Structural Diagnosis of the Roof Structure of the Apollo Gallery in the Louvre

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Introduction

First great building work under the reign of Louis XIV, the Apollo gallery of the Louvre lasted centuries and was subjected to many transformations.

In 1661, under the reign of Louis XIV, when a great fire damaged the Galerie des Rois, it became necessary to rebuild this part of the Louvre that had been greatly ravaged. The architectural works were handed over to Louis Le Vau who carried them out them between 1661 and 1663, while Charles Le Brun was entrusted with the decoration by Colbert. The sculptor Girardon was in charge of the stuccos. This was the first royal gallery intended for Louis XIV and it would later act as a model for the gallery of Mirrors in Versailles castle.

In 1848, the restoration of the gallery was entrusted to the architect Félix Duban who successfully applied himself to re-establishing the cohesion of the very weakened structure particularly along the Seine river. Duban completely restructured the façade, reinforcing the weakest parts and the cracks of the long barrel-vault shell and restored the paintings and the gilding. In particular, he ordered three paintings which had been sketched by Le Brun from the greatest contemporary artists, Delacroix, Muller and Guichard. The inauguration was took place on the 5th of June 1851, before completion of the work by Delacroix.

In 2003 and 2004, under the supervision of Michel Goutal, Chief Architect of the Historical Monuments, the Apollo gallery was once again restored to recover the colours, volumes and architectural rhythms of 1851 and to improve comfort and safety. This project involved the restoration of the vault and its decoration, the cleaning of the panelling and tapestries, the repair of the floor, of the service shafts, of the ribbed vault as well as the restoration of four new crossings integrating smoke extraction devices and the installation of artificial lighting.

Following the last renovation, traces of humidity were discovered along the bottom beam of the timber frame, on the side facing the Seine river (North). The diagnosis established with a Resistograph® confirmed the state of high degradation of the beam and of the lower parts of the top chords along the entire gallery, the central part of the gallery being spared. This degradation is probably due to ancient leaks in the flumes and a lack of ventilation maintained a high level of humidity in the bottom beam.

It is necessary to determine the impact of this degradation on the actual mechanical behaviour of the vault/framework complex in order to ascertain eventual consolidation works. The gallery having been entirely restored, the main constraint was the impossibility of an intervention that would require the demolition of part of the vault.

The mechanical behaviour analysis was established from two and three dimensional numerical models (ABAQUS® software). The random mechanical characteristics were simulated in a simplified manner (high and low values) to assess their sensibility.

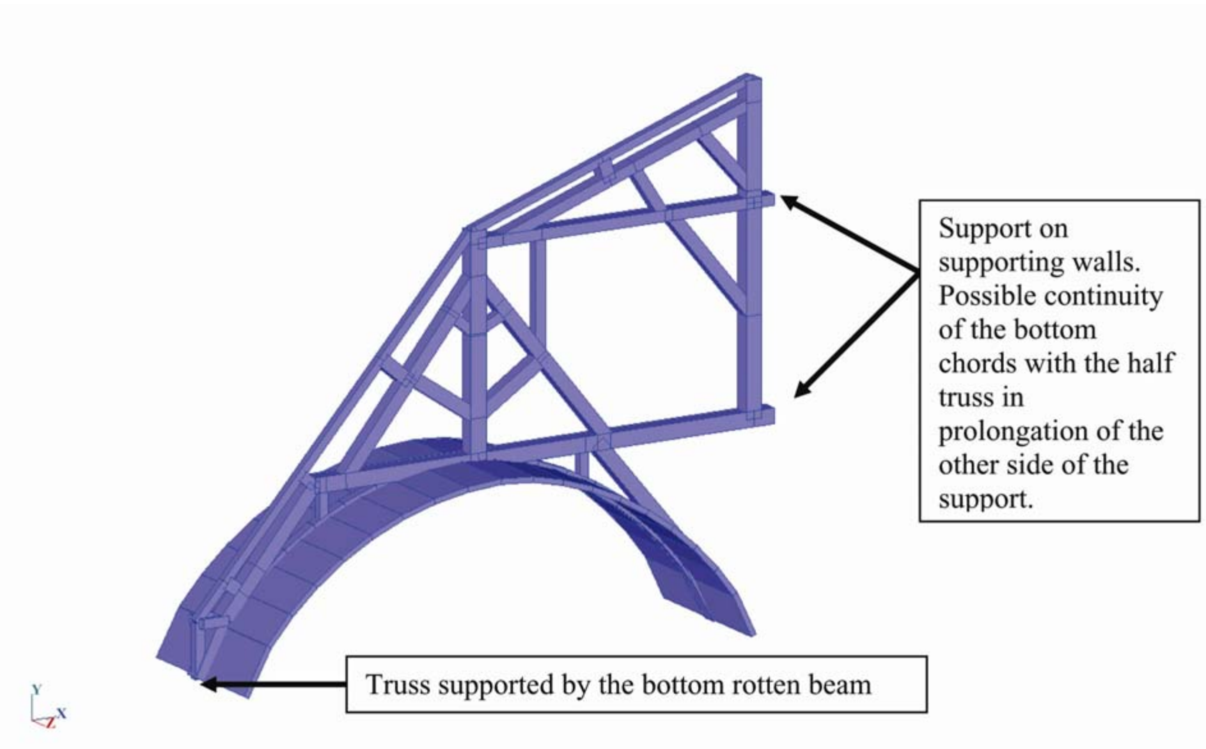
The retained method is therefore as follows:

