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The Failure of Ancient Towers: Problems of their Safety Assessment

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Summary

The safety of ancient towers has become a concern after some collapses which took place in recent years. Typical characteristic of most of these structures are not only the inhomogenity of the masonry itself but in many cases also the construction technique based on multiple-leaf walls, built in different phases with different materials. The survey carried out on the causes of the collapse of the Pavia Tower revealed a time-dependent behaviour of the material under heavy dead loads which was assumed to interpret the state of damage of a bell tower in Monza.

1. Introduction

Masonry is a composite material made with more or less regular layers of brick/stone and mortar. Its mechanical characteristics depend much more on the geometry of the components (shape, dimensions, thickness, etc.), on their mutual interaction, and on the way they are connected together, rather than on the mechanical properties of the components themselves.
In the past the global strength of the wall used to be increased by increasing the thickness of its section. Very often, for safety and economic reasons, building multiple leaf walls turned out to be more convenient. The way the leaves were connected together was depending on the shape and dimensions of the units, on the material used, on the construction technique which was different from site to site. Several times different materials were used in the leaves from regular stones and bricks to irregular stones, to concrete filling. The wall itself resulted a composite structure the response of which to dead and live loads is still badly known. For instance the application of modelling methods, like FE, or Discrete Element, is sometimes limited because suitable constitutive laws for these materials still have to be refined. Experimental results are still needed to understand the behaviour of these composite walls and learning from experience or even from failures can help to find the necessary information.
The results of two investigations will be briefly presented showing that the information collected after the failure of the Civic Tower of Pavia turned out to be useful for approaching the experimental study of the Bell Tower of the Cathedral of Monza.

2. Learning from a failure

On 17 March 1989 the Civic Tower of Pavia (Fig.1) suddenly collapsed killing four people. No apparent previous warnings were detected. Several hypotheses were formulated on the causes of the collapse, some of which were ruled out very soon. The construction took place in three to

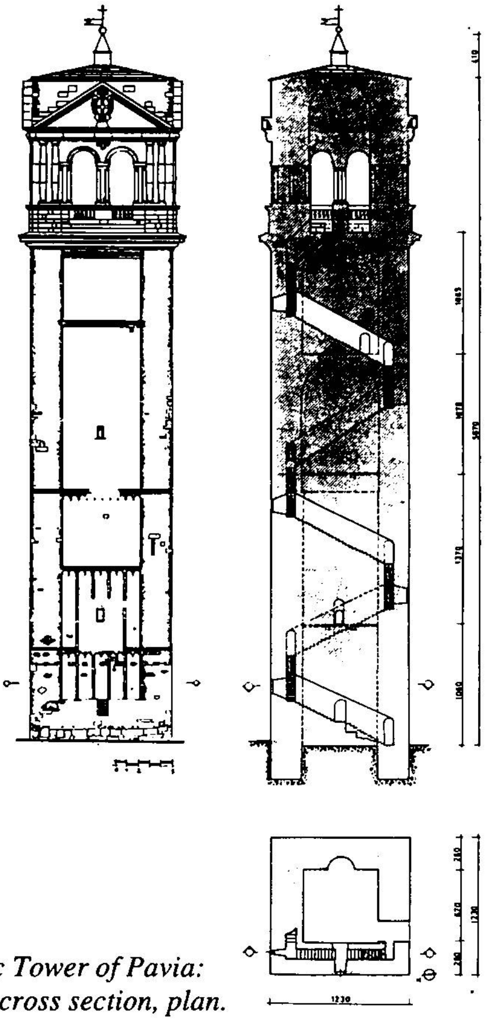

Fig. 1 Civic Tower of Pavia: front view, cross section, plan.

four phases, the first one between 1060 and 1100 AD, the second one between the XII and XIII century, while the belfry was added between 1583 and 1598.

For a thorough knowledge of the causes of the collapse an extensive experimental investigation was carried out on site and in the laboratory on the remainings of the tower. 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 [Binda et al., 1992]:

- search of documents on the history of the Tower;
- reconstruction of the geometry of the Tower;
- geognostic tests to define consistency and mechanical properties of the soil;
- chemical, physical and mineralogical /petrographycal analyses of the mortars, bricks and stones;
- compressive tests on prisms;
- stress analysis of the Tower.

