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Judgment of collapses and settlements from orthoimages: the method of pathological analysis in the Escuelas Pías church (Valencia)

The Escuelas Pías church of Valencia is a milestone of Neoclassicism whose architecture is compared to Agrippa's Pantheon. Its dome with a 24.5 m span has cracks in four sectors, just like in its drum. Thanks to a recent survey with a laser scanner (TLS), orthoimages have been obtained to follow a methodology for the study of collapses and unevenness, which have served to determine the diagnosis of the pathology. For this, the methodology is based in obtaining the heights on reference bases and capturing them on reference axes, resulting in a graphic that facilitates the reading of the interpretation of the pathological diagnosis of the monument.

Keywords:
collapses; settlements; orthoimages; Escuelas Pías

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INTRODUCTION

The church of the Escuelas Pías in Valencia (Spain) was built between 1767 and 1772, and declared a National Historic-Artistic Monument in 1982. The pathological state presented at the end of the 20th century was the origin for drafting its Master Plan in 1993 (Soler 1993), having to analyze the entire building and, especially, the structural damage and the possible causes. In addition, over the last 30 years it has been subject of different studies to determine the origin of these cracks that affect its masonry dome, with a span of 24.5 m and a single sheet of a foot and a half thickness, approximately 45 cm. The studies carried out so far were focused only on the dome and attributed the origin to stress problems due to thermal inertia, that is, the tractions due to thermal oscillation were not supported by the masonry due to its rheology (Soler 1995).
The mentioned cracks follow the direction of the meridians and are more or less centered. Located in the base of the dome, they extend up to approximately 3/5 of the development of the dome, approximately 10'74m, and in four of the ten sectors into which the dome is divided. Associated to these cracks, there are many other that may only correspond to cracking in the coating.
The question that motivates a more detailed study of the cracks is that there are also cracks in the drum of the dome and affect both the interior and exterior of the wall. Another relevant aspect is that the four affected sectors are facing each other, concurring as a double arch in the shape of a cross.
To draft the architectural project for the complete restoration of the dome in 2021, an exhaustive survey was carried out, one with 3D laser scanning and another with drone and modeling to obtain the photogrammetric images of the interior elevation and the dome, if well, this cannot be represented in true magnitude due to the complexity of the model and is an approximation.
After the direct analysis of the monument as the main source of information, it is necessary to turn to technology. Thanks to the studies and surveys carried out, all the documentation has been analyzed and both the dome and the masonry are studied in order to give a more precise answer to the presence of the cracks.

Fig. 1 - Interior view of the dome with the cracks.

Fig. 2 - Cracks in the lintel and flare of the drum window (left) and in the second ring of the drum where it meets the roof (right).

ESCUELAS PÍAS CHURCH AND ITS HISTORY

In 1597 San José de Calasanz founded the first public school in Rome, Europe since only the wealthy classes had access to education (Soler Blázquez 2017: 49), giving its name to "Escuela Pía". The order known as Piarists arrived in Valencia in 1737, where they began works on the school in 1739 and finished it in 1747 (Bérchez 1983: 492). In 1767 the works of the church began according to the plans arranged by the master builder Josef Puchol. The promoter of the works, Archbishop Andrés Mayoral, wanted a church whose composition stood out from the Valencian architectural tradition, sending the architect to visit the church of Las Religiosas Bernardas de Alcalá (Madrid) (Ponz 1774).
The church was initially designed and directed by Josef Puchol until he was relegated by Antonio Gilabert in 1768, also rectifying the project, pausing the works in 1769 due to the death of Mayoral and the lack of economic funds. After the vicissitudes due to the lack of funding, the church works would end in January 1771 and it would not be consecrated until 1773 (Zacarés: 450). Puchol's project established a third body that was taller than the one built later and that was reduced in size for economic reasons (Zacarés: 513).
Apart from these two architects, prestigious masters such as stonemasons Andrés Soler, José Pons, Juan Simarro, Tomás and Vicente Miner, Pedro Juan Guisart and Vicente Company worked on the project, Manuel Hernández carpentry, Jacinto Miralles the locksmith and José Meliá the tin shop (Zacarés: 514). The paintings and sculptures are by José Camarón, Luis Planes and José and Ignacio Vergara. (Ponz, 1774).
The Escuelas Pías school and church is located in the historic Velluters neighborhood, occupying almost the entire block, with the exception of the eastern corner, Santa Teresa street. The school has a rectangular shape. The church is located at the east end. It is embedded between the main

