HEALTHY BUILDINGS:
INNOVATION, DESIGN & TECHNOLOGY

ICAT 2016

ANTONIO GALIANO GARRIGÓS
TAHAR KOUIDER

CONFERENCE PROCEEDINGS OF THE 6TH INTERNATIONAL
CONGRESS OF ARCHITECTURAL TECHNOLOGY
UNIVERSITY OF ALICANTE 12-14 MAY 2016
UNIVERSIDAD DE ALICANTE
International Congress On Architectural Technology

Board Members

Dr. Niels Barrett
Copenhagen School of Design and Technology
Denmark
Chairman

Prof. Gareth Alexander
Ulster University
Northern Ireland

Prof. Elsbeth van Battum
Amsterdam University of Applied Sciences
Holland

Dr. Stephen Emmitt
University of Bath
England

Dr. Antonio Galiano Garrigós
University of Alicante
Spain

Prof. Malachy Mathews
Dublin Institute of Technology
Ireland

Prof. Tahar Kouider & Dr. Jonathan Scott
Robert Gordon University Aberdeen
Scotland UK

Prof. Norman Wienand
Sheffield Hallam University
England

ICAT 2016
12th - 14th May, 2016
Organised by
University of Alicante
Dr. Antonio Galiano Garrigós – Chairman
Roberto T. Yáñez Pacios – Departamento de Construcciones Arquitectónicas
International Marjal Healthy Chair

International Scientific Committee

Dr. Kemi Adeyeye
Prof. Gareth Alexander
Dr. Niels Barrett
Prof. Elsbeth van Battum
Prof. Abram de Boer
Prof. Noel J. Brady
Prof. David Comiskey
Dr. Víctor Echarri Iribarren
Dr. Stephen Emmitt
Prof. Emma Geoghegan
Dr. Ángel B. González Avilés
Prof. James Harty
Dr Barry Haynes
Prof. Jakob Kruse
Prof. Liz Laycock
Dr. Carlos L. Marcos Alba
Prof. Shane O’Brien
Dr. M. Isabel Pérez Millán
Prof. Catherine Prunty
Dr Kevin Spence
Prof. Hans ten Voorde
CONTENTS

FORWORD __________________________________________________ 11

WORKGROUP SESSION: BIM AND INNOVATION ________________ 13

NUCLEAR ARCHITECTURE: Perceptions of Architectural
Technology, Frances Robertson (Sheffield Hallam University, UK) and
Stephen Emmitt (The University of Bath, UK) ________________ 15

THE VIRTUAL INTERACTIVE RELATIONSHIP BETWEEN BIM
PROJECT TEAMS: Effective Communication to aid Collaboration in
the Design Process, Emma Hayes and Noha Saleeb (Design Engineering
and Mathematics Department, School of Science and Technology,
Middlesex University, UK) ____________________________ 35

THE BIG BIM BATTLE: BIM adoption in the UK for large and small
companies, Jake Loveday, Tahar Kouider and Jonathan Scott (The Scott
Sutherland School for Architecture and Built Environment, Robert Gordon
University Aberdeen, UK) _____________________ 53

THE CONSERVATION OF OUR BUILT HERITAGE, IN
PARTICULAR STATUES IN ABERDEEN, EVALUATED
THROUGH A SOCIAL AND HISTORICAL CONTEXT AND THEIR
IMPACT, THROUGH THE USE OF 3D SCANNING, Andrew Shaw,
Marianthi Leon and Jonathan Scott (The Scott Sutherland School for
Architecture and Built Environment, Robert Gordon University Aberdeen,
UK) ___________________________________________ 67

ARCHITECTURAL TECHNOLOGY AND THE BIM ACRONYM 3:
GETTING TO GRIPS WITH BIM, Tahar. Kouider, Graham Paterson
(Robert Gordon University Aberdeen, UK) and James Harty (Copenhagen
Technical Academy, Denmark) ____________________________ 95

SMES AND LEVEL 2 BIM, THE WAY FORWARD, Stephanie Mellon
and Tahar. Kouider (Robert Gordon University Aberdeen, UK) _____ 121

WORKGROUP SESSION: PROFESSIONAL APPROACH _________ 137

HOW BUILDINGS VISUALISE CLIENT AND ARCHITECT: The
problem that today’s user is typically not the client, Niels Barrett and
Jakob Kruse (Copenhagen School of Design and Technology, KEA,
Denmark) ____________________________________________ 139
IMPLEMENTATION FEASIBILITY OF A DIGITAL NERVOUS SYSTEM FOR THE CONSTRUCTION INDUSTRY: For Efficient and Effective Information Management across the Project Lifecycle, Rexter Retana and Noha Saleeb (Middlesex University, London, UK)  _ 159

