

## THE IMPORTANCE OF HISTORICAL DOCUMENTS FOR THE STUDY OF STABILITY IN ANCIENT BUILDINGS: THE FRENCH PANTHÉON CASE STUDY

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### ABSTRACT

The recent studies on the stability of the French Panthéon [1], commissioned by the French Ministry of Culture and Communication, enabled to spot the causes of the structural disorders, thanks to a balanced fusion of historical analysis, precision surveys, experimental inspections and numerical modelling.

The interest in these studies arouses also from the fact that the French Panthéon, designed by Soufflot with slender structures and innovative techniques and finished by Rondelet in 1790, can be considered as the first building for whom tests on materials and “modern” structural calculations have been carried out in a systematic manner.

**Keywords:** ancient buildings, historical documents, survey, numerical analysis

### 1. INTRODUCTION

The development of finite element codes has lead, in the latest decades, 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.

If these error factors can, in some way, be estimated statistically for new buildings, in the

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existing buildings, on the contrary, they represent factors strictly connected with their 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.

Prof. Roberto Di Stefano of Naples University wrote in 1981: *“The study of the static behaviour of ancient structure [...] is always historical inspection”*. In the case of masonry historical structures, this is true more then ever, as masonries have very complex behaviours, characterized by non homogeneity, non linearity, anisotropy and long-time complex behaviour; thus, most numerical methods encounter enormous difficulties in finding out acceptable numerical solutions in the static field and (overall) in the dynamic-seismic one.

The numerous and different 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. These arguments may seem obvious and banal, but invasive interventions on historical structures based upon mere structural calculations can still be seen with a worrying frequency.

## 2. THE SOUFFLOT'S PANTHÉON IN PARIS

The French Panthéon (Figure 1), started by Soufflot in 1756 as the biggest church in Paris, dedicated to Sainte Genevieve, patron saint of the town, and finished by Rondelet in 1790, is, probably, the first building to be calculated with modern methods of structural engineering. The need for these calculations was the consequence of the adoption of an innovative building technique (the reinforced stone masonry, see Figure 7) and of the reduced dimensions of wall structures, that did not follow the classical building rules. Still in the design phase, the first objections aroused from the architects linked to the old academic building tradition, particularly from Pierre Patte [6], 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 [3,5], demonstrating that the pillars had a cross section large enough to sustain the weight of the domes considering a centred load (Figure 2).

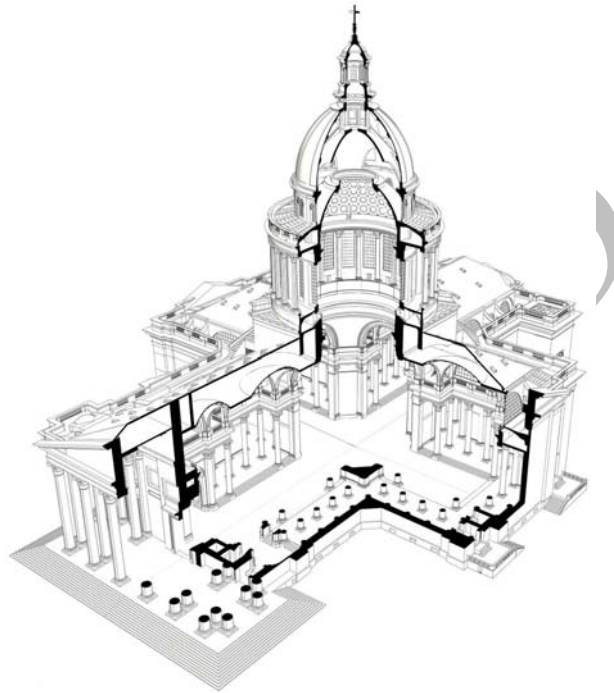


Figure 1. Axonometry of the monument with view of the inside [10].