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Fig. 3 - Detail of the view of Valencia where the volume of the Escuelas Pías in the city can be appreciated. Guesdon, 1832.

façade with the bell tower (south), two wings of the school cloister (west), an alley (north) and houses and light wells (east). For a better location, it was considered opportune to name the sectors, being A the one with the main entrance on Carniceros street; D access through the cloister; F the main altar; H and I the sectors facing the light well and J the access to the bell tower. In terms of volume, the dome with an interior light of 24.5 m stands out, divided into ten sectors, like the temple of Minerva Médica, but whose architecture was inspired by the Pantheon of Agrippa (Bérchez, 1987). The interior plan is circular with ten exedras that stand between the trapezoidal buttresses about 3 m thick. Becoming the space for the two entrances -one from the street and the other from the cloister of the school-, the main chapel and the seven chapels. Likewise, one of those chapels leads to the poché (Castellanos, 2012) between the main façade and the church fabric, which is where the stairs are located that lead to the upper levels and the bell tower. The wall that surrounds the church is about 50 cm thick. The second level presents spaces between the buttresses and the ándito (corridor) with a railing, forming a gallery for the choir and other uses. The third level is the one formed from the cornice higher than 21 m and on which there are the niches of ten apostles and the windows that form the drum. The next level is already the skeleton of the dome.

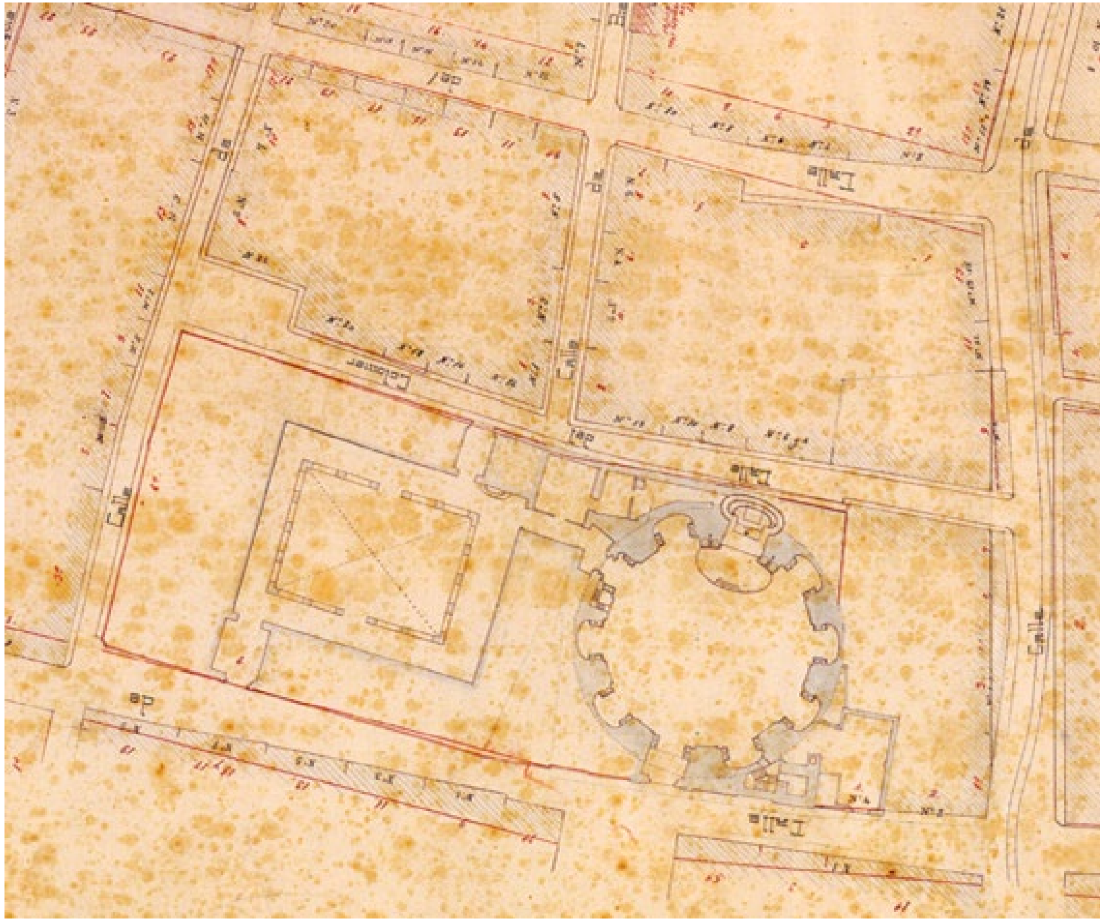

Fig. 4 - Partial geometric plan of Valencia, section 7. 1892.

