Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 70 (1993)

Artikel: Investigations on the masonry of the Leaning Tower of Pisa

Autor: Bartelletti, Raffaello / Finzi, Leo / Sanpaolesi, Luca

DOI: https://doi.org/10.5169/seals-53285

Investigations on the Masonry of the Leaning Tower of Pisa

Essais sur la maçonnerie de la Tour Penchée de Pise

Untersuchungen am Mauerwerk des schiefen Turms von Pisa

Raffaello BARTELLETTI
Prof. of Struct. Eng.
Univ. of Pisa
Pisa, Italy

Leo FINZI
Prof. of Theory of Struct.
Politecnico di Milano
Milan, Italy

Luca SANPAOLESI
Prof. of Struct. Eng.
Univ. of Pisa
Pisa, Italy

SUMMARY

An extensive programme of experimental tests was carried out on the masonry of the Leaning Tower of Pisa from 1984 - 87. These experiments were directed towards establishing a design for stabilization. The authors, who developed and carried out the programme, present the results of the individual tests and the conclusions that can be derived from the series of investigations executed during the programme.

RÉSUMÉ

Un programme très complet d'essais expérimentaux a été exécuté sur la maçonnerie de la Tour Penchée de Pise pendant les années de 1984 à 1987. Les essais avaient pour but la définition d'un projet pour la stabilisation du monument. Les auteurs, qui ont formulé et conduit le programme, présentent les résultats des essais et les conclusions du programme.

ZUSAMMENFASSUNG

Ein umfangreiches Programm experimenteller Untersuchungen am tragenden Mauerwerk des Turmes von Pisa ist in den Jahren von 1984 bis 1987 verwirklicht worden. Diese Untersuchungen waren auf die Planung der Stabilisierung des Denkmals ausgerichtet. Die Autoren dieses Beitrages, die das Programm erstellt und durchgeführt haben, berichten über die erzielten Ergebnisse einzelner Untersuchungen und über die Schlussfolgerungen, die aus ihnen gezogen werden können.

1.Foreword

From 1984-87 the authors led an extensive programme of experimental tests to learn the nature of the masonry structure of the Leaning Tower or Pisa. The authors present the investigations and conclusions in this paper.

It must be mentioned that in 1983 the Ministry of Public Works set up a design team composed of structural engineers, geotechnical engineers and an art historian, with the task of establishing a design for the definitive consolidation work to be carried out on the Leaning Tower. The authors of this article were the structural engineers of the design team.

The first job of the design team was to organize and study the existing documentation on the state and characteristics both of the elevated section and the foundation soil of the Tower.

The next task was the study and outlining of an extensive programme of experimental investigations on the Tower and its soil. A programme directed at the collection of specific information to allow for consolidation design. This programme, approved by the Ministry of Public Works in 1984 was executed in 1985-86 by ISMES (Institute for the testing of models and structures) and RODIO s.p.a., both completely reliable and competent bodies well suited to the delicate work in question.

It should be stated why it was necessary to perform experimental investigations on the Tower. The Tower in fact is well known in the scientific community for its inclination, related historical aspects and safety problems; such that it might appear that the critical point of the Tower lies in the foundation soil and that the possibility of crisis and collapse is to be found only here.

In reality this is not the case. The structure itself also shows critical aspects comparable to those existing in the foundation, fully justifying the attention given to learning the nature of the Tower's structure.

To close this foreword, although not entering deeply into the subject, the authors would like to point out that with the extensive knowledge obtained from the wide testing programme the design team was requested to stop its work, delivering the final plan for the consolidation work of the Tower to the Ministry of Public Works for a definitive and complete resolution of the problem, as foreseen by the original objectives.

2.Introduction

The programme of experimental tests - finalized as already described, not only to expand scientific knowledge but directed at the collection of data to permit the planning of consolidation work - was designed to supply information relating to:

- the structural conformation and characteristics of the Tower,
- the stress states existing in the most important areas,
- the mechanical characteristics of the materials.

To this end the following tests, briefly described in subsequent headings, were performed:

1. Sounding of the masonry.

2. Imaging of the walls' internal structure using television waves.

3. Core boring of the walls with the samples subsequently undergoing compression tests.

4. Testing with flat jack to determine the state of stress of the freestone.

5. Deformation tests performed inside perforations by means of a dilatometer.

6. Measurement of stress states using the doorstopper decompression technique.

7. Acoustic investigation.

8. Impregnation tests for the walls.

On the basis of the first three tests in the list - and in particular the tests with television waves - it was possible to better define the internal structure of the Tower's masonry already outlined and here briefly re-stated.

