Fractures and stability of the French Panthéon

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ABSTRACT. *The French Panthéon has showed, both in ancient and recent times, several fractures in the stones of its masonry, which also caused the partial closure to the public visits in the latest decades because of the fall of stone fragments. The French Ministry of Culture and Communication commissioned a new study [1] to identify the causes of the present disorders, whose results are presented in this paper. A multidisciplinary approach, with a balanced fusion of historical analysis, precision surveys, experimental inspections and numerical modelling, enabled to spot the damage mechanisms that have provoked the first disorders and the ones that are still active, giving hints on the possible solutions. The interest in these studies arises also from the fact that the French Panthéon, designed in the XVIII century with slender structures and innovative techniques, can be considered as the first building for whom tests on materials and "modern" structural calculations have been carried out in a systematic manner. The present studies can be thus seen as the prosecution of a structural inspection that started 250 years ago and is still ongoing.*

INTRODUCTION

In the latest decades we have witnessed a great development of finite element codes, that has lead to results numerically more and more precise and to the adoption of models for structural analysis more and more complex. The brilliant results obtained in the numerical field should not conceal the great approximations that still exist in passing from the real structure to the calculation model and in determining the great amount of parameters introduced. It is not only a problem of uncertainties on constitutive laws for the materials behaviour in the short period, but also on the various natural phenomena that can involve the buildings structures in their long life: the magnitude and distribution of loads, the deterioration phenomena, the constitutive laws depending on long and very long time-periods (i.e. those due to chemical-physical factors evolving very slowly), the alterations of subsoil, the man-made modification interventions, the strengthening operations themselves and all those events that are particularly complex to quantify numerically. The risk is to have more and more sophisticated calculation methods that produce only apparently precise results, as they are affected by errors in passing from the reality to the numerical model. These error factors can, in some way, be estimated statistically for new buildings, but in the existing buildings, on the contrary, they represent factors strictly connected with their specific reality. In particular, historical and monumental constructions, both for their building characteristics and for the historical vicissitudes they underwent, represent singular elements to which it is impossible to apply methods based upon statistical analysis defined over large numbers: each monument is a unique reality. The great difference between a numerical model for the design of a new building and a numerical model of a historical building is that in the first case the numerical model represents the reality to which the new structure (still virtual) will have to resemble, whereas in the analysis of a historical building, the reality is represented by the building itself, and the virtual model must be able to describe this singular reality. For this reason, the accurate identification of reality in all his aspects (geometry, history, traumas, deformations, materials, deteriorations, etc) constitutes the preliminary and fundamental phase of structural analysis: only the complete knowledge of reality and the agreement between the model results and the reality itself will be able to validate the structural analysis. In the case of historical masonry structures, this is even more true, as masonries have complex behaviours, characterized by non homogeneities, non linearities, anisotropy and complex long term behaviour, so that the majority of numerical methods encounters great difficulties in finding acceptable numerical solutions in the static and (overall) in the dynamic-seismic field.

Two phrases, on this subjecy, are particularly signicative. The first one is by Prof. Roberto Di Stefano of Naples University wrote in 1981: "*The study of the static behaviour of ancient structure [...] is always historical inspection*". The second one can be found in [2] written in 1989 by some Italian sesmic experts: *"For old buildings, and not only for mon uments, it is preferable to follow, as far as static perturbations are concerned, the empiric-experimental method"*.

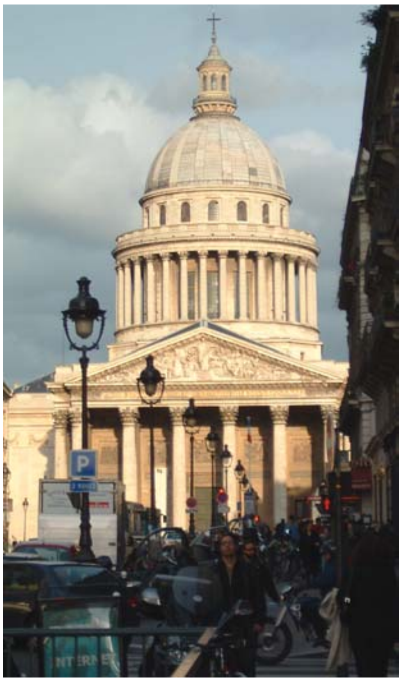
The studies that have been carried out to understand the causes of the disorders of the French Panthéon are a meaningful example of how only a close joint work between historical studies, accurate surveys, experimental analysis and numerical modelling can lead to an adequate response to the mechanical problems of complex historical buildings. At last, only an adequate knowledge of the previous behaviour can allow to use at best the historical structures reducing to the minimum the interventions needed for its strengthening, as required for each correct intervention on monuments, avoiding invasive interventions on historical structures that are often carried out based upon mere structural calculations.

