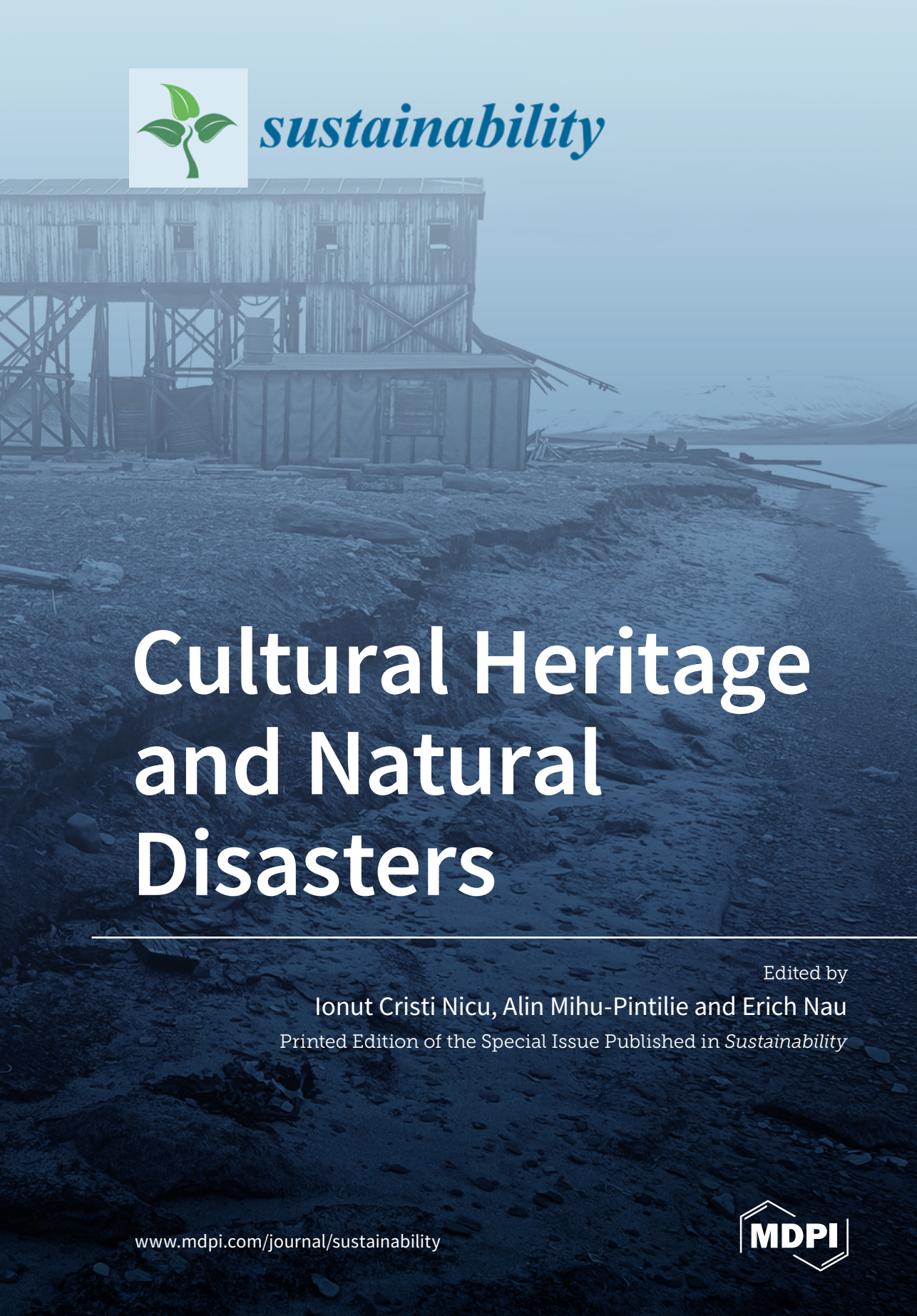

Cultural Heritage and Natural Disasters

Edited by
Ionut Cristi Nicu, Alin Mihu-Pintilie and Erich Nau

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Preface to "Cultural Heritage and Natural Disasters"

In recent decades, the intensity and increasing numbers of natural disasters have started to affect immovable cultural heritage around the world. This is important due to the high complexity and impossibility of recovering any kind of data from a cultural heritage asset destroyed by a natural disaster. This SI has brought to the attention of the readers a few significant studies that approach the issue of natural disasters and cultural heritage. Notably, the SI has published papers on topics of interest which were proposed at the beginning of the SI launch. In total, six papers were published as a result of applying different and new methods in the field of cultural heritage. They are spread over different parts of the globe, as follows: Romania (two studies), Svalbard and north Norway (two studies), Spain (one study), Canada (one study).

Three of the papers propose new methods to be applied in the field of cultural heritage: a new method for archaeological predictive modelling (APM), a method that employs image-based modelling to measure the erosion at archaeological sites, and a study that compares the performance of airborne laser scanning and remote sensing in Arctic landscapes. The other three studies employ methods and techniques that are well known and used in the field of cultural heritage; the use of old maps and new orthophotos, combined with field surveys were used to assess the erosion rates of coastal cultural heritage located in Svalbard. A 3D laser scanner was used to document and graphically analyze the pavilions muqarnas at the Court of the Lions in the Alhambra in Granada (a UNESCO World Heritage Site). The usefulness and applicability of satellite-based remote sensing was once again successfully applied to document, map and monitor archaeological sites in urban landscapes (Apulum, Alba Iulia, Romania). More efforts should be taken at an international level to develop new methods in the field of cultural heritage and/or to apply methods that are already used in studies at the border between cultural heritage and natural disasters, as cultural heritage represents the legacy of our ancestors.

Ionut Cristi Nicu, Alin Mihu-Pintilie, Erich Nau
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Article

The Pavilions at the Alhambra's Court of the Lions: Graphic Analysis of Muqarnas

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Abstract: This research documents and graphically analyzes the pavilions muqarnas at the Court of the Lions in the Alhambra in Granada, a World Heritage Site. In order to cast some light on the understanding and preservation of these 14th century architectural elements, after a brief report of historical data on catastrophes and restorations, a novel methodology for the case study based on three complementary graphic analyses is presented here: First, there is a review of outstanding images ranging from the 17th to the 20th centuries; subsequently, new CAD (computer-aided design) drawings from pavilions muqarnas testing the theoretic principles from their geometric grouping are accomplished for the first time; and finally, a 3D laser scanner is used to understand the precise present-day state from the point cloud obtained. Comparing drawings allows us to assess the muqarnas relevance while proving, for the first time, that the muqarnas of both pavilions have distinct configurations and different amounts of pieces. Besides, this process reveals geometric deformations existing in the original Nasrid muqarnas compositions, identifying small pieces hitherto unknown, plus additional deformations resulting from adjustments after important threats that both pavilions and their muqarnas overcame for centuries, despite their fragile construction.

Keywords: muqarnas; Alhambra; graphic analysis; drawings; 3D laser scanner; historical images; cultural heritage; UNESCO; Spain

1. Introduction

1.1. Background. Brief Historical Data on Catastrophes and Restorations in the Court of the Lions

The study target in this research is located at the Alhambra Royal House in Granada (southern Spain), a Medieval urban complex -Alhambra, Generalife and Albayzín- included by UNESCO in the World Heritage List taken into account several reasons, particularly the outstanding criterion IV [1]:

"The Alhambra and Generalife bear exceptional testimony to Muslim Spain the 13th and 15th centuries. They form a remarkable example of the palatine residences of medieval Islam, neither destroyed nor changed by the vicissitudes of time, as with the examples in Maghreb. The attributes contained in the inscribed property justify their exceptional position in the Islamic architectural tradition of the Early Middle Ages, and they express the authenticity in a reliable way. Since its conception as a palatine city, its architecture began from a proportional system, following the principles of area compartmentalization, no exteriorization and the typical acclimatized design of the Islamic culture. Together with this, it comes to fruition in a decorative program based upon geometry, epigraphy and vegetable decoration that attain its most characteristic expression in Mocárabe [muqarnas] vaults".