Essentially the elevated structure is formed by a hollow cylinder and in the foundation by a circular mass as the base. The elevated section is formed both on the external and internal face by two walls of squared blocks having a depth of about 40cm filled with mixed masonry of cobbles very good hydraulic lime and mortar which, however, contains numerous cavities and has far lower mechanical characteristics (see fig.1).

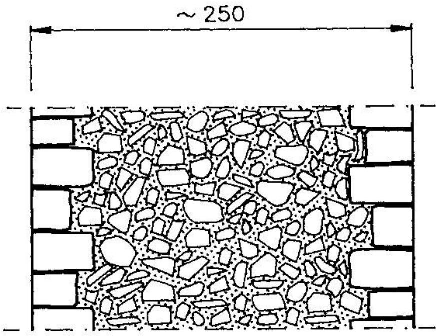

Fig. 1

The foundation is made of stone masonry and hydraulic lime mortar, consolidated in 1935, by Rodio, using cement grouting.

3. Mechanical tests on wall samples

The masonry of the monument was tested through 19 perforations. The total length of all these perforations was 96.02m. The boring was performed in the foundation, 1st and 2nd tiers. These perforations were made dry so as not to impregnate the permeable masonry and by aspiration so as not to induce dangerous stresses in the water table mortar and walls, using a diamond bit of 76/53mm diameter.

A high percentage of the boring core was obtained often reaching 100% of the bore length. Thus permitting a satisfactory knowledge of the Tower's masonry composition. 36 significant specimens were taken from the core samples and these were tested, some at ISMES in Bergamo and some at the Laboratory of the Istituto di Scienza delle Costruzioni di Pisa.

The samples were classified according to the area of extraction and composition in the categories: freestone, mortar, mixed masonry.

3.1 Freestone

The first group of samples numbers 12 test cylinders taken from squared stone blocks of calcareous stone in the Tower's external face. The dimensions range from 5.35 to 5.38cm in diameter and from a minimum height of 5.54 to a maximum of 10.60cm The unit mass is of 2.66 to 2.72 g/cm^3, with an average value of 2.69 g/cm^3 and standard deviation of 0.0176 g/cm^3 (0.65%).

In an attempt to normalise the compression test results, the varying height of the samples was taken into consideration using an appropriate correlation between strength versus the ratio of diameter to height.

The cylindrical strength (f) was between 69.7 and 152.8 N/mm^2 with the following average values:

148.3 N/mm^2 for samples taken from the foot of the first tier

91.8 N/mm^2 for samples taken from mid way up the first tier

89.1 N/mm^2 for samples taken from mid way up the second tier

The Young's modulus (E) was far more uniform than the strength, varying from a minimum of 71300 N/mm^2 and a maximum of 95300 N/mm^2. The average value is of 83636 N/mm^2 with a standard deviation of 7155 N/mm^2 (8.6%).

The samples pertaining to the external face also permitted the measurement of the thickness of the face itself, thereby obtaining the following average values:

lower part of the first tier (4 measurements) 40cm

mid section of the first tier (4 measurements) 32cm

mid section of the second tier (3 measurements) 23cm

While for the internal face there were no direct measurements available in as much as the core boring was stopped a few centimetres before it completely penetrated the wall itself. We can, however, assume that the thicknesses are of the same order of magnitude.

3.2 Mortar

The second group of samples consists of a series of eight results obtained from core samples taken exclusively from the mortar. Disregarding the anomalous result obtained from one test (0.80 g/cm^3), the average value for unit mass of the remaining seven samples was 1.54g/cm^3 with a standard deviation of 0.08g/cm^3 (5%).

The sample with a unit mass of 0.80g/cm^3 so showed a notably different value for cylindrical strength (22 N/mm^2) from the other samples, while for three samples it was not possible to determine the mechanical characteristic. The remaining four samples had diameters ranging from 5.27 to 5.32cm and height varying from 5.85 to 9.62cm. Again in order to permit a comparison of the results the compressive strengths were normalized to the cylindrical strength. Instead of using the above mentioned correlation, which is suitable for stone material, a correlation more appropriate to this type of material was adopted. The cylindrical strengths obtained vary from 10.2 to 13.3 N/mm^2, with an average value of 11.5 N/mm^2 and standard deviation of 1.29 N/mm^2 (11%).

3.3 Mixed masonry

The remaining 16 samples, obtained from the infill material contained between the faces, consisted of mortar comprising large pieces of stone material of extremely variable quantity. This is demonstrated by the unit mass which ranges from a minimum of 1.55 g/cm^3, virtually the same value as that obtained from the mortar to a maximum of 2.3 g/cm^3 which is quite close to the value obtained from the for the stone. The average result was of 1.90 g/cm3, with a standard deviation of 0.26 g/cm^3 (14%).