THE HISTORY OF THE PANTHÉON: MODIFICATIONS, DISORDERS AND STRUCTURAL STUDIES DURING TIME

The French Panthéon (Figure 1) was designed by Soufflot in 1756 to be the biggest church in Paris, dedicated to Sainte Genevieve, patron saint of the town. Due to the death of its designer, the construction was finished by Rondelet in 1790. The adoption of an innovative building technique (the reinforced stone masonry, see Figure 2) and of the reduced dimensions of wall structures, that did not follow the classical building rules, lead to the necessity of apposite calculations, that made the Panthéon become, probably, the first building to be designed on the base of modern methods of structural engineering.

Still in the project phase, the first objections aroused from the architects linked to the old academic building tradition, particularly from Pierre Patte [7], because the structures did not respect the canonical proportions: pillars too slender, domes masonry too thin, windows too large. To answer this first campaign of polemics, Jacques-Germain Soufflot and Emiland-Marie Gauthey, director of the prestigious "École des ponts et chaussés", carried out the first systematic compression tests on stone specimens and the first calculations [4,6], demonstrating that the pillars had a cross section large enough to sustain the weight of the domes considering a centred load.

Unfortunately the pillars masonry, realised with the new building technique, showed problems and crushing fractures since the construction phase, stirring up new polemics, inspections and calculations. Thus, the second phase of the debate concentrated on the eccentricity of the load on the pillars and, as a consequence, on the thrust of the domes and on the possible strengthening systems. The controversy compressed between the opinion of Gauthey [4], who wanted to oppose the domes thrust with new buttresses, and the opinion of Rondelet [3], who thought that the domes did not thrust, thanks to the many metal rings in the stone of the dome and that the cause of the fractures in the pillars was to be found in the bad execution of the pillars masonry. The assays made by Rondelet showed that the thickness of mortar beds was few millimetres on the external surfaces, while it was some centimetres on the inside. The whole load weighted thus only on the boundary of the pillars.



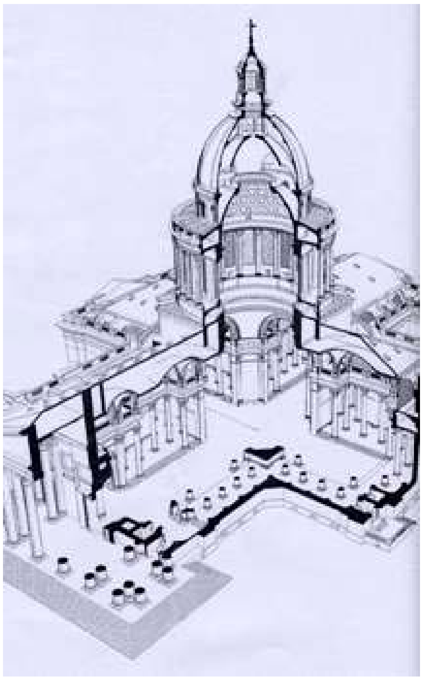


Figure 1: The Panthéon today: a picture and an axonometry with view of the inside.

Napoleon entrusted Rondelet with the strengthening of the pillars in 1806.

New fractures showed up later in the centuries in other parts of the monument and recently some stone fragments fell from the ceiling. For these reasons the French Ministry of Culture and Communication decided, since 1980, to subject the monument to a programme of structural inspections, and, in 2005, to entrust Carlo Blasi with a specific and complete study on the stability of the monument and on the causes of the disorders, to ensure the required safety to the monument.

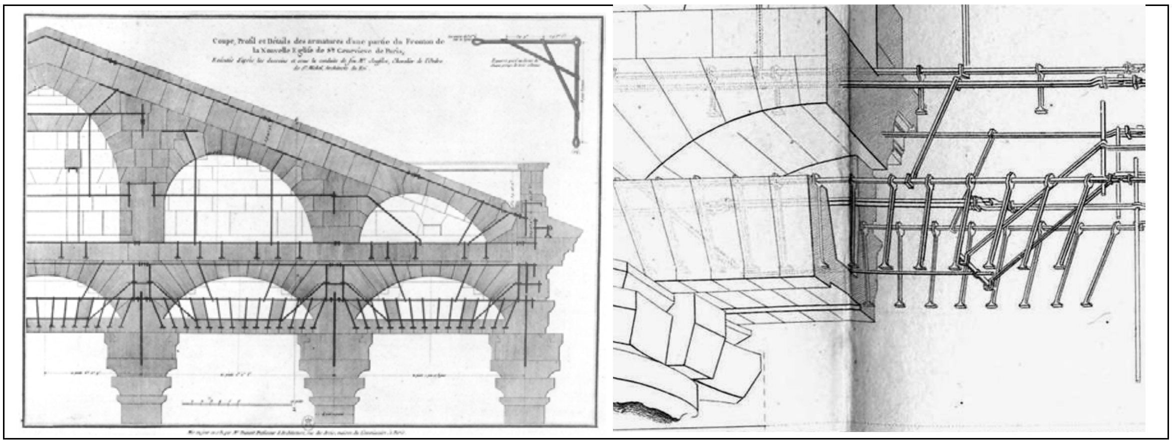


Figure 2: Rondelet's drawing of the reinforcement iron bars inserted in the stones of the flat arches, that in this way work as ties for the overstanding arches [5].

