ANALYSIS OF THE STRUCTURAL BEHAVIOUR OF THE HISTORICAL CONSTRUCTIONS: SEISMIC EVALUATION OF THE CATHEDRAL OF VALENCIA (SPAIN).

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ABSTRACT.

Analysis of the structural behaviour of the historical Constructions by the damage model through mechanical characterization of the material obtained by laboratory tests. This analysis has been particularly applied to the case historical construction of the Cathedral of Valencia (Spain), this is a representative example of Mediterranean Gothic with a structure formed by two sets of diaphragmatic walls, breaking with the Central European Gothic canons.

In this research we have been conducted laboratory tests of samples taken from the masonry, in order to use these mechanical properties of the material nonlinear numerical models so that the results will allow an accurate calibration of material behaviour for both gravitational and seismic actions.

The study carried out justifies the reasons of the differences between the Mediterranean Gothic and the traditional. The necessity of the walls continuity will be demonstrated by the flying buttresses that turn into authentic diaphragm walls.

KEYWORDS: Historic Building; Experimental tests; finite element model; damage model; seismic analysis; pushover; return period.

1. INTRODUCCIÓN

The structural system of the great central European Gothic cathedrals consists of ribbed vaults that allow gravitational loads to be concentrated on four columns. The wall losses its load-bearing function and become in large windows allowing light to get into the building (Zaragozá, 1990).

The structure of the Cathedral of Valencia diverges from the canons of Central European Gothic building. This is a representative example of the so-called Mediterranean Gothic architecture (Casinello, 2004; Cassinello, 2005), characterized by its low slenderness, by the difference in height between the nave and the side aisles and the decreasing surface available for stained glasses. Different hypotheses have tried to justify the reason for these differences, as well as weather-related reasons, compositional issues, the defensive nature of this type of building, etc.

Recent studies link these peculiarities of the Mediterranean Gothic with the geography where they are located. In particular, when overlapping its location with the seismic map of Europe it is made clear that they are located in high seismic risk areas (Roca et al. 2013).

This paper will show a seismic analysis of the Cathedral of Valencia (Llopis et al., 2016), from an EF computer model performing its structure. This model does not reproduce the whole of the Cathedral but it focuses on the characteristic walls structure of the Mediterranean Gothic and it analyses its behaviour against seismic efforts (Figure 1). This analytical model is modified through a selective elimination of flying buttresses, diaphragms and / or reinforcements, generates five variations, the analysis shows the function of each of these structural elements.

Structural analysis of the Cathedral, which includes seismic activity besides gravity loads will be made by means of the EF non-linear regime ANGLE software (Alonso, 2014). Seismic effects will be evaluated by one of the most advanced methods, the push-over analysis (Marques and Lourenço, 2013). The behaviour of the materials will be measured by the so-called "damage model" (Oñate et al., 1996). The results will provide an excellent knowledge of the structural behaviour of the Mediterranean Gothic.

2. VALENCIA CATHEDRAL

The Cathedral Church Metropolitan Basilica of Valencia (1262) is located on the ancient Muslim mosque. It is a Latin cross building with marked crossing, originally concieved by three naves and three bays (Figure 1).

The nave section is squared while side aisles sections are rectangular, with the major axis along the longitudinal axis of the temple, bounded by a series of chapels that make up the central space. It´s construction began in the ambulatory of pentagonal sections, delimited by a section of the main chapel and two apsidal chapels. These chapels are radially arranged with an uncommon layout taking into account a symmetry axis a column instead of a chapel.

In 1458 the Cathedral plan extension takes place: a fourth bay is added and the volumes of space of the Holy Grail Chapel and the belfry known as El Miguelete are connected to the temple this way (Figure 1).

