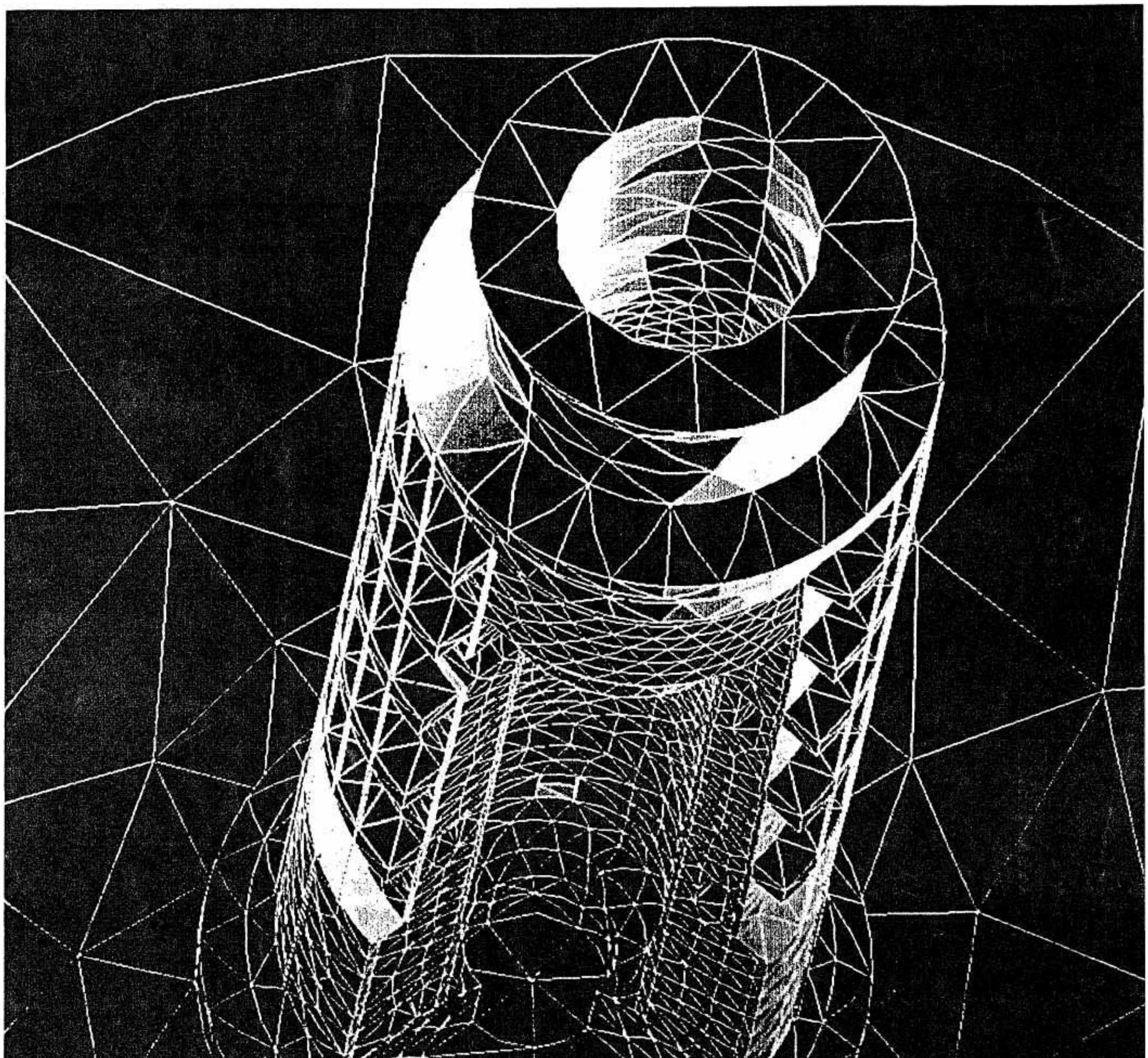
SEI Volume 3, Number 1 February 1993

Structural Engineering International



Journal of the
International Association for Bridge and Structural Engineering (IABSE)