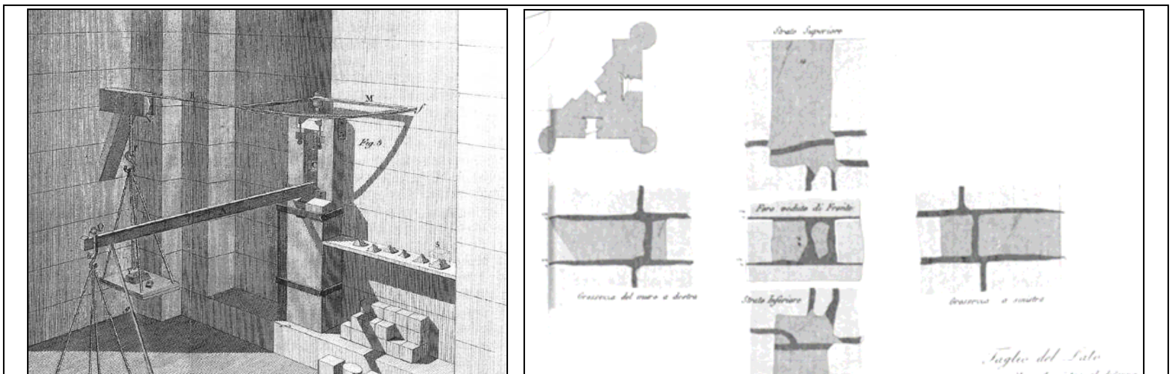


Figure 3: Gauthey's machine to carry out the first compression tests on building materials (left) and asseys made by Rondelet in the Panthéon's pillars (right) [5]. Thanks to the experimental tests, Rondelet could compare the existing stresses in the pillars and the cracking stresses, demonstrating that the dimensions of the pillars were correct. The asseys showed that the cause of fractures was in the bad execution of the masonry, with thin joints on the outside and thick ones on the inside [1].

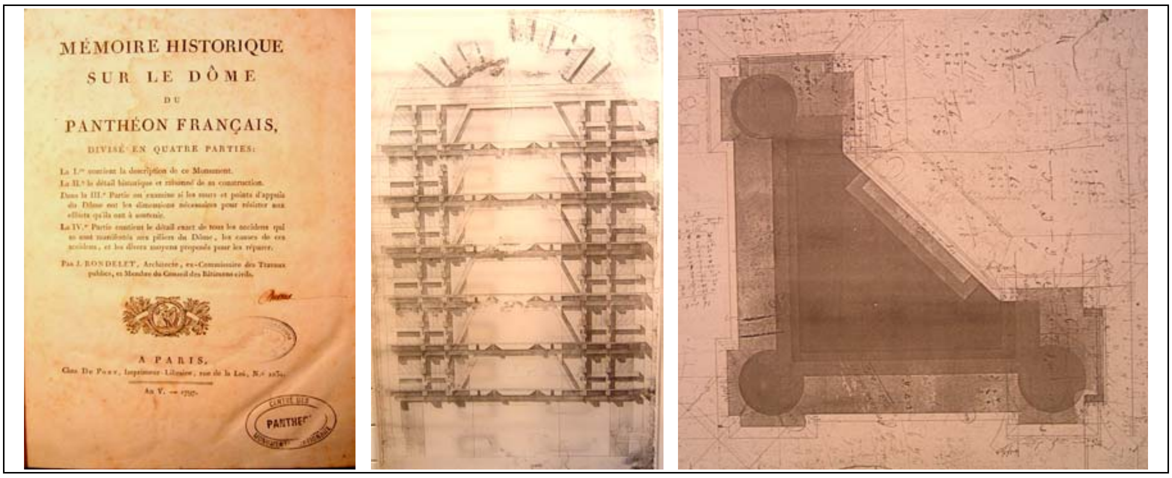


Figure 4: Rondelet's 1797 Mémoire on the stability of the dome of the Panthéon [3], with a system for the propping of the pillars and Rondelet's calculations and proposal for the reinforcement of pillars.

