Virtual Archaeology Review, **17**(35): In Press, 2026
https://doi.org/10.4995/var.2024.25063

Received: November 21, 2025
Accepted: January 26, 2026

VIRTUAL RECONSTRUCTION AND CONSTRUCTIVE MODELLING OF THE COFFERED CEILING OF THE SYNAGOGUE OF *EL TRÁNSITO* (TOLEDO, SPAIN)

RECONSTRUCCIÓN VIRTUAL Y MODELADO CONSTRUCTIVO DEL ARTESONADO DE LA SINAGOGA DE EL TRÁNSITO (TOLEDO, ESPAÑA)

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Highlights:

- This work focuses on a 14th century singular masterpiece of the Spanish-Muslim carpentry, which is in the Prayer Hall of the Synagogue of El Transito (Toledo, Spain).
- It analyses the geometrical design process and the coffered ceiling constructive configuration, thanks to a point cloud model obtained with a combined 3D survey methodology.
- Considering the analysis results, an idealised proposal of the coffered ceiling is presented together with 3D parametric models that show the process of assembling the pieces.

Abstract:

This article presents a work about the coffered ceiling of the Synagogue of *El Tránsito* (Toledo), an exceptional example of 14th-century Spanish-Muslim carpentry. Its structural model follows the typical geometric standards of the period, common to both Christian and Muslim traditions in 14th century in Spain. This work includes, on the one hand, the analysis of the coffered ceiling geometric design: first, a basic module has been identified, as well as the several patterns that were developed with its variations and combinations; secondly, the whole design has been fit to the global dimensions to generate an idealised whole layout of the structure. Finally, a comparison with the actual geometry of the building has been carried out to analyse the reasons of the differences between them. On the other hand, a study of the coffered ceiling constructive configuration has been developed: the pieces that form the structure have been first individualised to study their assembling process later. The research has been possible thanks to a three-dimensional (3D) survey done in the building, combining several techniques (laser scanning and photogrammetry). This generated a point cloud, which has been the geometric basis for the latter analysis and for the generation of 3D parametric models of the coffered ceiling pieces. The main results are the geometric layout, which could be used by carpenters to design the coffered ceiling, as well as the explanation of the wooden pieces and their assembly process. The paper is fully illustrated with two-dimensional (2D) drawings and images of the 3D models, thus helping to gain better knowledge, conservation, and dissemination of these types of historical wooden structures.

Keywords: coffered ceiling; historic carpentry; laser scanning; photogrammetry; 3D digital model; virtual reconstruction

Resumen:

En este artículo se presenta una investigación sobre el artesonado de la Sinagoga de El Tránsito (Toledo), el cual es un ejemplo excepcional de la carpintería hispanomusulmana del siglo XIV. El modelo estructural de esta obra se basa en los estándares geométricos usuales del periodo en que convivieron las tradiciones cristiana y musulmana en España durante este siglo. Este trabajo incluye, por un lado, el análisis del diseño geométrico del artesonado: en primer lugar, se ha identificado un módulo básico, a partir del cual se han desarrollado patrones de variaciones y combinaciones; después, el diseño completo se ha adecuado a las dimensiones generales del espacio para generar una propuesta de proyecto idealizado. Finalmente, este resultado se ha comparado con la forma real del edificio para estudiar las diferencias entre ambos modelos y sus causas. Por otro lado, se ha desarrollado un estudio de la configuración constructiva del artesonado: como primer paso, se han analizado individualmente las piezas, para estudiar después su proceso de ensamblaje. Esta investigación ha sido posible gracias a la realización de un levantamiento tridimensional (3D) en el cual se han combinado varias técnicas (escaneo láser y fotogrametría), aportando la base geométrica para el desarrollo de los análisis posteriores,

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así como para la creación de modelos 3D paramétricos de las piezas que conforman el artesonado. Así, los principales resultados son el diseño geométrico que pudieron haber usado los carpinteros para crear la estructura y la explicación de las piezas que lo componen y su montaje. El artículo está profusamente ilustrado con dibujos bidimensionales (2D) y con imágenes de los modelos 3D, que se espera contribuyan a un mayor conocimiento de estos tipos de estructuras de carpintería históricas, además de promover su conservación y difusión.

Palabras clave: artesonado de madera; carpintería histórica; escaneo láser; fotogrametría; modelo 3D digital; reconstrucción virtual

1. Introduction

1.1. Historical context of the building

The Synagogue of *El Tránsito* was built at the behest of Samuel ha-Levi Abulafia (the treasurer of King Pedro I of Castile) between 1355 and 1357, as a private chapel for the palace (Palomero, 2007). At that time, the three Abrahamic religions (Judaism, Christianity, and Islam) still coexisted peacefully in Toledo. This coexistence would gradually deteriorate, culminating in the Catholic radicalisation embodied in the Council of Trent (1545–1563) as a response to the Protestant Reformation. One of its consequences was the definitive expulsion of the Jews from Spanish territory, initially under the Catholic Kings and, ultimately, during the reign of Philip III with the expulsion of the *moriscos* (Muslims who converted to Christianity to remain in Spain after the *Reconquista*). Following the expulsion of the Jews by order of the Catholic Kings, the synagogue came under the control of the Order of Calatrava, which converted it into a Catholic church. In 1877, it was declared a National Monument, and it currently houses the *Museo Sefardí* (Figs. 1 and 2).

Figure 1: External view of the synagogue (south-eastern façade).

Figure 2: Internal view of the Prayer Hall, where the coffered ceiling is located.

1.2. Main restoration works carried on in the building

Following its designation as a National Monument in 1877, a restoration of the building was initiated in 1911. The first intervention, led by architect Santiago Martín Ruiz and sculptor Francisco Isidori, focused on the interior decoration. However, due to financial and legal difficulties, the works were halted. Some years later, Arturo Mélida developed a second project, which was only partially executed. Various factors delayed the restoration for decades, until the early 20th century, when the Marqués de la Vega Inclán and architect Eladio Laredo resumed the works, restoring the synagogue to its original splendour (Ortiz, 2004).