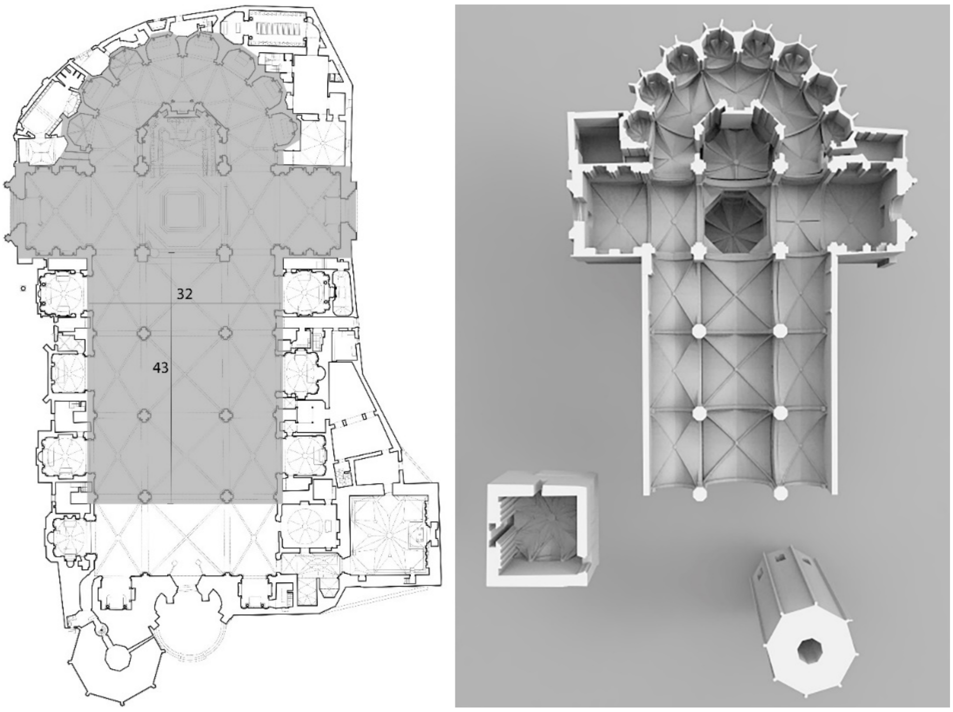

Figure 1: Cathedral of Valencia a) Actual Plan and XIVth Century b) Zenith 3D XIVth Century

It is in the cross section where the characteristics that distance Valencia Cathedral from the Central European Gothic proportion ideals are observed. On the one hand the slight difference in height between the nave and aisles implies a reduction of the area of the windows. On the other hand, the position of the flying buttresses above the thrust of the vault is highlighted, this situation has questioned its structural function. The primary structural system is made up of two sets of diaphragm-walls, longitudinal walls belonging to the nave and the transverse walls of each section (Figure 2), the whole forms a rigid box of strong walls.

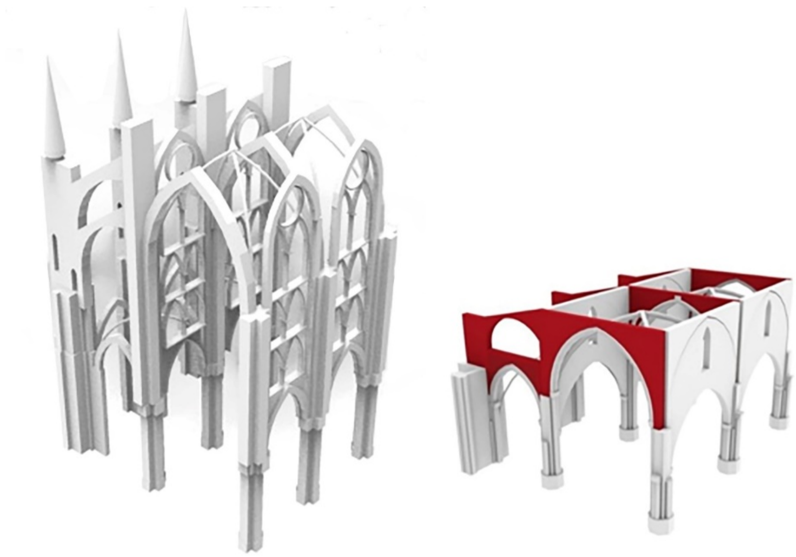

Figure 2: a) 3d Central European Gothic; b) 3D Mediterranean Gothic (Cathedral of Valencia)

The transverse diaphragm wall is perforated by the arches of the nave and aisles, and by a semicircular arch that allows walking over the roof. The buttress is part of the diaphragm, but it is really the result of the aforementioned arch perforation. This primary structure shows deformations in the intrados of the diaphragmatic arches and in the buttresses (Figure 3).

Figure 3: deformations in the intrados of the diaphragmatic arches of the lateral aisles and in the buttresses.

3. NUMERICAL ANALYSIS

Through the structural analysis it is possible to analyse and compare the behaviour of the Gothic primary structure of the Cathedral under seismic actions. Different calculation models have been developed paying attention to the presence or absence of flying buttresses, diaphragms ... while the effectiveness of constructive elements is evaluated. The finite element analysis is performed by means of the ANGLE software, from the current geometry and based on its constructive configuration the calculation models are generated with CAD tools. In order to evaluate the seismic performance of the Cathedral a nonlinear "push-over" (Vargas et al., 2013; Boscato et al., 2014; Orduña et al., 2007) analysis is used. The method used to simulate the behaviour of the stone and brick is the "damage model", one of the most rigorous methods to reproduce the response of fragile materials.