In this study, professors of different disciplines from the University of Parma have been involved (chemistry, mineralogy, metallurgy, fracture mechanics, geothecnics, precision survey) and experts in buildings humidity.

Only thanks to a strict interdisciplinary collaboration and to the study of all historical documents it was possible to reconstruct the deformations and the disorders form the construction until now, to model the structural behaviour of the building during time and to spot the damage mechanisms that have provoked the first disorders and the ones that are still active.

Apart from the authors, the others participants to the study were: Ivo Iori and Daniele Ferretti (structures modelling), Gianni Royer (stone fractures modelling), Sandrine Voyer (in situ inspections), Paolo Giandebiaggi and Andrea Zerbi (surveys), Alessandro Mangia and Giampiero Venturelli (materials analysis), Margherita Ferrero (geothecnics), Paolo Bresci and Leopoldo D'Inzeo (internal climatic conditions).

INSPECTIONS AND ANALYSES IN A MULTIDISCIPLINARY APPROACH

As shown in the previous chapter, the present study can be seen as the prosecution of a structural inspection that started 250 years ago and is still ongoing. The approach to this study was thus based first of all on the knowledge of all the historical documentation (designs, calculations, surveys and level measurements, tests on materials, disorders measurements) and developed, after a preliminary campaign of high precision surveys, with a continual comparison between the results of the numerical analyses and the observation of the behaviour of the monument during centuries.

In particular, before the proper structural analysis was started, the following studies have been carried out:

- Study of all design and calculation documents made by Gauthey and Rondelet [3,4,5,6];
- Study of all the surveys on fractures, the monitoring and the level measurements made in XVIII century [4];
- Survey of all the disorders at present (fractures, deformations, displacements, materials decay) and comparison with the data of XVIII century, in order to reconstruct the evolution of the disorders [1,8,9,10,11];
- Study of all the strengthening interventions carried out on the building during the centuries [3];
- Study of the mechanical behaviour of materials [1,10] .

Based upon these data, it was possible to spot all the pathologies that affect the monument. Only after the existing pathologies have been identified, the numerical models able to describe exactly these disorders were defined. To avoid models too cumbersome and unable to grasp the specificities of the different pathologies, partial models and different codes have been adopted to describe the different parts of the structure.

Figure 5: The types of fractures in the stones are very interesting: some are caused by structural disorders, some by the presence of traction in the iron clamps, some by the different thermic behaviour of different parts of the structure.

In particular:

- non linear finite elements analyses (ABAQUS code) have been carried out to model the static and thermal behaviour of domes (Figure 8) and “plafonds” (thin ceilings);
- non linear distinct elements analysis (UDEC code) have been used in the reconstruction of the disorders in the great arches that sustain the external colonnade of the dome (Figure 8);
- a variational non-local model of quasi-static crack evolution have been adopted to understand the typical crack pattern found in the stones of the Panthéon (Figure 9);
- a closed form solution for the visco-elastic problem of long-term strains and stresses in pillars have been carried out.

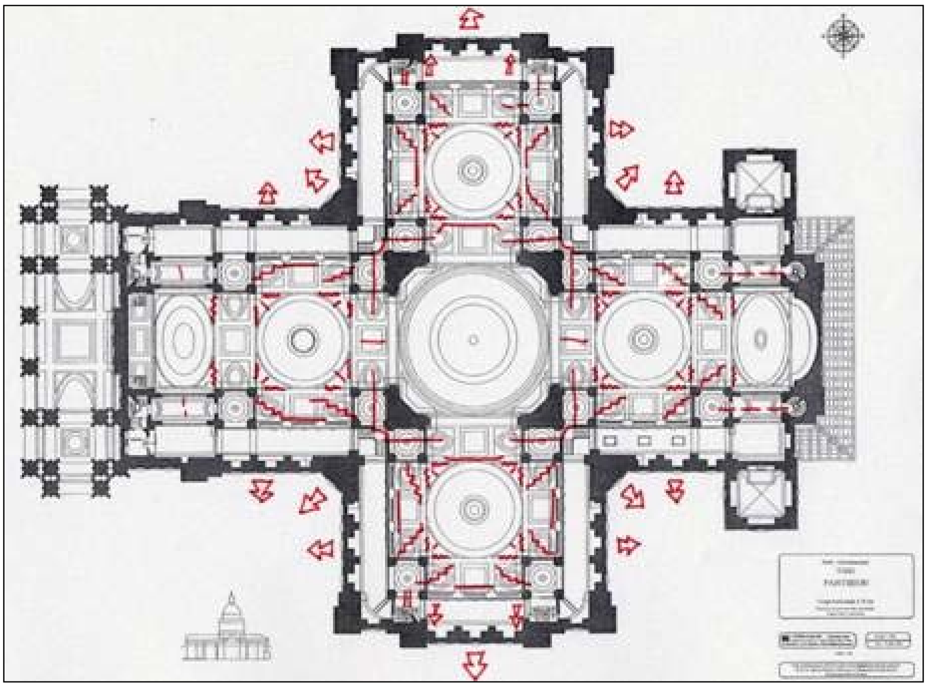


Figure 6: Scheme of fractures and main disorders: the symmetry of the pattern demonstrates that the causes of the disorders are intrinsic to the structure [1].