Reinforcement of Palazzo della Ragione, Milan

Lorenzo Jurina
Prof., Milan Polytechnic, Milan

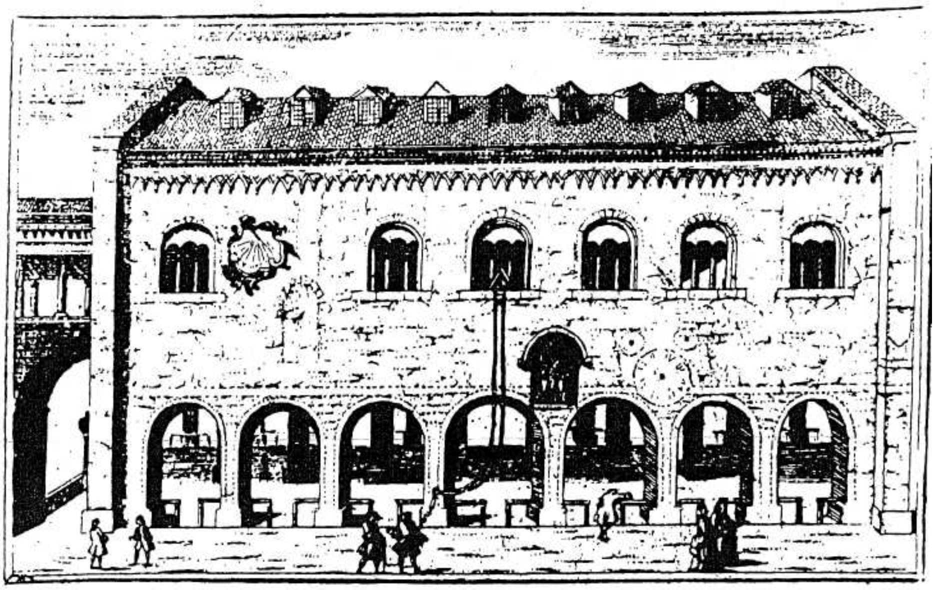


Fig. 1: Palazzo della Ragione, from an old engraving

Introduction

The Palazzo della Ragione is the oldest masonry public building in Milan. The building comprises a lower part from the 13th century with marked cracks on the external walls and an upper part from the 18th century, where poorer materials were used *(Fig, 1)*. During the last two centuries, until 1959, the building hosted the Notarial Archives of the town.

External dimensions are 18x50 m in plan and 28 m in height. The big room on the first floor is covered by masonry vaults and it rests on isolated columns at the ground level. 18 m long wood trusses were adopted for the roof. Further details can be found in [1, 2].

In the 1960s and 70s, very severe load conditions developed on the building, not only due to the excavation of the first underground line close to the foundations, but also due to the repeated vibrations induced by the nearby trains. Notwithstanding the installation of root piles to reinforce part of the foundations, the municipality and many local newspapers were still worried about the static condition of the historical building.

An authoritative proposal to remove the 18th century upper part was gaining ground in those years. Many architects and historians were opposed to this solution and at the end it was decided to try to consolidate the whole building as it was.

The aim of the initial investigations was to verify the real safety state and to propose interventions as minimal as possible within the concept of full respect for the building and its heritage.

Tests and Analyses

So/7 *Tests*

The existence of a remarkable crack pattern affecting the external walls suggested an investigation of the soil properties to evaluate possible lack of homogeneity and, hence, different rates of settlement to the foundations. Dynamic penetrometer and soil boring tests were performed near the building. Under the north and south corners, the most severely cracked, a looser soil was found which is probably due to the presence of an ancient channel crossing the area.

A disturbed refilling soil with a high percentage of organic content was observed up to a depth of 8 m. The column foundations reach the same level, very deep compared with the original height of the building. This level probably coincided with the water table level at the time of the construction.

