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A COMPARATIVE APPROACH TO MATERIAL CHARACTERISATION IN HISTORIC MASONRY BUILDINGS

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Abstract

The structural analysis of a heritage building involves, as in other cases, verifying that the stresses to which it is subjected are within admissible limits. For this reason, it is vital to characterize the constituent materials of any design model as precisely as possible. However, given the dispersion of the mechanical properties of the materials used in this type of construction, it is not easy to characterize them. This paper aims, through a real case, to show an approach to characterize the constituent particularities of the building. For this purpose, a sensitivity study will be carried out on a partial model of the temple, in which the influence of the variation of specific parameters of the ashlar masonry on the structural behavior will be analyzed. This study could serve as a basis for future analyses of a similar nature and, therefore, prevent future irreparable damage to our heritage.

Keywords: *Heritage; Conservation; Materials; Damage; Sensitivity study*

Introduction

The vulnerability of built historical heritage has been and continues to be one of the most studied and discussed topics in recent years. We all know about the aggressions it has suffered in different parts of the world, and if we focus on Spain, we cannot forget the earthquakes suffered in Lorca (Murcia) in 2011. Perhaps for this reason, it is becoming increasingly convenient to understand the behavior and vulnerability of these buildings to avoid and prevent further damage. However, it is often challenging to precisely define the constitutive characteristics with which our historic buildings were constructed to help us predict and understand the behavior of these structures. One of the main reasons for this difficulty centers on the versatility of the materials used and the diversity of origin of each one, which prevents us from extrapolating the characterization made from one construction to another.

However, there is a close relationship between the materials, the building components, and the construction as a whole. Given the difficulty of transport at the time, master builders and architects used materials extracted from nearby quarries in their works. In this way, the ashlars from a specific area have more or less similar constitutive characteristics, which may differ from

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others used in more distant locations. For this reason, if a heritage element is modeled to study it, it is necessary to investigate and characterize its constituent materials.

Research into materials is synonymous with progress. In the process of architectural design, materials represent the external expression intended by the designer – its aesthetic. As humanity has gained control over nature, the variety of materials, their typologies, and the construction techniques used with them have advanced.

For this reason, given the importance of materials and their properties in the configuration of the built element, this work aims to characterize the materials used to build one of the most important Gothic churches in Valencia (Spain), the Santos Juanes church. A proposal that can be extrapolated to other constructions of similar characteristics allows us to approach and get to know the compositional and aesthetic reality of the building we see today.

Santos Juanes church in Valencia as a case study. A short historical review

The Santos Juanes church is one of the most essential ecclesiastical monuments in Valencia (Spain). Located in the old La Boatella suburb, the church has changed its configuration over the years in terms of volume and style, influenced by the different artistic movements in which it has been involved. It is currently one of the most important religious buildings in the city. Belonging to the Ciutat Vella district, it occupies a privileged position in the Market Square. It shares the limelight with two enormously enjoyable and praised architectural elements, the Lonja de Mercaderes and the current building of the Central Market, the latter of later construction [1, 2].

Different phases can be distinguished in its structure, clearly identifiable in the building, and directly related to the historical events that unfurled in Valencia. For this reason, and to understand the constructive composition with certainty, it is necessary to summarize the evolution of the church and its impact on its current characterization [3].

The church dates back to 1240, when King Jaume I, during the Reconquest, donated the old La Boatella mosque to build a church dedicated to Saint John the Baptist. It was a way of reusing the existing buildings and, simultaneously, humiliating the reconquered inhabitants, even more so than any battle [4].

Galarza reveals that the first stage of the building would have consisted of five modules and a straight apse without a front doorway or communion chapel (Fig. 1, blue area). The solution adopted consisted of a single nave, typical of the churches of the period. Later, in the fifteenth century, the original building grew by one module, and a hexagonal apse was added to the chancel [5] (Fig. 1).