As a meaningful example of the results obtained, it can be noticed that the value of the secant elastic modulus that was adopted to reproduce the real deformations that manifested during centuries was very low. Although the models take into account the non linearities due to section partializations and although the stresses were far below the plasticity limit, the secant elastic modulus of the stone subjected to long time loads resulted 2000 MPa, i.e. over 10 times less than the value that can be obtained by short-time experiments. This value was confirmed in all the parts of the monument.

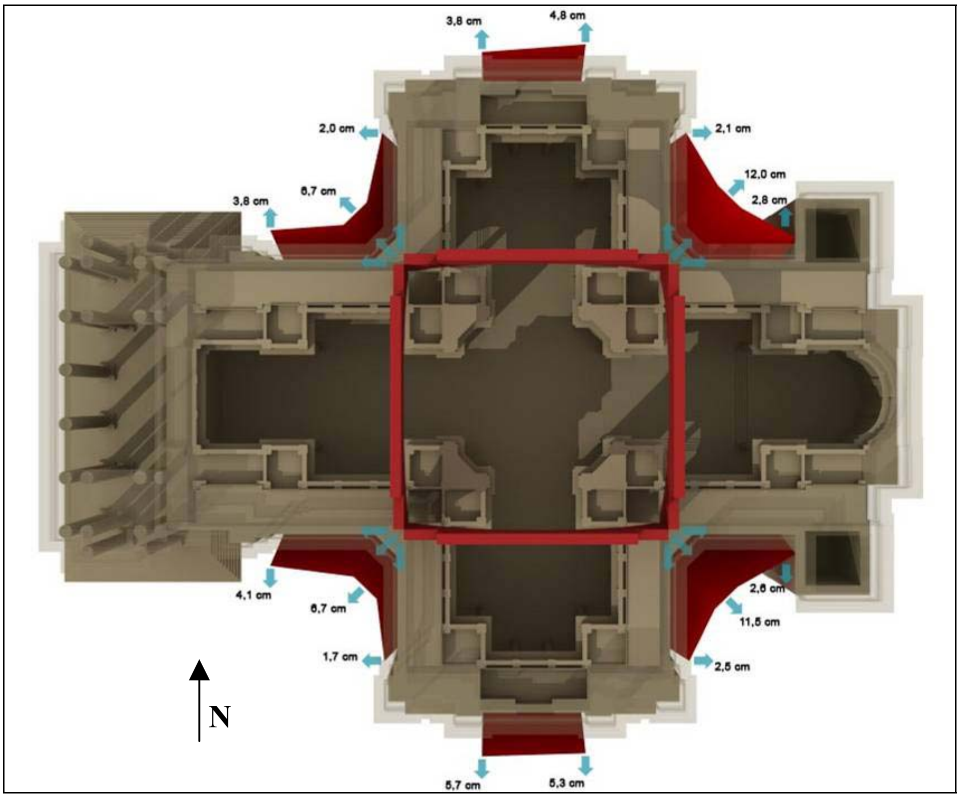


Figure 7: The precision measurement of the deformation of the outer walls [1] showed that the disorders are perfectly symmetric between the north and south sides, but not symmetric between the east and west sides, probably due to the effects on the dome of the dominant wind from west.