No other place in the Alhambra is as interesting as the Lions Palace and its famous courtyard, a masterpiece of Nasrid and Islam art in Spain, built during the reign of Muhammad V (1354–1359 and 1362–1391) [2]. The groupings of muqarnas pieces used in this environment are undoubtedly one of the most outstanding features of its architectural identity. The Court of the Lions has a rectangular plan measuring 28.50 × 15.70 m and formed by two perpendicular axes. Its elegant perimeter gallery rests on 124 white marble columns with ringed shafts that are grouped in subtle compositional rhythms (Figure 1).

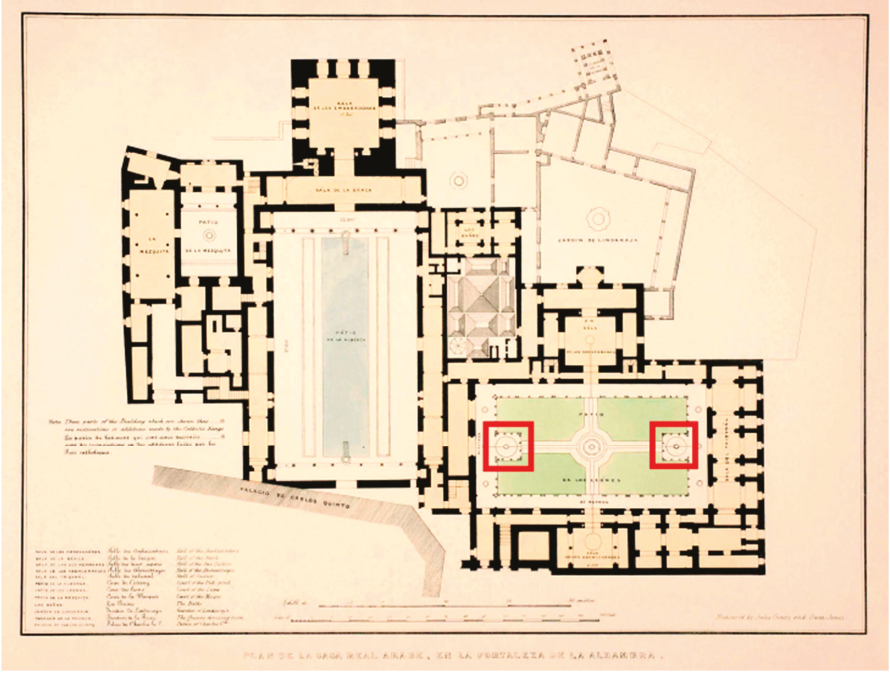


Figure 1. Owen Jones; Jules Goury. 1842. "Plan of the Royal Arabian Palace in the ancient fortress of the Alhambra" (red squares mark the Pavilions in the Court of Lions; top of the image facing North) [Plans, elevations, sections, and details of the Alhambra Vol. 1, plate 3].

In the middle of the smaller sides of the patio stand out two almost square-shaped temples which are considered authentic masterpieces of the Nasrid art (Figure 2a,b). Above their columns and abacuses there are brick pillars covered with fine plaster decoration, which support the beams on which eaves and roofs rest. This lintel-based layout freed the arcs from a structural or load-bearing function, and facilitated the inclusion of a beautiful openwork ornamentation that allows the passage of light and the incorporation of sophisticated compositions of muqarnas, the target of this study.

The pavilions's inner floor is made of marble and covered with stunning hemispherical wooden domes, which are one of the finest examples of 14th century carpentry works in Granada. Plaster muqarnas pendentives, which are also a target of this study, were designed as a transition from the square plan to the domes circular plan.

(**a**) (**b**)

Figure 2. Pictures from the Court of the Lions [taken by the authors]: (**a**) View to the western Pavilion (2004); (**b**) view to the eastern Pavilion (2018).

The Nasrid dynasty carefully chose locations for their fortresses and foundations, taking into account the important seismic activity in its kingdom and particularly in the citadel of Granada. The Alhambra underground, called "Formación Alhambra" by current Geology experts is quite suitable to reduce seismic risk. Both site and geological disposition have been crucial factors for the Palace's conservation thus far [3,4]. A historical document [5] reported the flood of the river Darro on 5 March 1600 that affected the base of the Alhambra hill, leading to significant landslides in what is nowadays known as 'Tajo de San Pedro', an area which keeps a part of the monument at geological risk.

The risk of ruin threatened the Court of the Lions many times, as indicated by the historical data outlined below. According to the most prominent Alhambra curator architect, Leopoldo Torres Balbás, the Nasrid decadence had a turning point on 27 June 1431, when a major earthquake collapsed some walls and towers, a few days after the entrance of John II of Castile II in the Vega de Granada starting the Battle of La Higueruela [6].

Repairs have been incessant in the Court of the Lions since both town and landmark passed into Christian hands in 1492 [7]. In documents from 1541 and 1542, mention was made of the replacement of plasterwork and the placement of braces to control the movements of the columns. In 1590, a fire and explosion occurred in a powder mill near the river Darro, on the north slope of the Alhambra, severely affecting the Palace of the Lions, blowing up glasses, doors, and windows. In the Hall of the Mocarabes, next to the western pavilion, its muqarnas vault was destroyed; and other emblematic architectural elements of the monument were also greatly affected, such as the nearby Comares Tower [8].

In 1626, 16 braces were placed in the Court of Lions due to major collapses; and between 1688 and 1691 the ruin was complete. For this reason, the pavilions' roofs were modified between 1691 and 1694, so that they lost their original aspect. The west pavilion nowadays keeps the roof built in the late 17th century, which replaced a previous one with a steeper slope, hipped and with glazed tile trestles [9]. In 1729, some repairs took place due to the arrival of Philip V of Spain, and new repairs occurred in 1744 and 1757. New reports dating from 1784 informed about an imminent ruin, aggravated by a lightning strike occurred on November 5, 1787.

In 1812 and 1820 some light works on the roofs were performed, and also at the beginning of the 19th century a garden was created in the Court and the irrigation water induced earth movements, so it was removed around 1844–1846 [10]. As described later, in 1858, an unfortunate restoration of the eastern pavilion took place; in 1889 it was rebuilt; and in 1910 the subsoil was repaired [11]. Towards 1934, Torres Balbás restored it again in the form it still has nowadays. In addition, in 1966, the architect Francisco Prieto-Moreno consolidated and restored the western pavilion.

Finally it should be remembered that along the history, there have been many natural hazards that have affected the archaeological sites or monuments, for example, of the Seven Wonders of the

Ancient World, only one of them—the Great Pyramid of Giza—has survived until our days. Regarding the other six, three have been damaged by earthquakes. The Colossus of Rhodes collapsed around 227 BC, the same occurred to the Pharos Lighthouse in Alexandria in the 14th century AD. Finally, the Mausoleum in Halikarnassos, destroyed by floods and earthquakes and rebuilt several times, eventually disappeared in the 15th century [12,13].

It is surprising how the Court of the Lions has been preserved until our days with such a fragile structure. As indicated above, throughout the history of the Alhambra, movements caused by earthquakes, explosions, or water leaks in the subsoil have been aggravated by neglect or lack of maintenance due to shortage of economic resources, by the effect of weather elements, or as a consequence of inadequate repairs. All these factors have caused on many occasions the detachment of plaster ornaments and the collapse of the columns.

1.2. General Objectives and Methodology

The pavilions at the Court of the Lions and their fragile muqarnas have barely been studied and, until now, no digital surveys have been made to reflect with precision their formal complexity. For this reason, the present research aims to document and graphically analyze the muqarnas, to facilitate their study and improve their future conservation.