Between 1987 and 1990, an intervention was carried out to preserve the structure. The adopted solution involved installing a second skin over the coffered ceiling, allowing for ventilation. Once the architectural intervention on the roof was completed, the need to assess the condition of the interior elements became evident. Consequently, an intervention was undertaken between 2002 and 2003 to remove the substantial dirt that had accumulated inside due to the previous works. Finally, in 2007, a roof repair project was carried out by the architect Ángel Luis de Sousa Seibane and the technical architect Federico Prieto Pequeño (2007).

1.3. Justification and objectives of the research

The coffered ceiling of the Synagogue of *El Tránsito* is a significant and unique structure that has not yet been studied from the perspective of its geometry and construction (Fig. 3). The primary objectives of this research have been, firstly, to analyse the structural design and the geometrical criteria employed in the layout of the pattern and in the sizing of the constructive elements; secondly, to determine the constructive configuration and the coffered ceiling's breakdown based on the previously defined design patterns; and finally, to establish an idealised design model as a hypothetical project for the execution of the structure, which has been compared with the existing built model. With such information, a virtual reconstruction of the idealized structure has been developed thanks to a 3D model of the constructive elements of the coffered ceiling. Additionally, the study aimed to produce a series of drawings that clearly and visually explain the research results.

2. Materials and methods

2.1. Methodology used for the research

This study has been made possible using graphic materials resulting from the architectural survey promoted by the *Museo Sefardí* (*Ministerio de Cultura, Gobierno de España*) and carried out between 2022 and 2024. Specifically, a complete 3D laser scan of the Prayer Hall (the main room, where the coffered ceiling under study is located) was conducted, along with a high-resolution 3D specific photogrammetric model of the coffered ceiling. A static terrestrial laser scanning was carried out using a Topcon GLS-2000S device. 7 stations were employed for the data acquisition to fully capture all the room elements. Each scan was carried out with a 6.3mm/10m resolution (distance between measured points/distance from the scanner) in 'standard' measuring mode, resulting in a 13min50s scanning time for each station. Regarding the photogrammetric survey, 206 high-resolution images (10 MP) were taken using an Olympus E-510 camera with a fixed focal length of 14mm and a maximum lens aperture of f/3.5. Given the distance from the room floor to the coffered ceiling, a scaffolding was installed inside the hall, allowing images to be captured from a maximum distance of 2m (Fig. 4). This allowed us to obtain a high-detail model of the wooden structure. Besides, the photographs were taking during the night with the support of artificial lighting to avoid the backlighting effect that would have been produced on the windows by the sunlight. Specifically, two spotlights were used for lighting to eliminate harsh shadows. Unfortunately, it was not possible to access to the extrados of the roof due to technical difficulties.

Figure 3: View of the coffered ceiling over the Prayer Hall of the synagogue.

As a result of the data acquisition and the latter data processing, two 3D point clouds were obtained. First, one of the entire hall with the terrestrial laser scanner was generated. The initial point cloud had 202,121,688 points, and it was then reduced setting a minimum 5mm distance between points, generating a final point cloud with 50,490,445 points (238,613 points/m^2). Afterwards, another point cloud of the coffered ceiling was created using photogrammetry. In this case, the initial point cloud had 60,635,772 points, and it was also reduced setting a minimum 5mm distance between points, generating a final point cloud with 12,156,370 points (57,450 points/m^2).

Then, the coffered ceiling photogrammetric point cloud was scaled and oriented in relation to the hall point cloud (obtained with the terrestrial laser scanner). For this purpose, 10 specific and easily recognisable points of the latter point cloud were implemented in the first point cloud as control points. Such points were selected to cover the coffered ceiling entire perimeter and volume. The maximum error obtained in the scaling and orientation process was 3cm, which is acceptable considering that the coffered ceiling has an approximate plan surface of 212m2 and a volume of 320m2 (Fig. 5). Finally, a 3D triangle mesh model of the coffered ceiling was created using the Poisson Surface Reconstruction algorithm and the photogrammetric point cloud. A photographic texture was then applied to the mesh model to obtain a realistic appearance.

Once that the 3D products were obtained (that is, point clouds and mesh model), several 2D graphic products were generated (del Blanco, González, Amengual, Sanz, Aira, Palma, García Morales & Sánchez, 2024) of both the hall and the wooden structure (Fig. 6). On the one hand, various orthoimages were created using the photogrammetric model of the coffered ceiling, including horizontal projections upwards (parallel to the ***almizate***[1] plane) and vertical projections (parallel to the walls of the room). On the other hand, several cross-plane sections have been extracted from the 3D point cloud generated by the scanner laser: one horizontal cross-section just in the lower level of the coffered ceiling (below the *arrocabe*[2]), one vertical and longitudinal cross-section (along the length of the hall), and three vertical and transversal cross-sections. Such graphic products have been the basis for the latter analysis of the coffered ceiling.

Based on these graphic data, the analysis has been developed into the following phases:

• Analysis of the main dimensions and proportions of the coffered ceiling: length and proportion of the supporting walls, slopes of the roof planes, as well as the height at which the *almizate* is located.

• Analysis of the geometrical layout of the coffered ceiling, including the design of the pattern and the modulation of the *almizate* and how it is linked and continues through the roof planes.

• Analysis of the construction of the structure and the assembly process. Study of the several wooden pieces

[1] *Almizate*: the horizontal element or plane in the coffered ceilings built using the *par-nudillo* system, formed by the alignment of the *nudillos* (see figures 8, 17).

[2] *Arrocabe*: a frieze supporting a coffered and frameworked structure (see figure 17).

that were employed and how could be the execution of the work.

• Development of an idealised design model of the coffered ceiling based on its geometrical analysis. First, a module has been defined, as as along with its variations, and an idealised geometric layout that fills the whole plane of the *almizate* has been obtained. Then, the true scale surfaces of the roof planes were drawn by virtually unfolding and rotating the actual planes until they were placed in a coplanar position with the *almizate*. After this, and linked to the pattern of the *almizate*, the geometric layout of each roof plane has been drawn ensuring an adequate connection with the elements of the *almizate* as well as with the adjacent roof planes. Finally, the patterns of the roof planes have been virtually returned to their actual inclined position to obtain the final 3D geometric layout. During the process of drawing the idealised patterns, the following criteria were considered: symmetry, equidistance and repetition of modules. Besides, the resulting layout was compared and checked with the orthoimages of the actual structure and with the cross-sections obtained from the 3D cloud points, trying to adjust the hypothesis to the actual data.

