

# Mediterranean Gothic Architecture and Its Constructive and Structural Logic: Mass, Buttresses, and Seismic Stability in Santos Juanes, Valencia, Spain

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**Abstract** Located in the city of Valencia, the church of Santos Juanes offers an exemplary case for analysing how Mediterranean Gothic architecture responded to the seismic conditions of its geographical context. In contrast to Northern European Gothic models, typically characterised by slender structural systems, thinner walls, and the systematic use of flying buttresses, the Mediterranean tradition evolved towards a more compact and massive tectonic solution based on the continuity of load-bearing masonry, increased material density, and lateral stiffening provided by transverse diaphragm arches. Within this architectural framework, the concept of *enjuta*, as formulated by Pepa Cassinello, serves as a useful interpretative tool for understanding both the degree of compactness and the underlying structural logic of these buildings. The analysis of this case study shows that the absence of flying buttresses was compensated by the use of exceptionally large buttresses, which, acting together with the diaphragms and the rigidity of the walls, generated a global structural response comparable to that of a closed-box system. Rather than constituting a simplified version of Northern Gothic architecture, this solution reflects a deliberate adaptation to local material resources and a territory historically affected by seismic activity. Furthermore, comparison with other contemporary

religious buildings, such as Valencia Cathedral and Tortosa Cathedral, highlights the specific characteristics of the Valencian example and confirms its relevance as a reference within Mediterranean Gothic architecture.

**Keywords** Mediterranean Gothic, Gothic Architecture, Diaphragm-Arch Buildings, Spandrel Structures, Pushover Analysis

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## 1. Introduction

Within the architectural landscape of Valencia, the church of Los Santos Juanes occupies a distinctive position due to both the complexity of its design and the significance of its urban setting. The building rises in the area historically known as the suburb of La Boatella, now the Market Square, a location that places it at the very heart of the city's civic and commercial activity. It stands adjacent to two major landmarks that have shaped the historical identity of this urban space: the Lonja de los Mercaderes, a key reference of civil Gothic architecture, and the Central Market, a landmark work of Valencian modernism from the early twentieth century. This spatial

arrangement cannot be regarded as coincidental, but rather as the result of an intentional planning decision that underscores the strong connection between the church and the economic and social life of Valencia. From its foundation, Santos Juanes was therefore embedded within one of the most dynamic and representative areas of the medieval city (Figures 1a and b).



A



B

**Figure 1.** A) View of the Market Square. In 1907. B) Peso de la Paja Street. In 1900.

This central condition has had a decisive influence on its formal, functional, and symbolic evolution. As Estellés Ceba (1986) notes, the temple ‘has been the setting for numerous events thanks to its important commercial position, and it also reflects formal conditions ranging from the dimensions of the large Baroque interior vault to the finish of the palace-style loggia and the Clock Tower on the apse façade.’ [1] (p. 2).

The history of the temple dates back to the old suburb of La Boatella, where it was originally known as San Joan de la Boatella, a name that reflects its location outside the city walls before becoming part of the consolidated urban layout [2] (pp. 329–330). Over time, the growth of the city

and the increasing centrality of the area led to a change in its name to San Joan del Mercat, in direct reference to the intense commercial activity that surrounded it. Finally, after Queen Isabella II's visit in 1858, the church was granted the title of ‘Royal Parish Church of Los Santos Juanes’, an institutional recognition that consolidated its importance within the Valencian ecclesiastical hierarchy: ‘...it is currently known as the “Royal Parish Church of Los Santos Juanes,” with royal title since 1858 by decree of Queen Isabella II after her visit to the temple on 2 June of that year’ [3] (p. 24).

This long historical process has left a distinct material imprint. Few churches in Valencia have experienced such an intense sequence of transformations over the centuries. Fires, renovations, reconstructions, and successive Baroque interventions progressively altered the building's appearance, resulting in a hybrid configuration in which different construction systems, materials, and stylistic languages coexist. Nevertheless, the interior continues to preserve the structural logic characteristic of Mediterranean Gothic architecture, only partially masked by later Baroque cladding. As recent studies have shown, this monument is deeply rooted in its historical context, with significant features present throughout the building that simultaneously reveal and conceal traces of the past in which it played a central role. The numerous symbolic elements still preserved within the temple reinforce its historical continuity and underline its value as both a historical and testimonial monument.

This palimpsestic architectural character has often hindered comprehensive analysis, demanding an approach that integrates history, technique, and architecture. Despite its prominence, the temple endured decades of serious technical and structural neglect, as documented in various newspaper articles. The most significant among them are: ‘*Los Santos Juanes: una obra incompleta*’, ‘*Los Santos Juanes, la joya olvidada*’ [4], and ‘*Llegó la hora a los Santos Juanes*’ [5] (p. 14). These publications denounce not only the progressive deterioration of the building but also the persistent failure to undertake interventions necessary for ensuring its long-term stability. Paradoxically, as noted in an article published in 2000, it is ‘the most documented parish in the entire diocese’ [5] (p. 23), a fact that highlights the gap between historiographical knowledge and the absence of in-depth technical studies.

Fortunately, in recent decades, several researchers have begun to address this gap. Among them, historian Manuel Galarza Tortajada stands out, having already warned of the difficulty of rigorously studying the building's origins: ‘Attempting to reconstruct the most remote origins of the construction of a temple and to clarify its historical background is an almost impossible task when dealing with a centuries-old building and lacking authentic documents to rely on. Such is the case of the Temple of Los Santos Juanes in the city of Valencia’ [6] (p. 12).

However, architect Juan José Estellés Ceba made the

most significant contribution to the technical study of the building, particularly through his work in the 1980s. His research identified construction stages, specific materials, and previously unknown structural mechanisms, thereby laying the groundwork for the present analysis. His study represented a decisive advance in establishing the church's construction phases, later modifications, and constituent elements [1].

In addition, the work of Arturo Zaragoz á Catal án made a decisive contribution to situating Santos Juanes within the framework of Mediterranean Gothic architecture. His definition of the diaphragm arch system, characteristic of churches built after the Reconquista, clarifies the tectonic principles on which the temple's original structure was based: 'Diaphragm arch architecture is defined by the construction of a series of masonry arches arranged transversely to the major axis of the building, equidistant from one another and capable of supporting a roof, normally made of wood' [7] (p. 3).

Finally, it is important to acknowledge the contribution of Professor Cassinello, whose work analysed the influence of seismic activity on the structural configuration of Spanish Gothic churches. Her typological classification, based on the degree of *jointing*, offers a valuable interpretative framework for explaining the markedly massive and compact character of the Santos Juanes building, located in a region of moderate seismic risk. As she states: "*In Spain, there are two clearly differentiated structural types: those built in the cathedrals of Castile and Galicia, which follow the French model, and another type built in Andalusia and Catalonia, where, as historical seismic data show, medieval master builders were aware of the need to modify their stone skeletons in order to ensure stability in the face of possible earthquakes*" [7] (p. 249).