The number of samples which underwent compression tests was 15. These having diameters between 5.30 and 6.16 cm and varying in height from 7.5 to 14.9 cm. Once again, in order to obtain the cylindrical strength an appropriate correlation was applied.

The average cylindrical strength varying between 7.3 and 18.8 N/mm^2, was 10.7 N/mm^2 with standard deviation 3.5 N/mm^2 (33%).

The results for the tests of Young's modulus carried out on these samples were of little significance due to their varied nature, including the presence of cavities and the varying sizes of the stone material. Indeed the values go from a minimum of 2840 N/mm^2 to a maximum of 39600 N/mm^2 , without the possibility of forming a useful correlation for unit mass. This is obviously also due to the presence of cavities.

4. MEASUREMENTS OBTAINED WITH FLAT JACK

For the experimental evaluation of the states of stress in the Tower's faces a total of 32 tests were performed with the flat jack technique. Jacks in the shape of a circular segment 4 mm thick were used, inserted into milled cuts along the horizontal face joints. Ten of these tests concerned the internal face in sections 1 and 3B.

The tests were performed at four tiers, more precisely indicated in fig.2.

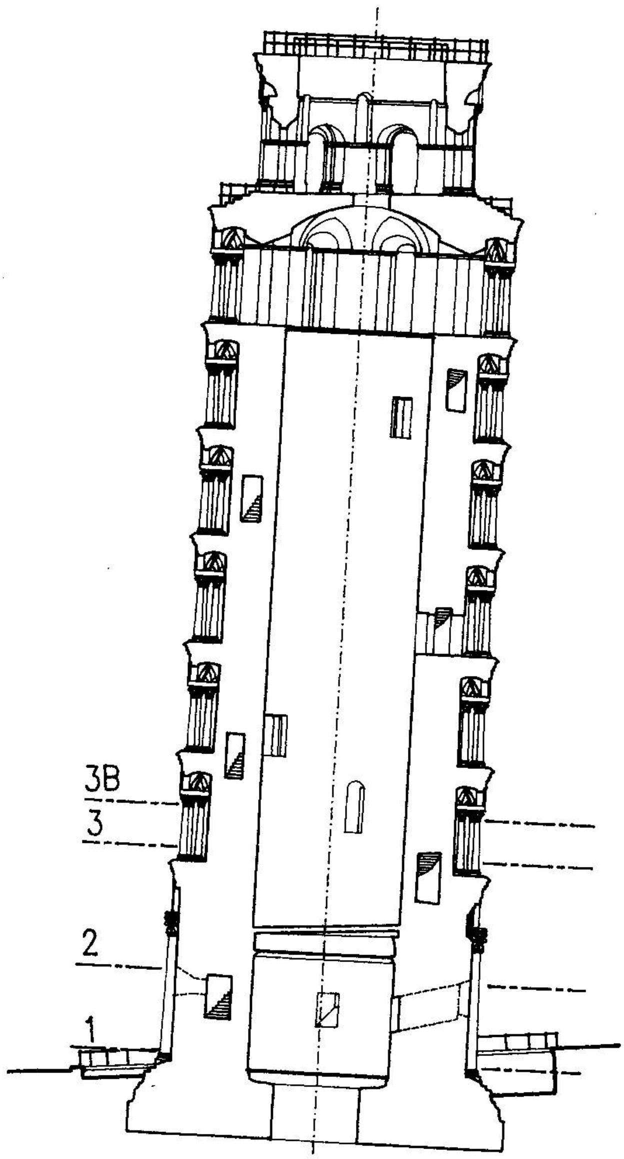

Fig. 2

These enabled the on site formulation of Young's modulus for the freestone face.

4.1 Stresses in the facing walls

The 32 values of stresses measured, with the exception of 4 results disregarded due to evident anomalies due to particular local conditions, proved to be, for each of the 4 horizontal sections investigated, virtually on the same plane. Thus permitting the formation of trapezoidal diagrams of the stresses referring to the plane of maximum inclination of the Tower with the following range of values:

Section 1:	σ_{min} = 0.29 N/mm^2 (0.12)	σ_{max} = 6.07 N/mm^2 (6.8)
Section 2:	σ_{min} = 0.33 N/mm^2 (0.75)	σ_{max} = 5.53 N/mm^2 (5.6)
Section 3:	σ_{min} = 0.65 N/mm^2 (0.6)	σ_{max} = 4.2 N/mm^2 (4.24)
Section 3B	σ_{min} = 0.65 N/mm^2 (0.8)	σ_{max} = 6.93 N/mm^2 (6.84)

The diagrams were obtained with the process of linear regression from all the useful stress measurements. The extreme values measured are indicated in brackets.