1. modelling of the geometry and of external loads,
2. modelling of the various support possibilities
3. sampling, testing and identification of the characteristics of the plaster from the vault
4. analysis of the results
5. sensibility study of the mechanical characteristics of the model (assemblies, beams)

I - Construction of the numerical model

1 - Geometry and loads

The geometry was defined from plans with dimensions. The lower values of the variable sections were considered. The model used is solely made up of wooden beam type elements. The plaster vault thus does not take into account its real particular behaviour as a shell/plate. However, this modelling enables to observe the global functioning of a truss, the various strains, constraints and movements of the structure as well as the observation of various down load possibilities.



For each truss, the permanent roof loads are 3,3 kN/m, and the climatic loads are limited to snow, more unfavourable than wind, i.e.:

For snow : a 20° slope $S_{20°}$ = 35 daN/m²
a 49° slope $S_{49°}$ = 20 daN/m²

Representing 133 kN per truss without any partial safety coefficients.

2 – Estimation of the mechanical characteristics

Current section:

The beams are all made of oak, visually classified as D30 resistance class.

Calculation of the mean transversal elasticity at the level of the sandstone /// sablière :

E=0.63 GPa (D30 transversal module)
S=260*300 mm² (section of the top chord resting on the sandstone /// sablière)
L=0,250 m
The result is k= ES/L =2.10^8 N/m