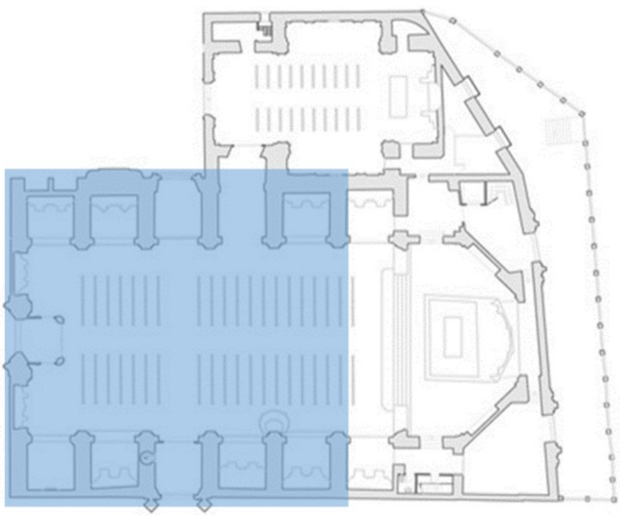

Fig. 1. Current floor plan of the building. Blue-area: first stage

From this moment on, the temple evolved to adapt to the new times, continuously shaping its presence in the immediate surroundings. However, these changes in the building came hand in hand with a change of style, the Baroque, and the appearance of architectural treatises such as those of Isidoro Aliaga and Carlos Borromeo, which were the basis of its transformation. Both of these two, representatives of the Catholic Church, implemented their treatises with resounding force, both in the Santos Juanes and in the rest of the constructions of the time. These treatises, which served as a framework for solving specific architectural challenges, played a crucial role in the construction of the main facade and the communion chapel, the last two elements built inside the church, excluding 'els porxets' [2].

Latest interventions in the Santos Juanes church. From the beginning of the twentieth century to the present day

Regarding the most recent interventions, the first reference, although not excessively relevant, dates from 1902. In it, an intervention was carried out on the facade of the 'Comunión' Place to repair part of the cornice and the opening of a small hole in the side wall of the chapel.

The minor intervention carried out in 1903 by D. José Camana, the diocesan architect, shows a request for the 12 windows on the facade of the Plaza del Mercado. The openings on this facade were already defined as a continuation of the modulation of the side facade on Peso de la Paja Street [6].

The Santos Juanes church did not undergo any other notable modifications until the Spanish Civil War, which seriously affected it. On 30 March 1939, many of the churches were severely devastated and plundered, one of them being the Church of Santos Juanes, which was cruelly damaged both internally and externally during the siege. The church suffered the third fire in its history, especially affecting the interior vault and the chancel.

On 1 May 1964, architect Juan Segura de Lago was appointed technical director of the restoration project. Among the numerous contributions he made in his project, the most interesting was the study of the state of conservation of the church after the fire during the Spanish Civil War. His contributions have been of great help and have been the basis for subsequent research [5].

In 1980 Segura de Lago ceased to be the architect responsible for the restoration of Santos Juanes Church, and the Valencian architect Agustín Ferrer i Ferrer was appointed by the Ministry of Culture, through the General Directorate of Heritage, and tasked with:

'The drafting of the restoration project for the Church of Santos Juanes, in Valencia. Amount five million pesetas [5].

If there is a relevant project from this period, it is the one drawn up by the architect Juan José Estellés Ceba. This hitherto unpublished documentation accurately details the constructive characteristics of the entire building, many of which were hidden by the Baroque transformation [7].

It consists of a preliminary intervention study, commissioned on 30 October 1984 by the Directorate General of Artistic Heritage of the Department of Culture, Education, and Science of the Generalitat Valenciana. The purpose of this study was:

'...the determination of the measures to be taken to maintain the temple of the "Santos Juanes" referred to in the best conditions of conservation, improving, if possible, the current appearance of the architectural and sculptural elements...' [5].

It was drawn up in March 1986 and is one of the first complete graphic documents on the church. It includes a pathological and geotechnical report that serves as the basis for the proposal of the interventions to be carried out in the Santos Juanes church [7].

The next intervention carried out by the architect involved the reform of the facade of the Plaza del Mercado. In it, work was mainly carried out on the stone by means of analysis and tests, obtaining the definition of the ashlars that make up both the facade and the tower [8].

The entire building is currently being restored by the Hortensia Herrero Foundation under the direction of the architect Carlos Campos. The aim of this intervention is to strengthen the building and restore its original image.

Experimental part

Materials

In order to characterize the mechanical properties of the materials that make up the model church of this study, several sources have been taken into account. Firstly, the results were obtained from the constitutive tests on the ashlars of the Trinity Bridge in Valencia (Spain), a construction quite close and contemporary to the Santos Juanes church [9]. Second, the tests carried out by Mas on this church [10] and the tests carried out by Professor Hernández on the masonry of the Lonja de Mercaderes, a building contemporary to and situated opposite the church [11]; and finally, the additional documentary based on the mechanical properties considered for other models. Among the materials defining the construction of the Santos Juanes church, masonry is one of the most important. Brick, wood, and steel are also present to a lesser extent. The latter has been used recently to reinforce certain construction elements.

With regard to the masonry, it is clear that the proximity of various quarries to Valencia meant that most of the buildings constructed with stone sourced their masonry from these nearby quarries. In this specific case, and as corroborated by Mas in his doctoral thesis [10], we could be talking about two different masonries, one dating from the fifteenth to sixteenth century and the other from the seventeenth. The results of the studies carried out by Mas classify the samples into two different typologies characterized by their porosity and related to the two main construction stages of the temple. Both samples are travertine limestone, those from the fifteenth to sixteenth century corresponding to the Gothic construction of the church, and those from the seventeenth to eighteenth century to the Baroque intervention and its reconstruction. However, various fires that have occurred in the temple have deprived the documentation of the first stage, leaving only the contract for the extension works of Les Covetes de San Joan (also called ‘porxets’), in which it was required that the origin of the stone be from the Tos Pelat quarry, as described by Gómez Lopera in his doctoral thesis [12].