In order to tackle the last objective, we propose a novel methodology for the case study based on an architectural graphic analysis including three types of drawings that complement each other. After reviewing the historical data, some important images from the pavilions extending from the 17th to 20th century have been compared in order to document and illustrate their transformations, as an initial reference for the CAD (computer-aided design) drawings. Subsequently, a digital model is produced to allow the comparison between the reality and the theoretical geometric principles that rule the assembly of muqarnas. Finally, a 3D laser scan provided new images from the point cloud, thus allowing a more precise understanding of their current state. A later comparison between drawings unveils new contributions about both the configuration and current state of the muqarnas, remarkable 14th-century architectural pieces.

2. Materials and Methods. Graphic Analysis of the Pavilions Muqarnas

2.1. The Pavilions and their Muqarnas Historical Images

In the first known views of the Court of the Lions, drawn and engraved by Louis Meunier around 1668 [14], the pavilions show a rudimentary but expressive aspect. Their roofs were quite steep, although the eaves representation is strange and the columns grouping patterns is inaccurate, casting doubt on the reliability of the details. Nevertheless, the pavilions seem completely symmetrical (Figure 3).

Figure 3. Louis Meunier, h. 1668. "El patio de los Leones in Grenada" [Spanish National Library, invent/19565].

This apparent symmetry is supported by a valuable drawing by the outstanding architect Juan de Villanueva toward 1766–1767, published in "Las Antiguedades Árabes de España" (1787) and edited by the Royal Academy of Fine Arts of San Fernando in Madrid [15]. There is a longitudinal section towards the Hall of the Abencerrajes (Figure 4) where the shading interior of the pavilions are drawn for the first time, but the roofs no longer had the hipped layout depicted by Meunier. The representation of the columns pattern is accurate and the arches ornamentation is schematically drawn, as well as the low-detailed pendentives of interior muqarnas, barely showing their groupings, but with no differences between both pavilions.

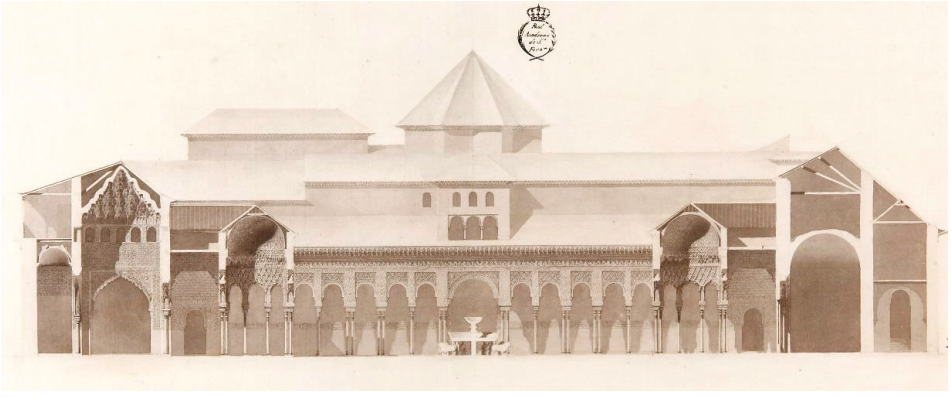


Figure 4. Juan de Villanueva, 1766–1767. Longitudinal section of the Court of the Lions. [Royal Academy of Fine Arts of San Fernando, Madrid, MA-0540].

Many other draftsmen accomplished outstanding views from the Court of the Lions in the late 18th century and the first half of the 19th century, similarly to what occurred with drawings from other Arab landmarks such as the Mosque of Cordoba [16]. Henry Swinburne published a drawing of the paved courtyard and the east pavilion in his book "Travels through Spain in the years 1775 and 1776 . . . " (1779). The accurate drawings by William Gell around 1801, hosted in the British Museum, show the aspect of the courtyard before the garden was created.

It is also worth noting the posthumous work of the Irish architect James Cavanah Murphy, "The Arabian Antiquities of Spain" (c. 1813–1815); and the detailed images by Alexandre Laborde included in his book "Voyage Pittoresque et Historique de l'Espagne" (1808–1820). It should be mentioned the beautiful views by John Frederick Lewis included in "Sketches and drawings of the Alhambra" (1835); de Joseph-Philibert Girault de Prangey in "Souvenirs de Grenade et de l'Alhambra" (1836); or by Nicolas-Marie-Joseph Chapuy in "Le Moyen Age Monumental et Archeologique" (n° 251, h. 1841–1846), separating from other authors that drew simplified muqarnas and did not understand their formal genesis.

The architects Owen Jones and Jules Goury deserve to be paid special attention, as they performed a scientific approach analyzing the ornaments of the Alhambra and researched the geometric construction laws of the muqarnas in order to draw them rigorously. Their splendid longitudinal section from the Court of the Lions pointing to the Hall of the Two Sisters (in the opposite direction to the section by Villanueva from 1766–1767) was published in 1838 (Figure 5), and included in their monumental book "Plans, Elevations, Sections and Details of the Alhambra" (1842).

Still nowadays no CAD plans have exceeded the exquisite level of detail of Owen Jones and Jules Goury's drawings. The pavilions were symmetrically drawn, with hipped roofs different from those drawn by Villanueva; the muqarnas are accurate and very detailed. In addition, Jones and Goury yielded many other drawings of muqarnas on cornices, arches, pendentives or domes, proving a deep knowledge and ability to represent them [17].

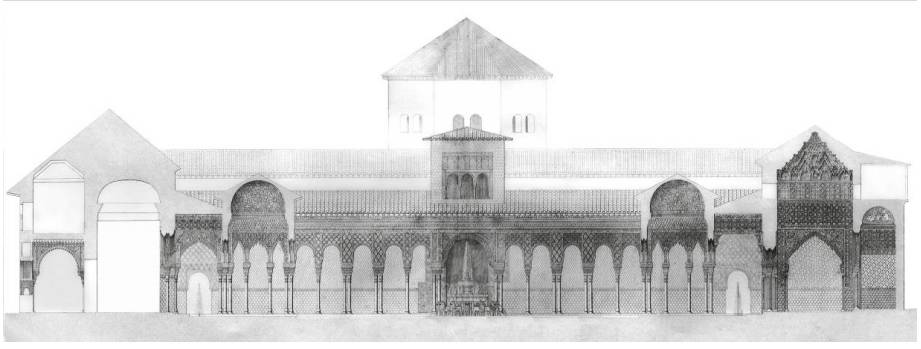
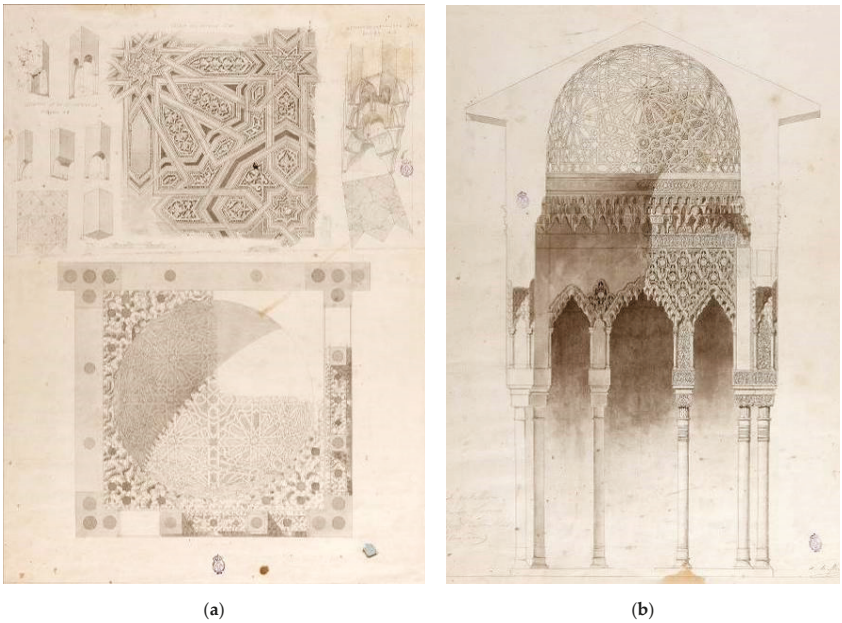


Figure 5. Jones and Goury (dib.); Kennion (grab.). Longitudinal section of the Court of the Lions, published by Owen Jones, 1838 [private collection].