Within this framework, the present research develops a detailed structural investigation of this monument, focusing on its capacity to resist both gravitational and seismic actions, as well as on the specific role played by the different elements composing its structural system. Special attention is given to the Mediterranean Gothic rib-vaulting scheme and to its particular adaptation in this case, where stability relies not only on diaphragms and lightweight roofing systems, but also on a powerful arrangement of buttresses that clearly differentiates it from other contemporary churches. Through the use of advanced calculation tools and representative numerical models, the study aims to clarify the mechanisms that have ensured long-term stability and to establish comparative hypotheses with other Gothic buildings from the same period. Ultimately, the research seeks to contribute a methodological tool capable of supporting conservation, intervention, and valorisation strategies for one of the most significant monuments of Valencia's architectural heritage.

## 2. Churches of the Reconquista and Mediterranean Gothic architecture

A comprehensive interpretation of the structural mechanisms of the Church of Saints John requires placing the building within its historical and architectural context. The construction of this temple, as in the case of many other Valencian churches, must be understood as part of a broader cultural, political, and urban transformation that took place following the Christian conquest of Valencia by James I in 1238. This event initiated a profound process of territorial reorganisation, in which the establishment of Christianity extended beyond the liturgical sphere to reshape the urban fabric, legal structures, and architectural configuration of the conquered cities. One of the key strategies in this process was the construction—or consecration—of parish churches, many of them erected on the sites of former mosques or within plots characteristic of Islamic urbanism, thus giving rise to a new sacred landscape that reinforced territorial control.

This context saw the emergence of a generation of religious buildings that became the architectural testimony of this cultural transition. These churches, most of which consist of a single nave with a rectangular floor plan, share formal and structural characteristics that allow them to be grouped into a common style, which architect and historian Arturo Zaragoz á Catal án has termed 'Mediterranean Gothic architecture' [7]. In contrast to the typologies developed in central and northern Europe—characterised by slenderness, transparent walls, and the systematic use of flying buttresses—the churches of the south are defined by their horizontality, the continuity of their walls, their material robustness, and a distinctive structural solution: diaphragm arches (Figure 2).



**Figure 2.** Convent of San Francisco de Morella. The accompanying figure shows the construction of the wooden roof [9]

These arches, arranged transversely to the longitudinal axis of the building, are masonry elements—usually of stone or brick—that divide the space into stable sections and facilitate roof construction. As Zaragoza á explains: ‘Diaphragm arch architecture is defined by the construction of a series of masonry arches, arranged transversally with respect to the major axis of the building, equidistant from each other and capable of supporting the roof, normally made of wood’ [7] (p. 10). This is not merely a structural device, but rather a solution adapted to a specific geographical and technical reality: an area with limited wood resources, restricted industrial capacity, and an economy in recovery after the conquest. Indeed, as he himself notes, these arches developed especially in ‘countries characterised by weak and poor forests,’ where ‘most of the wood that was extracted was used for shipbuilding’ [7] (p. 45), making it necessary to optimise its use in both civil and religious constructions.

The consequence of this material scarcity is an austere architecture, dispensing with unnecessary ornamentation and relying on solutions that could be easily executed by local builders. This explains why many of the temples of the Reconquista have sober interiors, without coffered ceilings or decorated vaults, where smooth walls and diaphragms set the spatial rhythm of the building. This technical logic, however, does not compromise monumentality. On the contrary, as Zaragoza á observes, these temples acquire great spatial depth through the repetition of sections, and remarkable durability over time thanks to the stability provided by diaphragm arches as transverse reinforcements. Moreover, their construction proved versatile enough to adapt to different scales, so this system was used not only in churches, but also in convents, hospitals, mills, ovens, and domestic buildings (Figure 3).



Figure 3. Social housing in Rodas [10]

‘This model of pragmatic and tectonic architecture represents a marked departure from the structural ideals of northern Gothic. While architects in France and Germany sought to lighten walls, open large windows, and raise

vaults with the aid of flying buttresses and pinnacles, in the Mediterranean region, more solid, enclosed, and darker buildings were constructed, responding to a logic of resistance and permanence rather than a pursuit of light and elevation. As Cassinello explains when comparing Central European and Mediterranean models: ‘They are functionally identical buildings, contemporaneous in time, but totally different in terms of construction. Central European Gothic cathedrals based their design on the principle of stability, focusing on relieving the load-bearing walls of responsibility by transferring the forces to flying buttresses attached to them, with the aim of opening large stained-glass windows through which light could enter’ [8] (p. 249). This fundamental difference is clearly evident when comparing buildings such as the Sainte-Chapelle in Paris or Notre Dame Cathedral (Figure 4) with contemporary Valencian churches (Figure 5).

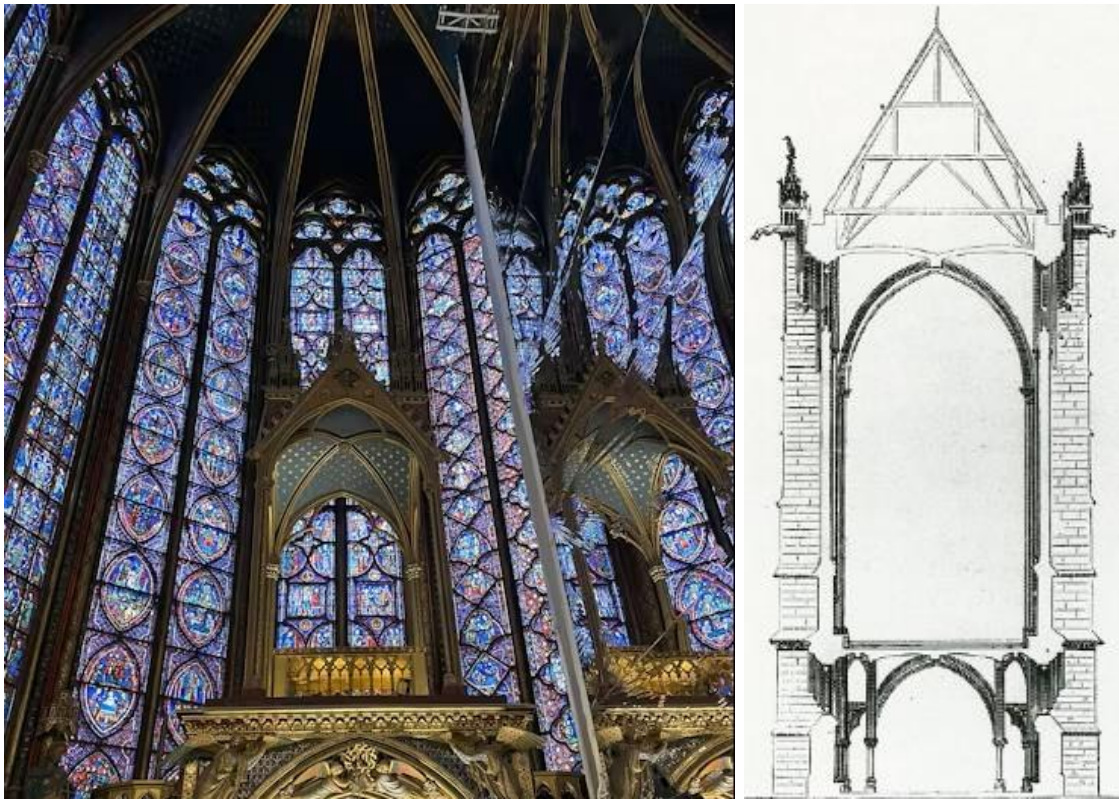
In contrast, in the Mediterranean region, more solid structures were designed, capable of guaranteeing stability. This resulted in interiors that were more enclosed and heavy, but also more compact and resistant to the seismic conditions of the territory. Within this context, diaphragms played a decisive role. They were not a marginal feature, but rather the key element articulating the constructive logic of Mediterranean Gothic architecture. In contrast to the structural dissociation of northern Europe, where flying buttresses absorbed the thrusts from the walls, in southern churches, diaphragm arches became the element that ensured the immediate stability of the building, allowing phased construction and securing the roof from the outset. Zaragoza á explains it clearly: ‘It can even be built as a temporary solution while waiting to provide the building with masonry vaults. In such cases, the vaults can be built comfortably under cover, with the only precaution being to supplement the diaphragm arches with buttresses to counteract future thrusts’ [7] (p. 22).