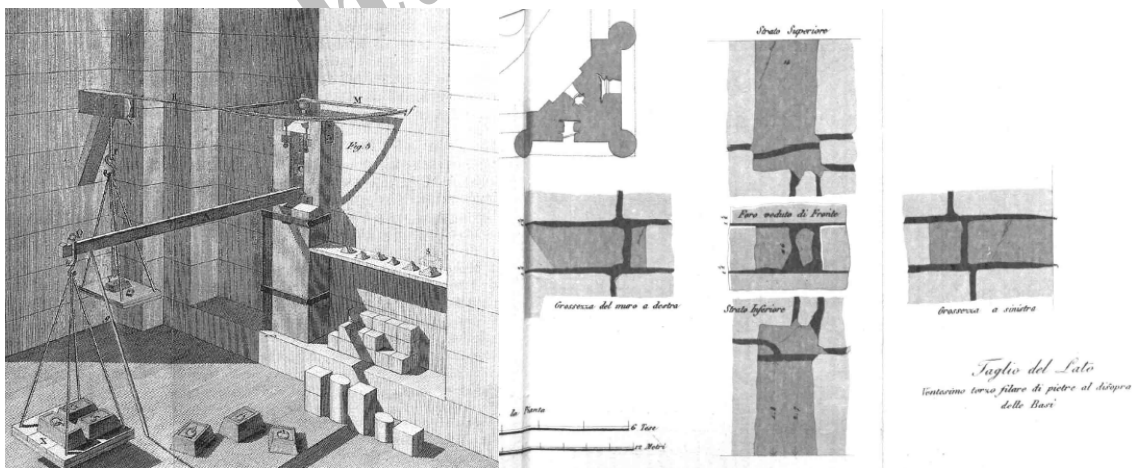


Figure 2. Rondelet's drawing of Gauthey's machine to test stone in compression [4] (on the left) and Rondelet's assays on the pillars [1] (on the right).

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 [3], who wanted to oppose the domes thrust with new buttresses, and the opinion of Rondelet [2], 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 searched 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 2).

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 to subject the monument to a campaign of new structural inspections to ensure the required safety to the monument.

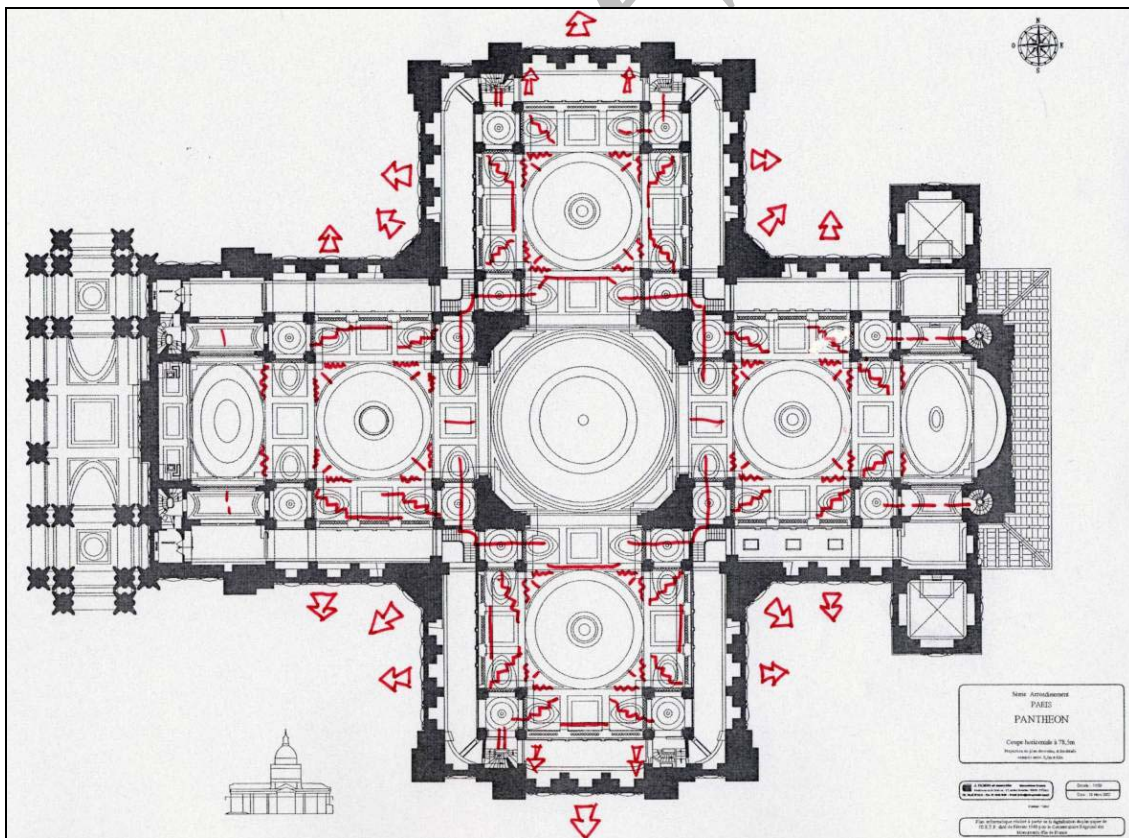


Figure 3. Schematic survey of the main crack systems (position and global interpretation) [1]