INTELLIGENT DECISION-MAKING SYSTEM FRAMEWORKS FOR A DIGITAL PLAN OF WORK: A Theoretical Investigation for the Construction Industry, Jack Dearlove and Noha Saleeb (Middlesex University, London, UK) __________________________ 177

THE IMPACT OF BIM ON THE DISTRIBUTION OF COST AND RETURN ON INVESTMENT IN UK CONSTRUCTION PROJECTS, Lucas. Cusack and Noha Saleeb (Middlesex University, London, UK) _ 193

WORKGROUP SESSION: TEACHING ___________________________  211

COMPARING COMMON DATA ENVIRONMENT PLATFORMS FOR STUDENT COLLABORATIVE WORKING: A Case Study from Ulster University, David Comiskey, Mark Mckane, Andrew Jaffrey (Ulster University, Northern Ireland) and Paul Wilson (Technical Director, Digital Project Delivery, AECOM) __________________________ 213

THE INFLUENCE OF SPACE LAYOUT, TECHNOLOGY AND TEACHING APPROACH ON STUDENT LEARNING: An Architectural Technology Perspective, David Comiskey, Gareth Alexander, Diane Hazlett, Kenneth Mccartan and Louise O’Boyle (Ulster University, Northern Ireland) __________________________ 233

TECHNOLOGY LANGUAGE AND FRANKENSTEIN STRATEGY, Manuel Pérez Romero (IE School of Architecture, Alcalá de Henares School of Architecture, Spain) __________________________ 249

HOW TO MEASURE HEALTHINESS IN BUILDINGS: Experiences in teaching with BIM tools, Antonio Galiano-Garrigós, Víctor Echarri-Iribarren and Almudena Espinosa-Fernández (Departamento de Construcciones Arquitectónicas, Universidad de Alicante, Spain) 263

ARE DRAWINGS DEAD? …and performance over aesthetics? James Harty (Copenhagen School of Design and Technology, KEA, Denmark) __________________________ 281

DETAILING FOR A RESEARCH CENTRE IN ANTARCTICA: An experiment to force students to be creative instead of copying standard solutions, Fatih Yazicioglu (Istanbul Technical University, Faculty of Architecture Taskisla, Turkey) __________________________ 295
STRUCTURAL ANALYSIS WITH ANSYS ON STONE CONSTRUCTIONS IN THE HISTORICAL SPANISH HERITAGE, Antonio Luis Lopez Gonzalez (Departamento de Ingeniería Civil, Universidad de Alicante, Spain)

THE RELEVANCE OF HARMONISING THE TECHNICAL LEVEL OF SOCIAL HOUSING WITH THE URBAN LEVEL OF THE NEIGHBOURHOOD THROUGH THE EXAMPLE OF THE 500 DWELLINGS IN ALBACETE, Cristina Caro Gallego (Escola d’Art i Superior de Disseny de València) and M. Elia Gutiérrez Mozo (Departamento de Expresión Gráfica y Cartografía, Universidad de Alicante)

NO EVOLUTION BUT REVOLUTION: The future of the Dutch terraced house, Robin Beers and Mauric Bohle (Amsterdam University of Applied Sciences, Amsterdam)

BUILDING FROM BUILDING WASTE: The development of an instrument to determine the circularity of materials from the existing building stock in order to maximise high quality reuse, Elsbeth F. Van Battum (Amsterdam University of Applied Sciences)

TECHNOLOGIES FOR SEDUCTION: “Espacio Doméstico” VideoArt Center in Blanca, Enrique Nieto ((Departamento de Expresión Gráfica y Cartografía, Universidad de Alicante)
STRUCTURAL ANALYSIS WITH ANSYS ON STONE CONSTRUCTIONS IN THE HISTORICAL SPANISH HERITAGE

ANTONIO LUIS LÓPEZ GÓNZALEZ.  
Departamento de Ingeniería Civil, Universidad de Alicante, Spain.  
alg.lopez@ua.es

Abstract. According to the importance of rehabilitation and recovery of Architectural Heritage in the live of people, this paper is aimed to strengthen the traditional methods of stone vaults calculation taking advantage of the technological characteristics of the powerful program ANSYS Workbench. As an example of this, it could find out the possible pathologies that could arise during the construction history of the building.

To limit this research, the upper vault of the main chapel of the Santiago parish church in Orihuela -Alicante- is selected as a reference which is a Jeronimo Quijano’s important building work in the XVI century in the Renaissance. Moreover, it is an innovative stone masonry vault that consists of 8 double intercrossed arches with each other and braced by severies. During the seventeenth century there was a lantern in the central cap and it is unknown why it was removed. Its construction could justify the original constructive solution with intercrossed arches that freed the center to create a more enlightened and comfortable presbytery.