3.1 Mechanical properties of materials.

A sensitive issue in all studies on the behaviour of historical structures is the characterization of the mechanical properties of materials (Ramos and León, 2013). Due to the restrictions provided by the protection regulations given the historical nature of the building, it is extremely difficult to extract specimens from the materials or carry out on-site tests of the masonry.

Therefore, in the present study the characterization of the properties of the materials has been made from the data obtained by two ways. On the one hand, it has been used the results of tests carried out on other buildings located in a close environment and similar materials and construction characteristics. Specifically, it has been reviewed the trials carried out on the ashlars of the Trinity Bridge (Navarro et al., 2009) and the flat jacks trials carried out at the Monastery of San Vicente de la Roqueta (Casar et al., 2013).

On the other hand, specialized technical bibliography has been used. Among the documents considered include the articles published on the analysis of the Cathedral of Mallorca (Roca et al., 2013) and the Monastery of Poblet (Saloustros et al., 2015)

In the present work four materials have been taken into consideration: the walls, columns, arches and flying buttresses, the filling of the masonry walls, the brick masonry of the vaults and the filling material of the vaults. The mechanical properties determined from all the elaborated information, are shown in table 1.

Material	D (t/m3)	E (N/mm2)	fc(N/mm2)	ft (N/mm2)	Gf + (Nmm/mm2)
Ashlar	2.2	21300	9	0,3	0.3
Ashlar filler	2.0	2500	5	0,05	0.2
Brick	1.8	6500	2	0,10	0.1
Vault filler	1.5	1000	1	0,05	0.15

Table 1: Mechanical properties of materials.

Figure 4. Stress strain curvature, obtained from the flat jack test.

3.2 Constitutive model: the damage model.

Damage mechanics introduces changes to the material at a microstructural level through internal variables. These variables modify the influence of the material behaviour history in stresses evolution. The fissures appearance and their evolution over time are described as the damaged points trajectories.

Cracking is represented as an effect of local damage, which can be characterized in terms of compressive and tensile strength of the material from the known material parameters and the functions that control the evolution of cracking under a successive state of the strains at each one of the points.

The structural analysis was performed using the finite element non-linear regime ANGLE software, taking into account the application of the isotropic damage model developed by (Oller, 2001). The damage model used is based on the different behaviour of this type of materials under compression and traction stress, the rigidity deterioration due to both the stress level and the response depend on the size of the finite elements mesh used.

The degradation in an area of the material which has a level of deterioration is represented by hollows in the fabric. Index d (1) indicates the deterioration degree of the material (0≤d≤1), being zero value the non-damaged state and the unit value for the total deterioration of the resistant area.

$$d = \frac{S - \overline{S}}{S} \tag{1}$$

Where S is the whole area and S' is the effective resistant area. The difference S-S' expresses the surface voids that produced in the material. The relationship between Cauchy´s tension ($\overline{\sigma}$ and the effective stress acting over the effective resistant section (σ) is calculated by the equilibrium condition (2):

$$\sigma = (1-d)\overline{\sigma} = (1-d)E\varepsilon \tag{2}$$

This scalar index is sufficient to adequately represent the behaviour of materials such as concrete, brick and stone (Figure 4).

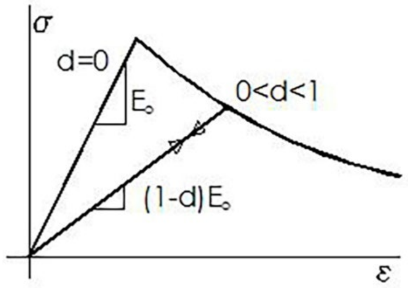

Figure 5: The effect on the mechanical behaviour of the material is a reduction of rigidity proportional to (1-d).

Where D is the elastic matrix for an isotropic material, constitutive matrix D´ is calculated as (3)

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

Therefore, the damage index is (4)

$$d = 1 - \frac{r_0}{r} exp\left[A\left(1 - \frac{r_n}{r} \right) \right] \tag{4}$$

Where r max {r0,rn} and A parameter that depends on the energy dissipated per unit volume for a process of uniaxial tension process.