This evolutionary character is particularly relevant in the case of Santos Juanes, where, although no remains of the wooden roof have been preserved, neither has any clear evidence of an initial vault been documented, suggesting a gradual transition from a diaphragmatic system to a vaulted one. This process of transformation can also be observed in other churches, such as Valencia Cathedral, whose structure corresponds to a mixed system of transverse arches and vaults, as demonstrated by Llopis in his doctoral thesis: ‘Valencia Cathedral responds to a hybrid system, as a result of transformations, achieving stability “section by section” through diaphragmatic arches, overcoming the disadvantage of the lack of solidity and durability of wooden floors thanks to the use of the vaulted system’ [10] (p. 132).

Thus, the churches of the Reconquista—including Santos Juanes, but also others such as the Church of Sang de Onda, Olocau del Rey, and Sang de Lliria—should not be regarded as minor examples of European Gothic. They are temples of great structural coherence, deeply adapted to their physical, economic, and seismic context. They

represent a rational response to the available resources and to the unstable conditions of the terrain. The austerity that defines them should not be mistaken for architectural poverty, but rather understood as a deliberate choice based on economy of means, durability of form, and the reliability of a tectonic system that, eight centuries later, continues to fulfil its function. In this context, the

construction solution adopted in Santos Juanes is particularly significant: whereas in Valencia Cathedral, also of Mediterranean Gothic affiliation, stability was achieved through systems reinforced with flying buttresses (Figure 6), in Santos Juanes it was decided to rely on exceptionally large buttresses, whose strength defined the tectonic logic of the temple from the outset (Figure 7).



**Figure 4.** Interior view and cross-section of Saint Chapelle<sup>1</sup>



**Figure 5.** Structural system of Los Santos Juanes

<sup>1</sup> Images from the web: Sainte-Chapelle, Paris | Book Tickets, Tours & More (25/07/2025)



Figure 6. View of the flying buttresses of Valencia Cathedral [10]



Figure 7. Buttresses of Los Santos Juanes

### 3. The Structural Logic of Los Santos Juanes: Corbelling, Buttresses and Seismic Response

To understand the resilient logic of Mediterranean Gothic architecture, it is essential to consider the concept of *enjuta*, formulated by Pepa Cassinello. This notion makes it possible to analyse buildings not merely as a collection of isolated elements, but as structures that are more or less compact and continuous, depending on the relationship between walls, diaphragms, roofs, and buttresses.

Within this framework, the concept of *enjuta*, introduced by Pepa Cassinello, becomes a fundamental analytical category for interpreting the structural logic of these constructions. Cassinello defines *enjuta* as the degree of structural compactness of a building, determined by parameters such as wall thickness and number, the

connections between them, the presence of diaphragms, and the ratio between mass and skeleton [8] (p. 249). On the basis of these criteria, she distinguishes two broad categories: open skeletons or low *enjutas* (type A), characteristic of a lighter architecture dependent on flying buttresses, and compact skeletons or *enjutas* (type B), defined by the continuity of walls, material density, and the pursuit of stability through mass (Table 1) [10] (p. 13).

There is a direct relationship here with the European seismic map, which accounts for the notable differences between northern and Mediterranean architecture (Figure 8). While the great French and German cathedrals were built in regions of low seismic activity—favouring the development of open, lightweight structures with thin walls, glazed windows, and flying buttress systems to relieve thrust—in Mediterranean territories, exposure to recurrent earthquakes led to much more compact and reinforced solutions. Medieval master builders were aware of this threat—albeit without the scientific precision available today—and consequently designed buildings that were robust in the face of earthquakes.

In this context, Santos Juanes stands as a paradigmatic example: seven pairs of buttresses, 1.50 metres thick and over five metres long, which could absorb and transmit the thrust of the vaults, producing a structural behaviour comparable to that of a ‘closed box’ [8] (p. 249). In short, it is a building with a flying-buttress construction system, conceived as a succession of resistant ‘boxes’ (see the diagram in Figure 9 of the cathedral, similar to that of Santos Juanes), which not only embodies the general strategy of Mediterranean Gothic architecture but also reaches its most extreme expression here as a deliberate response to the seismic threat.

“However, in addition to this construction system, the building incorporates—unlike other temples of the same period—a set of exceptionally large buttresses that further reinforce its stability against horizontal forces (Figure 9). As Estellé Ceba (1986) [1] noted, these buttresses were built with two layers of rough-stone masonry and a core of lime concrete mixed with gravel and crushed brick, resting on deep masonry foundations. Supported by them are long-span transverse arches (16.70 metres, compared to the usual 12–15 metres in other Valencian parishes) and smaller ogives, completed with double brick partitioning (Figure 10). The entire structure forms a solid and continuous framework, capable of responding effectively to dynamic stresses of seismic origin.

**Table 1.** Structural types of Spanish Gothic cathedrals [12]

SPANISH GOTHIC CATHEDRALS			
Structural Types			
DEGREE OF “ENJUTAMIENTO” CENTRAL NAVE	Type	Ship	Counterweight system Position
FORMERAS  <b>A</b>  Pitched roof	I	1	CI- NON-ARBOTANTS
	II	3/hHh	CE- ARBOTANTS
	III	3/HHH	CE- NON-ARBOTANTS
	IV	5/hhHhh	CE- -ARBOTANTS
FORMERAS  <b>B</b>  Terraced roof	I	1	CI- NON-ARBOTANTS
	II	3/HHH	CI- NON-ARBOTANTS*
	III	3/hHh	CI- NON-ARBOTANTS*
	IV	5/hhHhh	CI- ARBOTANTS

