XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
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Seismic Evaluation of the Cathedral of Valencia (Spain) applying a scalar damage model.

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Key words: Damage-model, analytical methods, no-linear, push-over, time-history análysis.

Abstract.

Ashlars structures in Gothic cathedrals are designed to allow light get into the building. For this reason exterior walls turn into glazed large windows. The structural system which permits achieving this target is formed by the ribbed vault resting on columns.

This Gothic system has an excellent performance against dead loads but its response to lateral loads produced by seismic movement is poor. The southern Mediterranean area is seismic zone and Gothic buildings raised there are different from the ones in the European centre.

This paper studies the Cathedral of Valencia structural system and its seismic behaviour is numerically analysed using software developed by the authors of this paper, which implements two continuum damage models for analysing masonry and ashlars:

An isotropic damage model is applied a nonlinear static pushover procedure. This procedure gives an appropriated approach to the structure response in a computational time relatively short. Too is applied a nonlinear structural dynamics is made in a whole model of the Cathedral. The application of efficient computational procedures as direct procedures to resolve systems of equations with sparse matrix are efficient and reduce computing time.

Comparing the results obtained by both procedures permits evaluating the state of the Cathedral structure.

1 INTRODUCTION

The Metropolitan Cathedral of Valencia, dedicated to Our Lady of the Assumption at the behest of Jaime I, was consecrated by Bishop Andrés de Albalat in 1238. Work on its construction commenced in 1262 on a site previously occupied by a mosque.

The floor plan is in the form of a Latin cross with a nave, two transepts and three aisles. The central nave is divided into three perfect squares, with a series of rectangular side-chapels on both sides (*figure 1*). The ceiling consists of simple cross vaults with four stone ribs and severies of solid brick laid endwise. The apse is in the form of a polygon with a surrounding ambulatory and has a number of chapels leading off it. The cathedral also includes spaces that formerly were separated from it but were incorporated into the main building during the renovation carried out under Francesc Baldomar in 1458. These areas include the Chapel of the Holy Grail (*Santo Cáliz*) and the bell tower familiarly known as *Miguelete* by the local population.