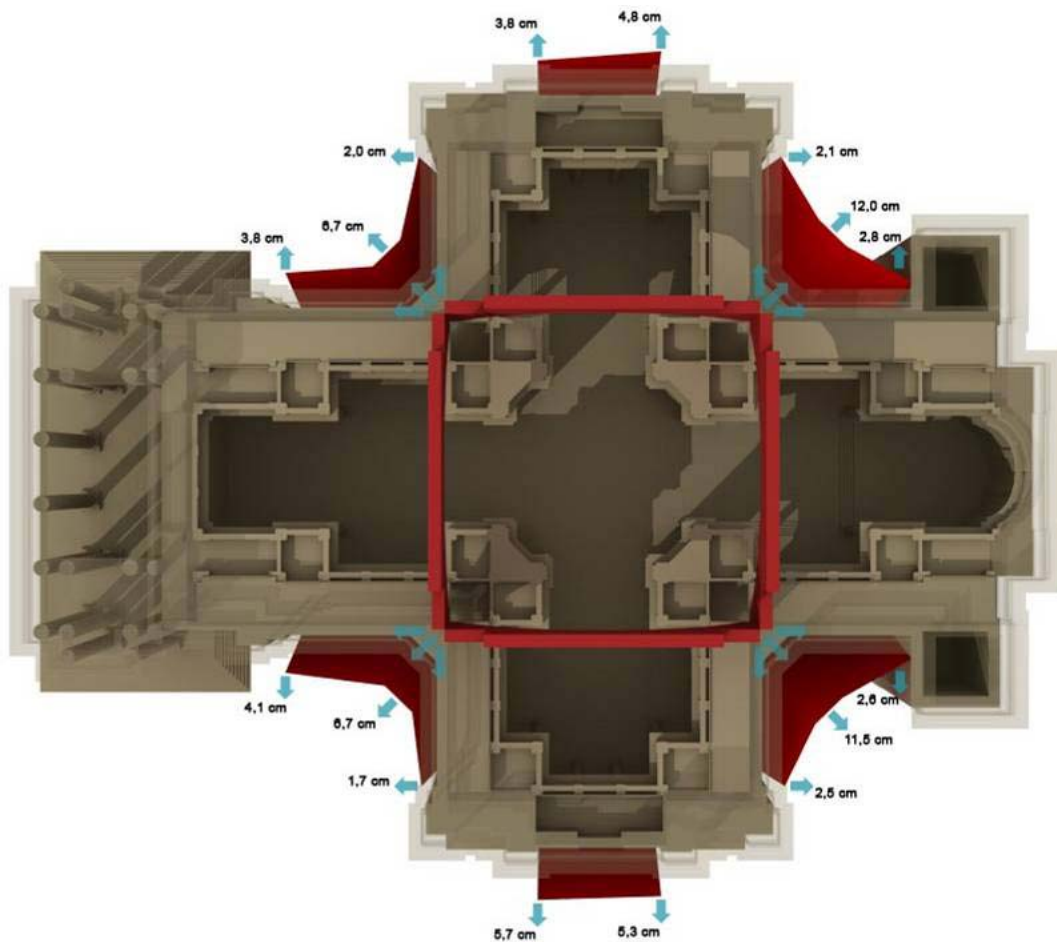


Figure 4. Survey of the rotation of the external walls [1]

### 3. THE OPERATING METHODOLOGY AND THE INSPECTIONS CARRIED OUT

Thanks to the French archives, it is nowadays possible to consult all the reports and, practically, all the drawings since XVIII century up to now, so we are able both to follow the evolution of the disorders since their first appearance, and to know the opinion of the different technicians.

The methodology used for these inspections was based 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 constant comparison between the results of the numerical analyses and the observation of the behaviour of the monument during centuries.

Before the structural analysis was stated, the following studies have been carried out:

- Study of all design and calculation documents made by Gauthey and Rondelet



- [2,3,4,5];
- Study of all the surveys on fractures, the monitoring and the level measurements made in XVIII century [3];
- 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 [1,7,8,9,10];
- Study of all the strengthening interventions carried out on the building during the centuries [2];
- Study of the mechanical behaviour of materials [1,9].

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 heavy and unapt to grasp the specificities of the different pathologies, partial models and different codes have been adopted to describe the different parts of the structure.

In particular, non linear finite elements analyses have been carried out to model the static and thermal behaviour of domes and “plafonds”, non linear distinct elements analysis have been used in the reconstruction of the disorders in the great arches that sustain the external colonnade of the dome (Figure 5) and a variational model of quasi-static crack evolution have been adopted to understand the typical crack pattern found in the stones of the Panthéon (Figure 6). Moreover, a closed form solution for the deformation of pillars have been carried out [1].