By similarity with other Quijano’s works, it is considered a small lantern drilling the central spherical cap. It is proposed to carry out a comparative study of it with different architectural solutions from the same period and based on several common parameters such as: a vault of square plant with spherical surround, intercrossed arches, a possible lantern, the dimension of the permitted space, similar states of loads and compact limestone masonry. The three solutions are mainly differentiated by their size and the type of lantern and its comparison lets us know which one is the most resistant and stable.
The other two building works maintain some connection with the Quijano's professional scope.

It has selected the particular case of the Communion chapel of the Basilica in Elche (a large prismatic lantern with a large cylindrical drum that starts from the own arches and an upper hemispherical dome), for its conservation, its proximity to Orihuela and its implementation during the century XVIII. Finally, a significant Dome Spanish Renaissance complete the selection: a cross vault of the Benavides Chapel of the Saint Francisco Convent in Baeza - Jaén-, designed by Andres of Vandelvira in the sixteenth century (a large hemispherical dome that starts from the own arcs).

To simplify the calculation and standardize the work that have to be contrasted, all of them were considered with some similar characteristics: 30 cm constant thickness, the intercrossed arches were specifically analyzed and had identical loads, Young's modulus and Poisson's ratio.

Regarding the calculation solutions, in general terms, the compressive stresses predominate, influencing on it the joint collaboration of the filling material on the vault, the vault itself, the thick side walls, the buttresses and the top cover weight. In addition, the three solutions are suitable, being the Orihuela one the safest and the Baeza one the riskiest for its large dimensions.

Thus, the idea of intercrossed arches with suitable thickness would allow carry out the heaviest lantern and this would confirm it as a Renaissance architectural typology built in stone.

**Keywords:** Ansys Workbench, intercrossed arches, stone masonry, geometry, truncated vault and strength.

### 1. Background.

Studying a historic building has two main objectives, among others: understanding the real behavior of the structure (the possible states of equilibrium) and analyzing and understanding the origin and meaning of the visible cracks, in other words, studying the possible moves that have produced to them. But all this is possible only if previously the true elements of the structure are identified. A possible classification, depending
on the type of historical building, could be identifying, on the one hand, the thrust of the vaults, and secondly, the abutments that counteract.

As it is known, a historic building is characterized by its heterogeneous construction process. Firstly, it should identify its different building elements, study how they interact and then check the overall mechanical behavior. In a first stage of analysis (XIX century), static graphics were used to understand the equilibrium conditions of the ancient structure. Ultimately, they were certain equilibrium solutions to respect the essential characteristics of stone, which only resist compression stresses (Huerta Fernández, 2005)

In the twentieth century, it has resorted to the method of calculation by finite elements, which are solved with software; but it should be wisely chosen for correctly validate the solutions obtained with them, because they not fully coincide with the real solution.

As an example of the above, the demonstrated ability of ANSYS program stands out, for reproducing of original shapes with high accuracy, drawing in 3 dimensions, and simulating its actual mechanical behavior or with variations such as loads, supports, dimensions, geometry, materials and thicknesses. In short, it allows us to analyze the behavior of the existing building, calculate reinforcements, make assumptions of alterations or additions possible (not necessarily the real solution), etc.

Although the structures have an engineering character, it is demonstrated that their application to the architectural technology is effective and necessary. In countries like Spain, an architect has a vocational training including structural calculations to define the building as a full entity, such as it is indicated by the Vitruvius’s theory.

2. Methodology and Objectives.

Based on the recovery of Historical Heritage, it intends to take advantage of the technological advantages of the powerful ANSYS Workbench
calculation program. That is, to make firstly a simple check with graphical statics, and then demonstrate the performance of a modern software to improve the accuracy of results in complex cases.

As a particular theme of architecture, it is selected an real example of historic building: the Santiago parish church in Orihuela –Alicante-, an important Renaissance building work of the architect Jerónimo Quijano; specifically, the upper vault of the main chapel. During the seventeenth century there was a lantern in the central cap and it is unknown why it was deleted.

To apply such architectural cases, it is proposed determining the feasibility of the original solution with a small lantern in the Orihuela case and analyze the suitability of the location of that lantern in the central cap, among the arches, and a comparative study among similar vaults of some historic buildings will be performed, with equivalent architectural solutions and based on certain common parameters such as: the configuration of intercrosed arches with thickness greater than the plementería one, thickness identical in arches and severies of all selected buildings, size of the hole among such arches, type of possible lantern, states of loads and types of employed stone masonry.

It should be recalled that Orihuela is located in an area of significant seismic hazard. Thus, this experimental model is suitable to analyze the real building nature, prevent possible structural pathologies in the future or to restore safely the possible existing damages in a historical building.

On the other hand, taking advantage of the ability of ANSYS to find out the real mechanical behavior of an existing historic building, it has tried to find out the feasibility of the original solution with a lantern, what type it might be and the possible pathologies that might arise with its construction.

In short, it does not try to calculate a single real vault (for it would be necessary know its constructive history) in an integral way. This would be the subject of another paper.