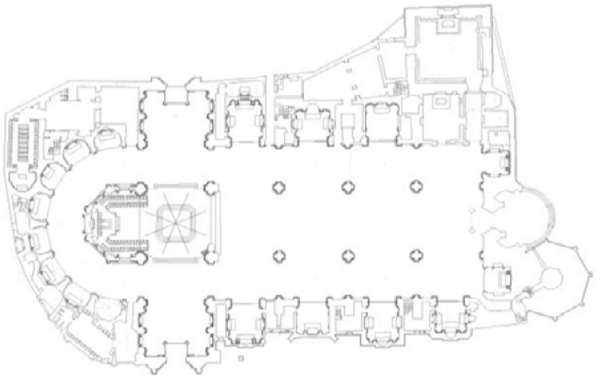

Fig.1 Plane of the Metropolitan Cathedral of Valencia

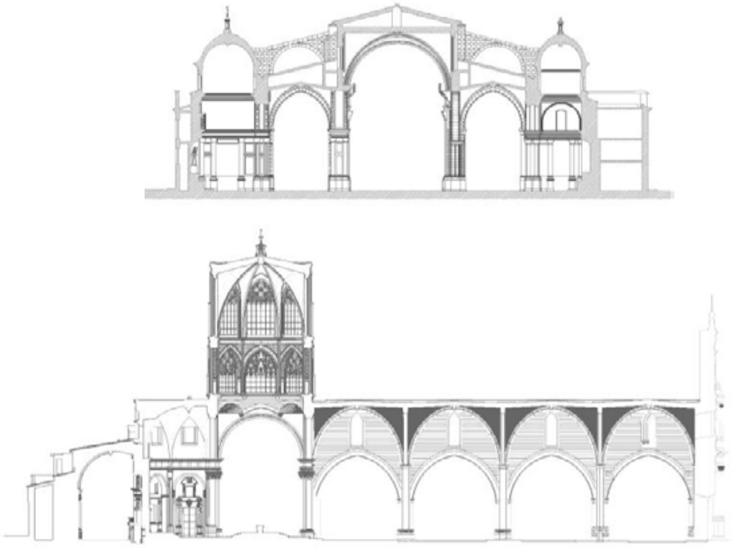

Fig.2 Section of the Metropolitan Cathedral of Valencia

The almost identical height of the nave and transepts do not wholly conform to the tenets of proportion according to French Gothic, but is evidence of the difficulty of transmitting loads from the nave to the transepts. M. J. Cassinello [1] found an explanation to these proportions when she carried out research by introducing new "light" elements and modifying the "stone skeletons" and finding improved behaviour of the structure in response to earth tremors. This, of course, fully justifies the Cathedral's unorthodox structure, as compared to other European cathedrals.

The octagonal dome, rising over the centre of the transept in two tiers, acts as a kind of lantern that floods the interior of the cathedral with light from the white panes of alabaster in the windows. Belonging to late Gothic architecture, its history is by no means clear; according to Segura de Lago it was built in the 14th century, with the first tier built by Nicolás de Autún and the second by Martín de Llobet in 1430.

The building was greatly admired by the Valencian architect and mathematician Tomás Vicente Tosca, who described the cathedral in his *Tratado de la Montea y Cortes de Cantería* (1712) in a chapter entitled "*How to create a vault with crossed arches over any polygon of four or more sides, that stays in place by its own weight, without any other support"* [2].

This octagonal lantern 19.20m high and 6.18m wide is composed of two very similar tiers, the upper being taller than the lower.. There are large windows in the walls with elaborate tracery work in between, which gives the Cimborio its light, delicate appearance. The tracery supports the sheets of alabaster that are the substitutes of the glass panes installed in the Middle Ages and that need constant maintenance to be kept in good condition.

2 STRUCTURAL SYSTEM OF DE CATHEDRAL OF VALENCIA.

The Cathedral of Valencia is formed by three naves; the central one is 19.30m height and the aisles ones are 12.5m. The main nave rises a bit more above the aisles. In fact, the vaults springing of the main nave are at the same height as the transverse arches of the aisles vaults, for this reason those arches work as flying buttresses to resist the pushing force of the arches of the main nave.

The main nave longitudinal stone masonry walls are stretch and with window in it relatively small if it is compared with the French Gothic big large windows.

In the naves cross direction the transverse arches built up a stiff diaphragm that grows up to the plane roof covering and the side walls. Outwardly the flying buttresses link the upper part of the transverse arch and the side wall with the buttress. Among the boxes formed by those diaphragm-arches the ribbed vault is built up with the masonry diagonal arches and the vault of brick masonry. (Fig.3)