3.3 Seismic action.

To analyse the seismic behaviour of the structure the method of the nonlinear static pushover analysis or incremental push is used (Milani et al., 2012; Cavalagli and Gusella, 2015). It is an efficient technique that allows studying the capacity and resistance-deformation of the structure under the influence of an earthquake. The seismic action is introduced by subjecting the structure to a horizontal loads pattern that is increased up to the maximum capacity of the structure. For its application the acceleration spectrum for the city of Valencia proposed by the Spanish norm (NCSE, 2002) is used (elastic, without ductility and for a return period of 975 years, which corresponds to structure type that is analysed). The assimilation of the capacity curve, the demand curve and the performance point is calculated according to the method specified in the attached Eurocode 8 (EC-8, 2004) (Figure 6).

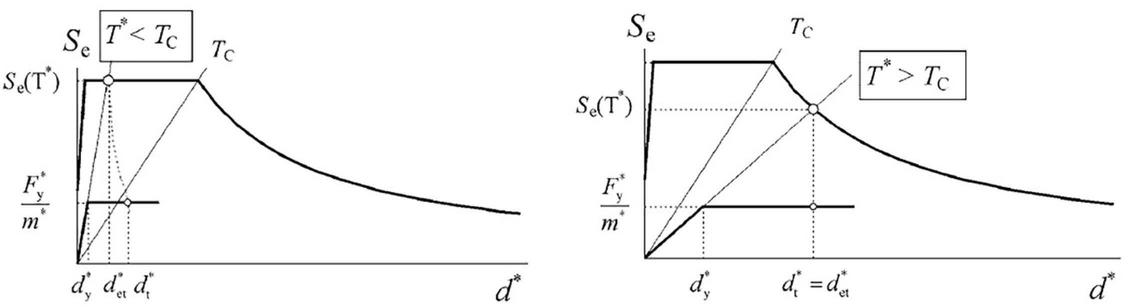

Figure 6. Indicative graphics of the Performance Point; a) Short period range; b) Medium and long period range.

The intersection between the demand curve and the capacity one defines the Performance Point. This point indicates the movement that can be expected in the highest point of the central section of the nave for calculating the seismic actions defined by the spectrum.

Statistical and probability methods have been applied to define the seismic action for calculation purposes. The return period of the recurrence interval is an expression of the average time period (in years) that elapses between the occurrence of an earthquake that causes damage of a severity that is equal or greater than a given one. The table 2 shows the values of the return periods used for the calculation (Figure 7):

Seismic Movement	Return Period (years)	Probability of Exceedance
Service Level	72	50% in 50 years
Design Level	475	50% in 50 years
Maximum Level	950	50% in 50 years

Table 2: Values of the return periods.

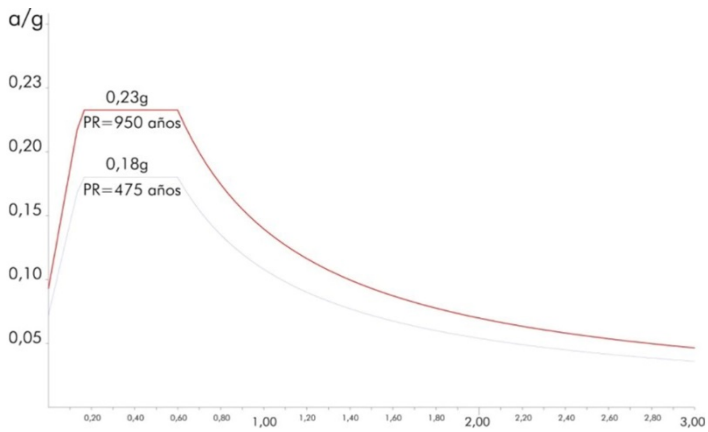

Figure 7. Response spectra in the city of Valencia. Return period of 475 years and 950 years.

From the performance point position regarding the points of yield strength and ultimate capacity the damage state limits (Sd) (Figure 8) (Table 3). The damage thresholds are established according to the formulation proposed in RISK UE (Mouroux, and Brun, 2006).

Figure 8. Damage state limits

Damage limits	Definition
Light	Sd1=0,7 Dy
Moderate	Sd2=Dy
Severe	Sd3=Dy + 0,25 (Du-Dy)
Great	Sd4=Du

Table 3: Classification of damage limit

3.4 Structural model.

The analysis is focused on the original Gothic structure to evaluate the behaviour of the own Mediterranean Gothic diaphragms, and justify the historical damages suffered in the arches of the lateral naves, to this end, the model reproduces the central section of the Cathedral; it is made up of three naves and two bays from the original layout.