The church presents in its interior elevation three levels, the lower one with a larger dimension with a Corinthian order, the intermediate one with a minor order and an intermediate portico in antis and the upper one with the before mentioned niches of ten apostles and large windows.

STATE OF THE ART

Even though the state of the Piarist dome has been the subject of scholarly discussions in the last thirty years, in its construction process it presented problems and when analyzing the masonry closely in its current restoration process, it has been possible to observe different repairs without

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being able to date them up to now (Cortés 2023). Already in full construction of the dome, before the alarm in Valencia for the safety in the construction of the dome due to its exceptional dimension, the Royal Academy of Fine Arts of San Carlos, the official body that regulated the profession of architecture from 1768, decided in January 1770 that the Directors of Architecture Vicente Gascó, Antonio Gilabert and Juan Bautista Mínguez make an opinion on the matter (RABASC). Unfortunately, there is no documentary evidence of the opinion, although in the RABASC meeting of April 18, 1770, "in accordance with the agreement that was agreed in said Meeting, and in view of what is stated in it by the written Opinions that present , it was agreed that these be present, to the Rector of the Piarists, so that in view of everything, they can take the most convenient security measures of said Church, and with this Agreement the Meeting was terminated..." (RABASC) (Berchez, 1987).

Alonso and Mrtínez (2003) carry out a virtual theoretical study of the thermal behavior due to temperature variations on the dome, concluding that the combination of thermal and gravitational load reaches traction values much higher than those that the masonry can support. However, they establish that the damages in the model do not correspond to the actual cracking state that was established in the Master Plan.

Masi, Stefanou and Vannuci (2018) study the cracks in the dome of Agrippa's Pantheon, performing a detailed three-dimensional simulation of finite elements, attributing the origin of the cracks to the contraction (shrinkage) of the concrete and the action of gravity by the different phases of construction of the opus caementicium.

Gil Saura (2015) collects the information from the historical point of view of the collapse of some Valencian domes in the 18th century, without carrying out a constructive architectural analysis, nor

Fig. 5 - Internal view of the Escuelas Pías church with its neoclassical architecture.

Fig. 6 - Scketch of Escuelas Pías for the Voyage pittoresque et historique de l'Espagne by Alexandre Laborde 1806-1820, François Ligier (left) and painting by Giovanni Paolo Panini of Agrippa's Panteon (right), circa 1734.

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determining the pathology and exact causes of the collapse. This study focuses mainly on the domes of the Virgen del Lledó in Castellón and Oliva (Valencia), demolished due to the excessive weight of the drum and alluding to the master masons, whose opinion about the stability of a masonry did not depend on the thickness of the walls, but in addition to the quality of the materials and their adequate disposition.

Rodríguez and Gil Piqueras (2020) study the lesions inside the dome after having carried out the planimetric survey with laser scanning (TLS) and modifying the color balance to observe the degradation, showing the possibility of chipping in a parallel arrangement to the dome due to the oxidation of the metallic rings that Zacarés initially manifested (1849). After a first study with georadar technology, it has been possible to verify the existence of some metallic rings cited by Zacarés (García, 2023), in the same way that Guastavino (1893: 39) drew brick dome with iron rings, understanding that said figure shown is the dome of the Pious Schools of Valencia.

Marín (2021) establishes an architectural comparison of the Piarist circular model with other models, establishing a trace hypothesis similar to those established by Carlo Fontana, but showing that the cracks can be attributed to the inevitable yielding of the drum during the construction process. In the same way, he alludes to the metallic rings mentioned by Zacarés, concluding with the study by Alonso and Martínez that the metallic reinforcements are not necessary once the dome is closed.

López (2023) analyze technical reports and studies made on masonry domes in 18th century, highlighting that the masters were applying the laws of mechanics and behavior of materials, related to the study of domes (three-dimensional structures) with the theory of arches and vaults (two-dimensional). In this line of research, Huerta (2004) studies and analyzes cases from the different historical stages to conclude that the balance of arches, vaults and domes is based on traditional calculation based on geometry, also relating the supported structures with the load-bearing ones (walls and stirrups).