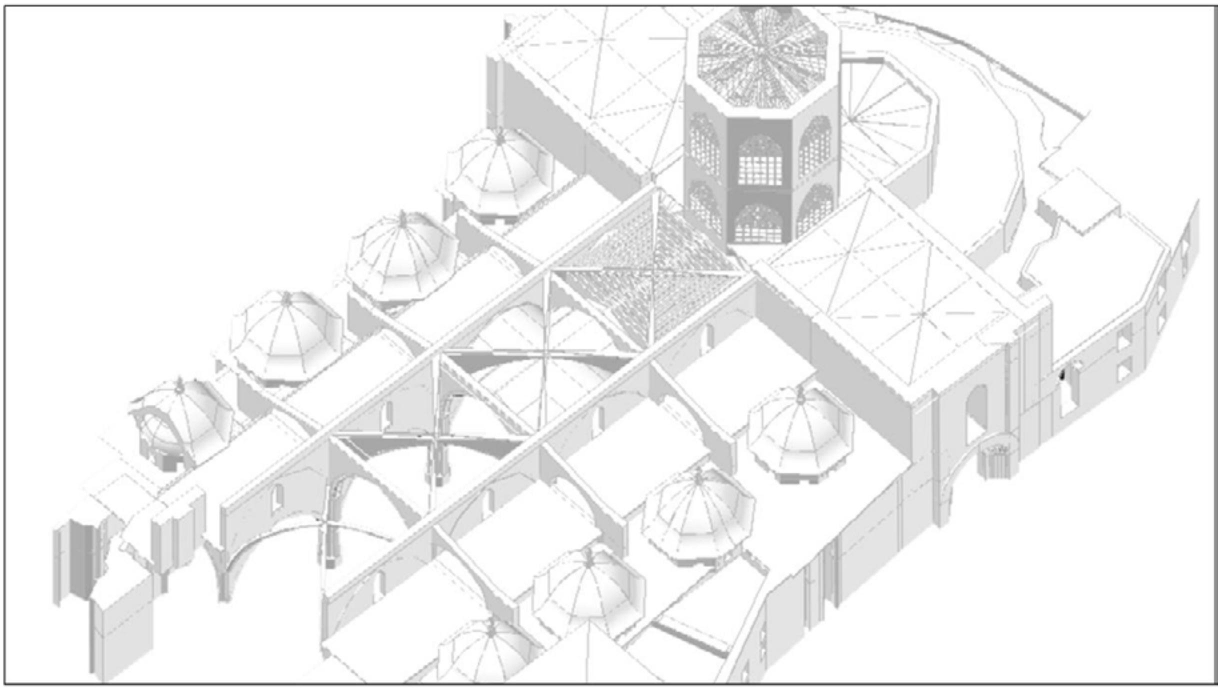

Fig.3 Structural system model of Cathedral

This structural system is observed to be different from the classical Gothic one, where the arches became more rigid making up diaphragm-walls, while in Central European Gothic arches are linear and walls nearly disappear by building up big large windows. It is a typical building way in eastern areas of Spain and central and southern Italy, named Mediterranean Gothic; they are appropriated to seismic risk areas.

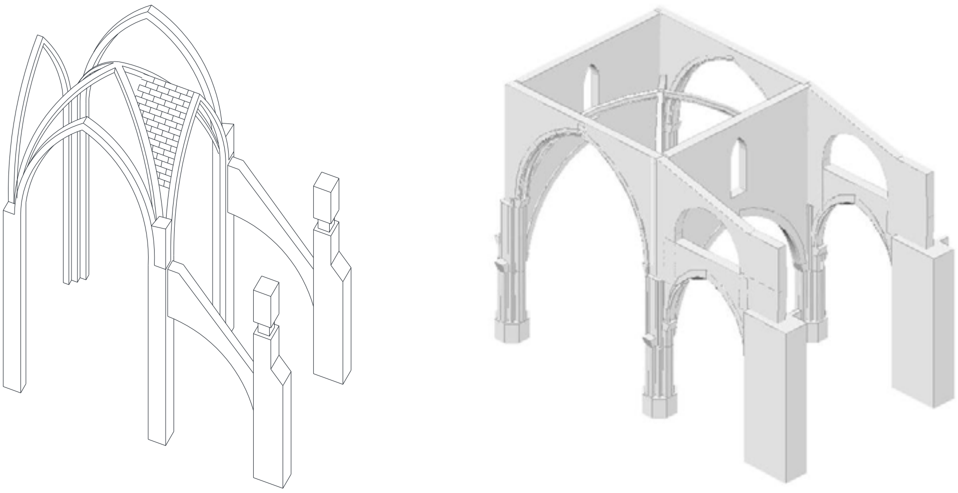

Fig.4 Mediterranean and European Gothic structural models (Cathedral of Valencia)

This building way is used in order to provide stiffness and resistance to the Cathedral structure against horizontal movements caused by earthquakes. The walls and diaphragm-arches work as "shear walls". In the European areas where there are not seismic events, cathedrals structure is diaphanous, with linear elements.

In order to test this construction system effectiveness a numerical analysis is executed to observe the system response to seismic action, by using the push-over and dynamic analysis.