(a) (b)

Figure 4: Survey and data acquisition of the coffered ceiling with scaffolding: a) South-western wall; b) North-eastern wall.

Figure 5: 3D point clouds used for the research: photogrammetric (top) and laser scanning (bottom).

• Comparison of the idealised design of the coffered ceiling with the actual measurements of the building obtained from the architectural survey, and interpretation of the differences observed.

• Creation of a virtual reconstruction (3D model) of the coffered ceiling main constructive elements based on the idealised design. For this purpose, the point cloud was used as an initial reference to ensure the geometric accuracy of the model; then, the modelling was developed according to the 2D projections of the idealised design. This virtual reconstruction of the *lazo* pattern and its structural framework was carried out using the so-called Constructive Solid Geometry or, in other words, manual or direct modelling (Voelcker, Requicha, Hartquist, Fisher, Metzger, Tilove, Birrell, Hunt, Armstrong, Check, Moote & McSweeney, 1978). This technique is based on standard modelling operations (extrude, revolve, sweep, etc.) and Boolean operations (union, subtraction, and intersection). It enables calculations of physical properties like volume, density, weight, and mass. The final 3D model is composed of Non-Rational B-Spline (NURBS) surfaces (explicit surfaces).

As a result of these analyses, a set of explanatory drawings of the idealised design was produced. It included partial 3D views of the breakdown of constructive elements, drawings of the layout of the pattern, as well as several plans and a vertical section of the coffered ceiling.

(a) (b)

(c) (d)

Figure 6: Graphic products: a, b) Orthoimages obtained from the coffered ceiling mesh model; c, d) Orthoimages obtained from the main hall point cloud.

2.2. General description of the coffered ceiling

The coffered ceiling of the roof examined in this study is located in the Prayer Hall (the main room) of the Synagogue of *El Tránsito*. This space has overall dimensions of 23m × 9.2m. The interior walls feature polychrome plaster friezes decorated with vegetal, geometric, and epigraphic motifs, as well as heraldic elements characteristic of the Crown of Castile. The ceiling of this hall is a timber frame structure of the *par-nudillo*[3] type, which ends with both semi-hexagonal finishings, and it has five double tie beams. It is a polychrome work executed on tin, utilising a colour palette of green, blue, red, white, and black (Fig. 7).

Figure 7: Detail of the semi-hexagonal finishing of the coffered ceiling.

The coffered ceiling is inscribed within a rectangular plan, with four pendentives (horizontal triangular sections) positioned at the corners, resulting in a semi-hexagonal finishing. The central horizontal section is known as the *almizate*, while the sloping planes connecting the *almizate* are the roof skirts. The entire structure is secured by five double tie beams.

Although the roof framework was constructed under Jewish cultural patronage, its design aligns with the artistic trends commonly found in the local Christian culture of Toledo during that historical period. The geometric pattern is based on the *lazo de 4*[4] (four-point interlace), which, unlike the wheel interlace patterns, is developed upon an orthogonal grid structure oriented in two directions. In Islamic geometric tradition, it was more common to use the circle as the foundational element for generating wheel interlace designs. Consequently, the *lazo de 4* pattern presented a less overtly Islamic appearance than the wheel-based interlace patterns (Figs. 8 & 9).

[3] *Par*: It is the most important structural element of the timber frame of the roof, as it defines and supports the roof skirts. These timber components are arranged in opposing pairs (see figures 17, 18).
Nudillo: A wooden piece positioned within a roof framework, which is arranged horizontally and connects at its ends to two opposing *pares*. The collective assembly of these pieces is referred to as the *almizate* (see figures 17, 18).

[4] *Lazo / lacería*: A decorative scheme primarily characterised by interlacing straight-line segments that generate geometric patterns based on regular polygons (see figures 9, 11).

Figure 8: Detail of the coffered ceiling and the *lazo de 4* pattern.

2.3. The so called '*lazo de 4*' pattern: a Spanish national standard

The *lazo de 4* pattern (four-point interlace) does not belong to the category of wheel interlace patterns, such as the Islamic designs based on wheels of 8, 9, 10, 12, 16, 18, or 20 divisions. Instead, its organisation falls within the group of grid interlaces, which follow a bidirectional matrix rather than radial or circular systems. Grid interlacing was characteristic of Christian Spain, in contrast to the Spanish-Muslim designs, possibly due to their easier association with the Christian symbol of the cross and their connection to Roman and pre-Romanesque traditions, as seen in patterns based on diagonals and crosses (de Miguel, 2019). Their early use in Castile began in the early 14th century, as exemplified by the Monastery of *Sancti Spiritus el Real* in Toro (Zamora). Founded in 1307 by Doña Teresa Gil, its foundation stone was laid on 28 August 1316 by Queen María de Molina, Lady of Toro. During the 14th century, the *lazo de 4* became a Christian standard, also adopted in prominent Jewish buildings such as the Synagogue of *El Tránsito* in Toledo (Franco, 2019). The Catholic Monarchs embraced it in the decoration of the coffered ceilings of the cloister of *San Juan de los Reyes* (Toledo), establishing it as a national standard (Nuere, Franco & Fernández, 2019). Its use extended throughout the 15th century and into the mid-16th century, as in the notable case of the Chapel of San Ildefonso at the University of Alcalá de Henares, completed in 1516. The same *lazo de 4* pattern can be observed in the *almizates* of the churches of *San Pedro el Viejo* (Madrid) and Almenara de Tormes (Salamanca). The gradual fusion between Spanish-Muslim and Christian cultures led to the evolution of the *lazo de 4* into an eight-point interlace, initially retaining a grid-lik