The calculation takes into account gravity loads and transverse seismic actions, acting on the central section. A model is developed by means of a "solid" type Finite Element of about 50 cm medium size, following the criteria of the so-called "macro-modelling" the most widely used in the analysis of complex structures (Roca et al., 2010; Cennamo et al., 2011). This allows a lower requirement calculation given the large size of the object under study that contains more than 15,000 items. Different variations of the model are set out according to the considered constructive elements.

The first model reproduces the situation including the reinforced concrete slab (built in at the intervention carried out in 1976) in addition diaphragms and flying buttresses are ensuring the continuity of the wall structure. The second calculation model keeps the concrete slab but gets rid of flying buttresses while keeping only the diaphragms, allowing us to check its structural function. For the third, fourth and fifth simulation the reinforced concrete slab is removed, to analyse the original structure of the cathedral and it is combined with and without flying buttresses and diaphragms.

The five model calculations are summarized in the following table and classified according to the constructive elements (Table 4):

Model	Nodes	Tetrahedrons	Hexahedron	Shells	Equations
slab, with flying buttresses and with diaphragms.	22983	5020	11496	4352	79635
slab, without flying buttresses and with diaphragms.	22227	4480	11136	4352	77367
with slab, with flying buttresses and with diaphragms.	22983	5020	11496	3992	78663
without slab, without flying buttresses and with diaphragms.	22227	4480	11136	3992	76395
without slab, with flying buttresses and without diaphragms.	21615	4192	10608	3992	74559

Table 4. Classification of the calculation models.

4 ANALYSIS RESULT.

In general, the results obtained indicate that, for gravity loads the maximum stresses (Sz) are produced in the base of the central columns reaching maximum values of 3 N / mm2 is well below the compressive strength considered in the calculation of the order of 9 N / mm2. The damage index is concentrated on the lower surface of the arches keys note that the higher buttresses are not taking part in the structure equilibrium (Figure 9). Besides, as the graph demonstrates, the fact of it being a rigid structure, the model dynamic properties are placed in the areas where the spectrum is higher and thus the effective accelerations are higher.

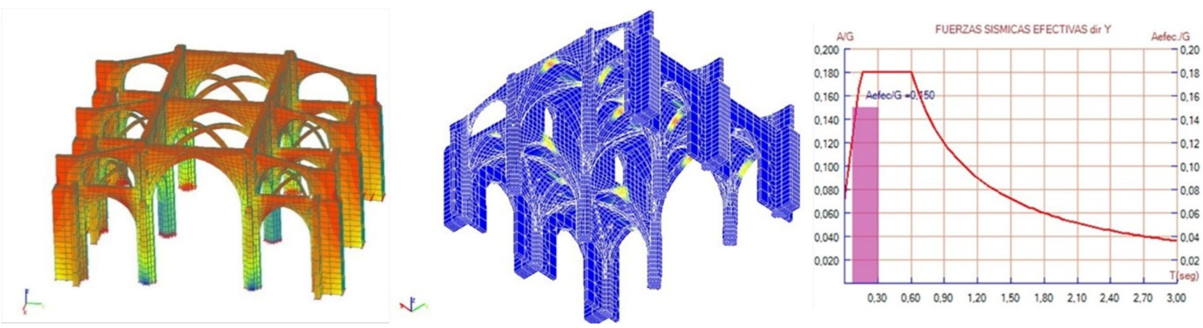

Figure 9. a) Stresses isovalues and gravity load damage index; b) Seismic forces in transverse direction, perpendicular to the longitudinal axis of the Cathedral.

4.1 Model with slab, buttresses and diaphragms

Through the non-linear static analysis, we can determine the Cathedral´s vulnerability against earthquakes, specifically two already mentioned scenarios have been considered, one of them with a return period of 475 years and the other of 950 years (Chellini et al., 2014; De Matteis and Mazzolani, 2010).

In the graphics the structure capacity (for the highest point of the central nave) and the demand due to ground motion are compared. The maximum horizontal deformation obtained corresponds to the performance point located at the intersection of the structure capacity spectrum with the demand curve. For an earthquake with a return period of 475 years, the performance point is located before the elastic phase therefore far to collapse (Figure 10-a). For the 950 earthquake the performance point indicates a medium-severe damage (Sd3) according to the table damage levels (Figure 10-b).In the image below illustrates how buttresses start to support loads, damage increases in the arch extrados just where its section decreases. Cracking is reached at the indicated areas but there is minor damage without the whole collapse of the structure (figure 10-c).