3 NUMERICAL ANALYSIS

To evaluate the structure behavior against seismic movements of the Cathedral, a modal analysis, a non-linear static (pushover) analysis and non-linear time-history analysis (dynamic) are done.

A linear static analysis was first carried out to evaluate the stresses in the masonry, leaving the existing cracks out of consideration, and concentrating only on the self-weight hypothesis.

We assumed the material, which was mostly masonry, to be homogeneous. As it was not possible to carry out tests on the dome itself, we had to resort to the data obtained from previous tests carried out on masonry from the Trinity Bridge in Valencia, which was of similar characteristics and had been obtained from the same quarry [3]. The results of the tests are given in Table 1.

Table 1 Results of the tests**.**

Test cylinders	**Density T/m^3**	**C. Breakage N/mm^2**	**$\Delta\sigma$ N/mm^2**	**$\Delta\epsilon$**	**Module E N/mm^2**
1	1.949	7.05	2.6738	0.00175	1527.885
2	1.914	7.13	3.0680	0.00200	1534.000
3	1.891	9.57	5.4858	0.00452	1213.672
Average	1.918	7.916			1425.186

These values are significantly lower than the normal values for this type of stones. It is due to the fact that test tubes were taken from blocks located on the outside, where they have been subjected to environmental degradation for centuries and they have lost density. Therefore to the structural analysis slightly higher property stone values are considered. The Table 2 gives the most important mechanical properties used in the numerical model:

Table 2 Mechanical properties.

Stone masonry	
Density	2,200 T/m^3
Module of deformation	7000 N/mm^2
Poisson's ratio	0,2
Compressive strength	12,00 N/mm^2
Tensile strength	0,40 N/mm^2
Fracture energy	0,5 Nmm/mm^2

Brick masonry	
Density	1,800 T/m^3
Module of deformation	4500 N/mm^2
Poisson's ratio	0,2
Compressive strength	5,00 N/mm^2
Tensile strength	0.15 N/mm^2
Fracture energy	0,1 Nmm/mm^2

3.1 Non-linear analysis damage model.

In order to get the non-linear response of these structures, the fissures appearance and their development have to be calculated as well as the maximum structural load. The so-called isotropic damage model was used in this study within the ANGLE finite elements software [4].

Damage mechanics is a branch of Continuum Mechanics, which, by means of internal variables introduces micro-structural changes into material behaviour.

The fissures emergence and their evolution over time in materials such as concrete and masonry can be described as the course followed by several points of damage.

If a damage function is defined representing correctly the response of the material, both in compression and traction, then the non-linear masonry behaviour can be represented in a model.

Cracking is represented in this case as an effect of local damage that can be defined according to the material known parameters and to functions that control the damage evolution with the successive tension loads at each point.

Concept of isotropic damage

A point in the material with a certain degree of damage is considered, deterioration is represented as hollows in the fabric. The damage variable "d" is defined thus:

$$d = \frac{S - \bar{S}}{S} \qquad (1)$$

Where: S= is the total surface under consideration; $\bar{S}$ = the effective resistant area; and S-$\bar{S}$ = the hollowed surface. This index expresses the material deterioration degree. The zero value represents the undamaged state, while 1 is the total damage of the resistant area.

The relationship between Cauchy's standard tension and the actual tension acting on the part of the effective resistant section is derived from the condition of equilibrium:

$$\sigma = (1 - d)\bar{\sigma} = (1 - d)E\varepsilon \qquad (2)$$

This scalar index is sufficient to adequately represent the materials behaviour such as concrete, brick and stone. The effect on the mechanical behaviour of the material is a reduction of rigidity proportional to (1-d) (*figure 5).*

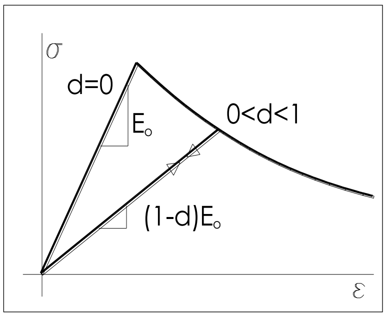

Figure 5: The effect on the mechanical behaviour of the material is a reduction of rigidity proportional to (1-d)

In the repeated FEM process the constitutive matrix$\overline{D}$ is calculated as:

$$\overline{D} = (1-d)D \qquad (3)$$

Where: *D* is the elastic constitutive matrix.