It is interesting to look for other more precise sources of information. Among them were the results obtained from the tests on the Trinity Bridge stone. As in the case of the Santos Juanes church, it is a limestone with similar characteristics. The tests on the bridge resulted from the structural consolidation carried out in 2006. Several samples were extracted for mechanical analysis. The conclusion drawn from these tests is that the compressive strength of these stones was lower compared to the specimens extracted directly from the nearby quarry, in this case, the Godella quarry, due to different environmental conditions [9]. The first test shows a compressive strength of 22.91N/mm^2 compared to 45.9N/mm^2 for the quarry.

However, a more recent study has also been conducted on the stone that makes up the Lonja de Mercaderes [11]. For this purpose, two samples were taken from the Godella quarry, which, according to the documentation collected, could be the origin of the stones that make up this facade and, in turn, could be a reference due to their similarity in time and execution to those used on the facade of the Santos Juanes church facing the marketplace. The tests carried out on both samples taken from two different layers offer a disparity of results between them and the previous ones. The one corresponding to the most superficial layer obtained a compressive strength of 24.82N/mm^2, and the one from the deepest stratum of 66.87N/mm^2. The latter strength is outside the usual characteristic range.

Another exciting value to highlight is the apparent density of the material. As in the previous case, Bosch compares samples from the Trinity Bridge with those from the quarry. Values of 1918kg/m^3 from the bridge are extracted, compared to 2346kg/m^3 from the quarry [9]. According to historical data, Mas also studied the apparent density of the Santos Juanes stone, analyzing samples from different construction stages and comparing them with the current one (Table 1) [10]. Two of the three samples analyzed were taken directly from the temple, representing the two primary construction phases identified. At the same time, the third was sourced from a nearby, now inactive, quarry that may have supplied the original materials. The conclusions show values that differ to some extent from the previous ones but have similarities when compared with each other.

Table 1. Santos Juanes and quarry-tested samples

Sample	Density (kg/m^3)
MXVI	2713
MXVII	2896
Quarry Stone	2930

The values obtained from the study of the Trinity Bridge [9] were also analyzed, adding the value of the modulus of elasticity, which was not considered by any of the authors, as this value was irrelevant in their studies. However, given the disparity of the results obtained, it is considered appropriate to broaden the spectrum of values by comparing them with those proposed by other authors in similar studies. To this end, we have considered the documentary research by Llopis in his doctoral thesis [13].

Other studies [14, 15] show differentiated specific weight values for buttresses and vaults (2100kg/m^3), and others for pillars and flying buttresses (2400kg/m^3), similar to the previous one. As for Young's modulus, the results are more disparate, being 2000 and 8000 MPa, respectively. Finally, it states that the tensile strength adopted for the calculation will be 5% of the compressive strength.

On the other hand, in the analysis carried out in the Cathedral of Syracuse (Sicily, Italy), Casolo and Sanjust evaluate some mechanical characteristics that are shown in Table 2 [16]:

Table 2. Values used in the analysis of the Cathedral of Syracuse

Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	ν
Walls and columns	4500	2200	2.00	0.20	0.2
Other walls	3000	2200	3.00	0.35	0.2
Masonry walls and backfill	2000	1800	7.40	0.74	0.2

In the case of the Basilica of Santa Maria all'Impruneta (Florence, Italy), a study of vulnerability to earthquakes was carried out, mainly to analyze the behavior of traditional Italian masonry [17]. The following values are extracted for the study of this Romanesque church, as can be seen in Table 3:

Table 3. Values used in the analysis of Santa Maria all'Impruneta (Florence)

Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	ν
Ship	1400	1900	0.15	7.5	0.2
Apside	1530	2000	0.15	8.5	0.2
Columns	14500	2300	3.50	40	0.2

In addition, this study has consulted the data reflected in the monograph on structural analysis by Mas-Guindal [18]. The author characterizes the mechanical properties of bricks and masonry used in historical constructions. The importance of his analysis lies in his consideration of the material in terms of form and shape.

This comparative study of the characteristic materials represents just a sample of the many available references on the topic. However, due to the variability of data provided in these references and the lack of precise results characterizing all the materials used in the Santos Juanes church, we have adopted values within a safe range for this work. Additionally, other materials such as wood and more recent metal reinforcements are present in the church, but they were not the focus of this research.

Consequently, in order to be able to determine the characteristics of the materials used in the construction of the Santos Juanes church, a 3D model will be made which, through the application of different loads (self-weight, seismic) supported by the structure throughout its history, will give us results that coincide with the current situation of the building.

Methods

In order to determine the safety of buildings, it is necessary to pay attention to their vulnerability to earthquakes. As described above, the building that is the subject of this case study is in Valencia, which has suffered different seismic episodes throughout its history. For this reason, it is essential to include this effect in the calculation proposed for the intended characterization.