In 1859 and 1862, Nicomedes de Mendívil y Quadra produced splendid drawings from a pavilion, both preserved at the Royal Academy of Fine Arts of San Fernando in Madrid. They were published as isolated print plates in "Calcografía Nacional" belonging to the outstanding "Los Monumentos Arquitectónicos de España" (1856–1882).

The drawings fill two plates, the first plate representing the plan, details from the muqarnas and the half dome, and the other one representing the section [15]; the pavilion depiction is very reliable and was carefully shaded (Figure 6). The author does not indicate whether if it is the east or the west pavilion the one that is drew on the plate. The plan only contains two out of four arcades, probably because he assumed they were symmetric, although this is not true as we will explain later. The plate published by Nicomedes de Mendívil y Quadra neither finished the other two arcades.



(**a**) (**b**)

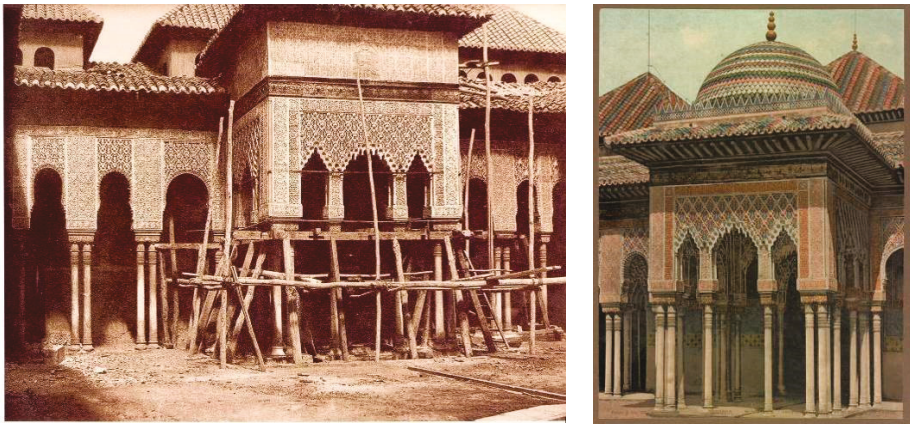
Figure 6. Nicomedes de Mendívil y Quadra. Pavilion at the Court of Lions: (**a**) Interior details, 1859; (**b**) section, 1862 [Royal Academy of Fine Arts of San Fernando, Madrid. MA-0210; MA-0211].

Many photographs were taken from the Court of the Lions shortly after the appearance of this technique, all of great documentary interest [18]. A recent exhibition has brought together many of those photographs by various authors [19]: Pablo Marés (h. 1852), Felix Alexander Oppenheim (1852), Alphonse de Launay (h. 1854), Charles Clifford (1854), John Gregory Crace (1855), Jules Palanpin-Dufresne (1856), Eduardo García Guerra (h. 1856), Joaquín Pedrosa (1857), Alexis Gaudín (1858), Jakes August Lorent (1858), Gustave de Beaucorps (1858), and others.

These photographs show the braces placed to prevent the columns from collapse, a threat aggravated by the irrigation of the garden created at the beginning of the 19th century and eliminated around 1844–1846 because the water would cause serious problems in the foundations [20]. The disturbing state of conservation in the Court of the Lions led to a delirious proposal by architect Salvador Amador in 1846, which proposed the complete demolition and reconstruction of the Arab palace, which fortunately was never undertaken [21]. An expressive photograph by Gustave de Beaucorps taken in 1858 shows the east pavilion fully propped up to reinforce its foundation and fix its tilt (Figure 7a).

The aforementioned photographs also show the aspect of the east pavilion prior to the radical intervention of Rafael Contreras, Alhambra curator from 1858 to December 1859 [22], who removed the 17th century roof and the upper plaster walls in order to build a new dome covered with glazed ceramic (Figure 7b). The main problem of this intervention, and others accomplished by Contreras, is that it tried to beautify the monument without a scientific basis and without any rigor, so that original elements were replaced by unrealistic ones, something that fully clashes with the current principles of restoration in architectural heritage.

The new external dome built by Contreras caused rainwater drainage problems that damaged the interiors. After renovating the structure, Torres Balbás commissioned a new tile which was quite controversial due to the marked slope roof [23], removing the upper plaster walls by Contreras that Torres Balbás did not rebuilt. From then until now, two different roof solutions cover the eastern and western pavilions.



(**a**) (**b**)

Figure 7. Eastern pavilion: (**a**) Gustave de Beaucorps, 1858 [Legacy from Ortiz Echagüe, University of Navarra]; (**b**) Purger & Co., c. 1902, after the restoration of Rafael Contreras in 1859 [private collection].

2.2. *New CAD Drawings Following Theoretical Principles on Muqarnas Grouping*

Muqarnas are small prismatic pieces grouped on complex patterns or sequences shaping cornices, capitals, arches, pendentives, or vaults which were a symbol of the Alhambra Nasrid architectural identity. It is necessary to carefully draw the plans of muqarnas to understand their complex geometry,

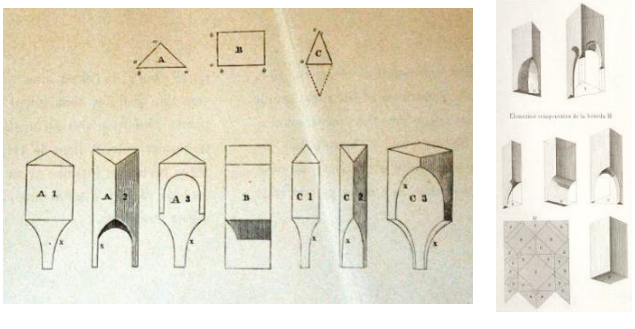
their proportions and compositions. The aforementioned plan does not require a scale number to obtain the valuable information referred to: Pieces identification and their grouping.

This research has accomplished the first CAD drawings of plans of the pavilions of the Lions and all their muqarnas pieces using the software ArchiCAD. To achieve this goal, essential references concerning the rules about muqarnas layout have been used: Diego López de Arenas' treatise published in Seville in 1633 [24], Fray Andrés de San Miguel's manuscript from the first half of the 17th century, published in 1969 [25], and a recent reinterpretation of this text by Enrique Nuere [26,27]. References to Eastern muqarnas geometry can be seen in Dold-Samplonius (2015) [28] and Garofalo (2010) [29]. Both papers refer to a treatise by the mathematician Al-Kashi from 1425, which is a fundamental reference for studying muqarnas in the Eastern world.

A review of Owen Jones and Jules Goury's muqarnas drawings has been undertaken, as they propose an elementary grammar on their grouping [17] starting from three flat Figures A, B and C, two triangles and a rectangle, that make up the base for seven key muqarnas pieces, A1, A2, A3, B, C1, C2 and C3, which allow various muqarnas compositions (Figure 8a).

The pavilion plan drawing by Nicomedes de Mendivil includes muqarnas elementary pieces, but the muqarnas grouping does not match the real ones at the pavilion. Mendivil draws six pieces identified from A to F, but he did not sort them according their flat figure shape, nor did he indicate the linkage between the sides from different pieces (Figure 8b).

It should be noted that other authors have proposed a different number of basic pieces or consider that some of them are divided in others [30]. In any case, the three flat figures proposed by Jones and Goury do not resolve the great diversity of muqarnas groupings existing in the Alhambra, where other auxiliary geometries, such as small triangles or squares, frequently appear to enrich many compositions.