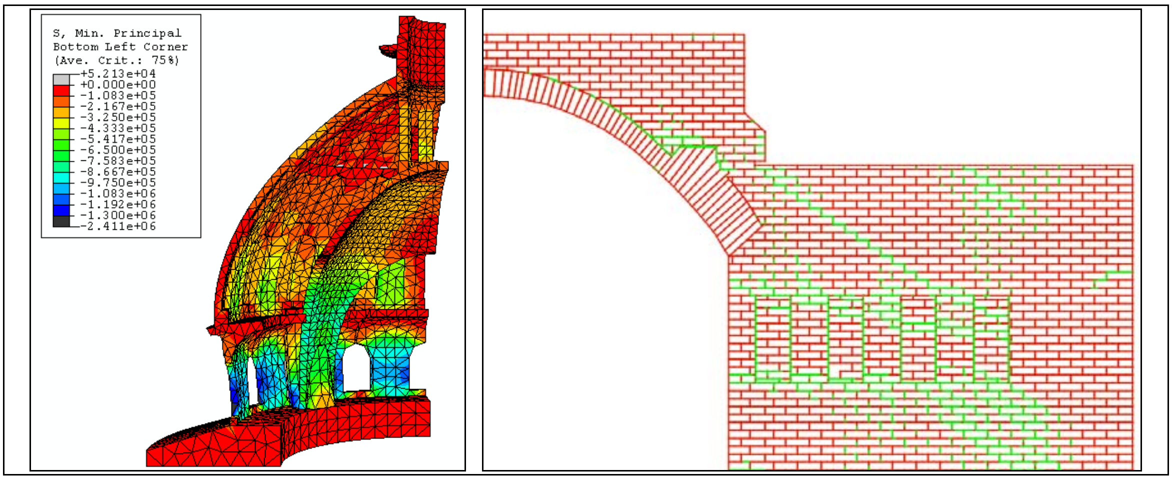


Figure 8: On the left: a non linear finite element model (ABAQUS) of the two outer domes. On the right: a distinct element model (UDEC) for the analysis of fractures in the great arches and in the outer walls [1].

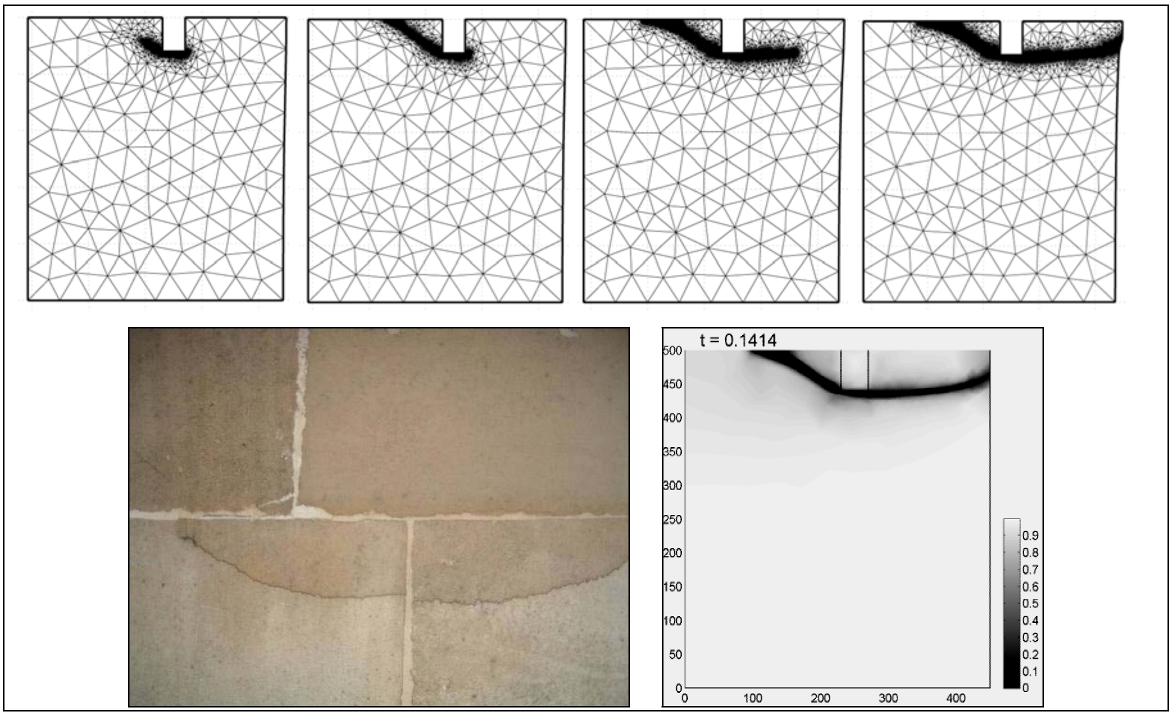


Figure 9: Crack propagation in the stone, induced by the tensile stresses in the iron clamps, obtained through a costitutive model with non-local damage based upon energetic criteria (Royer, in [1]). The comparison between a recurrent fracture type in the masonry and the results of the analysis shows a close similarity.

THE CAUSES OF THE MAIN DISORDERS

The stone masonry reinforced with iron clamps and ties was a building technique completely new at the time of the construction of the Panthéon, made possible by the spreading of iron due to the technological development at the beginning of the industrial era. This new technique allowed Soufflot to realize very slender structures, comparable only with the structures that one century later will be made with reinforced concrete. Indeed, looking at the drawings depicting the iron clamps in the flat arches, it seems to look at drawings of reinforced concrete trusses (Figure 2). Soufflot has developed his design basing only upon his structural intuition and also the calculations made by his friends and co-workers Gauthey and Rondelet are little compared to the complexity of the problems posed by the new structures.

