ABSTRACT: The facade of St. Peter's Basilica suffered a considerable differential settlement during construction (between 1608 and 1612), which gave rise to large sub-vertical cracks of the walls and longitudinal cracks of the vaults. The simulation of the settlements by a FEM analysis found a reasonable agreement with the historical description of the pathology and with modern surveys.

1. INTRODUCTION

When Bramante heard that Pope Julius II had in mind of "pulling down St. Peter's Church and rebuilding it" (Vasari 1550), prepared the drawings for a new Basilica. During the year 1506 the foundation stone was laid.

The new church was a centrally-planned building, centred on the burial chapel of the Apostle, and therefore somewhat shifted toward the West in comparison to the existing Basilica built by the emperor Constantine (nearly 1200 years before), partially on the ruins of the Circus of Nero (Poleni 1748). The position of the building was farther from the Tiber, therefore founded on a better soil than the Nartex of the Old Basilica, whose stability problems were partially due to the weak foundation (Fig 1).

On the already built pilasters (having however greatly increased their size) Michelangelo undertook the construction of the drum, on his own innovative design of the great dome. In 1590 (27 years after Michelangelo death) the dome was completed.

At that time, some suggestions began to arise for a substantial change of the central plan into a Latin plan with a long nave. Pope Paul V planned the completion of the new church with the nave and the shift of the facade position toward the river.

Carlo Maderno won the competition for the construction of the nave and of the facade for the Latin cross. The works began in 1608 (Fig 2)

2. HISTORY OF THE PATHOLOGY

The choice of the new position of the facade proved soon to be unfortunate. A famous etching (Fontana 1694. Fig 3) shows the situation in the subsoil: the depth of the good soil (the Vatican loam rock) is variable along the facade, from about 15 m at the Northern edge to about 25 m at the Southern one (left edge).

The difficulties found in building the foundations at such a depth in presence of water springs (Hibbard 1971), the different depth of the soft soil along the building, the presence of the remains
of the Circus of Nero and, last but not least, the weight of 140,000 tons of the huge Facade were the reasons of large differential settlements during and after the construction works.

The history of the damages is complicated by the fact that the Facade (a block 115 m long, 23 m wide and 49 m high) was built in three phases: first the central section and then the two towers. The foundation of the Southern edge of the central section did not succeed in reaching the good soil and the entire building rotated for the differential settlement and a first crack pattern appeared and involved the vault of the "Loggia delle Benedizioni" (Fig 4).

When the construction of the southern Tower began (1618) a special foundation by pits and piles was adopted, but when Bernini in 1638 tried to superimpose his campanile the size of the cracks increased and the campanile had to be demolished.
The main pathology already present at that time was formed by four subvertical large cracks (called "cretti", Fig 5), having a maximum width of some 22 cm and extended from the top of the wall to the foundations. Such cracks are cutting the facade wall into nearly independent blocks.
The differential settlement is at present 40 cm and the "cretti", although repaired on the travertine surface, are still there.

Figure 5: "Cretti" (large cracks) shown on the photogrammetric view (Enitecnologie)

3 GEOMETRICAL SURVEY

When in 1997 the "Fabbrica", together with its partner and sponsor ENI, undertook the restoration of the Facade for the degradation of the stone, one of the first works was a photogrammetric survey that was the geometrical support of the entire project and allowed also to check the irregularities arisen by the ancient pathology. Together with the subsequent physical surveys, photogrammetry precisely confirmed the position of the old cracks and measured the out-of-plumb of the pilasters, providing in this way precious elements for an assessment of the building.

Two components of the deviation from the vertical line were measured:
- the out-of-plane deviation, which shows an overall tendency to rotate toward the Piazza;
- the in-plane deviation, which is a consequence of the differential settlement along the Facade.

Measured on an height of only 20 m on the gigantic columns, both deviations reach a maximum of about 20 cm:
- transversally (out-of-plane), the deviation is nearly constant for a considerable length of the central section; it is much lower for the Towers; it is correlated with the longitudinal cracks of the vaults already known at the time of the works (1617);
- longitudinally (in-plane), the deviation is concentrated on the Southern part of the central section and on the Southern tower (left), showing its clear correlation with the differential settlement and the formation of the "cretti".
4 INVESTIGATIONS AND MATERIAL TESTING

Among several investigations, most of which were dealing with the crack pattern and its monitoring, some were addressed to provide geometry and nature of the foundations and the mechanical properties of the structural elements of the Facade.

Radar and sonic tomography (Fig 7) provided more details of the "cretti". Drilling cores and corresponding endoscopy and laboratory tests allowed to get material properties for the numerical model. Radargrams allowed to define the mean thickness of the travertine stone and the residual part filled with the very soft tuff conglomerate (Fig 8).