In this regard, several research projects have been developed in recent years to establish the basis for classifying seismic risk, including HAZUS99 and Risk UE.

The Risk UE project classifies buildings into basic typologies, characterized by basic vulnerability indices. However, these indices are not sufficient. The particular characteristics of each building, such as its height or number of floors, as well as the level of seismic protection it has, must be considered as a modifying factor of this basic index.

Determining the seismic vulnerability of a building involves several uncertainties, necessitating the use of approximate and uncertain reference data. One such uncertainty is the characterization of the stresses induced by earthquakes, as seismic actions are difficult to predict in terms of both timing and magnitude. Additionally, the response of the structure is complex, particularly in historic buildings where the materials are heterogeneous and their properties are often unknown [19].

Pushover analysis (PA) has been used to determine the seismic vulnerability of such structures. This method focuses on non-linear calculation and gives reasonably accurate results compared to reality.

The pushover method, developed by Freeman in 1998, is characterized by the comparison, using a graphical method, of the capacity of a structure against the damage caused by the ground as a consequence of an earthquake [20].

The seismic action is introduced by subjecting the structure to a pattern of lateral loads Fi, which increases monotonically until the maximum capacity of the structure is reached. The loading pattern used in this study is that of modal distribution.

The structural response capacity is represented by the capacity curve relating the base reactions, basal shear Vb, and displacements D at the top level of the structure (Fig. 2).

Specifically, in our case, and analyzing the Earthquake Standard (NCSE-02) [21], compulsory in Spain, we can see that it uses two seismic movements depending on the return period. The first is the design spectrum, corresponding to a return period of 475 years; the second is the maximum earthquake, with a return period of 950 years.

The point of intersection between the capacity spectrum and the demand spectrum is called the ‘performance point’ of the structure (Fig. 3). It evaluates the limiting behavior of the structural elements according to the expected seismic demand.

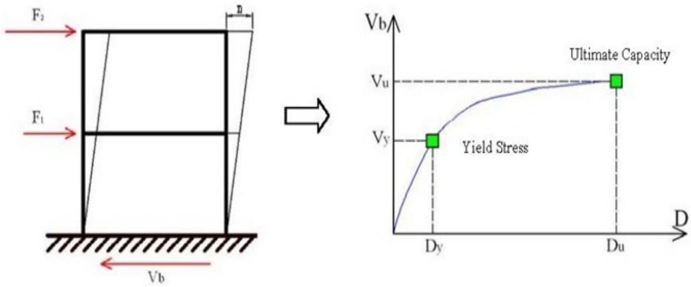

Fig. 2. Load pattern applied in the Pushover method and capacity curve [14]

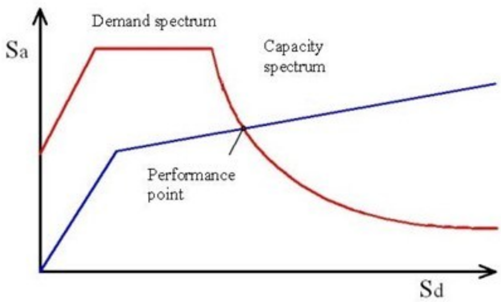

Fig. 3. Capacity spectrum [20]

Currently, there are some methods to relate the capacity curve and the demand to obtain the performance point [20]. To compare both curves, demand and capacity must be transformed into a homogeneous format called the acceleration-displacement response spectrum (SARD).

Subsequently, this curve is simplified into a bilinear plot, which must meet the following requirements: the area under the two curves must be the same; the coordinates of the point of maximum displacement must coincide; and the slope of the initial branch must be the same for both curves.

The bilinear graph (Fig. 4) is wholly defined with two points corresponding to a spectral displacement (S_d) at the end of the elastic branch (S_{d2}) and a spectral displacement at the end of the plastic branch (S_{d4}), which are damage thresholds [22].

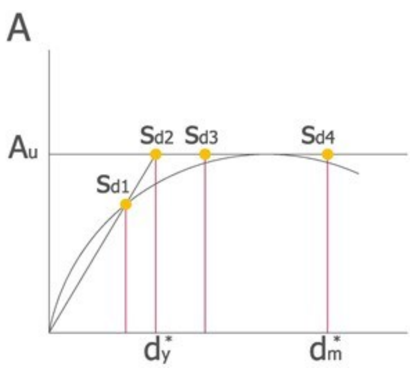

Fig. 4. Damage state thresholds [22]

Based on the RISK-EU definition, five states or damage levels are obtained, which can be seen in Table 4, having defined two more thresholds corresponding to the special shifts S_{d1} and S_{d3}:

Table 4. Damage states according to EU Risk[1]

Damage Level	Lower Threshold	Upper Threshold
Null	Origin	Sd1
Slight	Sd1	Sd2
Moderate	Sd2	Sd3
Severe	Sd3	Sd4
Complete	Sd4	--------

Constitutive model

The 3D calculation model will be created using the BOVEDAS 3D. This is a computer-aided design (CAD) plug-in developed by Prof. Adolfo Alonso Durá at the Universitat Politècnica de València, designed to model this type of historical structure [23]. Its work focuses mainly on meshing the characteristic geometric elements of these buildings in a more or less straightforward way. The 3D model obtained was introduced into the ANGLE analysis software, which Professor Alonso also developed [24].