The slenderness of the structures, together with the real long time deformability of the masonry has, however, produced large deformations on structures, unforeseen and inconsistent with the fragility of reinforced stone masonry. The presence of iron clamps, indeed, produces, under long time loads, stress concentrations in the stone and consequent fractures. The characteristic shape of the cracks in the stones due to the presence of the iron clamps was exactly recreated with numerical crack models. In brief it was demonstrated as the cause of fractures, repeated in a perfectly symmetric way in the whole building, is to be traced back in the global deformability of the masonry, associated with the local fragility of connections [1]. In particular, the structural elements that mainly show problems and deformations are the four great arches, with a span of over 30 metres, that sustain the external colonnade of the tambour. These arches thrust on the boundary walls both with high static horizontal forces (about 3300 kN) and with dynamic actions caused by the wind.

Figure 10 shows the deformations of the outer walls, perfectly symmetrical and accurately surveyed. These walls involve in their deformations also the thin ceilings, that consequently get fractured, and induce torsional phenomena in the overstanding circular galleries (Figure 11).

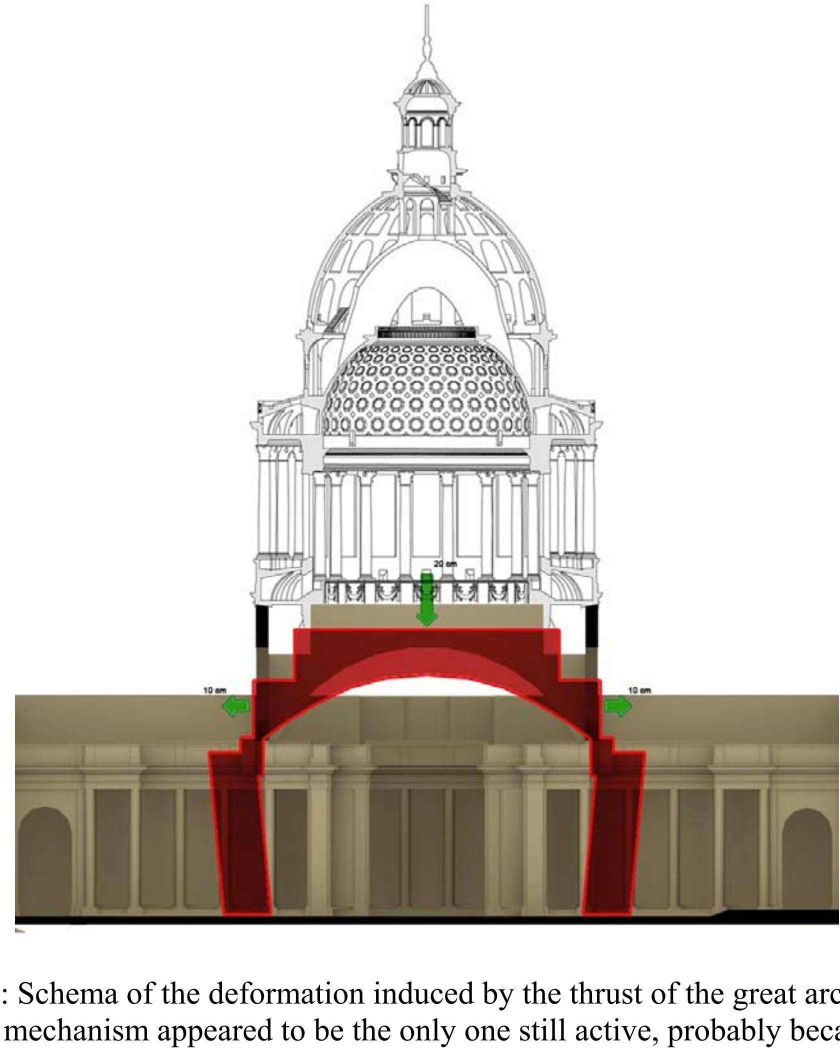


Figure 10: Schema of the deformation induced by the thrust of the great arches: the described mechanism appeared to be the only one still active, probably because it is cyclicly triggered by the action of wind on the dome [1].