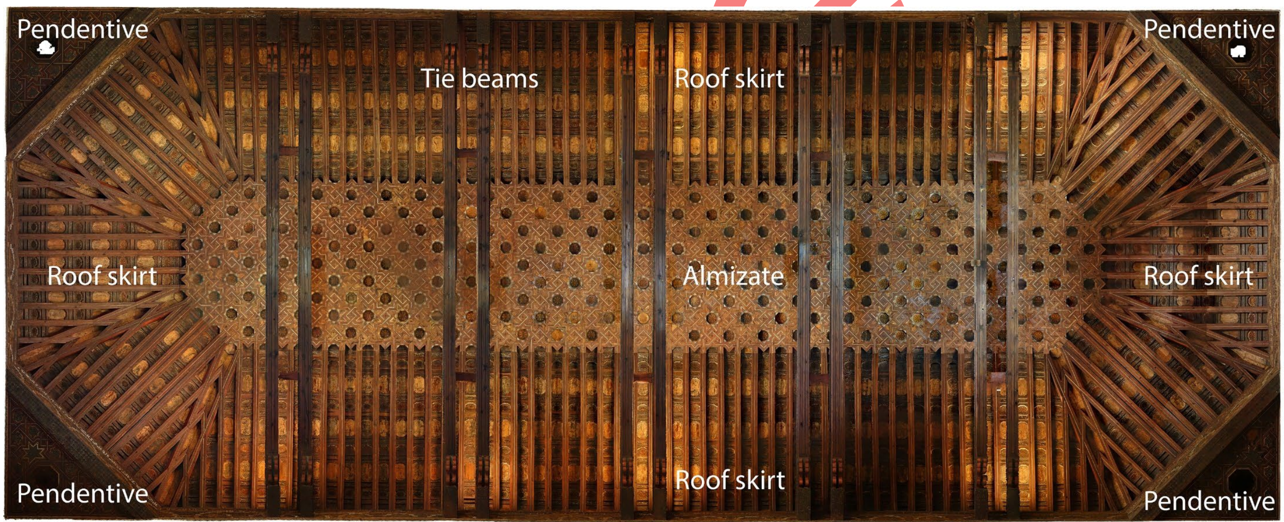


Figure 9: Orthoimage of the coffered ceiling with its main constructive elements.

character (e.g. *Santa María la Blanca*, Madrid), then transitioning into hybrid 4–8 interlaces (Fernández, 1975) and eventually transforming into fully Islamic-style wheel patterns, as seen in the Oratory of the *Partal* in the Alhambra (Granada).

Similar *almizates* featuring the *lazo de 4* pattern appear in numerous coffered ceilings from the 14th to the 16th centuries, suggesting the possible circulation of templates or drawings used in construction contracts signed by carpenters (Fernández, 1991; Fernández, 1997). This type of *lazo de 4* has been the subject of various studies, including the coffered ceiling of the church of *San Pedro* in Madrid (Nuere, 1994), the roof of the parish church of Almenara de Tormes in Salamanca (Fernández, 2011), and the broader study of *lazo* frameworks in Toledo (Nuere, Franco & Fernández, 2019)

2.4. Formal and stylistic similarities between the Synagogue of *El Tránsito* and other buildings

Synagogues in Spain during the 14th and 15th centuries exhibit a consistent stylistic and formal pattern, as can be observed through comparison of various contemporary examples, such as the Synagogue of *Santa María la Blanca* (Toledo), the Synagogue of Córdoba, the Synagogue of Seville, among others. The use of lobed arches, horseshoe arches, and a range of geometric motifs with *ataurique*s[5] (vegetal ornamentation) lends these buildings a visually coherent appearance.

Cultural exchanges between Spanish-Muslim and Christian cities were common even prior to the conquest of Granada and the full Christianisation of the Iberian

[5] *Ataurique*: vegetal motifs in Islamic ornamentation.

Peninsula. For instance, the 54cm *codo*[6],a historical unit of measurement (de la Cuadra, 2009; Puig y Larraz, 1857), appears in several buildings of the Alhambra and other constructions from Nasrid Granada (such as the *Corral del Carbón*), as well as in Christian Spanish architecture, including the Palace of Tordesillas. This unit is also found in Toledo, in the Synagogue of *El Tránsito*, the *Taller del Moro*, the *Casa de Mesa*, and the Palace of *Suer Téllez de Meneses*. These buildings in Toledo are closely related to the constructions in Tordesillas, as well as to the *Alcázar* of Seville, which date from the Nasrid period.

3. Results

3.1. Geometrical analysis of the coffered ceiling

As previously noted, the design of the *almizate* is based on a *lazo de 4* (four-point interlace) pattern. The symmetry of the composition is developed over a bidirectional orthogonal network with square proportions. It is important to highlight that the only set square required for this layout is the 45-degree set square. This tool is used both in the interlacing layout of the *almizate* and in the angled cuts of the *pares* and *nudillos* that form the sloped sections of the roof structure (100/100 = 45°). This significantly facilitated the layout process for Christian or Spanish-Muslim carpenters with limited knowledge of geometry through set squares.

Based on the actual measurements obtained from the architectural survey of the structure, a hypothesis of an idealised geometric design has been developed, closely adjusted to those measurements and guided by principles of equality, symmetry, and equidistance derived from the logic of construction.

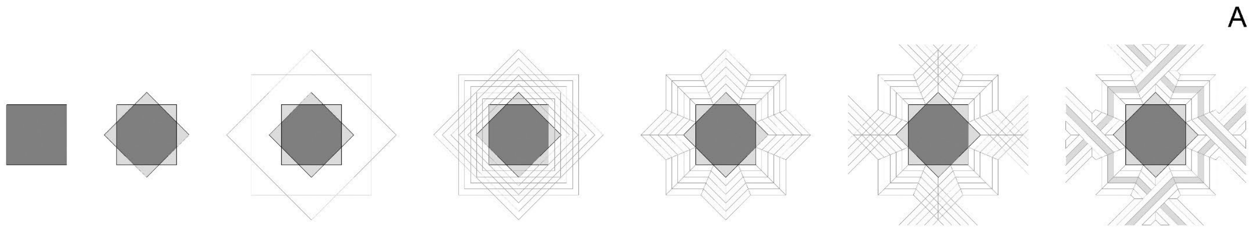


Figure 10: Design of the standard pattern starting from the square module (A).