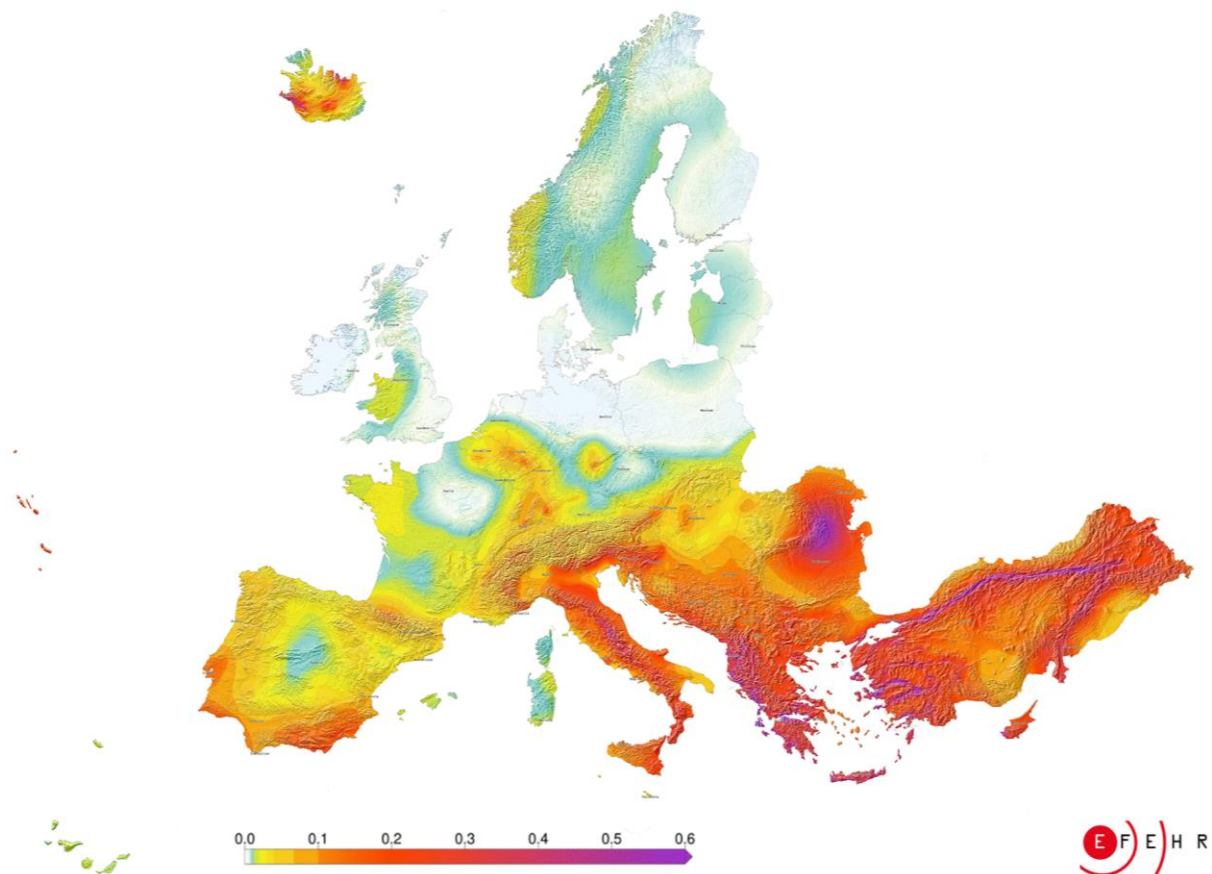
CI- Interior counterforts

CE- External buttresses

hHh- Three taller buildings, the central one

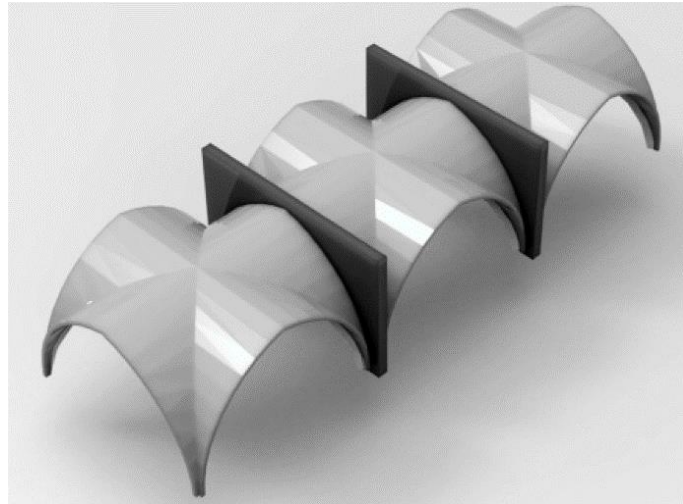
HHH- Three ships at the same height

\* There are some cases with flying buttresses.

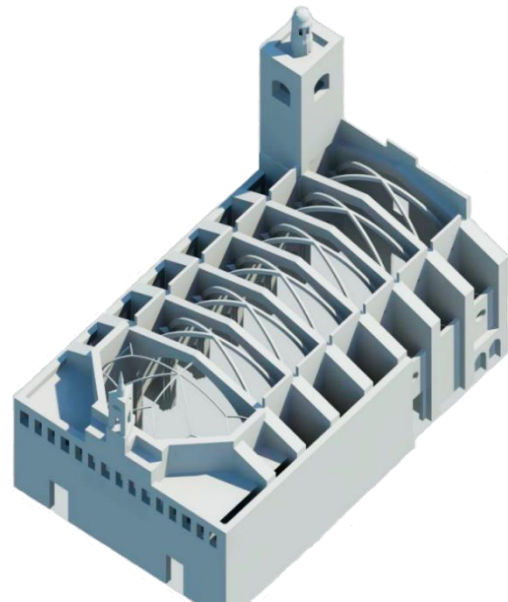
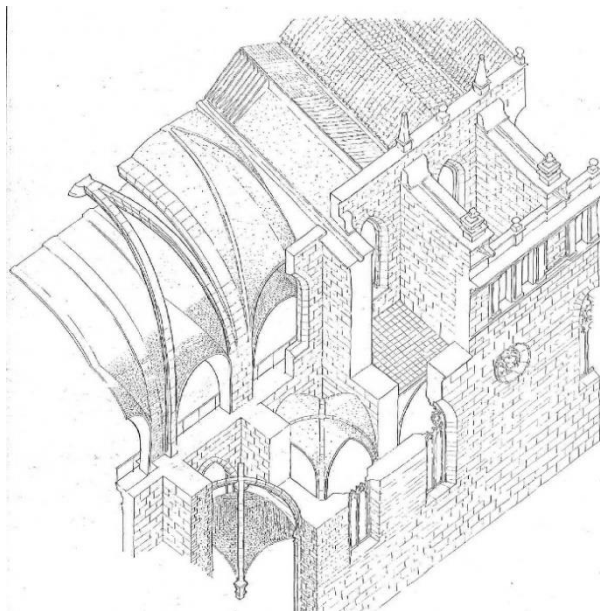


**Figure 8.** Seismic map of Europe <sup>2</sup>

<sup>2</sup> Image of EFEHR | The earthquake hazard map of Europe. 06/02/2026



**Figure 9.** Diagram of the diaphragm vaults in the central nave of Valencia Cathedral [11]



a) Sketch of Los Santos Juanes by Estellés [1]. b) Three-dimensional model of Los Santos Juanes created using Estellés' drawings

**Figure 10.** Description of the structural model



**Figure 11.** Tortosa Cathedral <sup>3</sup>

In Los Santos Juanes, the absence of external flying

buttresses and the thickening of the walls push this logic to the extreme, producing a system that is far more rigid (Figure 7) than those of its contemporaries in Valencia, Seville, or Tortosa (Figure 11). Although the passages between the buttresses allow for external circulation, their narrowness underscores the priority of compactness over formal openness.