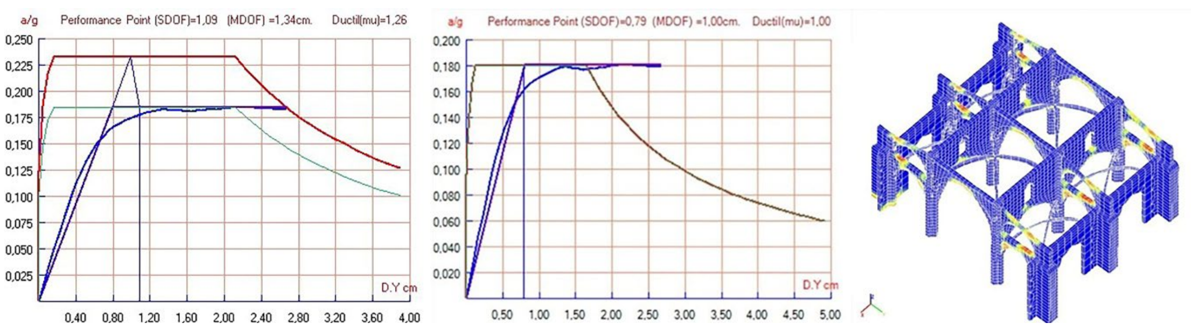

Figure 10. Performance point determination.: a) a 475 years return period seism, a 950 years return period seism. b) Damage Index for the maximum displacement.

4.2 The buttresses function: A model with slab, diaphragms and without buttresses

Once again, for an earthquake of 475 years the performance point is located in the first section of the inelastic phase (Figure 11-a) which means slight damage. In the case of an earthquake with a return period of 950 years the performance point is located close to the failure point (Figure 11-b) and therefore damage is severe.

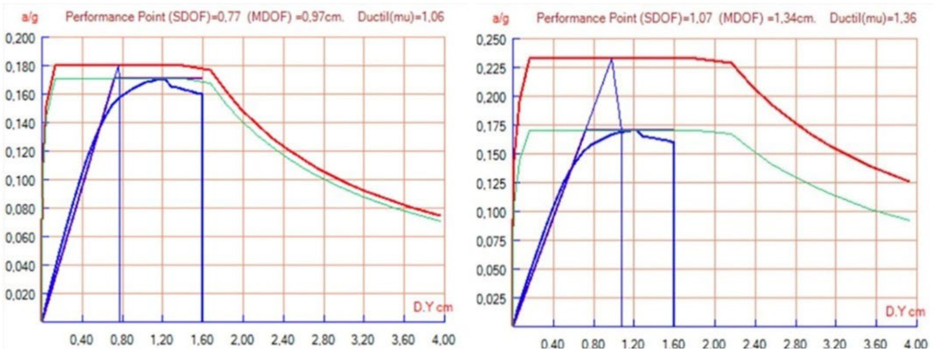

Figure 11. Performance point determination. a) 475 years return period seism; b) 950 years return period seism.

It can be observed that the damage is concentrated in the arches intrados of the nave and in the arches extrados of the aisles (Figure 12). Although damage is severe at these areas a global collapse is not reached.

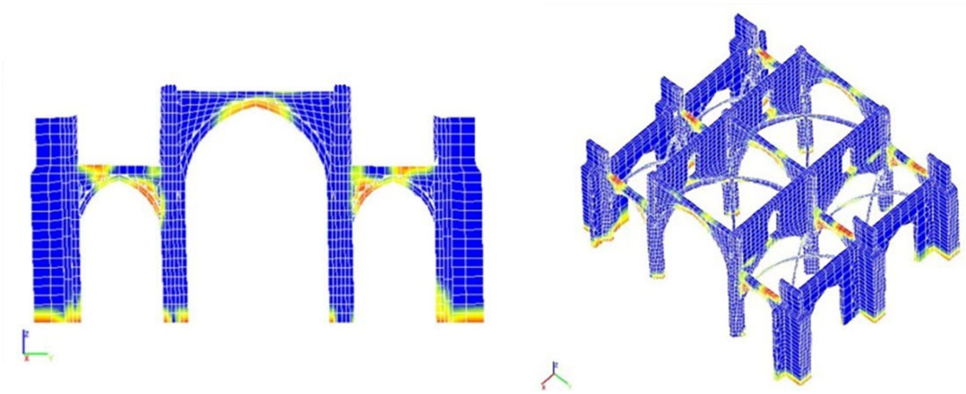

Figure 12. Damage index of the maximum displacement for an earthquake with a return period of 950; a) elevation; b) perspective.