With regard to the program's calculation method, following current lines of research, approximations based on continuous media, such as damage theory, are incorporated to calculate this type of structure. Its objectivity allows specific problems, such as the dependence on the model's size, to be calculated and discarded.

Damage mechanics is considered to be one of the branches of continuum mechanics. In it, microstructural modifications are introduced into the material due to internal variables. These variables shape the material's historical behavior in the stress evolution [25].

The consequence of this is the appearance of cracks and their evolution over time when applied to materials such as masonry. It can be described as the trajectories of the various damaged points [13].

Fracture is represented as a local damage effect, which can be characterized according to the compressive and tensile strength of the material, the known parameters of the material, and the functions that control the evolution of the cracking according to the successive state of the stresses at each point.

In this case, the masonry to be analyzed consists of ashlar masonry, with the interior filled with mortar (Fig. 5). This results in a lack of continuity between joints that can be seen from the outside. Given this construction arrangement, the continuous isotropic damage model is used to model the material's behavior [26].

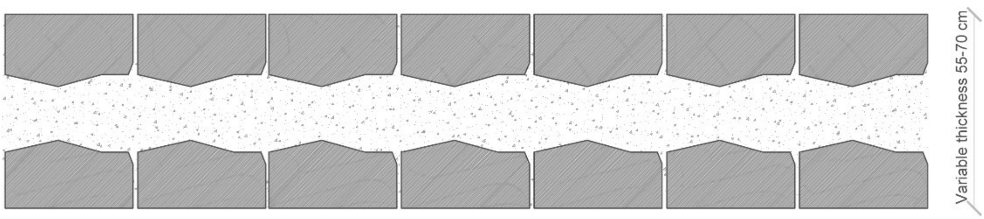

Fig. 5. Constructive section of the 'Santos Juanes church construction

Consequently, the ANGLE program used for the calculation has incorporated an application of the isotropic damage developed by Hanganu [27] and Oñate [28]. This makes it suitable for the analysis of this type of structure. The model used focuses on the difference in the compressive and tensile behavior of this type of material, the degradation of its stiffness due to the stress level, and the effect on the response depending on the mesh size used in the finite

1 Author's table of damage states according to Risk EU (2016).

element modelling. All of this is to achieve a correct model of the non-linear behavior of this type of material [13, 24].

Within this context, a material point with a level of deterioration is considered. This degradation is represented as voids that the material has endured. Taking S as the total estimated surface area and S' as the effective resistant area, then (S-S') is the surface area of voids. Consequently, the damage variable 'd' is defined as (Eq. 1):

$$d = (S - S')/S = 1 - (S/S') \tag{1}$$

If a uniaxial tensile state is considered (Fig. 6), the usual Cauchy stresses σ and the effective stresses σ' are applied in this section.

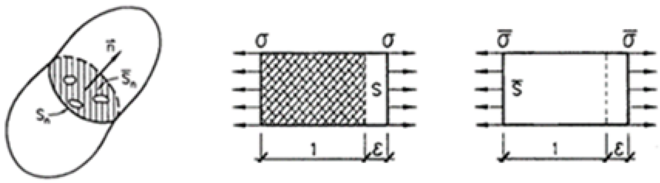

Fig. 6. Uniaxial state of stresses

$$N = S \cdot \sigma \quad N = S' \cdot \sigma' \tag{2}$$

Then, the Cauchy stress to effective stress ratio (Eq. 3).

$$S \cdot \sigma = S' \cdot \sigma' \qquad \sigma = (1 - d) \cdot \sigma' = (1 - d) \cdot E \cdot \varepsilon \tag{3}$$

Figure 7 shows this graphically.

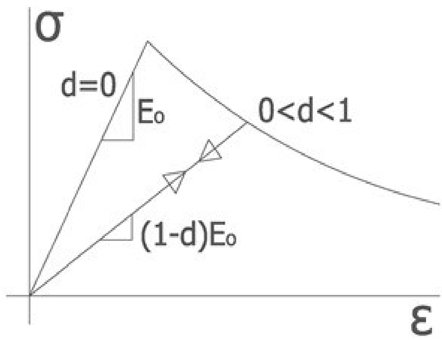

Fig. 7. Damage Model. Evolution of the uniaxial stress-strain curve [13]

The d index indicates the degree of deterioration of the material ($0 \leq d \leq 1$), considering zero as the virgin material, undamaged, and one as the deterioration of the resistant area [29]. Therefore, as we can see in the figure above, it is a reduction in stiffness proportional to (1–d) in the mechanical behavior of the material. Consequently, this index is sufficient to perfectly represent the behavior of this type of masonry, mainly made of brick or masonry.