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

- the Tower was built in three to four different phases, using bricks and rubble materials until the belfry, which instead was built with granite blocks;
- a staircase built within the loadbearing wall ran along all the four sides of the Tower from the south-west corner up to the belfry;
- the total estimated weight of the Tower was 120,000 kN, while the weight of the belfry was 30,000 kN. The walls were multiple leaf walls with the external leaves were made with regular brick layers, the internal one was a sort of concrete made with layers of broken bricks and stones alternated with thick layers of mortar (Fig. 2);

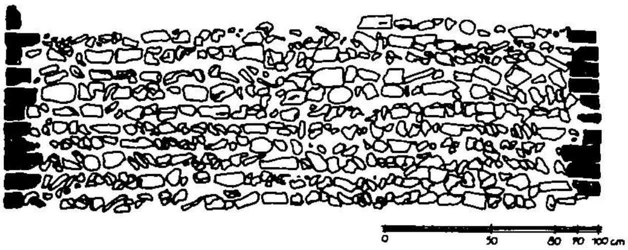

Fig. 2 - Cross section of the wall of the Civic Tower of Pavia

the lower part of the Tower was overstressed under its own weight. In fact maximum values of 1.7 to 2.0 N/mm^2 in compression were found by a FE elastic model, against experimental strength values ranging between 1.8 and 3.5 N/mm^2;

the material of the tower shown a time dependent behaviour under high stress level, which can bring the structure to collapse in a long time.

3. Behaviour of masonry walls as composite structures.

As mentioned above, the Tower of Pavia was made of multiple leaf walls, which is a typical technique frequently adopted in ancient buildings. The role of the leaves in load bearing walls is not always clear. It can range from the case of a main role of the external leaves, being the internal one a simple filling, to a load bearing role sheared among the three leaves, to the case of internal leaf which is the main one and the external ones play only the role of confinement or even framework. Moreover the leaves may be well connected horizontally with stiff long stones at given intervals or simply resting on continuous vertical mortar joints and when modelling the behaviour of this composite structure this should be taken into account [Binda et al. 1991, 1994].

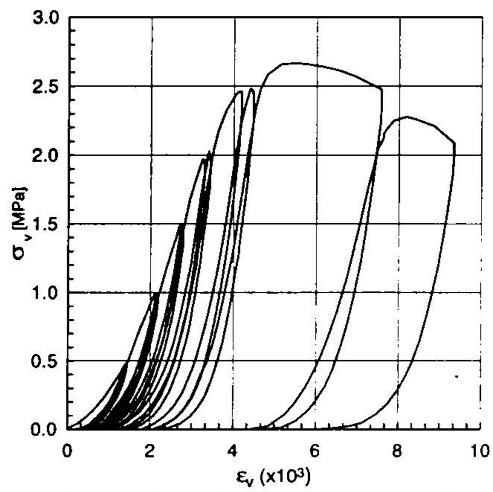

Fig 3 - Results of a test on a prism (400 x 600 x 700) mm^3 belonging to the masonry of the Civic Tower of Pavia.

In the case of the Pavia Tower the walls were continuous, more than 45 m high, 2800 mm thick, except where the staircase was running in a stairwell 800 mm wide. The thickness of external leaves was ranging between 150 and 450 mm only, that is 6 to 20% of the total thickness of the walls. They could have never supported a weight of 120000 kN without the collaboration of the internal leaf, which had actually to have played a loadbearing role.

In order to understand the mechanical behaviour of this masonry, mechanical tests had to be carried out on specimens representative of the inhomogeneity of the material of the internal leaf. Different kinds of compressive tests were carried out including tests applying unloading reloading cycles (fig. 3) and fatigue compression tests carried out to simulate the effects of the wind [Binda et al., 1992]. Creep tests were also carried out showing that these materials can be subject to an increasing damage when constant compressive stress is greater than the 50 to 60% of the peak stress; this damage can lead the material to failure when the stress value is higher than the 70% of the peak stress [Anzani et al. 1995].

Such a behaviour, the effects of which may be particularly heavy in the case of multiple leaf walls, is however typical also of the single components and of solid brick masonry. Therefore it has to be taken into account where the acting vertical stress is particularly high, as in the case of the dead load of ancient towers.

4. Experimental survey on the bell tower of Monza Cathedral

The bell Tower of the Monza Cathedral is a solid brick masonry structure dating from XVI century. This tower shows a considerable crack pattern which also in this case is probably due to the dead load, therefore many of the observations and hypothesis made in the case of Pavia Tower can be applied here, despite the different construction technique.

In order to investigate its behaviour experimentally, but having no possibility to sample a significant amount of material for testing, two wallettes have been cored, during the works for opening a door, from the crypt of the Duomo which has been built during the same period and reasonably likely with the same technique as the tower.