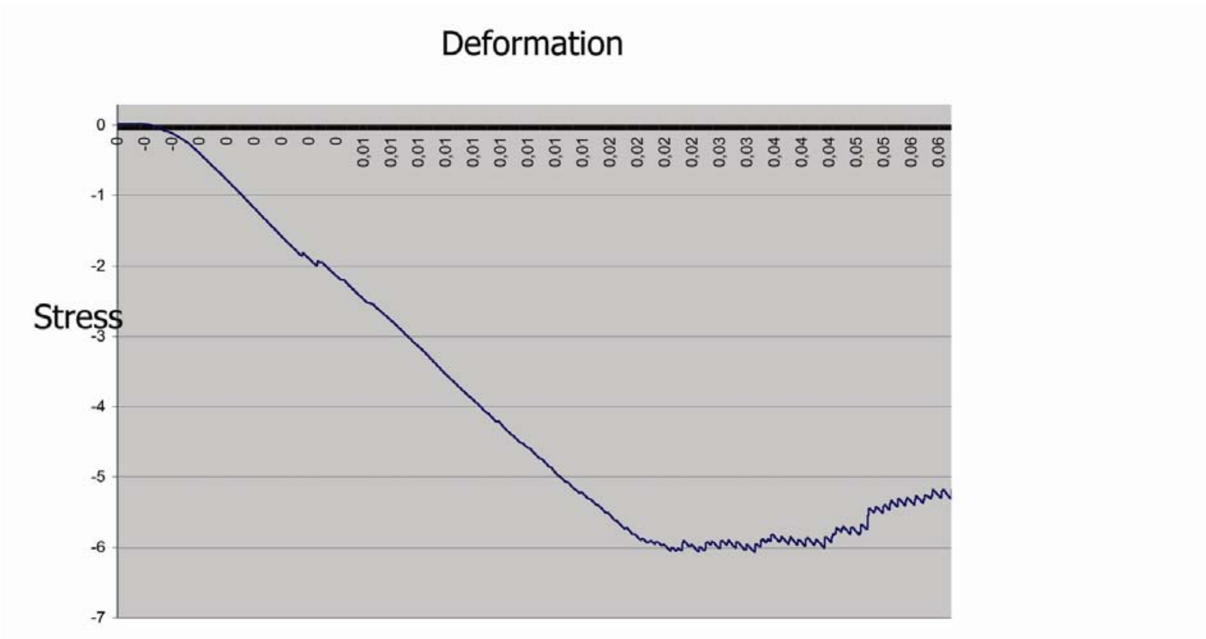
Calculation of assembly rigidity

Calculation of the shear modulus of the loosening on the x (or y) axis for a peg or coach screw type assembly (Eurocode 5 part 1.1 section 7.1) :
$K_{ser} = \rho_m^{\ 1,5}.d/23$ (en N/mm)
With ρ_m = 640 kg/m^3 and d=25mm
The obtained result is about k=$1,8.10^7$N/m. This value will be considered as the mean value.
The low value will be k/100 and the high value k x 100.
For the rotation :
$K=e^2.\ K_{ser}$
e = 0,1 m distance from the edge of the piece /peg
The obtained result is K = $1,8.10^5$ N.m/rad

Measurements of the plaster characteristics:

The plaster characteristics can only be approximate as, in fact, the plaster of the vault is very heterogeneous and includes a lattice. Its resistance could only be measured using a core sample taken from the superior part of the vault. This sample does not allow to take the lattice into account and is not orientated along the down load path. The obtained values can only provide an approximation of the Young Modulus and of the plaster resistance.

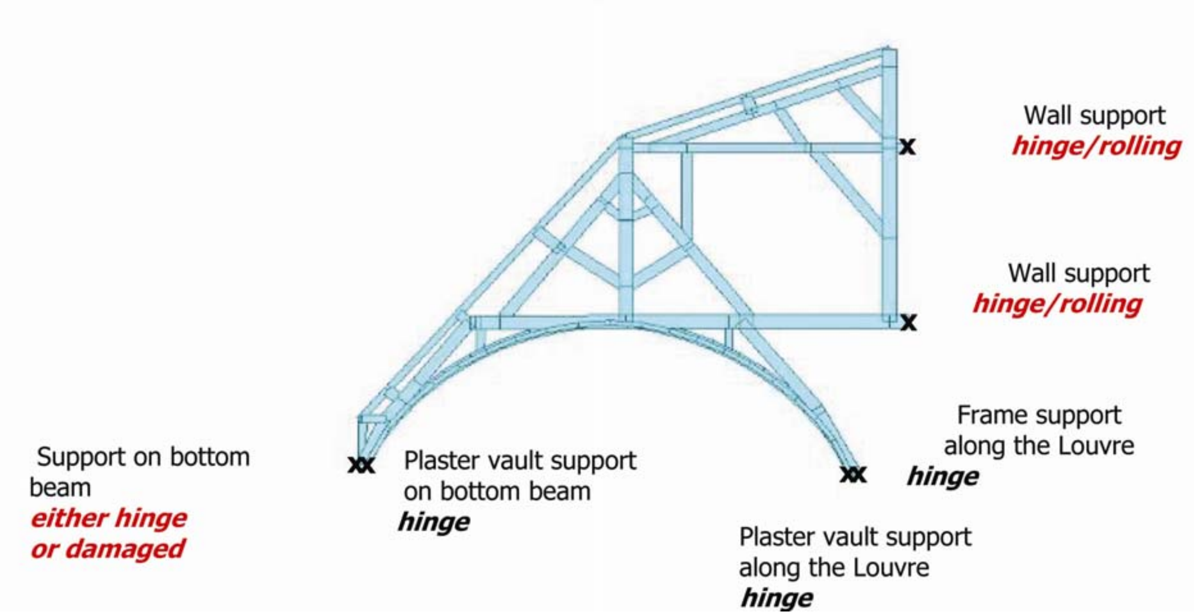
Stress/srain measurement
core sample N°7 compression test



Young Modulus E = 365 MPa

Failure stress = 6 MPa

3 – The various support configurations
Presentation of the support cases:



The unknown supports (bottom beam and wall supports) vary :

- The bottom beam is either intact: hinge, or damaged: no support.
- The wall supports rely on a continuity of bottom chords along the supporting wall (continuity = hinge; discontinuity = simple or rolling support)

II – Truss behaviour analysis
1 Model identification and setting

The strain values for the bars were observed to determine the strains of the assemblies. The state of the assemblies is a source of information regarding truss behaviour: for example, the assembly between the vertical beam and the bottom chord was open in the case of almost all the trusses. It is then necessary to determine the traction between the bottom chord and the vertical beam in our model. This approach only leads to immediately rejecting the models which do not satisfy these conditions, but it does not enable the determination of the global functioning of the truss. In fact, the state of the assemblies at the time of Duban remains unknown. It is possible that the opening of the assemblies do not entail traction. The first conclusions are as follows:

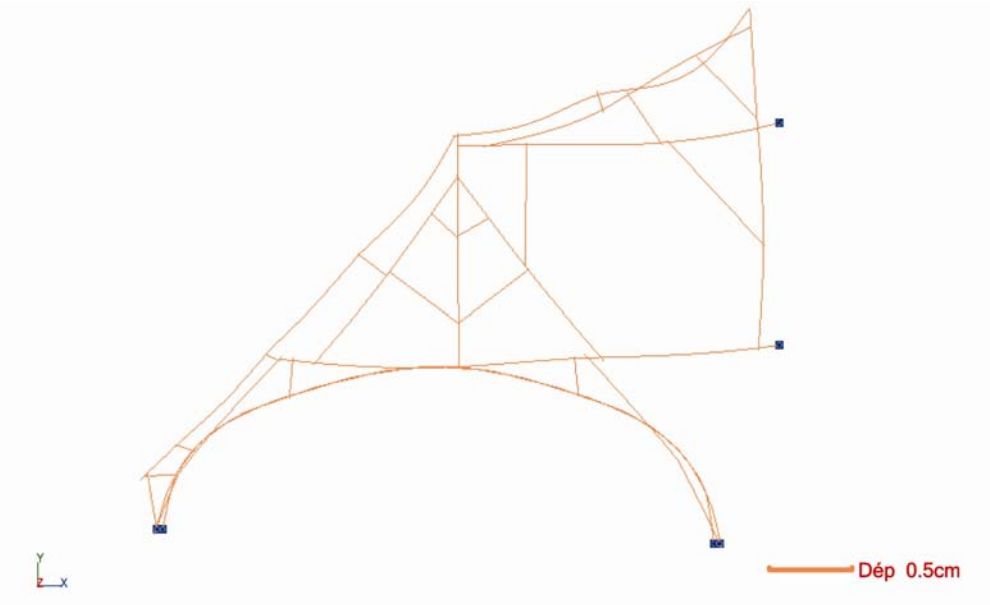
1 – Load repartitions were compared depending on the various load cases, with and without bottom timber beam. Because of a major permanent load, the various load cases (wind, snow) showed identical load repartitions.

2 – Strain, constraints and displacement values were analysed in the case of various support conditions.