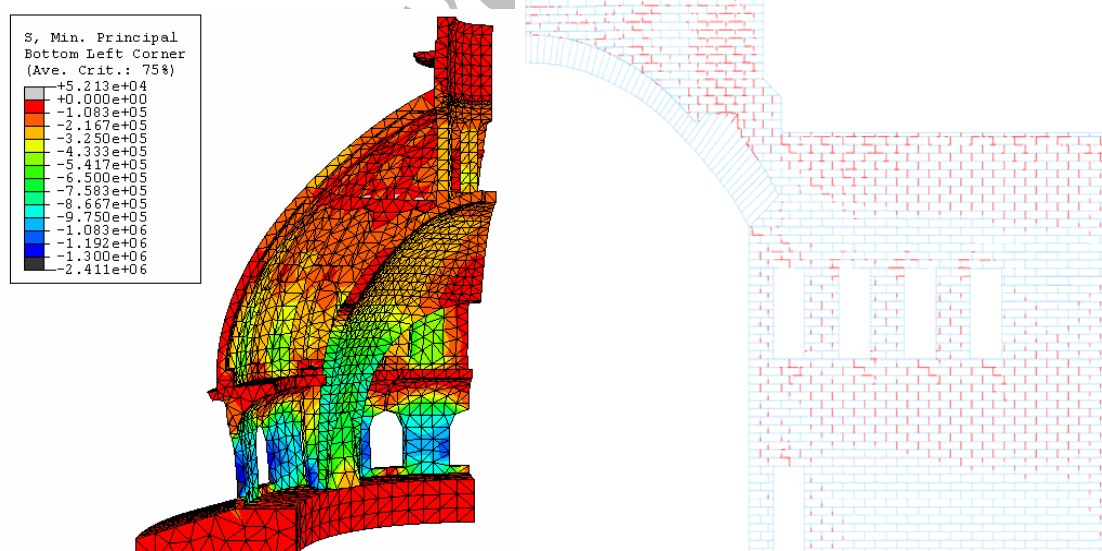


Figure 5. Finite element modelling of the two outer domes (left) and distinct element model of a great arch, that exactly reproduces the crack openings in the external walls (right) [1]

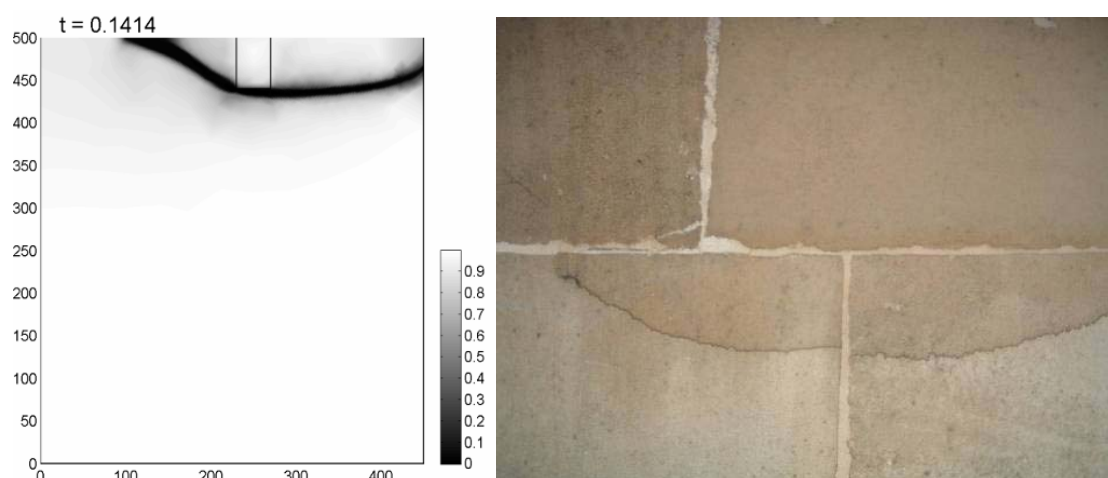


Figure 6. Comparison between the non linear numerical modelling of cracks due to traction phenomena in the iron clamps and a typical real crack [1].

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.

#### 4. THE CAUSES OF THE MAIN DISORDERS

The reinforced stone masonry was a building technique completely new at the time of the construction of the Panthéon. It was 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 7). 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.