The stability of Los Santos Juanes cannot be understood as the result of a single element, but rather as the interaction of a corbelled load-bearing system—defined by the compactness and continuity of its structure—together with the strength of its buttresses and the effectiveness of the diaphragms bracing the nave transversally. These solutions should not be regarded as a simplification of northern Gothic architecture, but as a conscious adaptation to the specific conditions of the Mediterranean: a territory

<sup>3</sup> Image from the archive of Juan Gomis (1998).

marked by seismic threats, limited material resources, and an economy of means that demanded permanent and solid construction. The resistance shown by the temple in the face of the earthquakes that have struck Valencia over the centuries confirms the suitability of this model, in which functional *utilitas* and constructive *firmitas* are integrated into a tectonic strategy that constitutes one of the keys to its heritage value [6].

## 4. Comparative Analysis and Structural Model

Within the Mediterranean building tradition, the case of Los Santos Juanes stands out for a tectonic logic strongly conditioned by the need to respond to seismic risk. This example is particularly revealing for understanding how Gothic architecture in southern Europe departs from northern models, not only through the massiveness of its walls and the continuity of its masonry, but also through the incorporation of elements such as diaphragms, which provide effective transverse bracing to the structure. In this context, the concept of *enjuta*, formulated by Pepa Cassinello [12], constitutes a key interpretative tool for analysing the structural stability of the building.

The study of the structural response of historic buildings represents a multidisciplinary research field that lies at the crossroads of construction history, structural mechanics, and heritage conservation. Unlike contemporary architecture—where materials are standardised, design hypotheses are codified, and structural performance can be experimentally verified—medieval churches were conceived according to empirical construction knowledge transmitted through guild practice and built using heterogeneous masonry and locally sourced materials. Consequently, evaluating their current structural behaviour

necessitates a tailored methodological framework capable of combining historical evidence, classical masonry concepts, and advanced numerical analysis tools. Within this framework, particular relevance is given to the theory of limit analysis for masonry structures, originally formulated by Heyman [13] (p. 63), which is founded on three fundamental premises: masonry does not resist tensile stresses, it behaves predominantly in compression with theoretically unlimited compressive strength, and failure by sliding is neglected. As emphasised by Huerta Fernández [14] (p. 15), structural stability is guaranteed as long as it is possible to define a line of thrust that remains fully contained within the geometric boundaries of the structural element.

### 4.1. Damage Modelling Approach

Due to the heterogeneous composition of the temple's masonry, consisting primarily of rough-hewn stone blocks bonded with mortar, the structural behaviour was simulated using a continuous isotropic damage formulation. This modelling strategy allows the progressive degradation of the material to be captured by representing the evolution of the masonry microstructure under loading conditions. Material deterioration is introduced through a scalar damage variable ( $d$ ), which accounts for the gradual reduction of the effective resistant surface of the material, following the formulation described in [15] (p. 167), and schematically illustrated in Figure 12. Furthermore, Figure 13 provides a detailed representation of the adopted damage law, clarifying how the effective response of the material evolves as damage accumulates.

$$d = \frac{S - S'}{S} = 1 - \frac{S'}{S}$$

Equation 1. Expression of deterioration

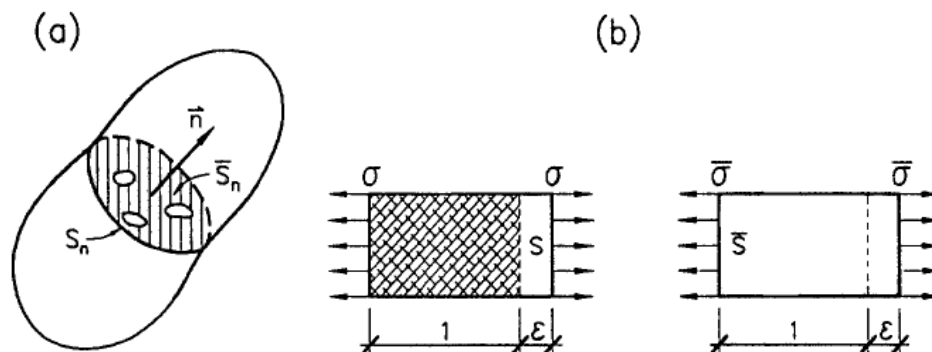


Figure 12. Model a illustrates the damaged surface, while model b shows the corresponding Cauchy stress,  $\sigma$  (effective stress)

If you have to:

$$N = S \times \sigma \quad N = S' \times \sigma'$$

So:

$$S \times \sigma = S' \times \sigma'$$

$$\sigma = (1 - d) \times \sigma' = (1 - d) \times E \times \varepsilon$$

Graphically:

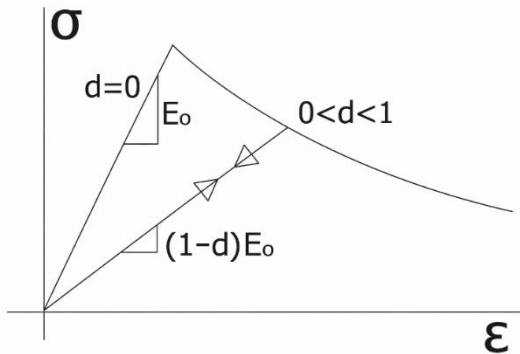


Figure 13. Evolution of the uniaxial stress–strain relationship

The numerical formulation was implemented using the ANGLE software [16], following the constitutive approaches proposed by Oñate [17], Oliver [18], Oller [19], and Hanganu [20]. This formulation allows the material response to be differentiated under tensile and compressive stress states, while also accounting for the influence of finite element discretisation on the numerical results

obtained [11]. Owing to its computational efficiency and the possibility of adapting key variables to the specific characteristics of the temple, this modelling strategy proves to be particularly suitable for the structural assessment of historic masonry.

Within this framework, the damage index  $d$  constitutes the principal state variable of the model and quantifies the degree of material degradation, varying within the interval  $0 \leq d \leq 1$ . A value of  $d = 0$  corresponds to the undamaged condition, whereas  $d = 1$  represents the complete loss of effective resistant surface [15]. According to the formulation of the model, the evolution of this parameter produces a proportional reduction in material stiffness, expressed by the factor  $(1 - d)$ , thus allowing the mechanical response of historic masonry—especially brickwork and stone assemblages—to be reproduced in a manner consistent with their observed structural behaviour.