Masonry Tests

Mechanical characteristics of brick masonry walls and their in situ state of stress are usually difficult to obtain, especially when only a limited number of small sized specimens can be extracted and tested. To solve this problem a new testing technique, similar to the flat-jack test used in rock mechanics, was adopted for the first time in masonry.

Useful results were obtained concerning in situ stresses at different locations, deformation parameters at different stress levels and limit strength values for the masonry. Details of the test method can be found in [3, 5, 6]. The obtained in situ vertical stresses varied between 0.2 and 1.2 MPa; the elastic modulus ranged from 3450 to 5100 MPa.

Numerical Investigations

Serious cracks, apparently due to foundation settlement, could be observed in the masonry walls and an out-of-perpendicular displacement of about 30 cm was reached by the masonry walls near the top. In order to design structural reinforcements, an appropriate knowledge of the actual state of stress, mainly due to dead weight and to foundation settlements, is always required. As the settlements were difficult to identify, even by means of accurate in situ and laboratory tests, an auxiliary procedure was proposed. This procedure was based on the simulation of the crack pattern present on the masonry walls, using a numerical model for the whole building.

An accurate survey of the existing cracks was previously prepared and complete information about geometry, loads and constitutive laws of the materials was introduced into a finite element model (FEM) of the structure.

Undamaged masonry was considered orthotropically elastic and the main cracks were modelled simply by disconnecting the nodal points. Reinforcing

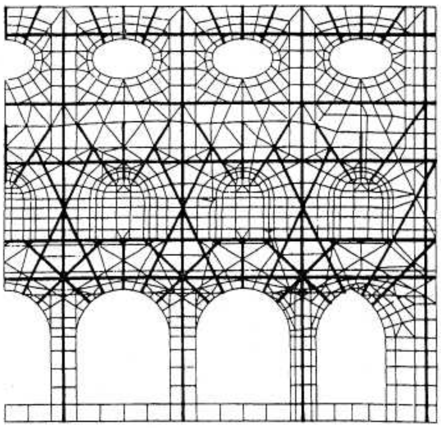


Fig. 2: FEM with reinforcements introduced

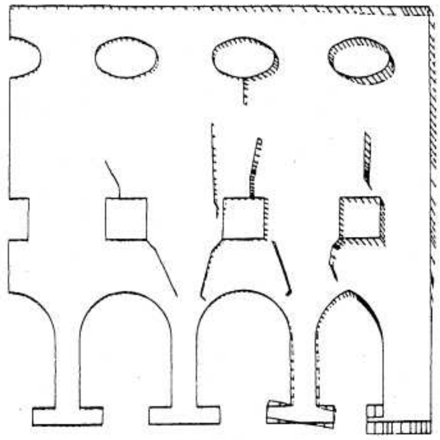


Fig. 3: Settlement-induced cracks in FEM

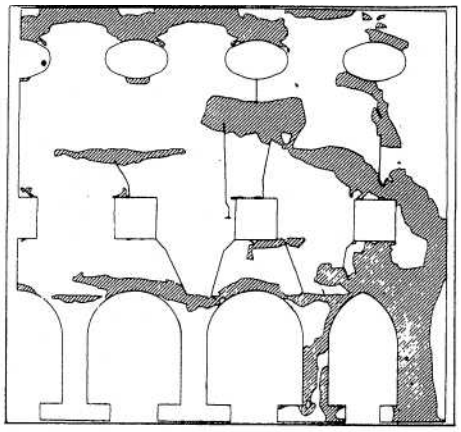


Fig. 4: FEM design of reinforcement

bars located at different positions can also be introduced into the model *(Fig. 2).* Individual distorsions imposed on the base of each column cause relative displacements of the opposite sides of all the cracks, which can be calculated and recorded.

