation of the evolution of the structure behaviour during its life time and a more effective assessment of the structural safety: the dynamic identification techniques are referred to.

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