By extending this constitutive relationship to the full stress tensor, the following expression can be derived:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = (1 - d) \times [D] \times \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_x \\ \gamma_y \\ \gamma_z \end{bmatrix}$$

In this expression,  $D$  denotes the elastic stiffness matrix of an isotropic material. In the finite element formulation, however, the constitutive matrix  $D'$  is obtained as follows [21]:

$$D' = (1 - d) \times D$$

$D$

$$= \frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)} \begin{vmatrix} 1 & \frac{\nu}{(1 - \nu)} & \frac{\nu}{(1 - \nu)} & 0 & 0 & 0 \\ \frac{\nu}{(1 - \nu)} & 1 & \frac{\nu}{(1 - \nu)} & 0 & 0 & 0 \\ \frac{\nu}{(1 - \nu)} & \frac{\nu}{(1 - \nu)} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1 - 2\nu}{2(1 - \nu)} & 1 & 0 \\ 0 & 0 & 0 & 0 & \frac{1 - 2\nu}{2(1 - \nu)} & 1 \\ 0 & 0 & 0 & 0 & 1 & \frac{1 - 2\nu}{2(1 - \nu)} \end{vmatrix}$$

The determination of the damage parameter during the successive stages of loading and deformation involves the calculation of the scalar quantity  $r_n$ , which is derived from the strain tensor and defined by the expression that follows:

$$r_n = [1 + \theta(n - 1)] \sqrt{\sum_{i=1}^3 (\sigma_i^{p,0})^2}$$

Within the adopted model, the parameter  $n$  is defined as the quotient between the material's uniaxial compressive strength and its uniaxial tensile strength:

$$n = \frac{f_c}{f}$$

Furthermore,  $\theta$  is defined as the parameter characterising the predominant behaviour under compression or tension, obtained through the expression:

$$\theta = \frac{\sum_{i=1}^3 [\sigma_i^{p,0}]}{\sum_{i=1}^3 |\sigma_i^{p,0}|}$$

The stress terms corresponding to the intact material state, together with the Macaulay operator applied to the principal stresses prior to damage, are introduced through the following expressions:

$$\begin{aligned} \sigma' &= D\varepsilon \\ [\pm \sigma'_i] &= \frac{1}{2}(\sigma_i \pm |\sigma_i|) \end{aligned}$$

The onset of material degradation is defined by the condition  $r_n > r_0$ , where  $r_0$  represents the reference value from which damage evolution is measured.

$$r_0 = \frac{f_t}{\sqrt{E}}$$

For the purposes of the analysis,  $r$  is taken as the maximum value recorded during loading.

$$r = \max\{r_0, r_n\}$$

The damage variable corresponding to each loading and deformation stage is given by:

$$d = G(r_n) = 1 - \frac{r_0}{r} \cdot \exp\left\{A \left(1 - \frac{r_n}{r_0}\right)\right\}$$

The values of the parameters  $r$ ,  $r_0$ , and  $A$  are derived from the expression formulated by Oñate [22] (p. 9), where  $G_f$  denotes the fracture energy per unit surface area. Furthermore, the characteristic length assigned to each location within the finite element discretisation is established on the basis of the volume  $V$  associated with the corresponding solid element [23] (p. 169).

$$A = \frac{1}{\frac{g_{ft} \times n^2 E_0}{(\sigma_0)^2} - \frac{1}{2}}$$

$$g_f = \frac{G_f}{l_0}$$

$$l_0 = \sqrt[3]{V}$$

## 4.2. Methodological Advances and Seismic Analysis

### 4.2.1. Advanced Historical Factory Models

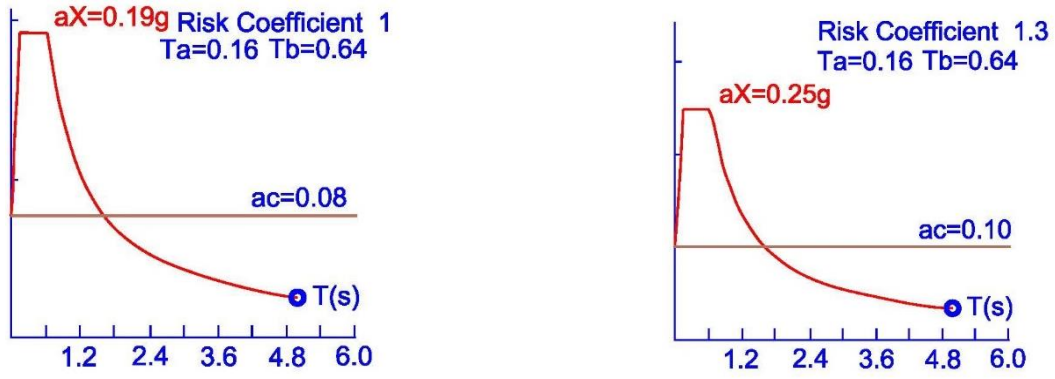
The progressive recognition of the structural complexity inherent to masonry constructions has led to the continuous refinement of analytical approaches, particularly within the field of finite element modelling. In this context, advanced formulations developed by Roca, Cervera, and Pelà [24,25] have made it possible to describe masonry behaviour in a more comprehensive manner, accounting not only for its stiffness and load-bearing capacity, but also for the energy dissipation processes associated with the nonlinear and inelastic response. Along similar lines, studies such as those conducted by Mallardo et al. [26] have addressed issues related to long-term cracking phenomena and viscoelastic effects, while further research by Cervera et al. [27] has explored the directional characteristics and localised progression of damage. Taken together, these contributions reflect a clear methodological evolution towards modelling strategies that more accurately reproduce the actual mechanical behaviour of historic materials.

### 4.2.2. Seismic Vulnerability Assessment

The seismic performance of the temple was evaluated through a combined analytical strategy that integrates nonlinear static (pushover) analysis with dynamic time-domain analysis. The use of both approaches within the same numerical framework allows the seismic vulnerability of the structure to be assessed by relating its response capacity to the demand spectra established by the NCSE-02 regulations for the city of Valencia [28] (Figures 14 and 15).

Three seismic demand levels were analysed, corresponding to different return periods: service conditions (72 years), design earthquake (475 years), and maximum considered event (975 years). For each scenario, the resulting spectral curves were expressed in the Acceleration–Displacement Response Spectrum (ADRS) format, enabling the identification of damage thresholds and a direct comparison between seismic demand and the structural capacity obtained from the numerical models (Figure 16).