The vaults object of this article has implicated certain spherical geometry, so it should pre-analyze some elements such as the dome and the truncate vault. Due to its compression performance, the stone has been the most used material in the construction of domes, with their form of voussoirs as meridians and parallels. The problem is that the domes did not exceed of 43.5m width, because of the appearance of tensile efforts that collapsed the structure.

The resistant mechanism of the domes has a feature that allows them to far exceed the structural capacity of the arches. Each meridian behaves like a funicular arch that is produced by the applied loads, ie, it resist loads without developing bending stresses, for any loads system.

The dome has several parallel that have restricted their lateral movement by developing annular stresses and it make possible the performance of membrane. In a recessed dome, with an angle less than 52º, the meridians are deformed inwardly, towards the axis of the dome, and the transverse parallel are compressed trying to stop it.

When the dome is high rise, under the action of loads, the highest points move inward, but the lower ones do it outwardly, ie, they away from the axis: the parallel below the angle of 52 degrees, are subjected to tensile efforts.

Thus, for all this to happen and the own dome possesses only membrane efforts, the edges have to experiment free horizontal movement in their support. In case that the dome was embedded in any wall, some small deflections which can be presented in the springing are absorbed very quickly by itself.

The dome can be imagined as segments or meridians arches whose bending is prevented by horizontal parallel or rings. In areas where the segments want to sink inward, the parallel prevent it by working on compression, and where the segments want to open, the parallel avoid it by
resisting the traction. The circumferential expansion tends to produce, in
the peripheral zone, any radial cracks.

The truncate vault can be considered for analysis as a derivative of
spherical dome. It has, under steady load, the traction areas below the
parallel at 45 °, the limit being 51 °. There are two main cases, according to
the boundary conditions, the building system and structural behavior
(Requena Ruiz, 2015).

- Stilted spherical cap on pendentives with radial cutting and
  performance derived from the spherical dome.
- Recessed domes, with a grid of arcs and performance derived from the
  translation surfaces.

There are cases where the above two appear simultaneously, each
somewhat. The dome of Orihuela is a hybrid of both.


4.1. INTRODUCTION. LIMIT ANALYSIS OF MASONRY.

The vaults calculation is based on the knowledge of the stress state
(essentially compression), to which the support structure is subjected and
the stability to turn over, and the potential slippage of the voussoirs. These
three points are fundamental to understand the calculation. Now, how do
we make the calculation of stress? There are many studies about it, even
though they made up only to s. XVIII. Mostly, they are graphic
calculations.

The first scientific theory about vaults that was developed in the
seventeenth to nineteenth centuries considers to masonry as a unilaterally
rigid material (which does not resist tensile). In the late nineteenth century,
the modern and correct theory on stone masonry arch was elastic theory.
Today, finite element method (FEM) has been applied to analysis of
structures vaults.

In conducting the studies, it has been applied the Limit Analysis Theory
of stone masonry structures, as Heyman has mainly developed in recent
years. The stone masonry structure formed by a rigid-sided material that resists compression but can not resist tensile is considered. That is, we imagine the stone masonry as a set of undeformable blocks in dry, in direct contact, and which maintains itself under its own weight. Also assume that the stresses are low. Once both the resulting weights and loads acting on the vault as its action line are known, for a symmetrical dome where the thrust should be horizontal at the key line, only remains to decide the thrust tilt, which is determined by the overall profile of the vault.

For analysis, it should be noted that the filler has some importance in relation to the set of loads. We must also consider the weight of the walls and overloadings applicable in each case. To calculate the thrust of the vault, its weight is first calculated. The volume of the various elements will be calculated and multiplied by a specific weight.

There are two sections that can be critical: the wall base and the vault abutment. At the end, the load that receives each considered critical section is calculated. But depending on the vault typology and all adjacent elements to it, these ones could vary (Grau Carreras, 2012).

Following with the exposure, in the twentieth century, Jacques Herman and Santiago Huerta have prominently among of the best technicians who have written about the calculation of stone masonry structures. Huerta, for instance, made a brief but interesting discussion of the calculation of these structures:

«...En primer lugar imaginemos la fábrica como un conjunto de bloques indeformables en contacto seco y directo que se sostienen por su propio peso. Es un material, pues, que aguanta bien las compresiones pero que no resiste las tracciones...» (Huerta Fernández, 1998).

Given its geometry, the restrictions on their supports and the value of the loads acting, the geometric safety coefficient is obtained as an indicator of the stability of the structure for the loads considered, and it is concluded that the structure is safe if it is approximately greater than 2.

In short, “the theory of limit analysis of stone masonry structures” is based on the assumption of three hypotheses:
- The compressive strength of the masonry is infinite, because of the
knowledge that the stresses transmitted by the structure are much lower
than the real resistance of the stone.
- The tensile strength of the masonry is null, a building is supposed as
built “to bone” and the resistance of mortars is underestimated.
- The failure by slippage of the stone pieces on one another is
impossible.