4.3 Original state of the Cathedral: model without slab, with diaphragms and buttresses.

In this case the performance point indicates a medium-severe damage (Sd3) for an earthquake with return period of 475 years. When the slab of the model is removed the yield point decreases making the structure more vulnerable. Damage obtained is between moderate and severe (Figure 13).

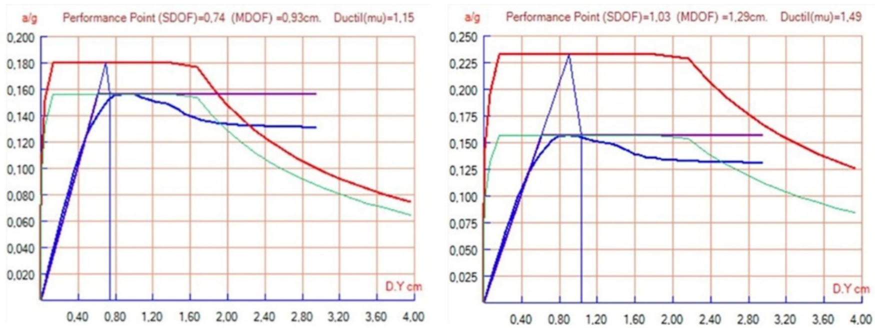

Figure 13. Performance point determination.: a) 475 years return period seism; b) 950 years return period seism.

The analysis explains the historical damage suffered by the Cathedral. As Figure 14-a illustrates, the damage in buttresses is concentrated in areas that have had to be intervened (Figure 14-b).

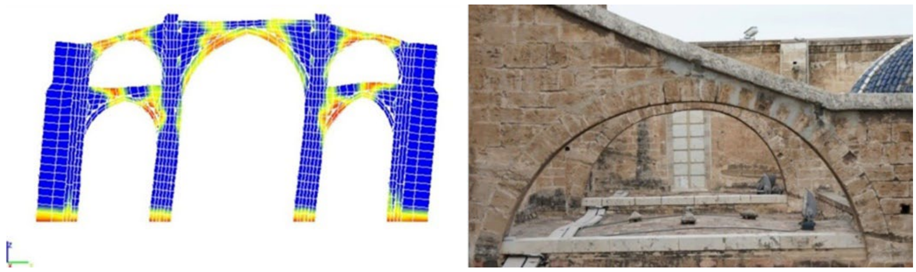

Figure 14. Maximum displacement damage index of the for a seism with a return period of 950 years; a) results on the model; b) damage observed in the flying buttresses.

4.4 Model without slab, without buttresses and with diaphragms.

In the simulation where the slab is removed and buttresses are not considered the performance point indicates a level of damage (SD4) (Figure 15-a). It is concentrated on diaphragms extending in the arches intrados and in the voids in the walls of the nave (Figure 15-b). Serious damage occurs reaching a global collapse for the scenario of an earthquake with a return period of 950 years.

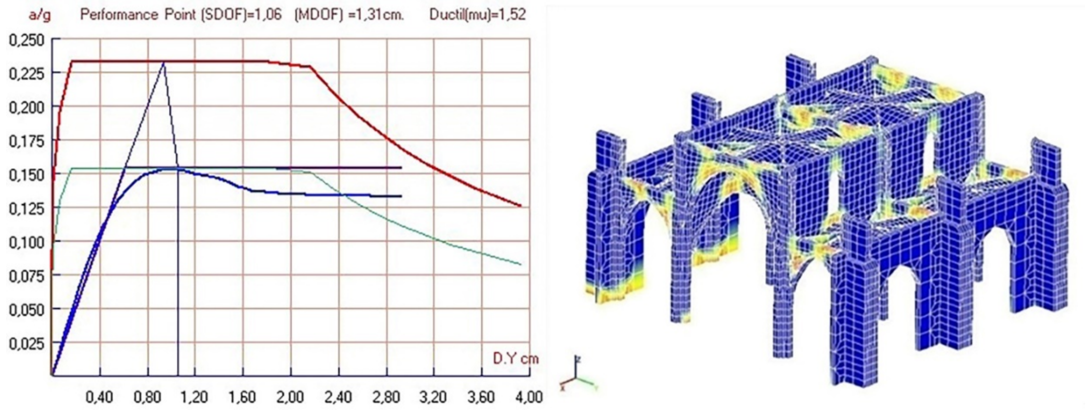

Figure 15. A seismic with a return period; a) performance point; b) index of damage.