Using the geometric basis of the aforementioned interlace grid, the layout of the *almizate* begins with a square module of approximately 21cm per side. Considering the historical units of measurement likely used in the 14th century, this dimension may correspond to the Castilian *palmo*[7] (a unit equivalent to three-quarters of a foot, with the foot measuring 27.96cm, thus yielding a span of 20.97cm). Accordingly, the module of the *calle*[8] (the distance between the pares) is defined as one *palmo* (the side of the square), and the *cuerda*[9] (the width of one par) as half a *palmo*, or half a square. These dimensions would correspond to 9” for the calle and 4.5” for the *cuerda* (given that one foot equals 12”). From the definition of the *calle* and *cuerda* modules, the design of the *almizate* follows a standard geometric pattern based on the rotation of figures (45°) and the intersection of the resulting lines. This generates a continuous interlacing of bands, in which some overlap others alternately, forming the *lazo de 4* grid that constitutes both the structural and ornamental framework of the *almizate* (Fig. 10).

From this initial pattern (A, Fig. 10), variations can be observed across the interlace grid depending on the position of the standard motif within the *almizate* and the intersections that occur (Fig. 11).

The entire *almizate* can be inscribed within a rectangle measuring 72 modules (or *calles*) in length and 15 modules in width, resulting in an overall proportion of approximately 5:1. On the shorter sides of this rectangle, semi-hexagonal finishings are drawn, extending a further 4.5 modules (i.e. 4 *calles* and one *cuerda*).

[6] *Codo*: a historical measurement unit equivalent to 54cm.
[7] *Palmo*: a historical measurement unit equivalent to three-quarters of a foot, that is, 20.97cm approximately.
[8] *Calle*: the distance between a couple of *pares* which form a roof skirt.
[9] *Cuerda*: the width of a par which forms a roof skirt using the *par-nudillo* system.

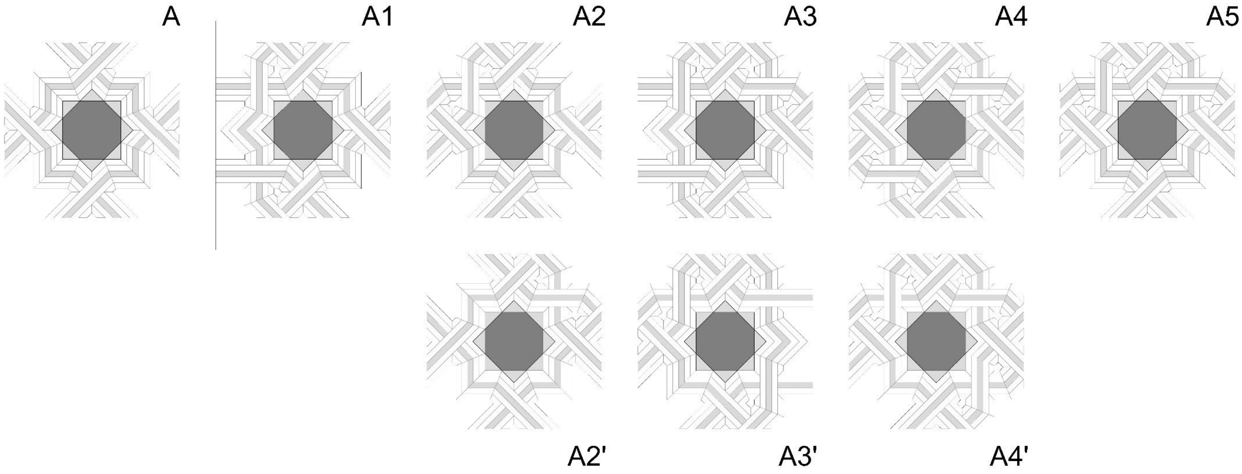


Figure 11: Variations of the standard pattern (A1-A4).

This yields the final outline of the *almizate*, inscribed within a rectangle of 81 by 15 modules. It can be observed how the interlaced grid adjusts perfectly to the various conditions of the outline. The geometric layout is always based on the alternation: that is, each band passes alternately over and under the other bands that it intersects. This feature gives a fluid and cohesive appearance to the overall composition (Fig. 12).

The layout of the *almizate* serves as the basis for determining the position of the pares* on the sloping sections (roof skirts) of the structure. Each par corresponds in width to one *cuerda*. When projecting the *almizate* and the roof skirts horizontally in their actual position (i.e. without unfolding), it becomes apparent that the width of the roof skirts aligns closely with a measurement of 14 modules (or *calles*). Thus, the total width of the structure (i.e. the full span) is equivalent to 43 modules, while the total length may correspond to 109 modules (Fig. 13).

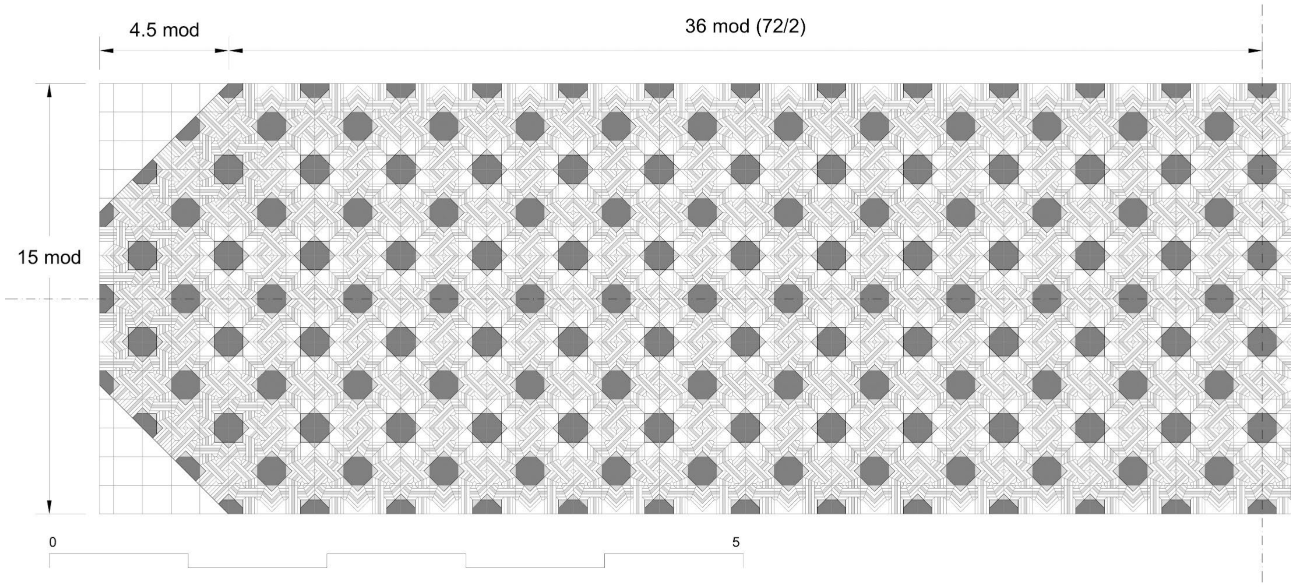


Figure 12: Overall composition of the *almizate* with the standard pattern and its local variations (only half of the element is represented).