Extending the above relation to the total stress vector, where D is the elasticity matrix for an isotropic material, we obtain a matrix relating stresses to strains as a function of damage rate.

Allocation of materials and configuration of the model

For structural analysis, ANGLE software is used [24], a finite element program that analyzes and reproduces the structural behavior of the building. The analysis model is introduced into the ANGLE through a 3D model in a CAD plug-in (Fig. 8), based on the study of the building, and with the help of the graphic information provided by Estellés (Fig. 9).

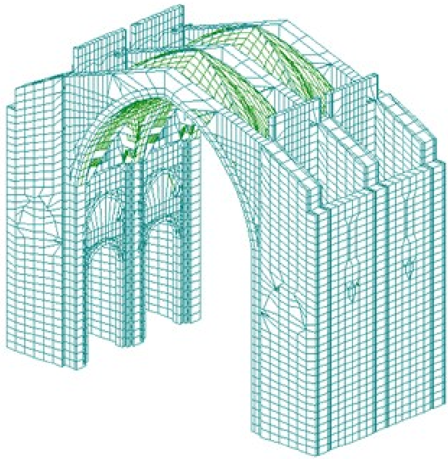

Fig. 8. Representative model. Two Modules

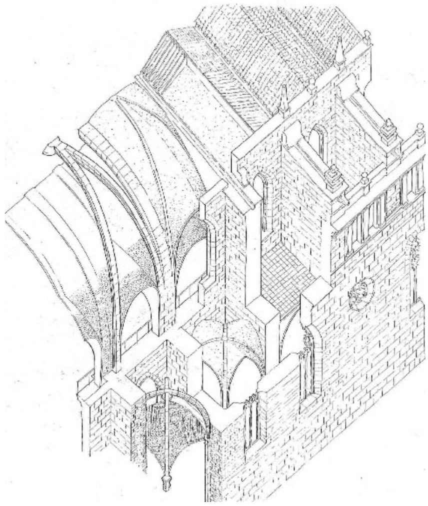

Fig. 9. Sketch of the Santos Juanes church by Estellés [7]

For the CAD model, two elements are distinguished: flat or plate elements and solid elements. The plate elements are defined by their thickness and the material they comprise, while the solid elements are defined only by the material. Three materials have been defined for the analysis of the church: filling ashlar, brick, and vault infill.

These values are taken from those proposed by various authors, adopting those of Llopis in his study of the Valencia Cathedral [13] and those of Mas in his doctoral thesis [10] (Table 5):

Table 5. Values for the calculation of backfill and brickwork

Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	ν
Filling Ashlar	2500	2000	8.00	0.25	0.20
Brick	3500	1800	3.50	0.15	0.10
Vault Filling	1000	1500	3.00	0.20	0.15

Results and discussion

The study is carried out on a model of the church, referring to its Gothic construction, without considering the later Baroque transformation, as it is considered irrelevant to the calculation.

Once the materials have been assigned, the study focuses on the model's behavior in the face of gravity loads and seismic actions acting on two modules of the church's central nave representing the global model. The results obtained make it possible to analyze the movements and behavior of the building locally, with appropriate boundary conditions to extrapolate them to the whole.

However, given the diversity of the characteristic values of the materials proposed in the previous point and before checking the structural behavior of the church, a sensitivity study and validation of the damage model used in the analysis of the Santos Juanes church is carried out.

Influence of tensile strength

For the different models in this section, only the tensile strength of the masonry will be varied, as shown in Table 6, analyzing its incidence within the structural assembly.

Table 6. Characterization of the ashlar masonry. Tensile study

Model	Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	Gf+ (Nmm/mm^2)
T-1	Ashlar masonry	7500	2200	12.00	0.1	0.30
T-2	Ashlar masonry	7500	2200	12.00	0.2	0.30
T-3	Ashlar masonry	7500	2200	12.00	0.3	0.30

Influence of compressive strength

In a similar way to the previous case and maintaining the magnitudes set for the rest of the materials considered in the calculation (Table 7), the compressive strength of the masonry is varied by analyzing its influence on the proposed 2-module model, the results of which are assimilable to the rest of the building [30].

Taking the set of values of the tensile strength study as a basis, the variation of compressive strength is incorporated as a new parameter. However, the value proposed for the T-1 model is disregarded, since the results obtained are far from the real structural behavior of the building.