If amplified properly, the effects of each individual settlement produce a distribution of openings in the cracks very similar to the actual ones [4], *Fig. 3.* It can be observed that the main damage is principally due to anomalous settlements of the corner columns and the ones adjacent in two locations of the building.

The calculated out-of-perpendicular displacements of the walls are also in agreement with the measured deviations. Geotechnical tests in situ have confirmed the particularly poor nature of the underlying soil, especially under the two mentioned corner zones. In situ stress values measured by flat-jacks in 8 locations of the walls were also in agreement with the numerical analysis.

Design of the Reinforcements

The same finite element model adopted to determine the actual state of stress was employed to define the minimum reinforcement needed to increase the local safety of the walls in order to make it homogeneous throughout the building *(Fig. 4).* The ratio between the radius of the limit Mohr circle and that of the concentric actual one was assumed to be the safety factor. The numerical model allowed study of different patterns of internal and external reinforcing bars in order to choose the most effective.

Mixed quartz-epoxy resin injections in the walls were simulated to locally improve the safety factor. Seven inox steel bars, 20 mm in diameter, were adopted for every arch, with a radial layout thus obtaining a sort of continuous steel truss in between the arches and the lower windows.

All around the floor of the large inner room, a strong C-shaped steel tie, continously connected to the walls, was proposed but local conditions better than expected made this provision unnecessary. A similar C-shaped continuous tie was, however, adopted under the roofs wooden trusses.

By introducing 14 pairs of X-crossed cables in between the roof trusses, a rigid diaphragm was obtained which strongly connects the four principal walls and makes them to work together. Another external steel cable was installed at the level of the original roof, all around the perimeter, below the 18th century upper structure. This cable is fixed to the wall every 7 m and tensioned portion by portion, thus confining the masonry in a zone with strong structural discontinuities.

Reinforcing injections were used at the tensioned cables' reaction points, where the heads of 17th century chains were present, too. Crossed bars were also used to reinforce the corners of the building, thus connecting the orthogonal walls. Using small diameter steel bars, the masonry vaults located below the first floor level were fixed to the principal walls, where they appeared to be disconnected.

No reinforcements were adopted for the foundations, as no more differential settlements were expected.

Works ended with cleaning of the 18th century masonry walls and with local nailing of the protective mortar plaster. The temporary steel ties connecting all the columns on the ground floor since 1959 were then finally removed.

Conclusions

In 1984, the oldest civil building in Milan was given back to the town in the same form it had had since the 18th century, but strongly reinforced. The dramatic proposal of demolishing the upper part had been avoided in the end.

Dynamic tests to record the global behaviour of the building were performed before and after the execution of the consolidation works. Trains in the underground close to the foundations were used as input dynamic loads. A regular repetition of the same dynamic tests would be useful in evaluating the effectiveness and durability of the adopted proposals.

References

[1] BONALDI, P., JURINA, L., ROSSI, P. P. *Indagini sperimentali e numeriche sui dissesti del Palazzo della Ragione di Milano,* 14th Nat. Geotech. Conf., Firenze, 1980.

[2] JURINA, L. *Valutazione del degrado strutturale di edifici in muratura.* Conf. on «Il recupero del patrimonio edilizio storico», Ancona, 1981.

[3] JURINA, L., PEANO, A. *Characterization **of brick masonry stiffness by numerical** modelling,* 6th IBMAC, Roma, 1982.

[4] BONALDI, P., JURINA., L. *Determination **of foundation settlements.*** **Through *analysis of cracks in old masonry buildings.*** ICSMFE, Stockholm, 1981.

[5] BINDA MAIER, L., ROSSI, P. P., SACCHI LANDRIANI, G. *Diagnostic analysis of masonry buildings.* IABSE Reports Vol. 46. IABSE Symposium Venice, 1983.

[6] CALIFANO, R, JURINA, L. *Flat jack: evolution of the test technique.* AIPnD Int. Conf. on Monitoring and Predicitive Maintenance of Plants and Structures - Firenze, 1992.