4.5 Model without slab, with flying buttresses and without diaphragms.

In this analysis the highest value of the performance point is obtained for all the simulations (Figure 16-a) which leads to a damage classified as severe that could produce the collapse. By not considering the diaphragms or the slab, the box concept is lost, so the transverse seismic capacity of the structure begins to be insufficient. Displacements are higher as a result of the whole unity loss. The damage is concentrated in transverse arches and at the top and bottom of the voids of the arches in the walls, achieving the collapse of the flying buttresses in the area where the arch section is reduced, due to the fact that is the weakest point facing failure (Figure 16-b).

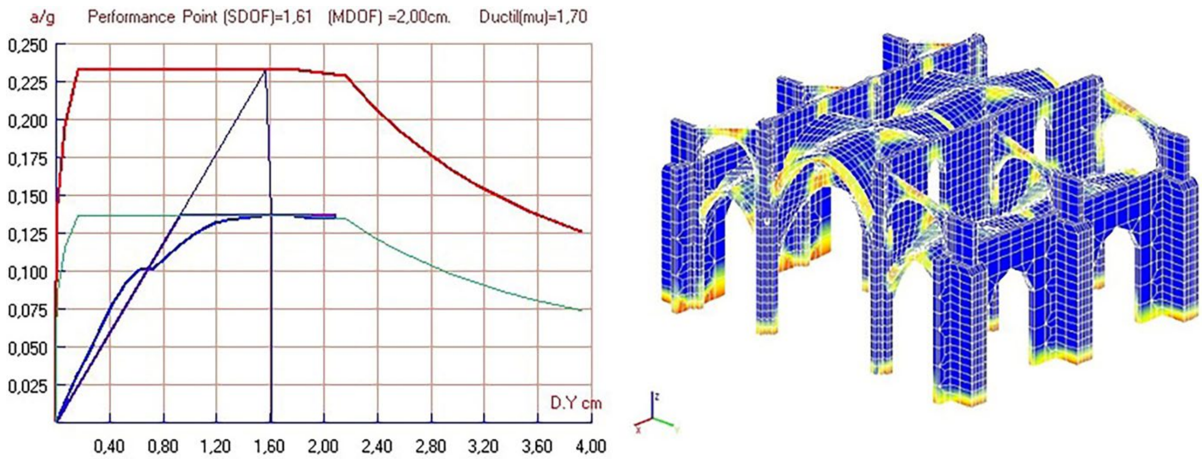

Figure 16. Earthquake with a return period of 950 years; a) performance point; b) damage index.

5 CONCLUSIONS

Given that it is a rigid structure the oscillation periods obtained are low so they are placed at the demand spectrum where accelerations are higher.

It has been found that the seismic capacity of the Cathedral of Valencia, in the current situation is sufficient to withstand an earthquake with a return period of 475 years. The expected damage, if any, would be minor. The situation gets worse when considering an earthquake with a return period of 950 years. The main damage is caused in the arches intrados and it extends to diaphragms and buttresses.

Removing the buttresses prevents the continuity in the walls system, losing the connection between diaphragms and buttresses. The obtained damage is serious although it doesn´t mean the overall collapse of the structure.

The simulation in which the slab is removed but diaphragms and flying buttresses remain, which coincides with the primitive state of the cathedral, reproduces the historical damage suffered and the current deformations in the flying buttresses.

When neither the flying buttresses nor the slab are take into account, the damage level begins to be severe as in the diaphragms on in the top and bottom of the voids of the nave walls. This is due to the stiffness loss provided by the slab to the whole and the independence of movement. In this simulation severe damage that would lead to collapse is produced.

The model without slab or diaphragm represents the most vulnerable place because the wall structure sense is lost, resulting in collapse.

In the light of the different results, it becomes clear that both diaphragm and flying buttresses are necessary for the correct performance of the structure of the Cathedral against an earthquake. However, it must be highlighted that for the behaviour of the whole, the diaphragm loss is more decisive.

The shape and position of the flying buttresses provides, the arches to become diaphragms ensuring continuity with the buttresses and generating a wall structure that braces transversely, functioning as "shear walls". This orthogonal walls framework is characteristic of the "Mediterranean Gothic" and gives the structure of the Cathedral the stiffness and strength required while setting the shape that has the best response against earthquakes.

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