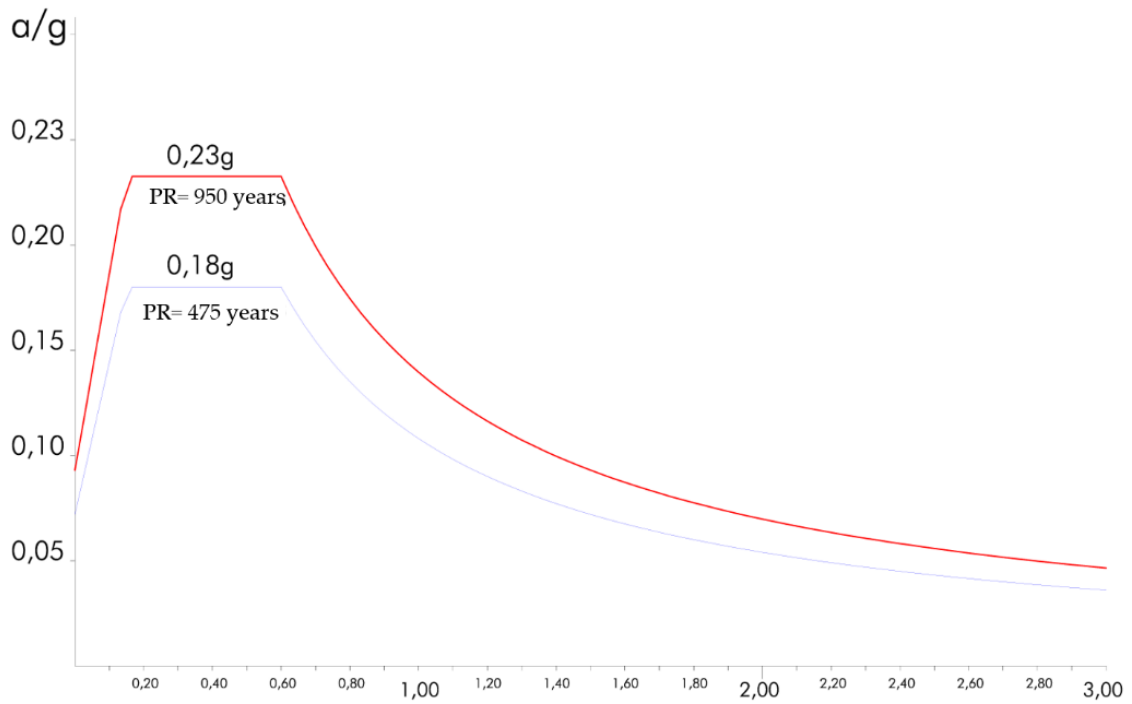
The intersection between the capacity spectrum and the seismic demand spectrum, shown in Figure 17, determines the structural performance point. This value serves as a fundamental indicator for assessing how the structural components behave as seismic loading approaches their response limits.



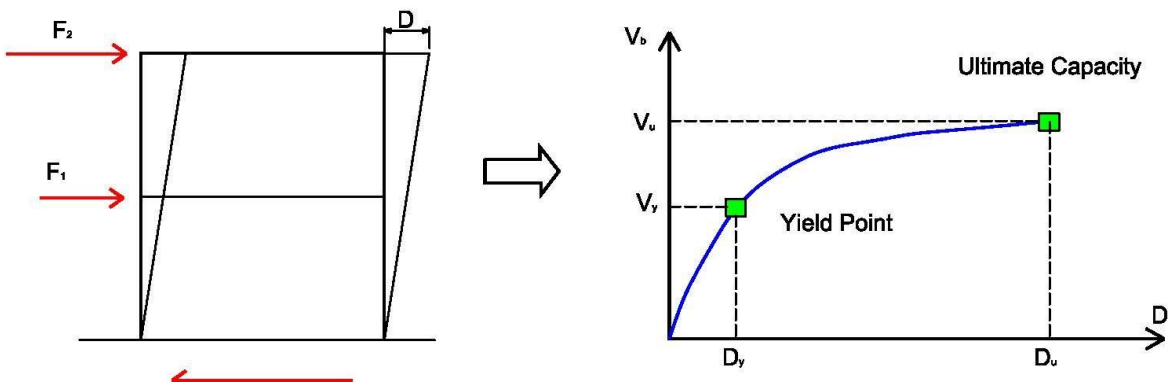
Response spectrum corresponding to a 475-year return period

Response spectrum corresponding to a 950-year return period

**Figure 14.** Elastic design response spectra defined for the city of Valencia [23]



**Figure 15.** Design spectra for Valencia considering seismic events with return periods of 475 and 950 years [11]



**Figure 16.** Load distribution adopted for the pushover analysis and corresponding capacity curve [29]

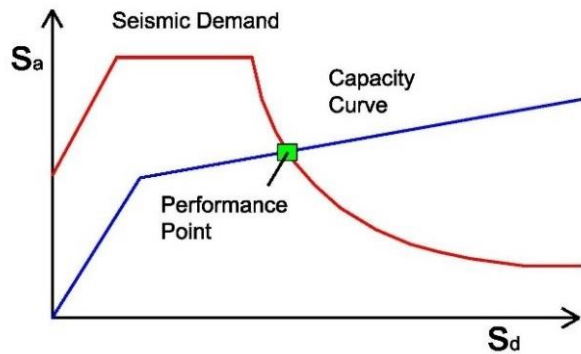


Figure 17. Capacity spectrum [29]

Several methodological approaches have been proposed to establish a comparison between structural capacity and seismic demand for the purpose of identifying the performance point [30] (p. 52). In order to carry out this comparison, both response curves are converted into a unified representation known as the Acceleration–Displacement Response Spectrum (ADRS), in which the structural response is expressed in terms of spectral acceleration versus spectral displacement (Figure 18).

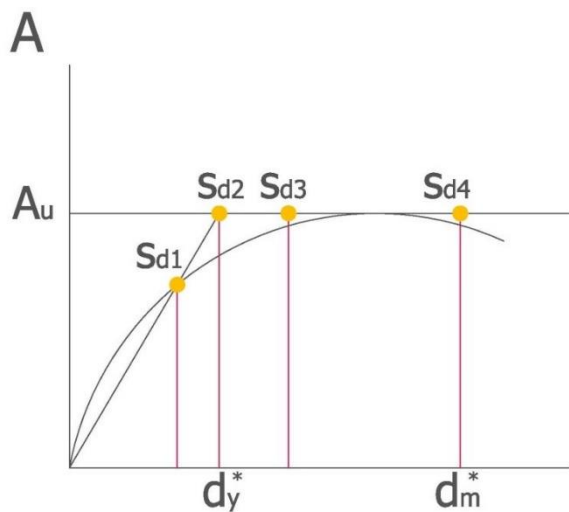


Figure 18. In the ADRS domain, the capacity curve and its bilinear approximation allow the identification of yielding and ultimate capacity, while the position of the performance point defines the associated damage thresholds for the structure [32]

The capacity curve is then simplified through a bilinear approximation that satisfies a set of consistency criteria, including equal enclosed areas, matching maximum displacement values, and identical stiffness in the initial elastic branch. This simplified representation is defined by two key spectral displacement values:  $Sd_2$ , marking the limit of elastic behaviour, and  $Sd_4$ , corresponding to the end of the plastic range. These parameters establish the damage thresholds adopted in the analysis, which are summarised for clarity in Table 2.

Table 2. Classification of damage thresholds<sup>4</sup>

Damage threshold	Definition
Slight	$Sd_1 = 0.7 D_y$
Moderate	$Sd_2 = D_y$
Severe	$Sd_3 = D_y + 0.25 (D_u - D_y)$
Complete	$Sd_4 = D_u$

The bilinear idealisation presented in Figure 17 is defined through two key spectral displacement values: one associated with the limit of elastic behaviour ( $Sd_2$ ) and another corresponding to the termination of the plastic response ( $Sd_4$ ). Together, these reference values establish the damage state thresholds adopted for the seismic evaluation of the structure.

The numerical simulations were conducted using a stepwise loading scheme. In the first phase, comprising ten load increments, the self-weight of the structure was progressively applied. This was followed by thirty additional increments in which horizontal seismic actions were introduced according to a modal distribution approach. For each configuration analysed, a total of twelve vibration modes were taken into account.