The scalar variable of damage is:

$$d = 1 - \frac{r^o}{r} exp\left\{A\left(1 - \frac{r}{r^o}\right)\right\} \qquad (4)$$

Where: The *r, r^o, and A,* values are obtained as in reference [5, 6].

3.2 Model calibration.

Described model has been implemented in ANGLE software by the author [7]. Attempting to calibrate this model with ashlar tests it results extremely difficult due to calibration is made with experimental concrete models, those are concrete elements with a similar behaviour to masonry, particularly Walraven tests on a reinforced concrete beam have been employed, and the tests made at University Polytechnic of Valencia by Valcuende and other authors [8] about concrete non-reinforced beams. (Figure 7)

The results of the developed numerical model have a precise adjustment to the experimental results:

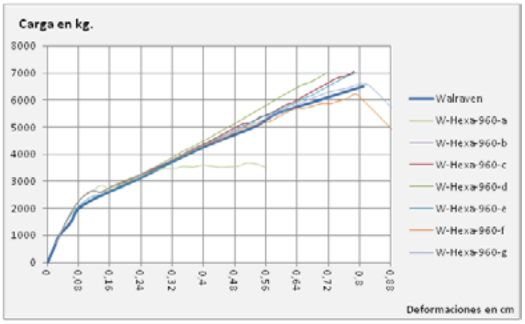

Figure 6: Load-Deflection, comparative between the experimental and numerical model.

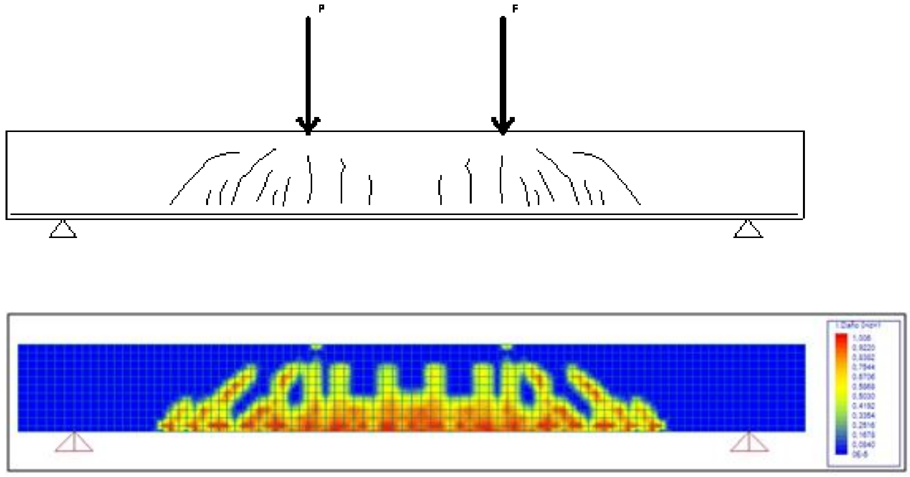

Figure 7: Strength distribution and cracking map.

3.3 Seismic action

To the pushover analysis an acceleration spectrum is used for the area of Valencia and for a mean return period of 950 years, as it is specified in EC8 [9].