Prisms of about 200×200×500 mm have been obtained from the wallettes and have been subjected to three series of uniaxial compression tests of different type after being characterised

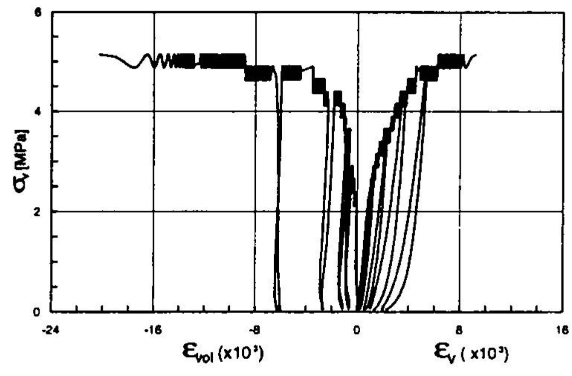

Fig. 4 - *Results of a fatigue test carried out on a prism (200 x 200 x 500) mm^3 belonging to the crypt of the Cathedral of Monza*

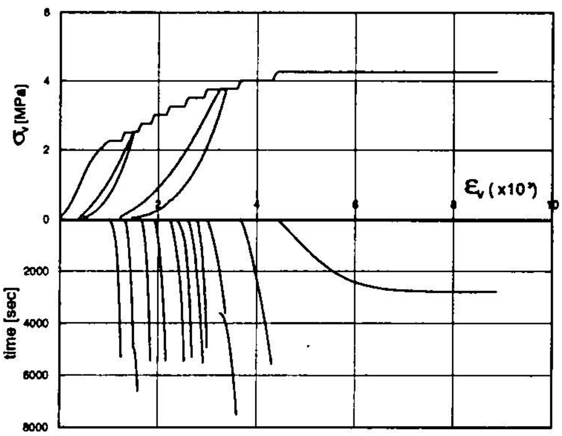

Fig. 5 - *Results of a test with subsequent load steps carried out on a prism (200 x 200 x 500) mm^3 belonging to the crypt of the Cathedral of Monza*

through sonic tests: (i) monotonic tests have been carried out initially to have a first indication on the compressive strength of the masonry; (ii) cyclic tests were carried out subsequently during which cycles of ± 0.15 MPa at 1 Hz were applied at increasing stress levels; (iii) finally, compression tests were also carried out applying the loads in subsequent steps kept constant for a defined time interval of about 1.5 hours. Because any single test lasted more than one day, the samples were unloaded before night, for safety reasons, and reloaded the day after.

In fig. 4 the vertical stress vs. vertical and volumetric strain are shown, obtained with a cyclic test. It can be observed that during the application of the cycles a deformation takes place the amount of which becomes higher when the stress level is higher. Moreover, considering the volumetric strain, it appears that dilation occurs since the beginning of the test.

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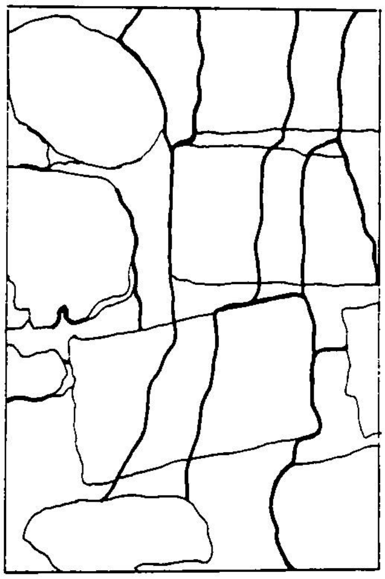

Fig. 6 - *Crack pattern of the prism tested as reported in fig. 5.*

In fig. 5 the vertical stress vs. vertical strain and the vertical strain vs. time are shown, obtained with a test performed with subsequent load steps. Creep strain can be clearly observed during while load is kept constant, with the appearance of tertiary creep during the application of the last load step.

In fig. 6 the crack pattern at the end of the test of fig. 5 is shown, where vertical and diffused cracks can be seen indicating a severe damage of the material; this can also be detected if the increase in apparent volumetric strain and the apparent dilation of the material reported in the plot are examined.

Different in-situ tests have been performed to better understand the behaviour of the tower, like flat-jack test to measure the vertical stress and the stiffness of the material, together with an accurate geometrical survey and a description of the overall crack pattern.