Table 7. Characterization of the ashlar masonry. Compression study

Model	Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	Gf+ (Nmm/mm^2)
C-1	Ashlar masonry	7500	2200	6.00	0.2	0.30
C-2	Ashlar masonry	7500	2200	8.00	0.2	0.30
C-3	Ashlar masonry	7500	2200	6.00	0.3	0.30
C-4	Ashlar masonry	7500	2200	8.00	0.3	0.30

Influence of the modulus of elasticity of ashlars

This section aims to analyze the influence of the modulus of elasticity on the proposed two-span model and, consequently, on the structural assembly. Therefore, six study models are proposed, having defined the mechanical characteristics of the rest of the materials that make up the church's construction, brick, and infill (Table 8).

Among the mechanical variables that define these models, the tensile and the compressive strength values above are taken for the analysis. As in the previous case, the value of the tensile strength proposed for model T-1 is disregarded, as it is far from the real structural behavior of the church.

After specifying the values of the tensile and compressive strength, the variation of the modulus of elasticity is incorporated as the last parameter to be analyzed.

Given the parameter to be studied, the displacements in the weakest axis, the ‘y,’ are analyzed to check the influence of the stiffness variation in each model.

Table 8. Characterization of the ashlar masonry. Influence of the modulus of elasticity

Model	Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	Gf+ (Nmm/mm2)
M-1	Ashlar masonry	3000	2200	6.00	0.2	0.30
M-2	Ashlar masonry	5000	2200	6.00	0.2	0.30
M-3	Ashlar masonry	9000	2200	6.00	0.2	0.30
M-4	Ashlar masonry	3000	2200	6.00	0.3	0.30
M-5	Ashlar masonry	9000	2200	6.00	0.3	0.30
M-6	Ashlar masonry	5000	2200	8.00	0.3	0.30

Among the results extracted from the different previous studies, the most important is the effect that the variation of the modulus of elasticity has on the deformations of the building.

If the different models are analyzed individually, it can be seen that as the modulus of elasticity increases, the deformations in the weakest axis, the y-axis, are significantly reduced. Much more conservative, the latter reflects the values of the real deformations of the Santos Juanes church according to the results obtained from the scan, compared with those defined by Estellés in his intervention project [7].

However, the increase in modulus does not have a linear response. Although the change in the E modulus from a value of 3000N/mm^2 to 5000N/mm^2 improves the deformations, notably reducing them by half, the change from 5000N/mm^2 to 9000N/mm^2 does not represent a significant variation.

On the other hand, if the incidence of modulus E is examined together with the rest of the parameters studied in previous sections, the compressive and tensile strengths, respectively, it can be seen that the models with the lowest modulus of elasticity (M-1 and M-4) present similar deformations despite the increase in tensile strength.

Discussion

Consequently, given the results obtained in these studies, a summary table is drawn (Table 9), reflecting the mechanical characterization of the ashlar masonry proposed for the structural analysis. It is important to note that the mechanical parameters used to define it focus on comparing the results obtained from the different studies with the reality of the church, based on those proposed by the different authors and within the range of safety.

Table 9. Characterization of ashlar used

Material	E (MPa)	Density (kg/m^3)	fc (MPa)	fc (MPa)	Gf+ (Nmm/mm2)
Ashlar masonry	7500	2200	12.00	0.35	0.30

Once the sensitivity study of the calculation model has been carried out by varying the characteristics of materials, from the results of the first study (Table 10), in which the tensile strength of the material is varied, it can be observed that the increase in the strength of the ashlar masonry proposed in the last two models, T-2 and T-3, substantially improves the damage index of both and shows results that could be comparable with the fundamental behavior of the Santos Juanes masonry.

Table 10. Tensile study. Damage level of the models

Model	Dy (cm)	Du (cm)	PD (cm)	Sd1 (MPa)	Sd3 (MPa)	Damage	%
T-1	2.39	2.39	0.87	2.39	2.39	COMPLETE	100%
T-2	0.38	1.46	0.30	0.266	0.65	SLIGHT	29.82%
T-3	0.37	1.43	0.27	0.259	0.635	SLIGHT	9.91%

Finally, analyzing Figure 10, which represents the capacity curves of the three proposed studies, it can be seen that as the tensile strength of the ashlar masonry increases, the load capacity of the model increases, decreasing the deformations.

When analyzing the influence of the alteration of the compressive strength on the damage stages proposed for this study (Table 11), it can be seen that, to the extent that it increases, the damage index improves appreciably.