Parameter sensibility

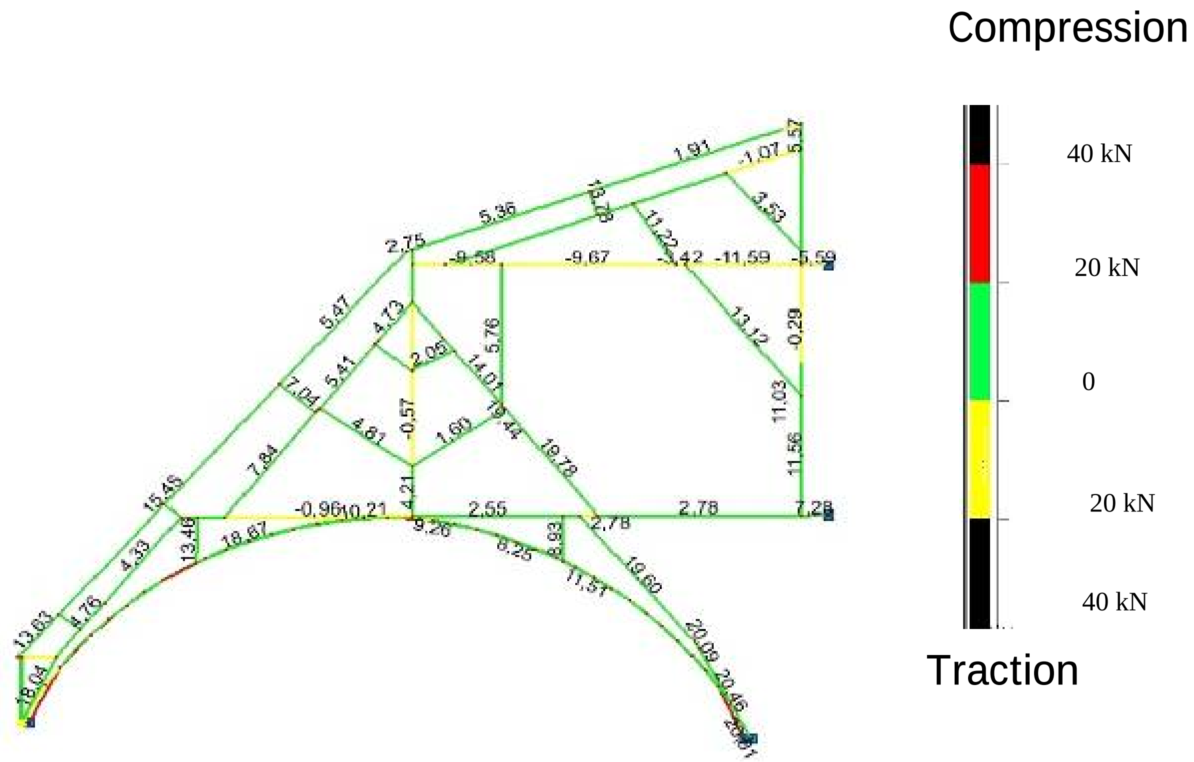
2 Deformation appearance

The most critical data concern the plaster vault, it is in fact the most distortable part, and also the part on which we do not want to intervene.



3 Strains

Each case of support conditions shows a different functioning. Below is shown the most unfavourable case for the plaster vault. From case to case, the strains do not vary greatly, only the inversions in the functioning of the bars provide information on the model which is closest to reality. And none of these models enable us to obtain the functioning observed on site.



Normal strain in the bars (in kN)

4 Analysis

Modelling with the bottom timber beam shows a very healthy functioning: strains and constraints remain very weak in regard to the supposed resistance of the wood, whatever the load and support conditions.

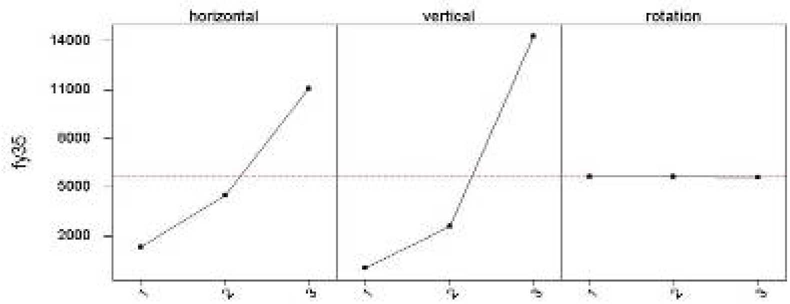
When the bottom timber beam is removed to study the actual behaviour of the framework, a transfer of the load on to the plaster vault can be observed. This foreseeable transfer considerably alters the functioning of the framework. The structure then becomes more sensitive to support conditions, the different load cases all provide a similar behaviour. Hence only support conditions and their impact on the structure were compared. The most unfavourable case is in the case of hinge supports on the walls. In fact, this is the configuration in which the greater constraints are exerted on the vault: this is due to a bending of the vault. This bending, provoked by the compression of the upper part of the vault (see deformation), locally increases the normal constraint. The constraints in the vault remain weak because of its thickness and its length; the loads in the vault, even if important when the bottom timber beam is absent, lead to acceptable constraints in view of the compression test (this is due to the dimensions of the vault).

The analysis of the strain variations within the vault shows two fragile areas. The area situated under the bottom chord is compressed, leading to a pinching of the two areas situated at the point where the plaster vault and the hoops join. These two areas are submitted to major bending, which increases strains and displacements in these areas.

As this model does not take into account the functioning of the vault as a shell, the loads cannot be diffused, a plate model is therefore necessary for 3D modelling in order to observe the diffusion of strains in the vault.