Based on these three principles, the fundamental theorems of limit
analysis are set out. It is concluded that if there is a situation of loads that
simultaneously satisfies the three theorems; we say that that load is the real
collapse one of a stone masonry structure.

Graphic statics is the most common method of analysis of stone
masonry structures in order to solve the equilibrium equations. It is to
replace numerical methods, for certain geometric rules by using the vector
equilibrium. The result is a line of thrust which when it is compared to the
geometry of the structure, the above mentioned “geometric safety
coefficient” is obtained. In an arche, for instance, it is the ratio of the
thickness of the actual arch and the arch thickness limit.

As Heyman and Huerta said, the goal of balance is achieved if the thrust
line is not pulled from the geometrical boundaries of the section of the
element to be analyzed, along its length, and a joint cracking it will form if
the line passes very close to such limits, which occurs in certain joint
between pieces. The collapse mechanism (kinematically admissible) will be
activated if there is a sufficient number of cracking joints (similar to plastic
joints), or if the thrust line is beyond the geometrical boundaries of the
structure.

4.2. CUTTING METHOD IN A DOME.

During the late Gothic, some treaties of Gothic architecture were outlined,
in which the structural rules are displayed, for sizing the walls, pillars and
buttresses of Gothic churches. The most important structural rules during
the sixteenth and seventeenth centuries are refer to the dimensioning of the
abutments of the vaults, since they represent the most of the materialized
structure and they support the building. All they contribute to the sizing of abutment according to the width of nave.

The Blondel’s geometric calculation rule was the most widespread and it is named because appearing in his treatise of 1698. In the segmental arches, a thicker abutment is needed and at the lanced arches, it need less thickness because of generating of minor thrusts. It is also recommended loading the flanks at half the height of the arch, as is the usual construction practice and is essential to stabilize the arches and vaults.

Because of the graphic rules are only applicable to static structures whose polar diagrams are flat, it is necessary to divide the overall structure into simpler elements by cutting in planes. This make difficult the study of structures of irregular geometric shapes which not likely to be divided into defined flat elements. In case of a dome, the resulting elements of cutting are extrapolated to the overall three-dimensional element. Thus, a dome is divided into segments by cutting planes whose plant projection is radial. Two opposite segments will be considered like an exempt arch. At the end, the total thrust surface and its geometric safety coefficient (which should be greater than 2) is derived by comparing the limit geometry with the real geometry obtained.

The appearance of any cracks would occur, on the one hand, by way of a parallel on the intrados or the extrados of a spherical structure (concentric lines), and secondly, as any meridian line due to act of pressing radially and outwardly, causing thrusts in their springings.

Setting a lantern on the dome could improve its stability as long as the thrust line is too open and close to limits. The weight of the lantern could help enclose the line and bring it closer to the curvature of the structure, could reduce the thickness of the dome boundaries and could increase the geometric security ratio (Ayensa Pardo, 2011).
5. Advanced methods.

However, progressing on the calculation procedures, the easiest method for modeling of stone masonry structures is based on representing it as a combination of structural elements, such as bars, beams, plates or shells. This is the case of the simplified methods through macroelements. However, such simplified elements usually provide a thick description of the behavior of real stone masonry element. The Paolo Lourenço’s Macro-model systems also stood out (1998): in this case, the brick, the mortar and the brick-mortar interface are represented by a single finite element. The material is studied at macroscopic level and is modeled as a homogeneous, continuous and orthotropic element. He also sayd:

«...In micro models, masonry units and mortar are separately discretised using continuum or discrete elements, whereas in the macro model (also known as equivalent material model), masonry is modelled as a single material using average properties of masonry» (Senthivel and Lourenço, 2015).

This type of discretization typically belongs to the homogenization techniques, that basically consist of replacing the complex geometry of the basic cell for a simplified geometry, so that it is possible a closed and homogenized solution of the problem. These homogenization techniques can establish constitutive relations in stress terms and average strains from the geometry and the constitutive relations of the individual components. The problem arises with structural elements such as vaults, in which there are no periodic repetition elements, without a recognizable basic cell and, instead, an irregular bond of segments occurs, based on an unknown construction process. Perhaps, the discretization technique in identical cells is most appropriate for stone masonry walls. In addition, sophisticated mechanical means would be required to test with stone voussoirs.

The distribution of voussoirs and joints arch (real or imaginary) are factors of the solution of the problem of arch balancing. The influence of the adequate representation of the units of the stone masonry is a problem that will reappear in the development of other methods, based either on the
homogenization (macro models) or discrete representation of the units (micromodels) (Mira Díaz, 2012).