It should be remembered that the old masters sized the historic domes based on geometric proportions in relation to the radius of the dome (Fontana, 1694), not least the dome of the Escuelas Pías (Rodríguez, 2020).

Fanelli (Fanelli, 2022) studies the lesions in the Fiore dome, also analyzing the fabric and the pillars, analyzing the structural behavior of the drum and using color representation for stress distribution.

In January 2023, on the beginning of the restoration of the Piarist dome, the Royal Academy of Fine Arts of San Carlos in Valencia held a symposium on the pathology of the dome, concluding Soler and Benlloch (2023) that the thermal and rheological actions due to the construction system used based on brick and lime masonry are the cause of the damage. González (2023) goes further and analyzes the entire building, dividing the formation of the cracks into four sectors, proposing the hypothesis of injuries due to gravitational action and the lack of a counterbalance in the wall for satisfactory balance.

Many of the historical and current studies have been based on studying only the behavior of cracks in domes, and the walls and foundations must also be analyzed. If the ground or foundation gives way, that is, a settlement is produced, cracks will appear at the base of the walls and, consequently, on the masonry and the dome. It may also be the case, like the dome of St. Peter's in the Vatican, that the cracks were at the level of the dome and drum (Poleni, 1748), so in cases like this it is not necessary to study the wall structure or the foundation.

The study of the cracks in the dome and interior of the Escuelas Pías church must be carried out globally, both dome and the structure that supports it. It is no coincidence that some of the cracks inside are also reflected on the outside, either at the level of the drum or the dome itself.

METHODOLOGY

The methodology of any study on a patrimonial building should start with the study in situ, to get to know the built element better and first-hand. After the first phases of study carried out, in addition to the obligatory bibliographic search, to address the analysis of the pathology of the dome and its walls, this study has required an optimal graphic survey and with a low margin of error (Crespo, 2014).

This study began using a survey methodology using active sensors, carrying out an exhaustive survey with a laser scanner (TLS), using the faster and more precise phase variation measurement system for the 3d survey, using a Leica RTC360 scanner. , taking a total of 60 scans, 48 clouds for the interior space and 12 for the exterior. In the office work, the clouds were downloaded and the

Fig. 7 - One of the orthoimages obtained to carry out the study, specifically sector F that corresponds to the altar.

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Leica Cyclone Register360 software was used to obtain a single model, with a minimum precision of 1 mm outside and 2 mm inside (Rodríguez-Navarro 2020).
After processing the cloud of points, 10 orthoimages of the interior of the church were obtained in order to have the elevations of the ten sectors that make up the interior elevation represented. Since it is complex to read cracks and other pathologies with the images from the scanner survey, images were taken with a Mavic Air 2 drone (Rodríguez-Navarro, 2022) and the photogrammetries were obtained using the Agisoft Metashape Standard program.

Fig. 8 - Real model built to test settlement cracks.

This documentation served to graphically represent all the architectural elements of the architectural project and later, to study the possible settlements, collapses and turns at different levels to obtain the necessary results and be able to determine the origin of the pathology.
The methodology used for the study of settlements and collapses is based on taking measures of heights on the orthoimages obtained in the 3d laser scanner. To do this, having previously inserted the orthoimages in the AutoCAD software, a reference baseline was drawn and the others at the height of each of the 3 levels of the church -9'44 m, 16'65 and 21'11 m -, in addition to some marked axes to delimit each sector. These axes were used to have the reference point of each level in the vertical plane and to be able to obtain its height, and also as a horizontal axis where the obtained value is represented.

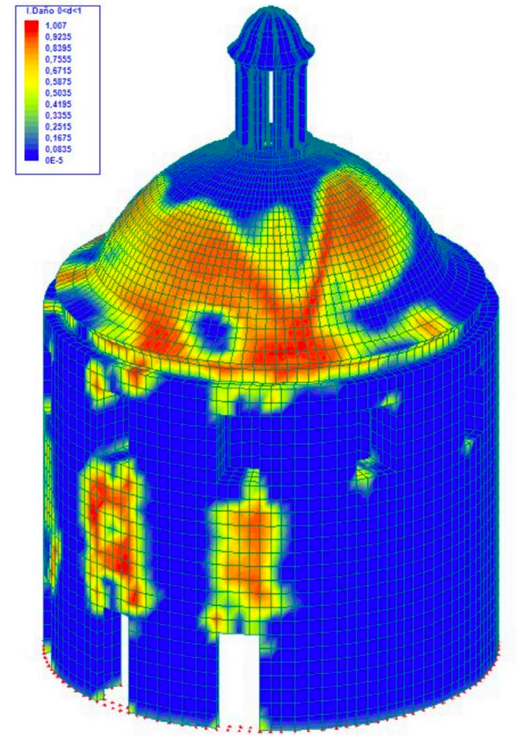

Fig. 9 - Verification of the structural behavior of the dome by settlement in Angle.