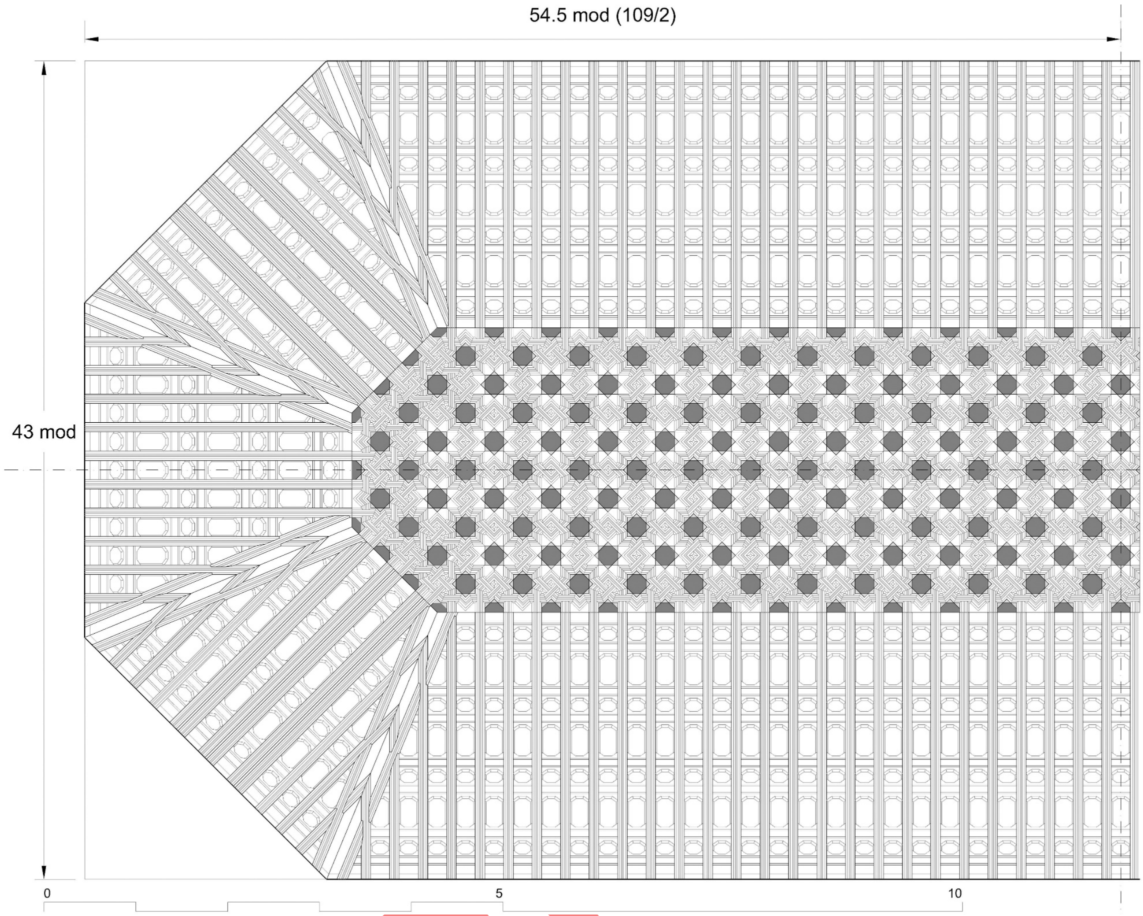
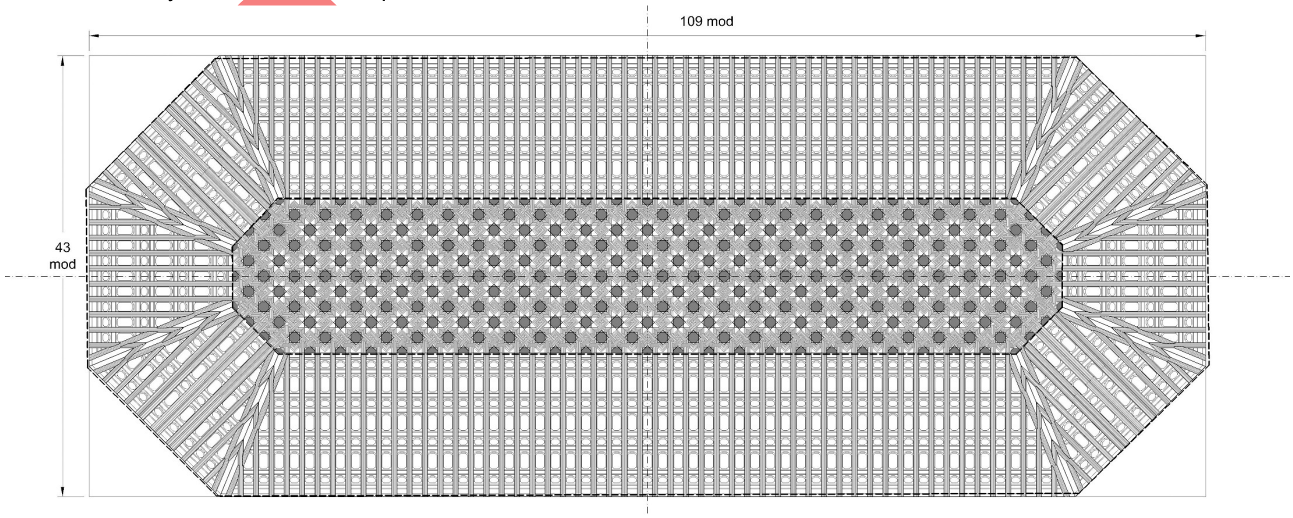