5 NUMERICAL MODELS

The first aim of the numerical models was to follow the history of the works and of the settlements in order to give a consistent explanation of the crack pattern and provide probable values of the present state of stress in the different sections of the building.
Modelling the great structure posed difficult and essential problems of boundaries, which had to find their solution in assumptions based on the history of the works or on physical evidences (results of the investigations, presence of large cracks, measured displacements).

Three main problems arisen.

a) Thickness and shape of the two longitudinal foundation walls and possible existence of transversal connections: the geometry of the Eastern wall was measured, and no element of connection was found, so that the walls are considered as independent.

b) Connection of the Facade block to the nave of the church: the great vault of the nave was built in 1613-1614 (Hibbard 1971), at the same time of the Northern tower (1612-1614) but before the works of the Southern tower (1618-1621), so that a different kind of connection might be considered for the two towers; the structure of the central section of the Facade was finished in 1612 (in 1613 the statues of the attic are positioned), so that it should have behaved as an independent body during the first soil settlements; the assumption of independence from the nave was also supported by the consideration of the observed out-of-plane rotation of the section (considerably higher than for the towers), and the evidence of old cracks at the connection between the Facade and the church walls; as a consequence, a first model considered the central section alone, and the following models included also the towers; both cases of connection with the nave and of lack of connection were considered, looking for the differences between the extreme assumptions.

c) Connection between the central section and the towers: there are no expansion joints, and the construction was done at a different time but in continuity; for this reason, and for the fact that a part of the settlement took probably place when the continuity was reached, some models considered the Facade as a whole.

The finite element mesh used 8 node brick elements and 4 node shell elements. Several models of increasing complexity were built; the maximum size was 357,000 degrees of freedom.

Five different materials with different E moduli were introduced into the model, E being variable from 1000 MPa for the foundation masonry to 90,000 for the monolithic columns. Such a great rigidity difference has the consequence of stress concentrations on some elements to an amount that was difficult to imagine by simple intuition, but was proved by the evidence of local compression damages on capitals and column bases.

Figure 9: Differential settlement.

The apparent solidity of the building, with its walls 5 m thick and with the gigantic columns of 2.7 m of diameter, is contrasting with the real fragility due to the lack of any efficient connection.
between the two huge walls: the 82 m long central section has only two transversal structural elements: the two slender brickwork vaults of the Portico and of the Benediction Loggia, both having a thickness of about 40 cm. (Fig 10).

Under the only effect of its own weight, and by a simple linear analysis that does not take into account its damage pattern, the structure appears to be subject to considerable deflections and state of stress. The compression reaches 2.0 MPa in the infill conglomerate, 7.0 on the travertine at the basis of the towers, 9.0 in the monolithic columns.

However, the two vaults are the most stressed structural elements, and their longitudinal cracks, for which the soil settlement had probably the essential role, could be justified by the tension itself already present under permanent load (Fig 11).

6. SIMULATION OF THE PATHOLOGY

The aim of the numerical models used for the simulation of the pathology was twofold:
- to understand the formation of the "cretti" by their correlation to the soil settlement
- to check the state of stress of the structure taking into account the effects of the existing damages.

The effects of the differential settlement of 40 cm that took place during and after the construction could not be studied by application of such an imposed displacement at the basis of the complete building under linear elastic assumptions. The displacements were in fact imposed, during the time of the works, to a variable structure, very slender and deformable at the beginning and of increasing height and stiffness with time. The displacements continued after the completion of the Southern tower, after many years, and creep of the masonry should have affected essentially the state of stress reducing it with time.
Therefore, the settlement resulting from the measurements, nearly linear from the axis of the central section to the Southern edge (Fig 9) was scaled to 1/8, i.e. 50 mm., for the application to the linear elastic model. Such an arbitrary value was sufficient to create a state of stress that may be considered immediately preceding the crack formation.

Fig 12 shows the resulting tensile stress contour, which suggests a reasonable correlation with the real position of the cracks (specially the 4 "cretti", see Fig 5).

![Figure 12: Tensile stresses on the central section under the effect of the settlement.](image)

The second aim, the state of stress of the damaged structure, was researched by introducing the large main cracks in the model as discontinuities. The four "cretti" were simulated as vertical cracks for the entire height of the Facade, transversally extended from the front wall up to the axis of the vaults. The main effect is observed between "cretti" II and III, where the two cracks cut a slice of the facade that has tendency to move independently.

7. CONCLUSIONS

This case study is one of the most consistent examples of the general methodology that should be used for the assessment of historical constructions (Macchi 1997), where experimental studies and numerical analysis should help each other, and an essential contribution may be found in the historical analysis.

Also in this case, as in the previous one of Pavia Cathedral (Macchi 1998), the conception of the building had an essential role in the development of the pathologies.
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