The apparently anomalous low values of the stresses on section 3 are possibly explicable due to local redistribution phenomena of the stresses which particularly concern the external facing wall, caused by sudden variation in diameter between the second and first tiers of the Tower.

4.2 Young's modulus for the treestone

Young's modulus were obtained from the results of each point measured. These were very disparate due to unavoidable errors in measuring variations where stresses were very small. Therefore, excluding the points where stresses were less than 1 N/mm^2 (11 points), we obtain an average modulus value of 54000 N/mm^2 with a standard deviation of 10280 N/mm^2 (19%).

4.3 Considerations on the flat jack measurements

The maximum and minimum stresses obtained from the tests were about 7 and 0.1 N/mm^2 respectively, while the Young's modulus varies between about 50000 and 66000 N/mm^2 .

Furthermore we can observe that both the stresses and the modulus were determined with reference to the stress states and deformation of a homogeneous half-space in the presence of fissures. In effect the measurement was taken with the flat jack inserted into a gap along a mortar joint to a presumed depth of half the face's thickness. One can therefore, assume a notable influence on the results due to the varied nature of the material (fill material, mortar and stone), tending towards an overestimate of the acting stresses and an underestimate of Young's modulus.

5. DILATOMETER TEST

To obtain information concerning the elasticity of the wall fill 18 dilatometer tests were performed using the bore holes of the core sampling.

Based on the total experimental values obtained, the average value for E is:

E_m = 8758 N/mm^2, st. dev. = 4322 N/mm^2 (49%)

However, some considerations must be made about the validity of these results, because the standard deviation shows that the average is the result of widely scattered values.

The reasons for this dispersion seem essentially to lie in the local conditions of the bore hole test area, influenced by the cavities and composition of the mixed masonry.

In brief the dilatometer tests studied, although supplying less reliable results than those obtained with the flat jack, have enabled the calculation of Young's modulus value for the mixed aggregate wall fill in the order of 12000 N/mm^2 .

6.OTHER TESTS AND INVESTIGATIONS

The last three tests listed in point 2 (doorstopper, acoustic, and impregnation) supply specific data which are less reliable and less significant than those illustrated in the previous points. The decompression test by means of the doorstopper technique directed at determining the main stresses on the fill wall, seem strongly influenced by the presence of micro fissures, by the choice of values for E and the lack of uniformity in the material under study (mortar or stone).

The acoustic investigation supplied a qualitative evaluation of the material examined, including the noting of discontinous surfaces (as for example between foundation wall and soil), while the propagation velocity, linked to Young's modulus E, was strongly influenced by the presence of cavities or fissures in the wall such that it is of no significance reporting the values.

The impregnation tests, carried out by filling the hole bores from the core sampling with a mixture of water, cement and additives, to determine the wall's suitability for low pressure impregnation, have enabled the assumptions to be made concerning the impregnation of the mixed masonry.

7. CONCLUSIONS

From the investigations performed and from an analysis of the results shown above it is possible to conclude as follows:

<u>Nature of the walls</u>

The masonry of the foundation ring, comprising a mixture of lime and sand mortar with calcareous stones and having a thickness of about 4 m is thoroughly cemented and contains no cavities as a result of the cement injections carried out in 1935.

The elevated part of the wall is formed by two freestone faces in calcareous marble enclosing mixed masonry of calcareous stone and mortar and contains many cavities.

Mechanical characteristics of the wall

For the freestone:

f_{min} = 80 N/mm^2 E_{min} = 70000 N/mm^2

For the inner masonry:

- Mortar f_{min} = 10 N/mm^2 E_{av} = 6000 N/mm^2
- Mixed $f_{av.}$ = 10 N/mm^2 E_{av} = 12000 N/mm^2

The maximum stress measured on the outer freestone is 7 N/mm^2.

With reference to the last piece of information, the maximum stresses existing clearly seem high and far above those in similar buildings.

Concerning the stone material and mortar, both seem to have excellent mechanical characteristics with high strength values. The nominal stresses existing in the inner masonry are noticeably lower, in comparison to the values noted above, for the lowest Young's modulus which characterizes this material in comparison to the freestone.

However, there are many other elements which make this picture far from satisfactory. With regard to this we can only mention the followings:

- the existence of mortar joints, occasionally of great thickness in mixed masonry;
- the varied nature of the fill material and its high percentage of cavities;
- the numerous individual areas, first among which is that between the 1st and 2nd tiers where the outer face is supported by the mixed masonry;
- the presence of the stair well which creates discontinuity and forms a further particular area.

In conclusion a thorough evaluation of the problem requires an accurate analysis and modelling of the structure, for which the data resulting from the experiments conducted by the authors, and briefly reported in this paper are a necessary starting point.