As a result of the problems mentioned above, in this research we focus on arch-vault elements as homogeneous and continuous parts. To standardize somehow structural analysis, a comparative study among some similar construction elements of significant buildings of a certain time will be made, i.e., a “sui generis” and suitable selection of important building works in Architecture will be done. It suffices for this to choose suitable comparison parameters, so that it can ignore the possible error from a method of continuous elements with respect to the discretized elements such as elementary cells. And for comparing the computer method with the graphic one, the structures will be analyzed in linear regime, such as the prescribed static graphics.

Currently, for the modeling of stone masonry the finite element method (FEM) is used as a tool for calculation and as a description of the behavior of the material to constitutive level.

Also, masonry modeling by finite element requires the characterization of the material as deformable solid. Masonry is modeled through continuous and homogeneous elements to try to determine their behavior in terms of stress and continuous strains, and a single material. It is the technique of the macro-models but excluding, in this article, the mortar joints such as a separate material.

Following, the selection of works chosen to implement the method of homogenization is shown.
6. A practical application of the method: the Jerónimo Quijano’s crossed vault as a reference.

6.1. GEOMETRIC-STRUCTURAL HISTORY OF THE TEMPLE HEADER.

In general terms, in Spain and specifically in Valencia and Murcia territories, a medieval tradition with a quality stonework stood out, which took advantage to play their own architectural forms of emerging Renaissance. Cutting and cuts of stone required the knowledge of geometry to ensure perfect assembly of the different elementary pieces called voussoirs and thus get the correct transmission of loads between them, resulting in the structural stability of the whole.

As an example of the Quijano’s innovative spirit, it has been focused on the upper dome of the main chapel of the Santiago parish church in Orihuela –Alicante- (Figure 1).

Approximately in 1550, Quijano designed the header as a nearly square plant space of 12.50 m of side (López González, 2013). The top dome is built by an original combination of different curves geometric shapes for the adaptation of a sphere to a square.

It contains 8 distorted arches made out of stone voussoirs that start out from the lower 8 pilasters and orthogonally crossing theyself on plant. This is a pseudo-truncate vault, in other words, spherical only up to the four virtual and intermediate arcs which are located between the arches that are currently built and whose projection on the plant is a square of side 3/5 square projected throughout the whole vault on the plant. The central spherical cap is made out of stone and plaster, based on some restorations during the seventeenth century and the severies are of stone the springings on sides and the corners (such as pendentives).
Figure 1. The upper dome of the main chapel of the Santiago parish church in Orihuela – Alicante.

The side buttresses absorb the thrust of the arches and are built-in the perimeter walls, which contain the springings of the great central dome. In the seventeenth century the central cap was drilled for setting a lantern and it weakened the whole. Then it turned to close the hole in the eighteenth century to stabilize the whole building.

Continuing with the explanation, it is interesting to follow with examples of cross vault, as the case of the Communion Chapel of the Santa Maria Basilica in Elche – Alicante (Figure 2). Its conservation, its proximity to Orihuela and its construction in the eighteenth century allow
to speculate on the nature of the Quijano’s vault and his influence on others, and especially including the option of the lantern.

Archpriest and Insigne Santa Maria Basilica is the most prominent church in the city of Elche. It is of neoclassical style, is longitudinally located at the temple header and its access to it is through the ambulatory. The building of Santa Maria Basilica was started in 1673 and lasted 111 years.

Figure 2. Cross vault, the case of the Communion Chapel of Santa Maria Basilica in Elche – Alicante-

Lorenzo Chápuli and José Gonzálvez de Coniedo (1782-1784), were responsible for the Communion chapel, the last part that was built, with neoclassical style. It has undergone two great restorations in the twentieth century: the renewal of its vaults and its dome were directed by Marcelino
Coquillat (1903-1905), and repairing the damage caused by the fire of 1936 was directed by Antonio Serrano Peral (1939-1954).

In the last place, it is interesting to carry out a comparative study with the cross vault of the Benavides Chapel of San Francisco Convent in Baeza – Jaén-, designed by Andres de Vandelvira, in which a large square space (16 meters wide) is raised, it's covered by a truncate vault, reinforced by four simple intercrossed arches and a huge, vaulted and very heavy central cap. It is the solution of “crossed vault” of the Alonso de Vandelvira’s treaty (Figure 3):

![Figure 3. The solution of “cross vault” of the Alonso de Vandelvira’s treaty. Benavides Cross Chapel of San Francisco Convent in Baeza vault – Jaén-](image-url)
The problem arose when the vault of Baeza collapsed during an earthquake in the eighteenth century and was sacked by Napoleon’s troops in the nineteenth century. Thus, we cannot know exactly how its magnificent vault was built and we have to settle with the graphics of Alonso of Vandelvira.

“Esta puesta por obra esta capilla en San Francisco en la ciudad de Baeza por mi señor padre y entiendo es la mejor capilla particular y más bien ordenada y adornada que hay en nuestra España, tiene sesenta pies de hueco sin los encasamientos que tiene 8 pies” (Palacios Gonzalo, 1990).