(**a**) (**b**)

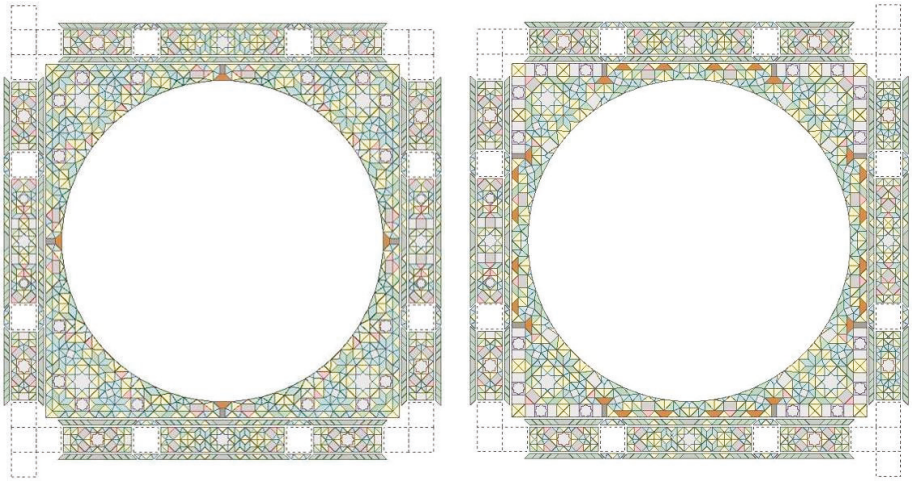
Figure 8. Key muqarnas pieces: (**a**) Jones and Goury (dib.) 1834 [Plans, Elevations, Sections, and Details of the Alhambra, plate 10, 1842]; (**b**) Nicomedes de Mendívil y Quadra (dib.) 1862; Esteban Buxó (eng., 1864) [Los monumentos arquitectónicos de España, no. 27, 1865].

From the aforementioned precedents and a careful observation of reality, this research identified the existing pieces in both pavilions to consequently draw their plans and basic volumes. Different colors have been assigned to each type of piece to facilitate its location in the subsequent drawings of groupings (Figure 9).

Figure 9. Pieces library from the pavilions at the Court of the Lions [authors' own drawing].

During the graphic analysis process, it was detected that the arcades' muqarnas are smaller than those of the pendentives and friezes placed in a higher position and at a greater distance from the observer. It has also been found that in higher ceilings, such as that of the Hall of the Kings, the pieces sizes are even larger.

Finally, it has been observed that the western pavilion displays 2258 pieces, with 1032 located in its pendentives and 1226 in its arcades; on the other hand, the eastern Pavilion has 2222 pieces, with 948 in its pendentives and 1274 in its arcades (Figure 10).



(**a**) (**b**)

Figure 10. Muqarnas plans: (**a**) Western pavilion; (**b**) eastern pavilion [author's own drawing].

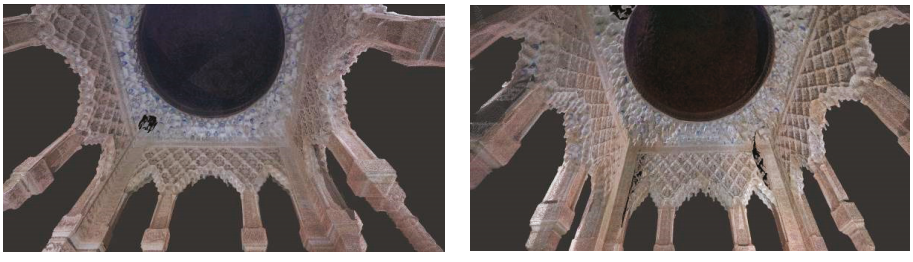
2.3. Images Rendered from 3D Scanners

Thanks to the valuable collaboration from Patronato de la Alhambra y Generalife, the scanning of the muqarnas groupings from both pavilions could accurately assess their current state. The point cloud was captured using a BLK360 laser scanner with a precision of 6 mm when the object is within a distance of 10 m, and 8 mm for 20 m. Three point densities are allowed by the BLK360: Low, medium and high that capture points separated 20 mm, 10 mm and 5 mm from each other when the object is 10 m away. This research worked with medium density and obtained data from the 360° environment. All scans were registered in the same reference system (Figure 11). To facilitate the 3D modelling, HDR pictures were taken setting the scanner to HDR mode.

Recap Pro software from Autodesk was employed to obtain the registration in both automatic and manual forms; the manual method would be used only if the automatic option failed. Three variables define the quality register for each scan: (a) Common volume between the current scan (not registered yet) and the scan/s previously registered, (b) the balance between the number of points scanned through

the 3 orthogonal spatial directions, the optimal scene is when the points equally expand the three spatial directions, and (c) percentage of points with a fitting error smaller than 6 mm.

Data analysis has covered various phases. Volumes of interest have been selected using AutoDesk Recap. Plans, elevations and sections have been obtained from the point cloud using Cloudcompare software. Then, key points on flat projections have been identified and line drawings have been made on the muqarnas assembly contours and the internal main axes. A 3d model could have been obtained by photogrammetry from a series of photos with targets, which coordinates were known, but the accuracy would be equivalent, as shown in [31].



(**a**) (**b**)

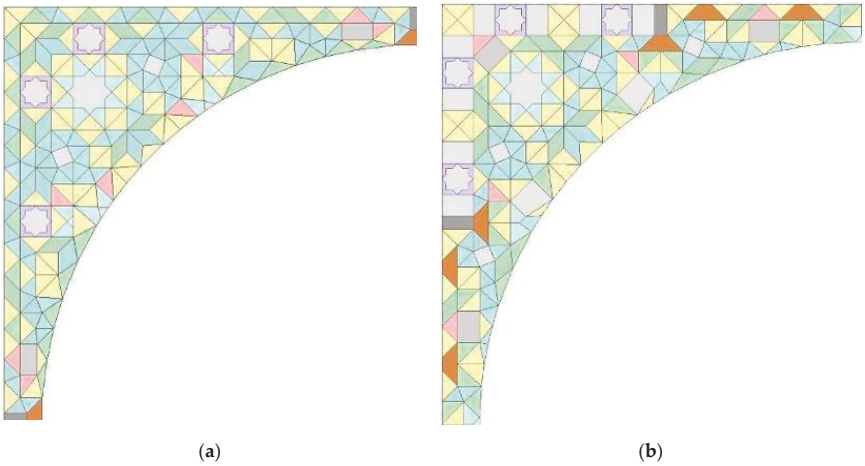
Figure 11. Views from the 3D laser scanner [authors' own drawing]: (**a**) Western pavilion; (**b**) eastern pavilion.

3. Results. Comparing Drawings

3.1. Comparing Different Pendentives

After drawing the muqarnas geometry, it was observed that their composition in the pavilions pendentives is different. It is easier to identify and visualize the number of pieces of each type and their locations when using different colors for each type.

For example, the naked eye may detect the different locations a trapezoidal muqarnas (marked in brown color) occupies on each pavilion (Figure 12). This muqarnas was identified in Jones and Goury's drawings and frequently occur in other Alhambra rooms.



(**a**) (**b**)

Figure 12. Pendentives composed of muqarnas [authors' own drawing]: (**a**) Western pavilion; (**b**) eastern pavilion.

3.2. Comparing Different Arches

Arcade muqarnas were made up by partial groupings separated by strips that layout the whole set. These strips are similar to those ones called "medinas" in the text by López de Arenas, but they were not drawn. In each arcade, it is a straightforward observable fact to identify both inner and outer muqarnas rows.

On the other hand, it should be considered that each pavilion includes three arches between columns, one central and two sides identical to each other. This local symmetry in each arcade is one of the few features common to all of them.

The 1226 muqarnas in the western pavilion arcades are located as follow: Northern 309, southern 309, western 307, eastern 301; while in the arcades in eastern pavilion there are 1274: Norhern 317, southern 317, western 301, eastern 339. Thus, considering both pavilions, there are six different types of arches (Figure 13).