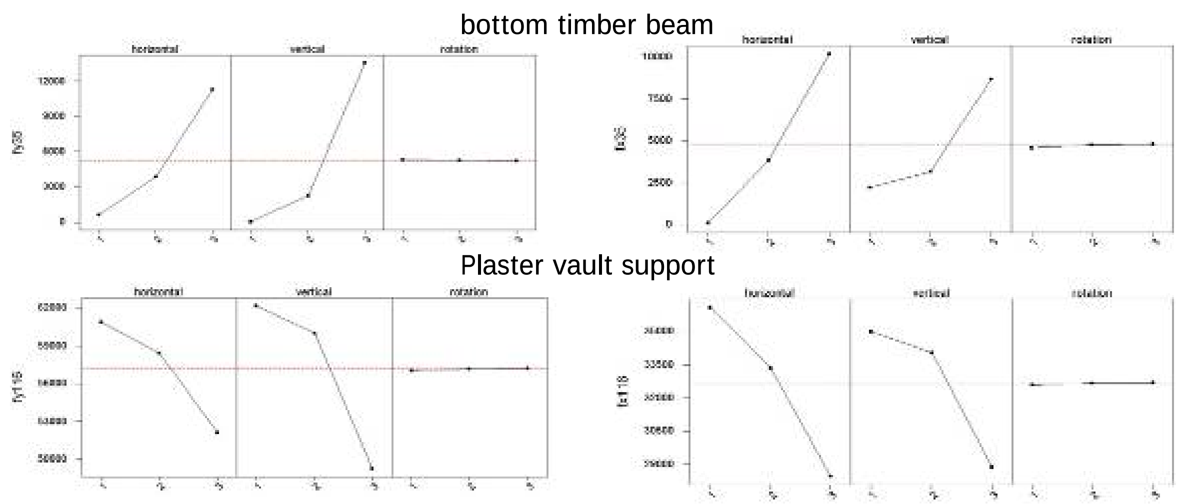
III – Parameter sensitivity
1 bottom timber beam parameters

The design of experiment can help define, for example, the influence of the rigidity of the bottom timber beam on a variable representing the behaviour of the structure as a whole. The sensitivity of three factors must be determined: the horizontal rigidity of the bottom timber beam, its vertical rigidity and its rotational rigidity. Each factor can have three values (called modalities), a low value, a mean value and a high value. So, after 27 tests and a statistical analysis, it appears that only the vertical and horizontal rigidities of the bottom timber beam have an impact on the structure.



The most influential factor on the vertical reaction of the bottom timber beam is the vertical rigidity coefficient.

By applying a design of experiment on the rigidity of the sandstone /// sablière and by observing the variations of the reaction values, it can be observed that as the rigidity of the bottom timber beam increases, the loads which do not go through the bottom timber beam anymore go through the plaster vault.



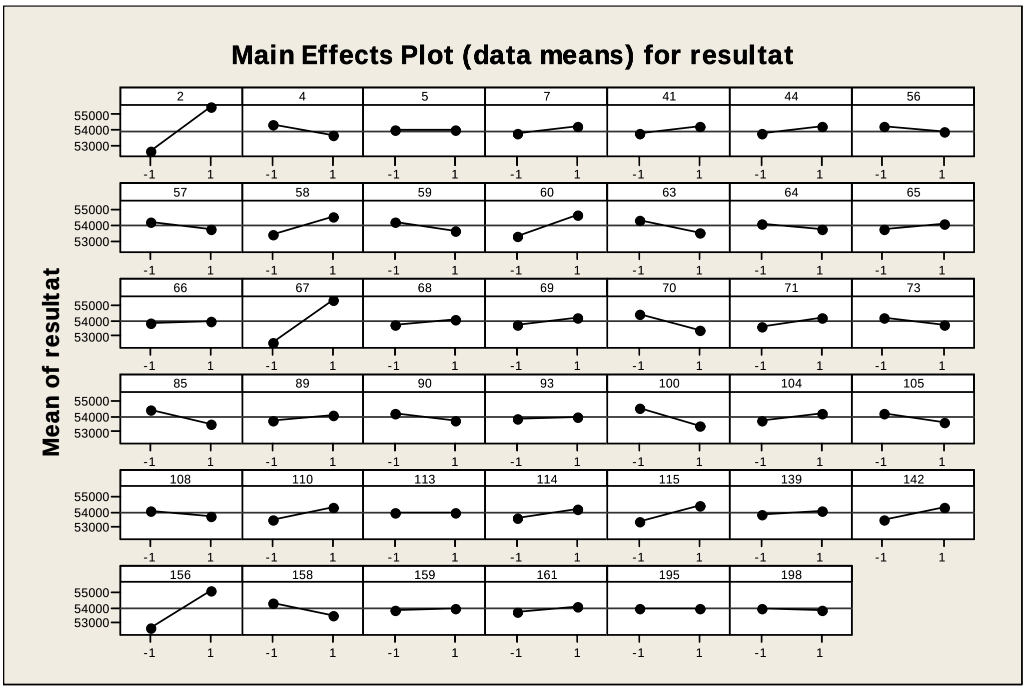
Load transfer from the bottom timber beam to the plaster vault

2 – Design of experiment on the assemblies

These tests are carried out directly without the bottom timber beam, their object is to minimise the strains in the vault by blocking certain assemblies. The most interesting would be to determine the evolution of the strains in the vault in relationship to the variations of assembly characteristics, but this study would require major program modifications. The output variable will therefore be the reaction at the bottom of the vault.