Parallel to this study, through the EMR chair of the Universitat Politècnica de València and taking advantage of the restoration process of the dome, a masonry model was made with adjustable metal feet to check the shape and arrangement of cracks when giving way controlled by one of the feet (Fortea, 2013). The result of the test was that when the bases were moved, cracks appeared on the edges.
In order to correlate the data obtained with this graphic method, the monument has been modeled and has been subjected to a virtual test of modeling of masonry structures with the Angle software, based on finite elements and the ideal program for appraisal of historical structures.

RESULTS AND DISCUSSION

The cracks in the vertical walls of some sectors of the church, especially in the sectors facing the light well, sectors H and I, gave false evidence of a possible settlement of the ground as the main cause of the structural pathology of the dome. These sectors are the ones that face a common light patio with the residential buildings located to the east of the plot and that present a very high slenderness, 0.5 m thick and 24 m high. These cracks can be considered as secondary being the consequence of a movement of the building, but without having to be directly related to a ground seat. Continuing with the reading of the exterior cracks, these would be concentrated mainly in four sectors, B, D, G and I (figures 9 and 10), specifically splitting the lintels of the openings of the windows in the drum and the masonry in the ring top of the drum (figure 1).
Inside, the cracks mainly affect the four sectors mentioned above, the most important being sector G and whose cracks ascend from level 2, starting from the floor level of the false organ and going up to 2/3 of the level of the dome in that sector.

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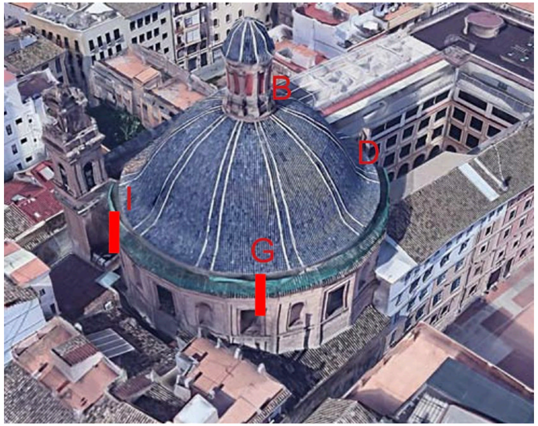

Fig. 10 - Aerial view from a northeast orientation with the definition of the sectors that present the large cracks.

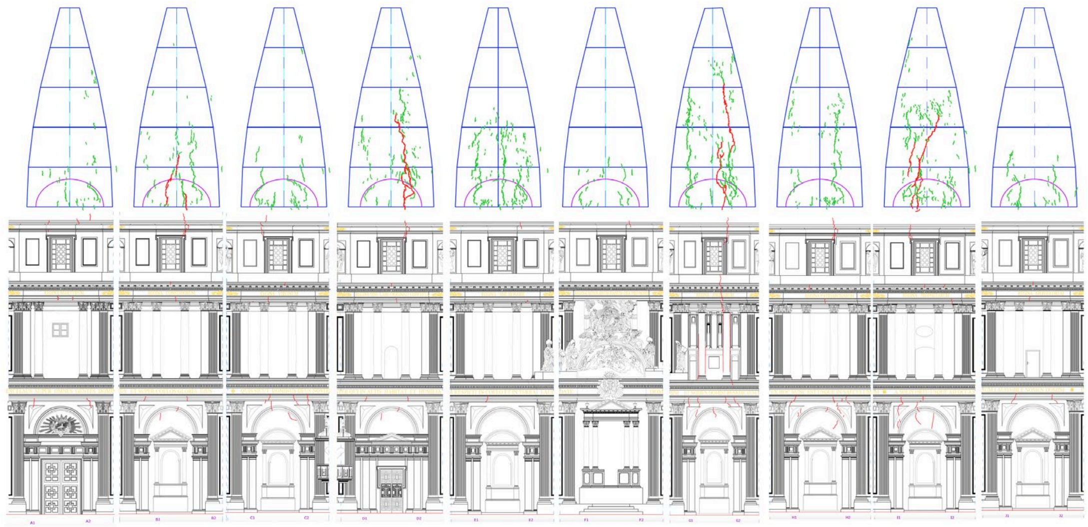

Fig. 11 - Graphic description of the cracks (in red) and fissures (green) inside the church. Named from left to right, the first being sector A and the last being J.