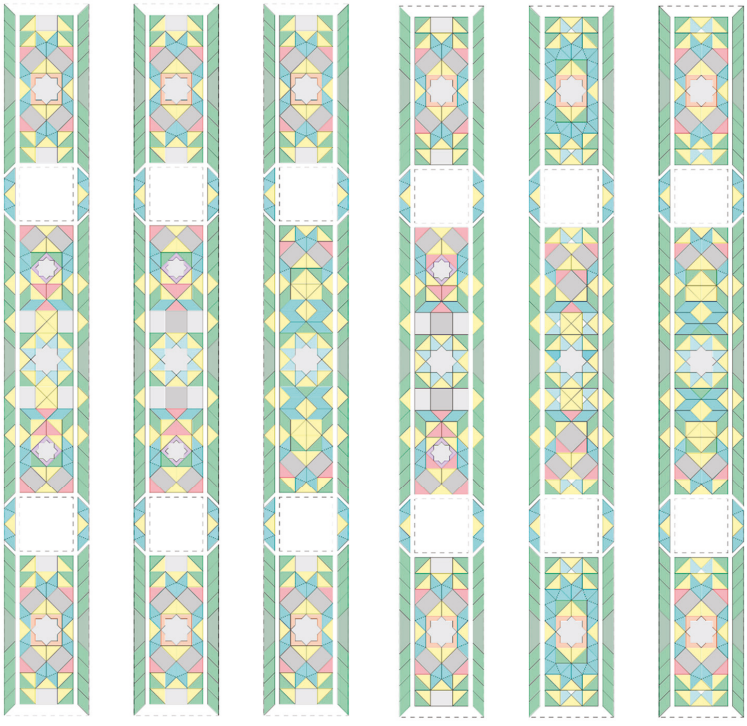


Figure 13. Different arches of muqarnas [own drawing]: West (western pavilion); east (western pavilion); north and south (western pavilion); west (eastern pavilion); east (eastern pavilion); north and south (eastern pavilion).

3.3. Comparing Different Floor Plans

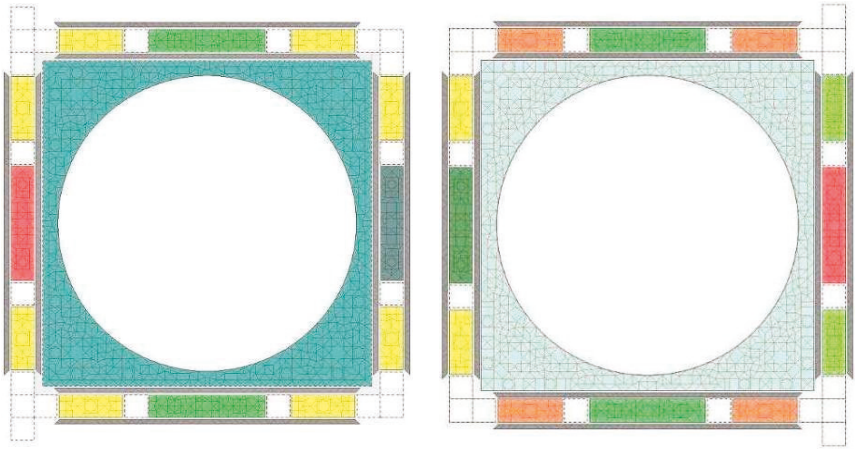
Differences between muqarnas floor plans from both pavilions are not so easily perceived due to their geometric complexity. Neither the models derived from the point cloud unveil the differences. For this reason, a layout displaying a color for each unique muqarnas group is provided in order to indicate the differences between pavilions (Figure 14).

Although both have different pendentives and arches, the plan shows an axis of symmetry that matches with the longitudinal axis of the courtyard. It should be noted that there are some groupings

duplicated in both pavilions. According to the plan provided in this research (Figure 14) the inner central arches (red) and the northern and southern ones (green) are the same in both pavilions.

Groupings in the western pavilion are simpler than the eastern ones, the differences are in small muqarnas groups with similar contour condition. In this case, every side arch in all arcades is identical (yellow). Central arches in western arcades (red) and eastern (dark blue) are different; although they are very similar to those of the eastern pavilion and just differ in two groups composed of four muqarnas replaced by a flat piece.

The eastern pavilion is more diverse with three types of side arches (yellow, orange and light green in Figure 14). The green arches are only in one arcade and the side arches are duplicated in the northern and southern arcades.



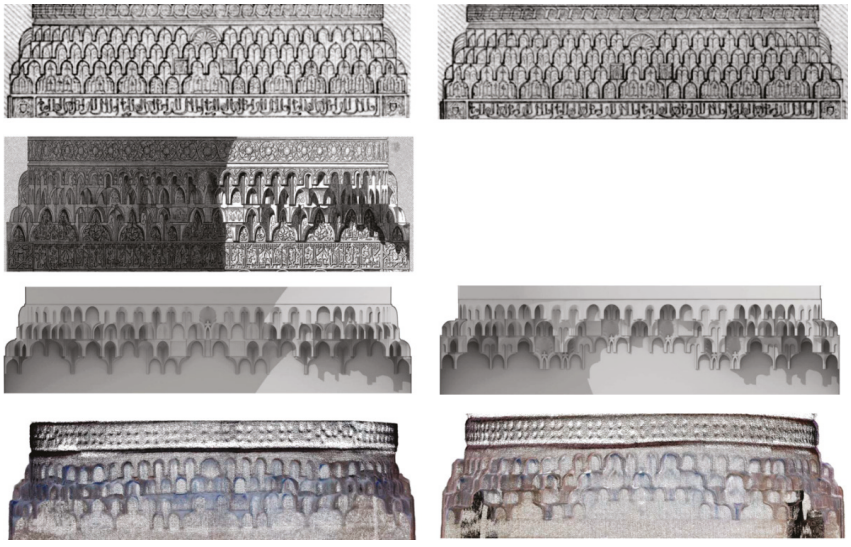
(**a**) (**b**)

Figure 14. Different groups of muqarnas [own drawing]: (**a**) Western pavilion; (**b**) eastern pavilion.

3.4. Comparing Pendentives Elevations

Comparative analysis between different pendentive elevations is of great interest to assess their accuracy level and their similarity to real works (Figure 15). Jones and Goury drawn identical pavilions more accurately than the previous drawing by Juan de Villanueva, as they drawn the muqarnas rows and a "shell" piece in the center, which is supported by another piece which was not featured, so that the shell piece was enlarged. Nevertheless, the lower level from muqarnas profile is represented with skillful precision, providing high thoroughness and amazing level of detail, particularly taking into account the drawing scale and the fact that it encompasses the whole Court of the Lions.

The comparison between Nicomedes de Mendivil's drawing and the CAD production shows the high accuracy achieved by Nicomedes, and proves that the pavilion produced by Nicomedes was the western one, a fact hitherto unknown, as the artist never indicated it. However, one outstanding finding, observed when comparing the 3D scans, is the significant geometric deformation of elements analyzed in the following section.



(**a**) (**b**)

Figure 15. Inner muqarnas pendentives at the pavilion according to Jones and Goury, Mendivil, and authors' own production: (**a**) Western pavilion; (**b**) eastern pavilion.

4. Discussion. Geometric Deformations

4.1. Original Layout Deformations

In a recent paper on the Hall of the Bark in the Alhambra, the difficult geometric problem posed when designing a muqarnas pendentive was explained, as it has to be adapted to the circular shape from an upper dome starting from a square shape [32]. Nasrid artisans did not follow in this case the theoretical process described by Jones and Goury or later authors, but instead deformed and adjusted the muqarnas close to the circle, creating with great mastery and intuitively pieces shaped ad-hoc, barely noticeable to the naked eye.