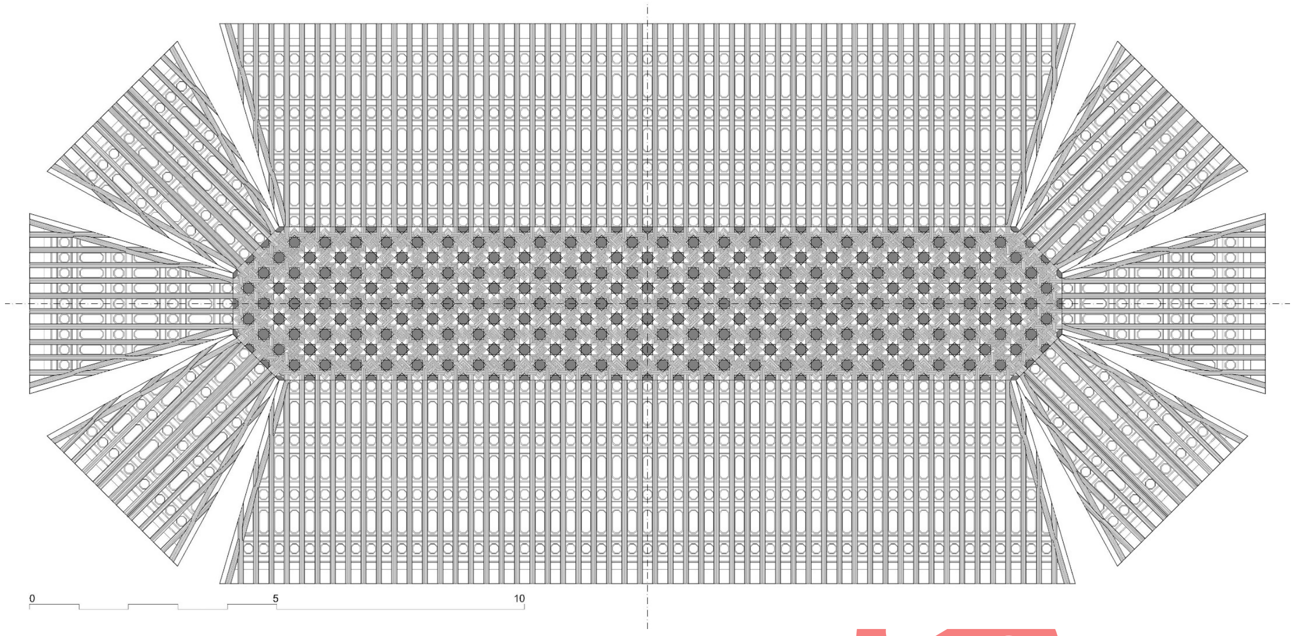
Figure 13: Drawing of the coffered ceiling frame with the *almizate** and the roof skirts (only half of the element is represented).

The resulting proportion of the structural footprint is approximately 2.5:1 (half the ratio previously obtained when considering the inner rectangle of the *almizate*). The entire structure is almost perfectly aligned with the initial module that defines the dimension of the *calle* and the side of the square. Even the dimensions of the room in which the coffered ceiling was constructed may relate to this modular system, as the comparison between the actual measurements and those of the idealised design shows a reasonably close correspondence (Fig. 14).

The transition between the semi-hexagonal finishings of the coffered ceiling and the walls of the room is achieved through triangular pendentives, in which the *lazo de 4* interlace grid is employed using the same *calle* and *cuerda* module as in the *almizate* (Fig. 15).



(a)



(b)

Figure 14: Drawing of the whole coffered ceiling with the roof skirts: a) Roof skirts in their folded position (the actual outline of the structure obtained from the survey has been represented using a dashed line); b) Roof skirts tilted on a horizontal plane (true size).

Although the triangular outline imposes more complex geometric constraints, the element is resolved using the same system of interwoven bands, alternating over and under at each intersection. Finally, the structure is completed with five pairs of tie beams, which are fully integrated into the same geometric pattern. Each tie beam has a width equivalent to one *calle* module and is positioned in alignment with the grid of the *almizate* (Fig. 16).

Ultimately, it appears that the module defined by the width of the *calle* may have determined not only the dimensions and proportions of the *almizate*, but also those of the roof skirts and the tie beams (or, in other words, of the entire structural system). This suggests a significant degree of planning and modular coordination in the design. Accordingly, the width and length of the room itself may have been conceived in relation to this module, which could have served as the basis for the design of the entire coffered ceiling.

3.2. Analysis of the construction of the coffered ceiling

The roof framework of the Synagogue of *El Tránsito* is based on the so-called *par-nudillo* system. The *pares** are inclined pieces that rest on the *estribo*[10] (a horizontal wooden piece that lies along the upper side of the walls) and form the roof skirts, while the *nudillos* are horizontal elements that define the *almizate*. The structure is secured at its base (where it rests on the walls) by pairs of tie beams, which connect the two longitudinal walls of the hall, preventing the framework from spreading. The junction between the structural system and the top of the wall is concealed by a series of decorated wooden boards forming the *arrocabe* (Fig. 17).

An analysis of the volumetric configuration of the coffered ceiling reveals that the roof skirts follow the slope defined by the so called *cartabón de 4*[11], that is, a 1:1 ratio or 45° inclination (Fig. 18). In Castilian timber frameworks from the 15th to 17th centuries, the slope of the roof skirts typically exceeds 30°, corresponding to a 1:2 ratio between the height and half the width of the nave (approximately 50%). Some frameworks, such as that of the church of *San Pedro de la Nave* (Zamora), exhibit a slope of 8:12, equating to 66% (Nuere, 1994). In the parish church of Almenara de Tormes (Salamanca), the slope is even shallower (Fig. 19).