The existing cracks in the rest of the sectors with this same arrangement also reach the same point, understanding that it is the complete compression due to the loads coming from the lantern and from that level traction could not occur.
Even though there are no cracks in the bases of the walls, a possible foundation of the masonry should not be completely ruled out, since there are cracks in the first entablature, but deepening in sector G. Furthermore, in that first entablature of the sector G, two iron staples have been found in the current restoration phase, understanding that there has already been a previous repair, which by technique could be understood from the 19th century.
As previously mentioned, the structure is based on pilasters with lowered vaults, hidden from view by the niche vaults of the side chapels, so that a movement on the pilaster would affect the entablature before the pilaster itself. . On the orthophotos, a study of collapses has been carried out, being irrelevant for this building because it hardly provides information due to the high number and volume of holes and elements that distort a completely vertical plane, in addition to the fact that the different levels have different planes. In this case, a study could be carried out with strain gauges, as has been done in Santa Maria del Fiore to obtain the deformations (Fanelli, 2022).
For information purposes only, the church stands on top of old buildings, there is a ditch (water pipe) that crosses the church, the soil is made of silt, presenting a stratigraphy with slight variations (Martínez, 1995) and there have been no earthquakes that have caused the general cracking.
Going from the vertical to the horizontal plane, when carrying out a study of levels is when we obtain data that allows us to determine a more exhaustive knowledge of the problem. In the study of level heights carried out in the three levels, a maximum difference of 14 cm is obtained in the length of a radius of 80 m, which may be considered excessive when it is understood that if the master builders were able to erect this architectural marvel without collapses, It is not understandable that the levels were lost either.
In this analysis, when graphically representing this elevation difference, for optimal visualization the axes are scaled from the reference elevation, obtaining a circular graph to be interpreted that represents the level curve. The results of this data collection show height differences in each of the levels, with the maximum height differences being 11 cm at level 1 (tribune cornice), 14 cm at level 2 (upper ring cornice) and level 3 (dome start cornice) of 13 cm. The graphs obtained are similar, posing different hypotheses, from the possible site of the factory in the DEFG sectors and that overlook the alley and/or the turn of part of the wall.
Following a logical sequence of work and using a similar methodology, on an orthophoto of the section of the wall that is supposed to have collapsed, the collapses of the rear elevation and the seats in the drum are analyzed, drawing lines perpendicular to the level plane 0 to obtain the slumps and horizontal reference lines for the seats. In this case, there is a drop towards the alley of the rear elevation (DEFG sectors) of about 36 cm, and there is also a seat of the entablature of the drum of 14 cm and both the starting of the lantern and

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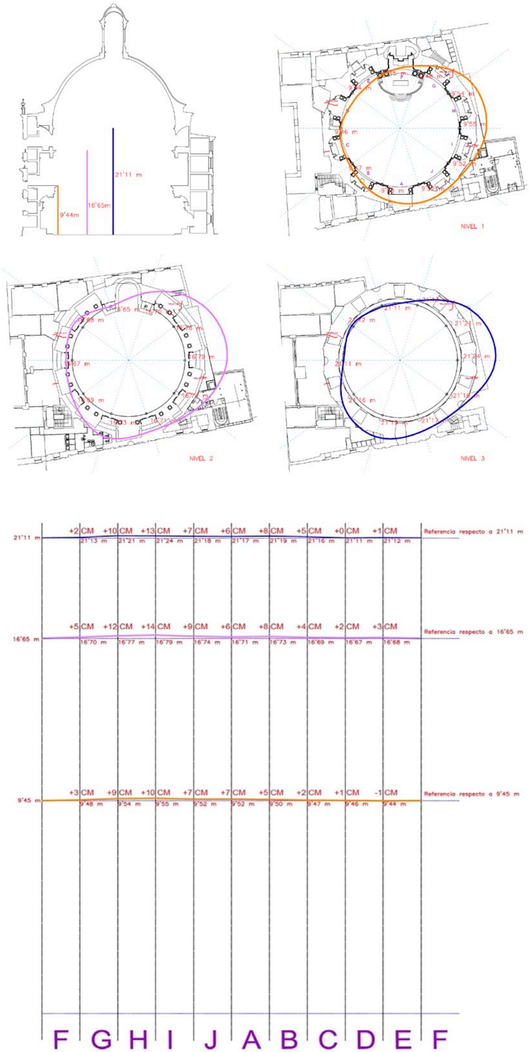