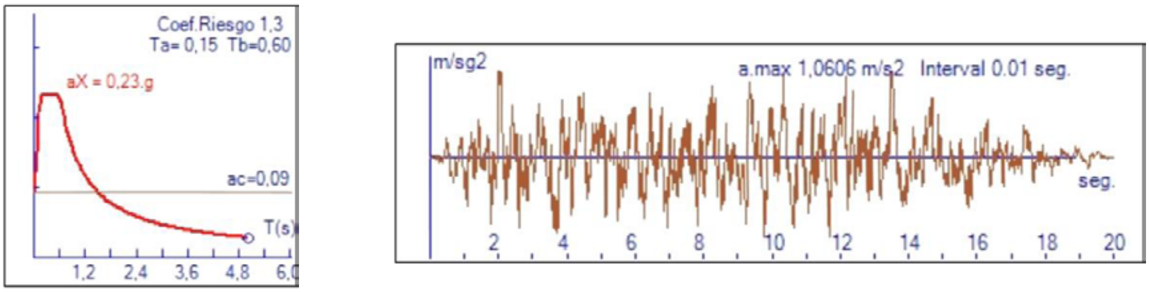

Figure 8: Elastic response spectrum. Artificial accelerogram.

To the direct dynamic analysis of time-history there are not enough real records about accelerograms of the area. Some artificial accelerograms were generated and are compatible with the spectrum defined by EC8, which had been obtained with the program SIMQKE_GR.

3.4 Structural model

To do the numerical calculation three parts of the nave have been modelled. The model consists of 23660 nodes with 17222 solid elements and 3368 shell elements to model the vaults of 0.45m thickness in the central nave and of 0.30 m the aisle nave.

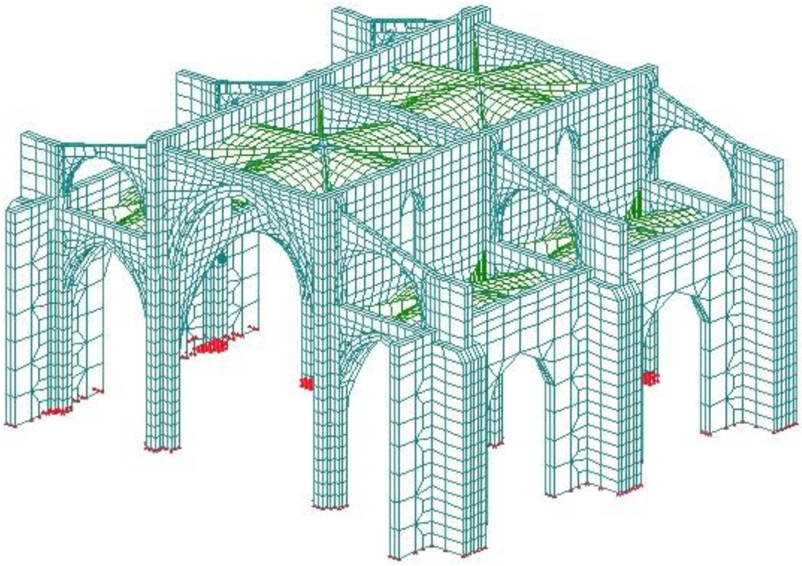

Figure 9: Structural model.

4 ANALISIS OF RESULTATS.

4.1 Flying buttresses model

Non-linear static analysis for gravitational actions shows that the superior flying buttreses hardly help to the structure equilibrium.

Pushover analysis results show that the structure response heads the flying buttreses capacity to the limit.