For each test, the down load figure is different: if the assembly rigidities are weak on the side of the bottom timber beam, the strains go through the opposite side, and inversely.

The designs of experiment that have been used are the Plackett-Burman designs, they enable the use of a great number of factors, but impose two modalities. In this case, depending on the models, there are about forty assemblies (and therefore factors) and, during the design of experiment, assembly rigidities only have two values (modalities): either a STRONG rigidity (functional assembly) or a very weak rigidity (open assembly). Once the design of experiment was carried out, the results were analysed:

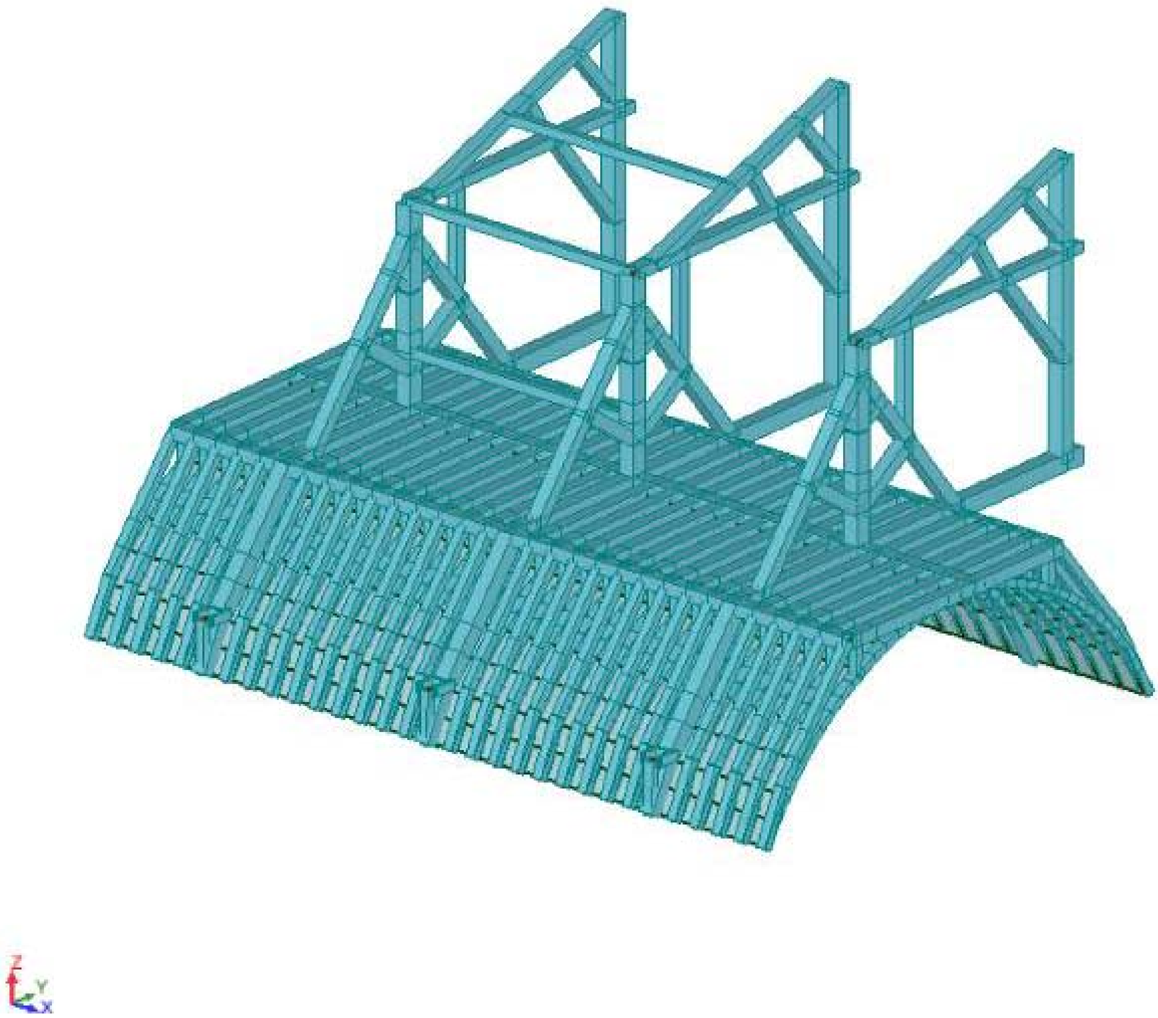


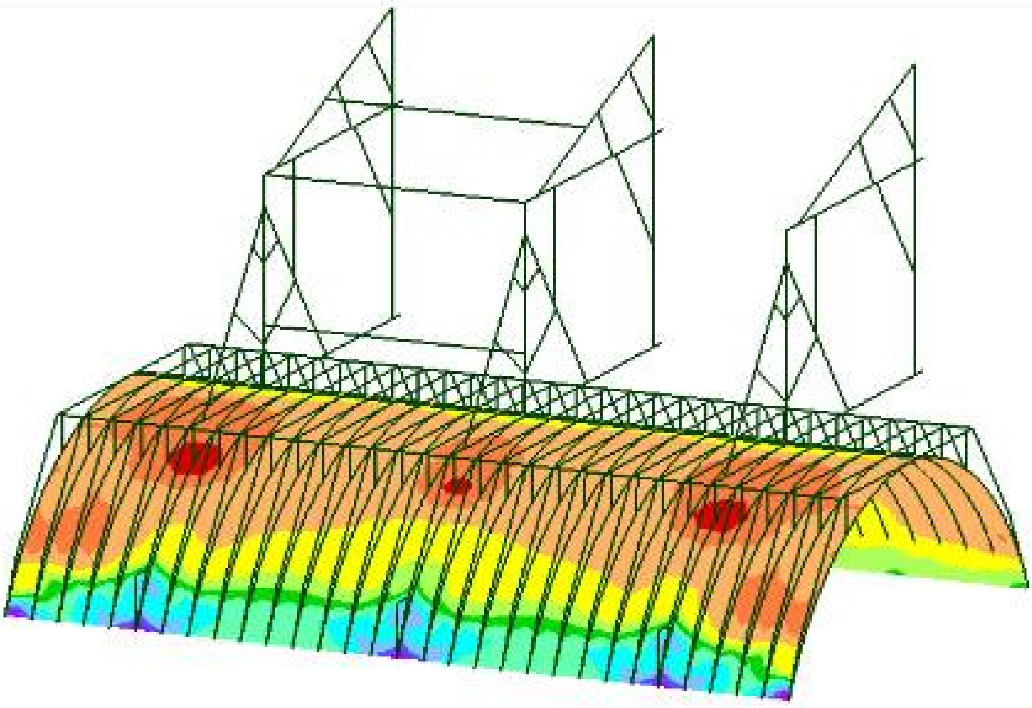
It can be noticed that certain assemblies have very little impact on our output variable (113 195…). Once the most influential assembly has been determined (bar 2), it is given rigidity values in order to minimise the loads from the plaster vault to the side of the rotted bottom timber beam (it would therefore be a low modality for the bar 2 assemblies). Once this is achieved, the down load path is not the same anymore, a new design of experiment must be carried out to determine the most influential assembly of this new structure, and so on until the set limit is reached (which would here be a maximal reaction at the foot of the plaster vault on the side of the damaged bottom timber beam).

A limit must therefore be determined; this limit can only be set with a greater knowledge of the plaster at the level of the support.

IV 3D model

A 3D model is implemented out to verify the previous conclusions (2D) considering a plaster vault with a plate type behaviour. Plate modelling of the plaster vault enables an observation of strain diffusion in the vault.





Inside-strain in the Nxx plate (kN/m) along the curve

In the 3D case, only strain diffusion in the plaster vault has been verified. It is now necessary to analyse the strains, constraints and displacements in this case, taking into account our knowledge of the assemblies. A modelling which would be very close to reality could be carried out by taking the characteristics of each assembly for each of the trusses. This study may be carried out in the future.

Conclusion

The designs of experiment allow for the determination of critical assemblies and it is possible to imagine solutions to modify the down load paths, but the main problem which remains is the direct result of modelling. In fact, despite the number of unknowns concerning the structure, the main problem here is to be able to verify the model with on-site tests and to observe the effects of assembly reinforcements on the structure. On the other hand, it is also necessary to better ascertain the characteristics of the plaster elements in order to determine a limit to be reached to be in a position to consider the structure as sufficiently secured.

The suggested modelling makes it possible to overcome the immediate risk of damage in the case of major climatic loads. It also enables for a precise diagnosis of the assemblies without consideration for the consequences of a limited degradation of the beams. Despite the fact that, so far, the vault seems to bear the strains of the framework with no damage and that the strains and constraints seem to be weak, it would not be desirable to transfer the structural strains to the vault, a supported element, as it would then become a supporting element instead.