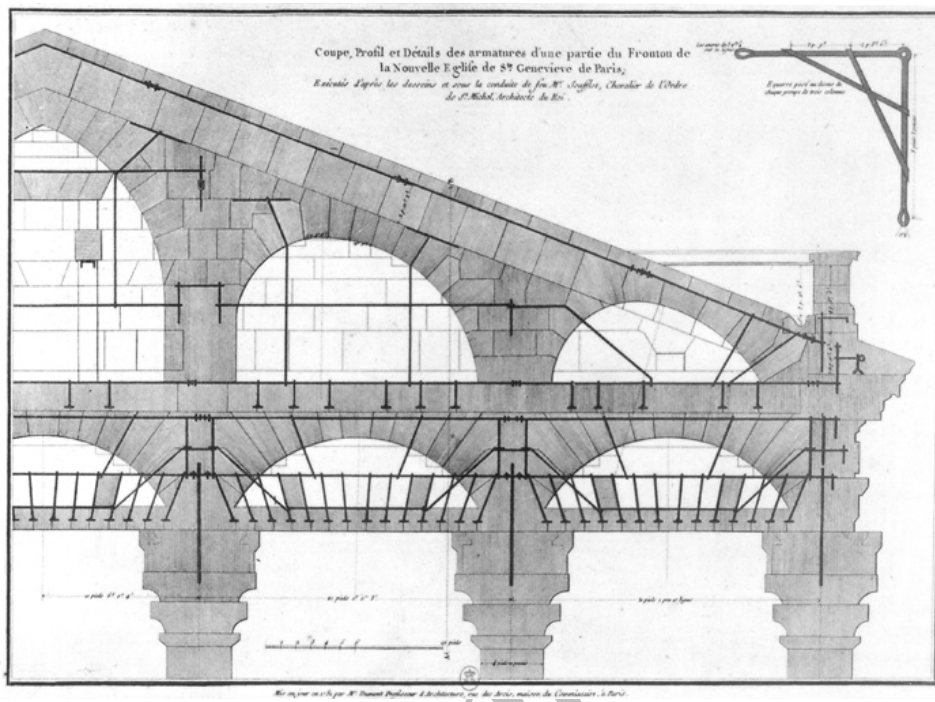


Figure 7. The drawing depicting the iron clamps in the flat arches clearly recalls reinforced concrete trusses [4]

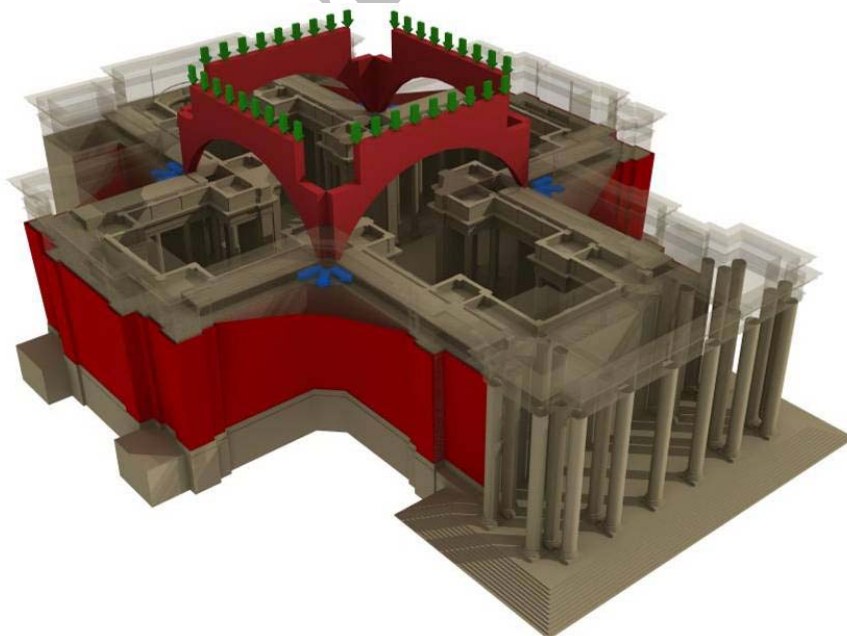


Figure 8. Scheme of the deformations and mechanisms that are at the origin of disorders in external walls (rotations and settlements) [1].



The slenderness of the structures, together with the real long time deformability of the masonry (2000 MPa) has, however, produced large deformations on structures, unpreviewed and non congruous 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.

## 5. CONCLUSIONS

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.

In conclusion, the designers of the French Panthéon, adopting, with substantially positive results, a new experimental technique on such a huge building, showed a high static sensibility, a remarkable inventive capacity and design courage. They could not preview creep phenomena, stress concentrations and plastic deformations under long time loads that have only recently been inspected.

On the other hand, as far as nowadays studies are concerned, only a global and accurate analysis of the behaviour of the structures all along their life allows us today to understand fully the magnitude of these slow phenomena that no short time experimental analysis could have adequately evidenced.

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