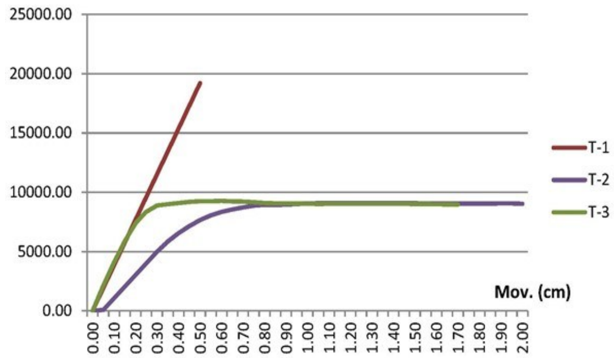

Fig. 10. Influence of tensile on the V-displacement graph

Table 11. Compression study. Damage level of the models

Model	Dy (cm)	Du (cm)	PD (cm)	Sd1 (MPa)	Sd3 (MPa)	Damage	%
C-1	0.38	1.38	0.28	0.266	0.63	SLIGHT	12.28%
C-2	0.38	1.46	0.28	0.27	0.65	SLIGHT	12.28%
C-3	0.37	1.36	0.26	0.26	0.62	NULL	100%
C-4	0.37	1.32	0.24	0.26	0.61	NULL	92.31%

On the other hand, the increase in compressive strength significantly affects the structure's capacity. Figure 11 shows that the four models present a similar capacity curve.

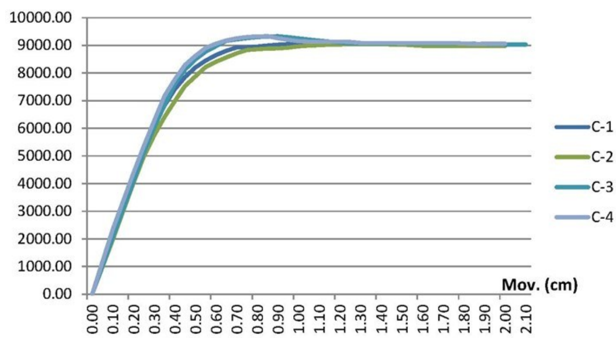

Fig. 11. Influence of compression on the V-displacement graph

With regard to the influence of the modulus of elasticity within the gradation proposed for this study in terms of the damage index, it is concluded that its variation contributes significantly to its behavior (Table 12).

Table 12. Elasticity modulus incidence study. Damage level of the models

Model	Dy (cm)	Du (cm)	PD (cm)	Sd1 (MPa)	Sd3 (MPa)	Damage	%
M-1	0.55	2.31	0.42	0.39	0.99	SLIGHT	18.75%
M-2	0.40	1.34	0.27	0.28	0.64	NULL	96.43%
M-3	0.33	1.55	0.22	0.23	0.64	NULL	95.65%
M-4	0.95	3.74	0.68	0.67	1.65	SLIGHT	3.57%
M-5	0,37	1.34	0.26	0.26	0.61	SLIGHT	0%
M-6	0.55	2.33	0.38	0.39	1.00	NULL	97.44%

When comparing models C-3 and M-4, both with the same compressive and tensile strengths but different modulus of elasticity, a slight increase in the damage index is observed in model C-3, which has a higher value of the modulus of elasticity. Similarly, when comparing models M-1, M-2, and M-3 with model C-1, all of them with the same compressive and tensile strength and different modulus of elasticity, there is a slight increase in the damage index in model C-3, which has a higher modulus of elasticity.

It is worth noting the influence of the modulus of elasticity in the control of building deformations and its low incidence in terms of the variation of the damage index (Figure 12).

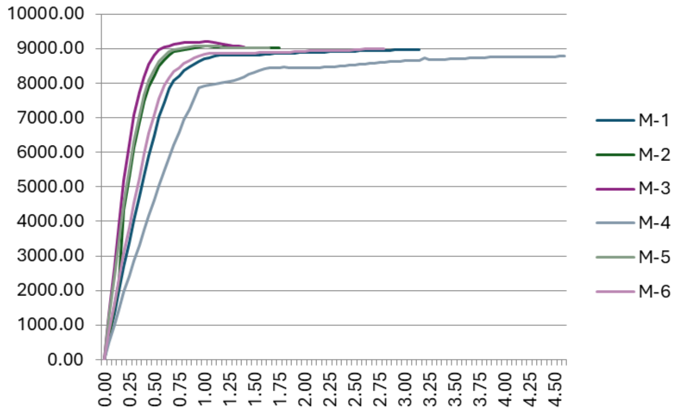

Fig. 13. Influence of elasticity modulus the V-displacement graph

Conclusions

This work shows the importance of the characterization of materials in any built element. Thus, when it comes to a historic building, the versatility of the materials used makes it very difficult to foresee the long-term behavior of a building and to take the appropriate measures, if necessary, to strengthen it.

The Santos Juanes church is an example of this. With a construction that spans different centuries and is of mainly stone materials obtained at different times and, therefore, layers, a study such as the one presented in this work is totally innovative and necessary and can be compared to other buildings of similar characteristics.

In conclusion, the study and the results of the sensitivity and validation of the calculation model have been vital in characterizing the ashlar masonry mechanically. They show the high incidence of the alteration of the tensile strength and the low influence of the alteration of the compressive strength on the structural assembly. Likewise, this analysis also reveals the direct relationship between the modulus of elasticity and the deformations with which the calculation model responds. These results have made it possible to determine reasonably accurate and approximate data on the real behavior of the masonry used in the building.

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