In order to assess this, a new plan drawing has been provided attempting to follow the geometric rules. It proven impossible to configure the upper levels without using special pieces, because in some areas the pieces overlap each other and other areas become empty. This made necessary the creation of small deformed pieces (darker color in Figure 16). As in the pendentives of the Hall of the Bark, the deformed muqarnas pieces were composed symmetrically in both pavilions.

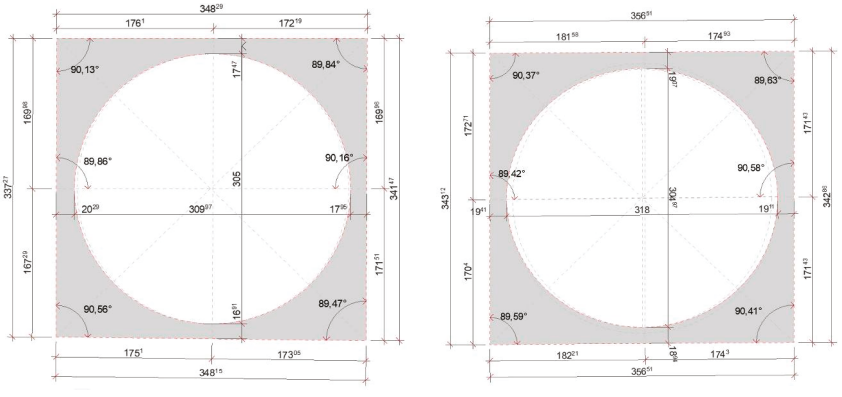
(**a**) (**b**)

Figure 16. Deformed muqarnas in western Pavilion pendentive [own drawing]: (**a**) Plan; (**b**) axonometry.

4.2. Deformations by Construction

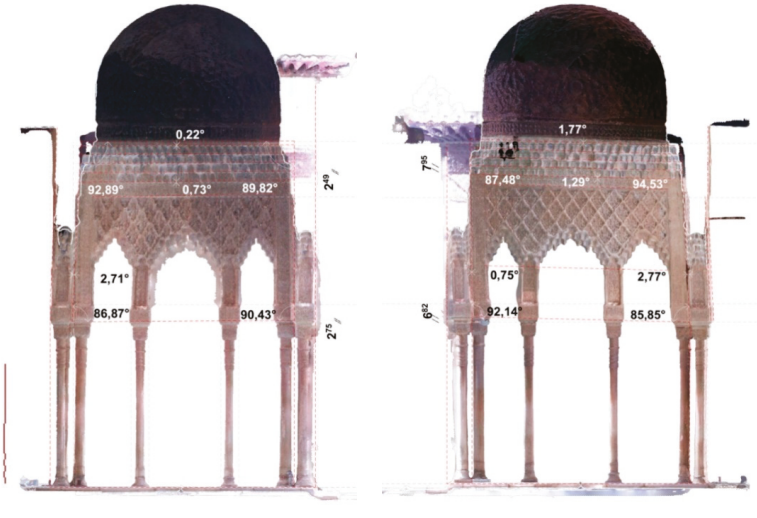
The point cloud from 3D laser scanner allows derive the pendentives contours from both pavilions, so that we can draw plans and sections in order to take accurate measures (Figure 17). Then we find out dimensional differences or deformations the ideal design (Figure 10) and the current conserved construction.

Analyzing both plans dimensional schemes, it was observed that they are not perfect squares, as expected, but instead they are stretched towards the courtyard center around 10–13 cm; although their angles are close to 90 degrees. Nevertheless, their diameters, i.e., the inner dome basis, have important deformations, close to 13 cm in the eastern pavilion, and 5 cm in the western one. Important angular deformations were also observed in sections that are obviously visible and close to 4 degrees in some of the cases (Figure 18).



(**a**) (**b**)

Figure 17. Plan deformations [authors' own drawing]: (**a**) Western pavilion; (**b**) eastern pavilion.



(**a**) (**b**)

Figure 18. Sections deformations [author's own drawing]: (**a**) Western pavilion; (**b**) eastern pavilion.

Some of these deformations were already described by architect Francisco Prieto-Moreno after the consolidation and restoration of the west pavilion in 1966 [33]. This revealed that the interior was deformed and turned towards the courtyard, probably because the nave pushed the pavilion and it was not possible to restore it to its initial location. For this reason, it was decided to advance the columns bases until achieving their verticality and, subsequently, to eliminate the braces.

A similar operation had to be carried out in previous consolidation works over the centuries, which in many cases were provisionally performed with braces. As plaster is a fragile material, there would be fissures, fractures, and even loss of parts. Thus, the current deformed state is a consequence of successive repairs in which fissures were filled or even new parts were inserted, consolidating their distortions. In this way, a material that could seem ephemeral has facilitated easy repair and conservation over time [34]. These types of repairs allowed other Nasrid buildings in Granada to survive, such is the case of the Corral del Carbón, currently showing important deformations [35].

5. Conclusions

Drawing is an essential tool for the analysis and sustainable conservation of architectural heritage. Without a deep knowledge about the reality to be preserved or restored, it is not possible to perform suitable actions for its protection. Throughout history, documentation techniques of the architectural heritage have been used with different accuracy levels depending on the needs, the means available, and the characteristics of the portrayed reality. A monument graphically documented in a suitable manner increases its probability to survive over time. In the worst scenario, when, unfortunately, the architectural heritage has been destroyed, its memory can be maintained if there are images that facilitate its virtual recreation or material reconstruction.

The aim of this research was to graphically document and analyze the muqarnas of the pavilions at the Court of the Lions taking into account their historical background. To achieve this goal, after providing a brief account on threats, catastrophes, and restorations over the centuries, an innovative methodology was carried out based on three complementary graphic analyses.

Firstly, this research reviews the main known historical images from the 17th to 20th centuries that clearly illustrate all the transformations undergone by the monument. In this sense, the drawings made with manual techniques in the 19th century are particularly remarkable. Jones and Goury were the first authors to accurately understand, identify, and draw pieces of the Alhambra muqarnas, although they only represented the ones at the western pavilion and assumed that both pavilions were symmetrical. The drawing by Nicomedes de Mendivil is of great quality, although he did not indicate whether the referred pavilion was the western or the eastern one, perhaps because he assumed that both were identical and locally symmetrical, and therefore he only drew two arcades not taking into account that the others are different. Nevertheless, this study concludes that the pavilion drawn is the western one.

This research produced the 3D CAD models or CAD plans for the pavilions muqarnas for the first time, illustrating with precision the formal complexity of muqarnas groupings, considering that valuable drawings from 19th century only included the western pavilion. After analyzing the pavilions in detail, and taking into account the theoretical geometric principles from muqarnas groupings, it has been possible to identify for the first time all their pieces: The western pavilion displays 2258 pieces (1032 on pendentives and 1226 on arcades), while the eastern pavilion has 2222 (948 on pendentives and 1274 on arcades). It has been observed that the pieces located at a higher height have a larger size than those located at a shorter distance from the observer. Schemes provided explain the subtle differences and symmetries between the various pendentives and arches in both pavilions, otherwise too complex to be observed, by means of photographs or 3D laser scannings.

Significant deformations, hitherto unknown, have been detected based on the laser scanner 3D point cloud results. It has been observed that the original design involved deformed pieces that Nasrid artists from the 14th century virtuously built to solve a difficult geometric problem: Adapting the pendentives upper rows to the dome circular base.

Besides, other significant deformations had been reflected in plan and sections schemes, resulting from columns tilts probably due to earthquakes, explosions, lightning, differential seatings or water leaks in the subsoil, aggravated by poor maintenance or by inadequate restorations. It is utterly remarkable how some pavilions supported on such slender columns and muqarnas built on fragile materials have survived over the centuries.

Finally, the graphic analysis provided by this research will hopefully contribute to a sustainable conservation approach towards both pavilions and their muqarnas. Similarly, the article is expected to contribute to the consolidation of the muqarnas significance as outstanding identity symbols of this beautiful Medieval palace in the Alhambra of Granada (Figure 19).