6.2. APPROACH TO CUTTING METHOD IN THE ORIHUELA VAULT.

As a reminder of the above, if the line of thrust passes through the nucleus of inertia of the element section in that joint it will have only compressions between its pieces (trapezoidal pressure distribution). In the joint, the line will have left the nucleus, and it will have tractions with compressions (that constitutes the contact area between parts), thus creating a triangular pressure distribution.

The proper construction with compensation elements (such as weight of fillers and walls) may greatly alleviate the occurrence of cracking, it being sufficient in this case an elastic analysis. Although reaching certain degree of approximation to reality and with the most extreme caution.

In the dome of Orihuela, it has been cut a segment through the geometric center and containing a transverse axis, in order to ensure the symmetry of the resulting part. The polar diagram is provided by the anti-funicular polygon and the thrust line. It is a simple verification of graphic statics, true to a traditional method. The real purpose of this paper is to demonstrate the advantages of new software, applicable to architectural technology.

The result shows that the line of thrust passes inside the nucleus of inertia, except for the flanks area, just where the dome backfill is located. Thus, the stress distribution in the different sections of the segment has a trapezoidal distribution (all compression), and at the flanks appear to have no tendency to crack due to traction (Figure 5). Due to that the weight of
filler is complicated to graph it, the convenience of using computer methods is appreciated; and such filler could alleviate the appearance of traction.

Moreover, the importance of the perimeter wall is observed. Indeed, being the vault built-in the wall, its springings have been rising, the thrust line is not pulled from the section and the thrust is absorbed by the wall, which makes the work of a strong abutment. This is a sensible and effective building process.

However, the purpose of this paper is to analyze the intercrossed arches, which do not allow cut a totally symmetrical segment and it would complicate much the method of static graphics. Thus, it becomes more convenient to use more sophisticated methods. Consequently, the finite element method through ANSYS Workbench program is proposed.

6.3. CALCULATION WITH ANSYS WORKBENCH.

After the above and recalling the general approach of this research article, the convenience of completing the graphical method for the calculation by using the finite element method will be demonstrated later. Indeed, in some cases the graphic method does not correctly reproduce the mechanical behavior of certain stone masonry building elements, not being regular geometric shapes. Ansys Workbench is a software ideal tool for such cases. However, the consideration of an elastic model is not fully adjusted to the actual building due to the existence of stone masonry pieces (thus because of its low tensile strength, causing inevitable cracks). Instead, it allows the location and direction of the maximum principal stress, and an acceptable approximation for the foreseeable strains from the considered actions.

Thus, the elastic analysis on selected works in this paper may be considered as valid, by choosing common analysis parameters of such structures. This facilitates the homogenization of the sample and does not require an independent exhaustive analysis of each.
To ensure standardization and facilitate comparison between the structural elements, they have chosen the following common mechanical parameters:

- Compact limestone with density $D = 2500 \text{ kg x m}^3$
- Young’s modulus $E = 5000 \text{ Mpa}$. Poisson’s ratio $= 0.20$.
- Compressive Yield Strength $= 10 \text{ Mpa}$. Tensile Yield Strength $\geq 0 \text{ Mpa}$.

As to the formal and structural characteristics:

- The vault of intercrossed arches arise from their own springings
- A vault with severies whose thickness is equal to 0.30 m. and the thickness of the intersecting arches is equal to 0.45 m. A lantern whose elements have a thickness equal to 0.30 m. The elimination of all building on the exterior surface of the dome. The bracing arches on her springings are to absorb thrusts by perimeter walls.
- The surface loads of fillers in the extrados and arches are of value equal to 0.01 Mpa. The surface loads on the lantern are of value equal to 0.005.

To compare homogeneously calculations, the following plans are proposed in common for the three vaults:

- A volume of the vault standing out the minimum principal stress (compression), and also standing out several significant points on a crossed arch.
- A compression stresses plane located approximately over the guideline of center section of a crossed arch to check the behavior of the nucleus of inertia. A volume of the vault, standing out the arch section previously calculated.

The evaluation of the stability factor of the compressive stresses compared to the compressive yield strength. For this we have used the theory of Mohr-Coulomb stress. After calculations with Ansys Workbench, they have obtained the following results:
The Cross Vault of the Santiago parish church chapel in Orihuela – Alicante:- The intercrossed arches, being double and equal to 12.5 meters diameter, increase its rigidity and the internal tensions are reduced (figure 4).

![Figure 4. The minimum principal compressive stress.](image)

The upper dome of the main chapel of Santiago parish church in Orihuela – Alicante-

The proposal lantern is small and it does not significantly increase the tensions in the arch, but frees the central space and helps to set the line of thrust inside nucleus of inertia (figure 5). In the geometric guideline of the arch, the minimum principal stress (compression) ranges from 41689 Pa (in the key) and 110910 Pa (at springing), as is shown in the figure 6.