Once the typological hypothesis situating Santos Juanes within the group of Mediterranean churches has been defined, the analysis focuses on verifying whether the logic behind the construction of the temple can be interpreted as a conscious response to seismic risk. To this end, specialised literature was used to characterise the materials, integrating data from studies by Estellés Ceba [1] and previous experimental campaigns on historical buildings [31]. However, given the variability of the masonry used in the building, it was considered necessary to complement this approach with a sensitivity model, developed from recent graphic surveys and scans [33]. The results of this characterisation and parameter adjustment process are summarised in Table 3, which presents the reference values used in the structural modelling.

The study model was based on two representative modules of the church, considered sufficient to accurately reproduce the structural behaviour of the whole. This strategy allows for a precise analysis of the impact of the different construction elements—load-bearing walls, buttresses, transverse arches, and partition walls—on the overall response of the building, without requiring a complete model.

One of the distinctive features of the church, which sets it apart from other buildings with similar characteristics, is its pronounced massiveness. Whereas in contemporary constructions such as Valencia Cathedral (Figure 6) or Tortosa Cathedral (Figure 10) stability is ensured by lighter systems based on flying buttresses, in Santos Juanes reinforcement is achieved through a powerful set of buttresses.

<sup>4</sup> Classification of damage levels following the Risk-UE methodology (2016).

























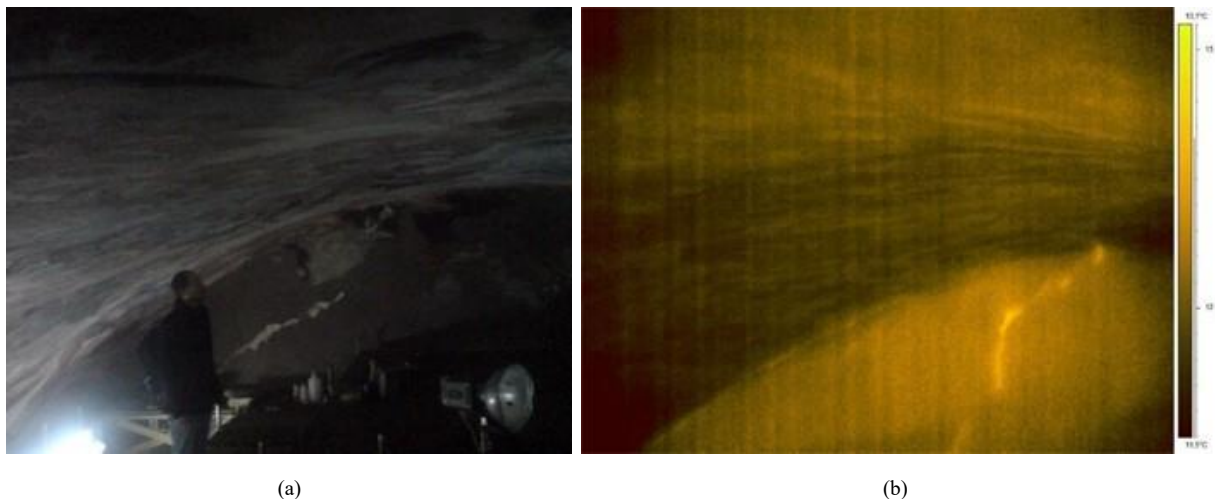








**Figure 57.** Spatial distribution of the damage index for the vault and the façade facing the San Juan cemetery square.



**Figure 58.** (a) View of the crack identified on the façade oriented towards the San Juan cemetery square, close to its connection with the vault; (b) infrared thermographic image of the same discontinuity. The agreement between the damage pattern reproduced by the numerical simulation and that observed in the existing structure, supports the validity of the adopted calculation model

The computational analyses further supported this assessment by pointing to the bell tower as the element most affected by seismic actions, a response primarily linked to its slender configuration and elevated position within the complex. This behaviour was later corroborated by nonlinear time-history simulations. As a precautionary intervention, plaster tell-tales were installed on the affected portion of the façade to enable long-term monitoring of crack development. The results of this monitoring confirmed the coherence between the initial diagnostic assumptions, the outcomes of the numerical models, and the actual structural behaviour observed in the building.

## 5. Conclusions

This study focuses on the constructive and structural configuration of the Church of Los Santos Juanes, a particularly representative case within Mediterranean Gothic architecture, characterised by an exceptional degree of material solidity. In contrast to other contemporary buildings—such as Valencia Cathedral—where structural stability relied on ribbed vaults supported by flying buttresses, Santos Juanes combines ribbed vaulting with a system of markedly oversized buttresses. From the earliest stages of its construction, this solution established a

specific tectonic framework whose implications extend beyond formal considerations, exerting a decisive influence on the structural response of the building, especially within a seismic context such as that of Valencia.

Following the historical and constructive characterisation of the monument, a series of numerical models was implemented to investigate the structural response of the main architectural components typical of Mediterranean Gothic churches and to evaluate their contribution to seismic stability. The first two configurations, corresponding to the current state of the building with and without diaphragms, reveal only minor differences in behaviour; in both cases, the performance point remains within the elastic domain and the response to seismic action is stable. These outcomes indicate that diaphragms are not a governing factor in the original structural conception of the church. Instead, stability is primarily ensured by the massive buttresses—measuring  $1.20 \times 6.00$  m in plan—whose dimensions and weight substantially exceed those found in lighter Mediterranean Gothic systems.

The analysis of Models 3 and 4, in which the volume of the buttresses was reduced by 38% to approximate their behaviour to that of a lighter system, produced markedly different results. In Model 3, even with the diaphragms intact, the structure exhibited greater vulnerability to dynamic stresses, although without reaching complete collapse. Model 4, by contrast—defined by both the reduction of the buttresses and the absence of diaphragms—suffered total damage, demonstrating that the simultaneous elimination of both resources leads to a critical loss of stiffness. This confirms that diaphragms, while not an essential component of the initial structural strategy, do become significant in scenarios where lateral mass is reduced.

Overall, the comparative analysis of the different configurations confirms that the exceptional massiveness of the buttresses is the key factor in the seismic stability of Santos Juanes. The diaphragms, rather than constituting a fundamental structural element, appear to be complementary, their relevance increasing only when the capacity of the buttresses is reduced. This conclusion is consistent with the absence of significant damage to the main structure over the centuries, even after the historic earthquakes documented in the city of Valencia.

This confirms the initial hypothesis: the solidity of the temple cannot be understood merely as another example of Mediterranean Gothic architecture, but rather as a particular variant in which the extreme rigidity of its buttresses operates in conjunction with the ribbed vault system. As demonstrated in Valencia Cathedral, ribbed vaults can be effectively supported by flying buttresses; however, this lighter solution does not achieve the structural strength provided by the buttresses of Los Santos Juanes. This comparison underscores the exceptional

character of the Valencian temple, whose resistant strategy diverges from the lightness prevalent in other contemporary European examples in favour of a solidity that has ensured its stability against earthquakes for centuries.

Finally, the conclusions drawn from the modular analyses were corroborated through the study of an additional three-dimensional model of the complete building. This global model confirmed that the structural behaviour observed in the partial configurations is consistent with that of the church as a whole, thereby validating both the modelling approach and the assumptions adopted regarding material characterisation and calculation procedures.

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