Fig. 12 - Interpretation of the data collection of the heights in the 3 levels marked in a circular graph.

its entablature a seat of 12 cm. cm. The data obtained inside and outside are very similar and all lead to the fact that there has been a collapse or twist -we won't say a seat for the moment- of the church towards the alley, which could be the main cause of the cracks in the dome. This collapse could have been caused by the lack of rigidity of the wall or lack of counterbalancing of the drum's thrusts, given that in other sectors there are annexed buildings and they act as the buttresses and buttresses of the Gothic cathedrals. On the other hand, thanks to the precision of the graphic survey, it is manifested that the lantern is displaced 29 cm from the axis of the dome, without attributing it to any pathology. It should be stated the difficulty of surveying to raise a 1000 m2 dome, 24.5 m internal light, at a height of 21 m and with the auxiliary means and technology of the 18th century.

CONCLUSIONS

The first of the conclusions of this article is that all the information must be analyzed, and an optimal architectural survey carried out to graphically capture all the information available in order to achieve the corresponding evaluation. Current technology allows the use of high-precision digital procedures that, together with computer tools, allow us to obtain the pathology of a monument in a less empirical way, being just as valid when obtaining data as expensive and long-lasting studies. In the case of the church of the Escuelas Pías in Valencia, since there are no cracks at the base of the walls, the seat in the foundation could be ruled out. Some of the cracks in the walls of the east patio would be due to construction difference cracks and their dimension is accentuated by the slenderness of the facing. However, the existing cracks in the interior entablature of the first level do show movement, either as a result of the collapse and/or rotation of the wall or even due to a possible settlement of one or more pilasters between sectors D and G.

The collapse of the exterior wall facing the alley, as seen in figure 12, would correspond to the interior sectors with the greatest unevenness, making it very difficult to numerically correlate the exterior or collapse with the interior unevenness. The external unevenness in the cornice of the drum and in two planes of the lantern is similar to that of the interior, about 14 cm, evidencing a turn and collapse of the wall towards the alley due to lack of counteracting thrusts.

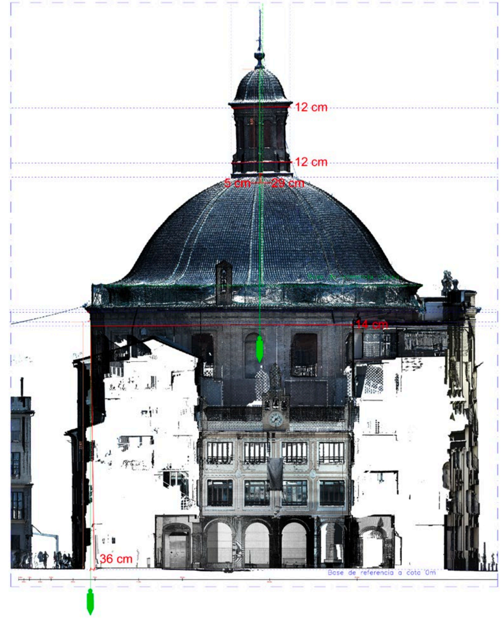

Fig. 13 - Interpretation of collapses of the alley's elevation and turns of the drum and lantern.

Having carried out an exhaustive study on walls thanks to an optimal graphic survey has allowed us to quantify collapses and unevenness, in addition to being able to determine that the origin of the cracks in the dome may be due to a twist and/or collapse of the masonry, reaching to recommend the installation of a compression ring in the upper body of the drum to avoid excessive stresses of the dome on the drum and even the provision of some constructive element to counteract the thrusts in the enclosing wall facing the alley. This last suggestion will be contrasted with the information available after the monitoring of the building and

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its study after a temporary period. Studies like this serve as a methodology to analyze the pathology due to collapses and settlements and, above all, to reduce costs in restoration interventions thanks to an adequate diagnosis.

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