(**a**) (**b**)

Figure 19. Photographs showing the current state in the Court of the Lions [authors' own production]: (**a**) Western pavilion view from interior of eastern pavilion; (**b**) eastern pavilion view from interior of western pavilion.

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References

1. Alhambra, Generalife and Albayzín, Granada [World Heritage List]. Available online: https://whc.unesco.org/en/list/314 (accessed on 25 July 2020).
2. Manzano-Martos, R. *La Alhambra: El Universo Mágico de la Granada Islámica*; Grupo Anaya: Madrid, Spain, 1992.
3. Orihuela-Uzal, A. *Casas y Palacios Nazaríes, Siglos XIII–XV*; Fundación El Legado Andalusí: Granada, Spain, 1996; p. 37.
4. García-Pulido, L.J. *El Territorio de la Alhambra: Evolución de un Paisaje Remarcable*; Patronato de la Alhambra y Generalife: Granada, Spain, 2013.
5. Salinas-Rodríguez, J.L. El medio geológico en el enclave monumental. *Cuadernos Alhambra* **1997**, *33*, 47–56.
6. Torres-Balbás, L. Los Reyes Católicos en la Alhambra. *Al-Andalus XVI Crónica Arqueológica España Musulmana* **1951**, *16*, 185–205.
7. Casares-López, M. *Las Obras Reales de la Alhambra en el Siglo XVI: Un Estudio de los Libros de Cuentas de los Pagadores Ceprián y Gaspar de León (1528–1627)*; Universidad de Granada: Granada, Spain, 2008.
8. Brazille-Naulet, V.; Orihuela-Uzal, A.; García-Pulido, L.J. La Torre de Comares en peligro de ruina. Afecciones de la estructura más significativa de la Alhambra en los siglos XVI y XVII. In *Defensive Architecture of the Mediterranean*; UGR: Granada, Spain, 2020; Volume X, pp. 21–28. [CrossRef]
9. Torres-Balbás, L. El Patio de los Leones. *Arquitectura* **1929**, *11*, 221–234. Available online: http://oa.upm.es/34174/ (accessed on 15 July 2020).
10. Tito-Rojo, J. Los Jardines del Patio de los Leones y del Patio Alhambra. In *El Patio Alhambra en el Crystal Palace*; Abada Editores: Madrid, Spain, 2010; pp. 41–103.
11. Sáez-Pérez, M.P. Estudio de Elementos Arquitectónicos y Composición de Materiales del Patio de los Leones. Interacciones en sus Casas de Deterioro. Tesis Doctoral Inédita, Universidad de Granada, Granada, Spain, 2004.
12. Migoń, P. Cultural heritage and natural hazards. In *Encyclopedia of Natural Hazards*; Springer: Dordrecht, The Netherlands, 2013; pp. 135–140.
13. Nicu, I.C. Natural hazards—A threat for immovable cultural heritage. A review. *Int. J. Conserv. Sci.* **2017**, *8*, 375–388.
14. Gámiz-Gordo, A. *Alhambra. Imágenes de Ciudad y Paisaje Hasta 1800*; Fundación El Legado Andalusí: Granada, Spain, 2008; pp. 114–126.
15. Almagro-Gorbea, A. *El Legado de Al-Ándalus: Las Antigüedades Árabes en los Dibujos de la Academia*; Real Academia de Bellas Artes de San Fernando/Fundación Mapfre: Madrid, Spain, 2015.
16. Gámiz-Gordo, A. La Mezquita-Catedral de Córdoba. Fuentes gráficas hasta 1850. *Al-Qantara Revista Estudios Árabes* **2019**, *40*, 135–183. [CrossRef]
17. Gámiz-Gordo, A.; Ferrer-Pérez-Blanco, I. A grammar of muqarnas: Drawings of the Alhambra by Jones and Goury (1834–1845). *VLC Arquitectura. Res. J.* **2019**, *6*, 57–87. [CrossRef]
18. Sánchez-Gómez, C. El patio de los Leones de la Alhambra: Imagen fotográfica e historicidad de un espacio monumental. *Cuadernos Alhambra* **2009**, *44*, 50–83.
19. Piñar-Samos, J.; Sánchez-Gómez, C. *Oriente al Sur. El Calotipo y las Primeras Imágenes Fotográficas de la Alhambra, 1851–1860*; Patronato de la Alhambra y Generalife: Granada, Spain, 2017.
20. Giménez-Serrano, J. *Manual del Artista y Del Viajero en Granada*; J. A. Linares: Granada, Spain, 1846.
21. Barrios-Rozúa, J.M. Una polémica en Torno a los Criterios Para Restaurar la Alhambra: Salvador Amador Frente a Narciso Pascual y Colomer (1846–1849). *Reales Sitios Revista Patrimonio Nacional* **2009**, *106*, 42–70.
22. Serrano-Espinosa, F. *Arquitectura y Restauración Arquitectónica en la Granada del Siglo XIX. La Familia Contreras*; Tesis Doctoral Inédita: Universidad de Granada, Granada, Spain, 2014; Volume 1B, pp. 285–298.
23. Vílchez-Vílchez, C. *La Alhambra de Leopoldo Torres Balbás: Obras de Restauración y Conservación, 1923–1936*; Editorial Comares: Granada, Spain, 1988.
24. López-de-Arenas, D. *Breve Compendio de la Carpintería de lo Blanco y Tratado de Alarifes*; [Printed by Luis Estupiñan]: Sevilla, Spain, 1633.
25. de San-Miguel, F.A.; Báez Macías, E. *Obras de Fray Andrés de San Miguel*; Universidad Nacional Autónoma de México: Mexico, D.F., Mexico, 1969.

26. Nuere-Matauco, E. *La Carpintería de Lazo: Lectura Dibujada del Manu-scrito de Fray Andrés de San Miguel*; Colegio de Arquitectos en Málaga: Málaga, Spain, 1990.
27. Nuere-Matauco, E. *La Carpintería de lo Blanco: Lectura Dibujada del Primer Manuscrito de Diego López de Arenas*; Ministerio de Cultura: Madrid, Spain, 1995.
28. Dold-Samplonius, Y.; Harmsen, S.L. Muqarnas: Construction and reconstruction. In *Architecture and Mathematics from Antiquity to the Future*; Springer International Publishing: Cham, Germany, 2015; pp. 709–719. [CrossRef]
29. Garofalo, V. A methodology for studying muqarnas: The extant examples in Palermo. *Muqarnas* **2010**, *27*, 357–406. [CrossRef]
30. Palacios-Gonzalo, J.C.; Alkadi, R.M. Muqarnas domes and cornices in the Maghreb and Andalusia. *Nexus Netw. J.* **2018**, *20*, 95–123. [CrossRef]
31. Karabörk, H.; Karasaka, L.; Yaldiz, E. A case study: Documentation method with close range photogrammetry of muqarnas which is to be an ornamentation type specific to the Islamic architecture. *Procedia Earth Planet Sci.* **2015**, *15*, 133–140. [CrossRef]
32. Ferrer-Pérez-Blanco, I.; Gámiz-Gordo, A.; Reinoso Gordo, J.F. New drawings of the Alhambra: Deformations of muqarnas in the pendentives of the Sala de la Barca. *Sustainability* **2019**, *11*, 316. [CrossRef]
33. Prieto-Moreno, F. Obras recientes en la Alhambra y el Generalife. *Cuadernos Alhambra* **1967**, *3*, 153–157.
34. Rubio-Domene, R. *Yeserías de la Alhambra: Historia, Técnica y Conservación*; Patronato de la Alhambra y Generalife: Granada, Spain, 2010.
35. Reinoso-Gordo, J.F.; Gómez-Blanco, A.J.; Rodríguez-Moreno, C.; León-Robles, C.A. Cultural heritage conservation and sustainability based on surveying and modeling: The case of the 14th century building Corral del Carbón (Granada, Spain). *Sustainability* **2018**, *10*, 1370. [CrossRef]

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