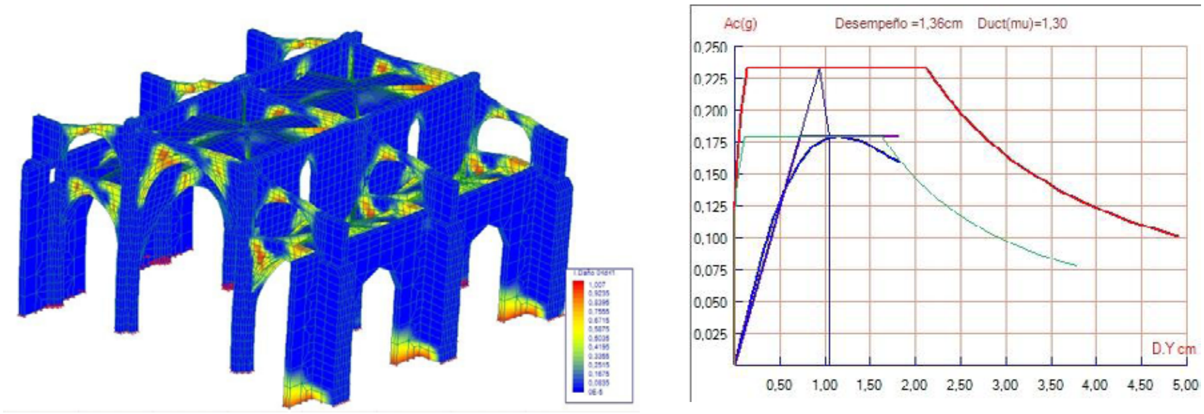

Figure 10: Pushover analysis and performance point for EC-8 demand spectrum.

The dynamic analysis gives similar results to the previous one, the flying buttresses work providing stiffness against horizontal seismic actions.

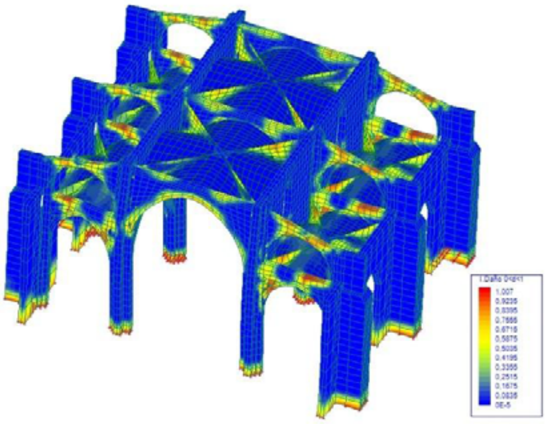

Figure 11: Dinamic analysis. Displacement of a point at the roof covering.

4.2 Non flying buttresses model

When executing a dynamic analysis for the non flying buttresses model a structure collapse is produced. This demonstrates that these buttresses function responds to resist seismic actions, and have no function against the gravitational action.

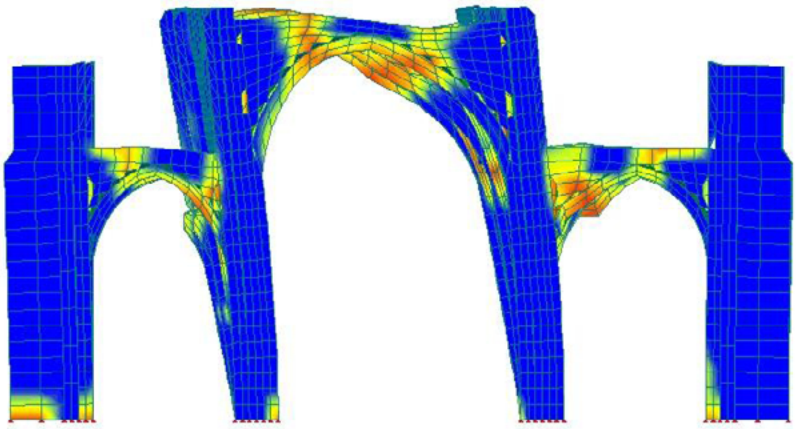

Figure 12: Dinamic analysis. Collapse state of the structure.

5 CONCLUSIONS

Cathedrals described as Mediterranean Gothic have in common the diaphragm-arches situation in both longitudinal and transverse directions. This feature which distinguishes this one from the French or Central European Gothic leads to suppose that they were built to resist seismic movements. To evaluate this hypothesis the Cathedral of Valencia has been studied by applying numerical methods that have been implemented in the ANGLE software.

By using the pushover method and nonlinear dynamic analysis a response to the seismic action of the structure has been obtained, the diaphragm elements are working well and the fact that they were built as "shear walls" to resist earthquakes hypothesis is confirmed.

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