In order to verify the response of the structure to dynamic loading and to verify the effect in terms of stress variation, two dynamic tests were planned using the environmental excitation: the first measured the

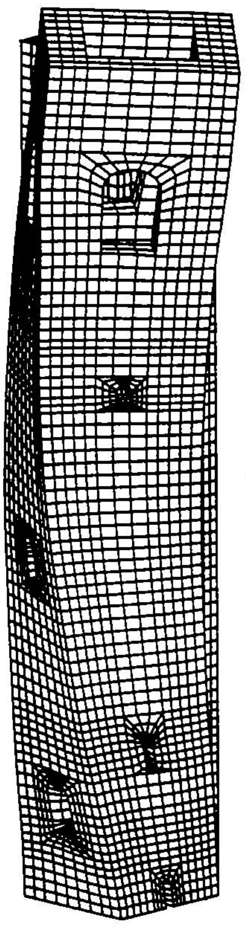

Fig. 7 - Modal form associated to the third frequency

effects of the bells ringing, the second one, not yet concluded, measured the effects of a strong wind. The response of six horizontal servo-accelerometers mounted in pairs at different height from the ground was monitored and elaborated, together with the readings of some transducers mounted across the major cracks near the front window at the base of the tower.
The sensitivity of the accelerometers is in the range of 0÷700 Hz, that is from the low (0.5÷5 Hz) frequencies expected for the tower movements to the frequencies associated with the sound propagation in the masonry.
By means of an appropriate analysis technique, acceleration histories are transformed in displacement histories at the different levels, giving a peak to peak maximum difference of nearly 4 mm in the W-E direction and of 1.9 mm in the N-S direction when all the bells ring together, and somewhat less (2.5 and 1.5 resp.) when only the major bell is ringing. In fig 7 the modal form associated to the third frequency of the tower is shown.
Also the transducers mounted across the major cracks are sensitive to the dynamic excitation induced by the bell ringing, giving a maximum peak to peak (opening to closing) of 28 μm, that should be compared. with a daily variation of about 100μm due to temperature effects.
The analysis of the collected data allowed also to detect an important structural property, that is the frequency of the first mode of vibration of the tower. This value can be directly compared to the frequency obtained from a F.E. model of the structure, allowing to identify a dynamic elastic modulus that can be subsequently employed to calculate the effects (in terms of stresses) of the applied force history. For a more realistic approach, the modulus obtained in the unloading-reloading branches of the tests of fig. 4 was calculated, obtaining an average value of 3742±314 MPa.
The value adopted in the analysis was 3400 MPa, corresponding to a lower limit (but the specimen were cut from the crypt) and giving a very close match to the first frequency (0.654 Hz). Tab. 1 shows the frequencies calculated for the first 6 modes of the structure.

MODE	FREQUENCY [Hz]
1st flexural E-W	0.654
1st flexural N-S	0.663
torsional	3.178
2nd flexural E-W	3.232
2nd flexural N-S	3.311
axial	5.715

Tab. 1

A first dynamic analysis was made applying an harmonic force calculated from the movements of the mass of the main bell, in the form $F = F_h \sin(2\pi f t)$, with $F_h = 24.7$ kN and f= 0.34 Hz is the frequency of the bell oscillation. These calculations gave displacements very close to those measured experimentally, encouraging the use of the model for other verifications.

5. Conclusions

The investigation carried out after the collapse of the Pavia Tower allowed to understand the behaviour of the materials and the structures of the ancient towers.
Towers are generally subjected to heavy dead loads due to their height and their massive construction technique. As a consequence, the state of stress at ground level can be not so far

from the compressive limit strength of the material with the development of increasing creep deformation under constant loads. In the long run this behaviour induces a continuous damage of the material and can lead it to the collapse.
Similarly, the action of cycling loads can also increase very quickly the local deformations. The combined effect of these factors is able to induce severe conditions to the building, therefore when its structural stability is to be safeguarded any possible source of stress variation must be carefully taken into account including stress concentration due to geometrical discontinuity and the effect of wind action, bell ringing, daily and seasonal temperature variations.
If the structure is made with multiple leaf walls, a careful insight must be carried out to detect the thickness ratio between the leaves and the type of constraints which may or may not be present between them. In fact, the advantages given by the presence of the external leaves acting as a confinement can vanish if the connections are lacking or damaged.
Dynamic tests based on active excitation of the structure can inform about possible difference in stiffness along the height of the tower due also to material damage or to different construction techniques.

Acknowledgements
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