Furthermore, the resulting security coefficient by dividing the minimum principal compressive stress by the compressive yield stress is greater than
15 over the entire cross arch. For example, near the arch abutment (maximum value):
\[ \frac{10^7}{2,0437 \times 10^5} = 49. \]

Figure 5. On the left: in the arch geometric guideline, the minimum principal stress (compression). An image in 2 dimensions: the Santiago parish church in Orihuela.

Figure 6, on the right. The thrust line in Orihuela –Alicante-

A cross vault of the Communion chapel of Basilica in Elche –Alicante. The cross arches, being simple and reasonably small in diameter (9 meters), they increase its rigidity but it reduces less the internal tensions. The proposal lantern is great, (it is a dome supported on a cylindrical drum) and this significantly increases the tensions in the arch, although frees the central space and also helps to set the line of thrust inside nucleus of inertia. In the arch, the minimum principal stress (compression), as in the figure 7, ranges from 383 200 Pa (along the drum) to 788 300 Pa (at the springing), as is shown in the figure 8. Furthermore, the resulting coefficient of security from the minimum principal compressive stress is greater than 15 in the upper section of the cross arch. However, near the base of the arch:
107 / 1.7527 x 106 = 5.7, Being 2.70 in the base and 1.70 as minimum

*Figure 7.* The minimum principal compressive stress

Unit: Pa. Cross vault, the case of the Communion Chapel of Santa Maria Basilica in Elche – Alicante
Figure 8. In the arch geometric guideline, the minimum principal stress (compression). An image in 2 dimensions. Cross vault, the case of the Communion Chapel of Santa Maria Basilica in Elche – Alicante-

The Crossed vault of the Benavides Chapel at the San Francisco Convent in Baeza – Jaén-

The cross arches being single and with a large diameter (> 16 meters), slightly increase its rigidity and the internal stresses are little reduced. (Figure 9)
The proposal lantern is great, according to the Vandelvira’s drawing (it’s a hemispherical dome) and it significantly increases the tensions in the arch, but releases a lot of the center and also helps to set the line of thrust inside nucleus of inertia. In the arch, the minimum principal stress (compression) ranges from 423220 Pa (at the key) and 950 230 Pa (at springing), as is shown in Figure 10.
As in previous cases, the resulting coefficient of security, from the minimum principal compressive stress, is greater than 15 in the upper section of the cross arch. However, near the base of the arch is:

\[ \frac{107}{1.9036 \times 106} = 5.5 \], Being 2.97 as a minimum value at the base.

7. Conclusions.

In defense of Historical Heritage, it has been done a approximate tensional check with graphic statics about certain building works and, after verifying
the limitations thereof, have been demonstrated the benefits of a modern software to improve the accuracy of results in complex cases. For which, they have been used certain advantages of the powerful ANSYS Workbench, that it has been applied on the architectural technology.

To limit this research was selected, as a reference, the upper vault of the main chapel of the Santiago parish church in Orihuela - Alicante-, an important Renaissance work of architect Jerónimo Quijano in the sixteenth century. It is an innovative stone masonry vault that consists of 4 double arches, which intercrossed each other and they are braced by severies. Supposedly, the intercrossed arches are designed to include in the central hole a lighting element such as a lantern. Assuming a small lantern in the case of Orihuela (a drilling the central spherical cap), in order to verify the structural suitability or not, they have selected two typologically equivalent building works of his time to compare and find the best solution. The comparison is ensured by choosing of three works with certain common parameters such as thickness, loads and analysis of crossed arches.

On the one hand, the case of the Communion chapel of the Elche Basilica (a large prismatic lantern with a large cylindrical drum that starts on the own arches and an upper hemispherical dome) are chosen and, secondly, a very significant vault in Spanish Renaissance has been especially selected: the crossed vault of the Benavides Chapel of the San Francisco Convent in Baeza - Jaén-, designed by Andres de Vandelvira (a large hemispherical dome that starts on the own arches).

Consequently, the three solutions are structurally suitable, being the Orihuela one the safest, by their double arches and light weight of his lantern. The Elche one supports on a heavy lantern and the Baeza one is the riskiest for its large dimensions. On the other hand, it might be possible to consider, in all cases, a vault with intercrossed arches and severies with the same thickness as a uniform structural shell, and to evaluate its possible structural problems.

In conclusion, the vault of intercrossed arches with adequate thickness allow carry out any solution of lantern with sufficient safety factor (other
else would check the real building system), and may be confirmed as an architectural typology of Spanish Heritage in Renaissance.

**References.**


GRAU CARRERAS, MÓNICA, 2012. Sistema estructural: cálculo de bóvedas. La fortaleza de Isabel II.


REQUENA RUIZ, IGNACIO, 2015. Análisis de tipologías estructurales, bóveda, lámina, cúpula y paraboloide.