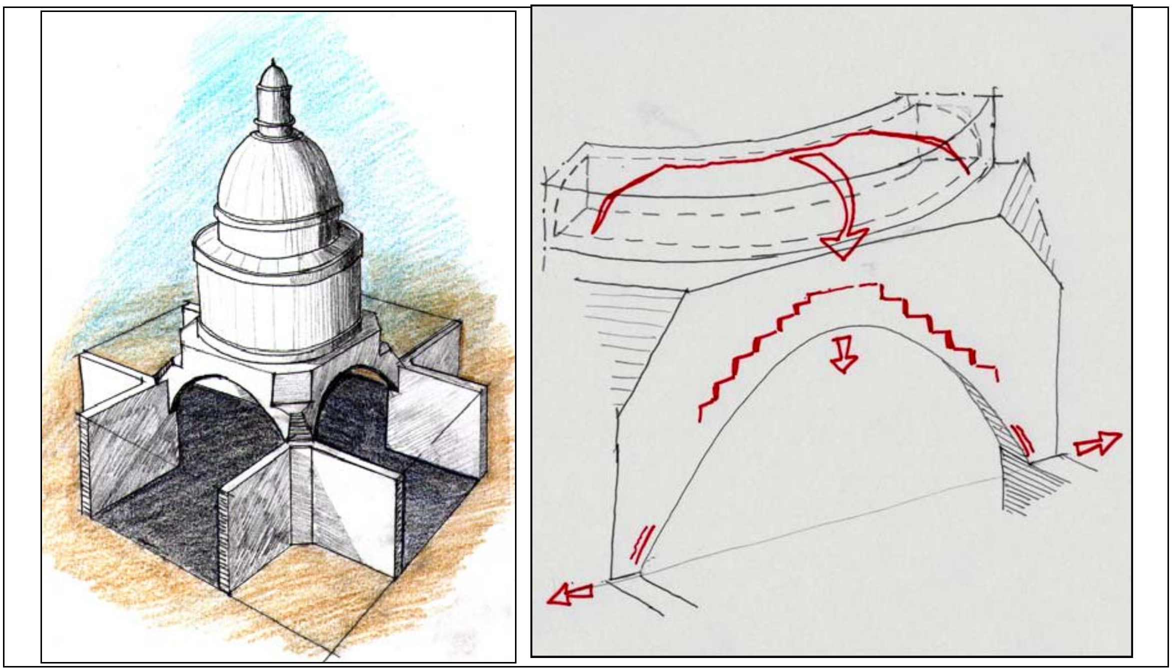


Figure 11: Schemes showing the behaviour of the great arches: the settlement of the top of these arches have induced torsional phenomena in the circular galleries.

CONCLUSIONS

A complete reconstruction of the historical evolution of the damage, of the strengthening interventions, of the many studies made, accompanied by a precision survey of the deformations and by analyses on the material properties were the prerequisites for the comprehension of the structure’s behaviour and for the correct formulation of numerical analyses. The cause of the cracks was identified in the fragility of reinforced masonry compared with long time deformations. The only mechanism that was found to be still active is the settlement of the great arches, triggered by the cyclic actions of the dominant West wind, that causes fractures in all the adjacent structures.

As it is clearly impossible to remove all the clamps between the stones without destroying the monument, the solution to hinder new fractures must be searched in the introduction of pre-stressing systems in masonry and, overall, in the active opposition to the thrust of the four great arches.

The designers of the French Panthéon adopted, with overall positive results, a new experimental technique on a huge building: they showed a high static sensibility, a remarkable inventive capacity and design courage, but they could not foresee creep phenomena, stress concentrations and plastic deformations under long time loads that have only recently been inspected. As far as nowadays studies are concerned, only a global and accurate analysis of the behaviour of historical structures all along their life allows us today to understand fully the magnitude of these slow phenomena.

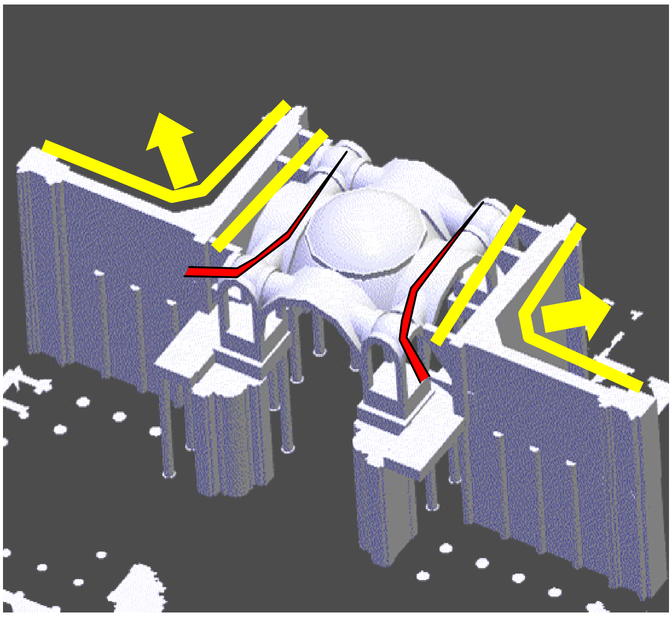


Figure 12: This schematic drawing summarises the crack pattern in the Panthéon induced by the deformations of the outer walls.

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