However, as previously noted, in the case of the Synagogue of *El Tránsito*, the roof skirts form a 1:1 ratio or 45° angle (*cartabón cuadrado*), which may be associated with standard proportions more commonly found in the Nasrid Kingdom of Granada. The joints between the *pares** at the intersections of the roof skirts are executed using a tenon and mortice joint (Fig. 20). At the ridge, a specially adapted *espiga* is employed to accommodate the right-angled connection. This is a common solution in Spanish timber roof carpentry (Martín, Cabo, García & del Blanco, 2024; del Blanco, Cabo, García & Martín, 2022), as well as in traditional timber structures abroad (Chen & del Blanco, 2022). Notably, a ridge beam is absent, a feature also observed in other contemporary frameworks in Toledo, such as the convent of *Santa Úrsula*, which employs a similar construction system to that of the Synagogue of *El Tránsito*, including the use of double tie beams (Fig. 21).

[10] *Estribo*: The horizontal wooden element that allows the *pares* to rest upon it, thereby transmitting their loads and thrusts. The *estribo* is the structural component of the roof framework that initially bears all inclined loads resulting from the angular configuration of the roof (see figure 18).

[11] *Cartabón*: A fundamental tool used for marking cuts on coffered ceilings. It typically takes the form of a scalene right-angled triangle (with one 90º angle and two unequal acute angles), except in the case of the *cartabón de 4*, which is an isosceles right-angled triangle (with two 45º angles and one 90º angle).

The *nudillos* that define the plane of the *almizate* are positioned at approximately two-thirds of the total height of the coffered ceiling, measured from the level of the upper side of the *estribos*, where the *pares* rest (Fig. 18). The joints between the *pares** and the *nudillos* are similar to those used in Al-Andalus during the same period: a *garganta y quijera*[12] joint (Fig. 22).

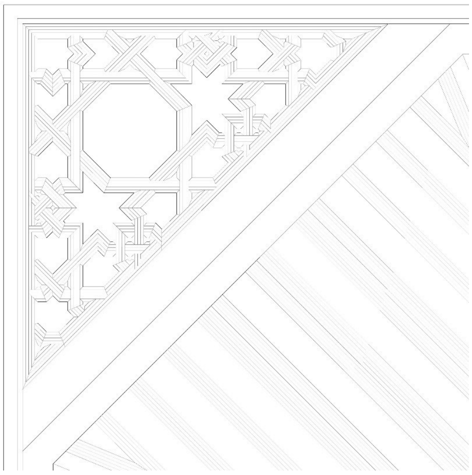


Figure 15: Drawing of one pendentive at the corner of the coffered ceiling.

It was common practice for the carpenter to make slight adjustments to the height of the *almizate* plane in order to better accommodate the modular system imposed by the interlace pattern in the transverse section of the framework. Once the transverse modulation was established, the carpenter had an additional strategy for adapting the structure to the longitudinal dimensions of the room: making minor modifications to the slope of the semi-hexagonal finishings at the gable walls. In the case of the Synagogue of *El Tránsito*, it is noteworthy that no such longitudinal adjustments to the slope of the semi-hexagonal finishings were necessary. This appears to be more than a mere coincidence, and it is plausible that the builders of the room's walls were already working from a carpentry design for the roof structure and thus adjusted the wall dimensions to match those specified in the original design.

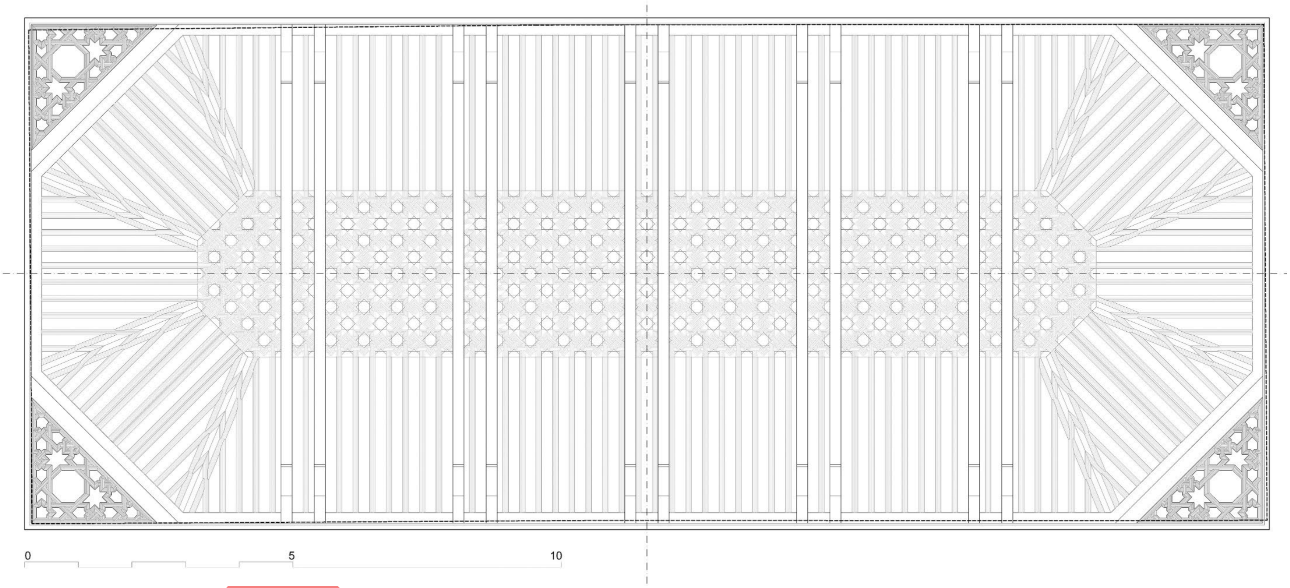


Figure 16: Drawing of the whole coffered ceiling with the *almizate*, the roof skirts, the pendentives and the tie beams. The actual outline of the structure, as obtained from the survey, is represented using a dashed line.

[12] *Garganta y quijera*: a characteristic joint between the *par* and the *nudillo* that consists of carving an enveloping shape at the end of the *par* (the *quijera*) to embrace and hold the *nudillo* just in a place where its section has been reduced (the *garganta*).

Figure 17: Coffered ceiling with its main constructive elements.

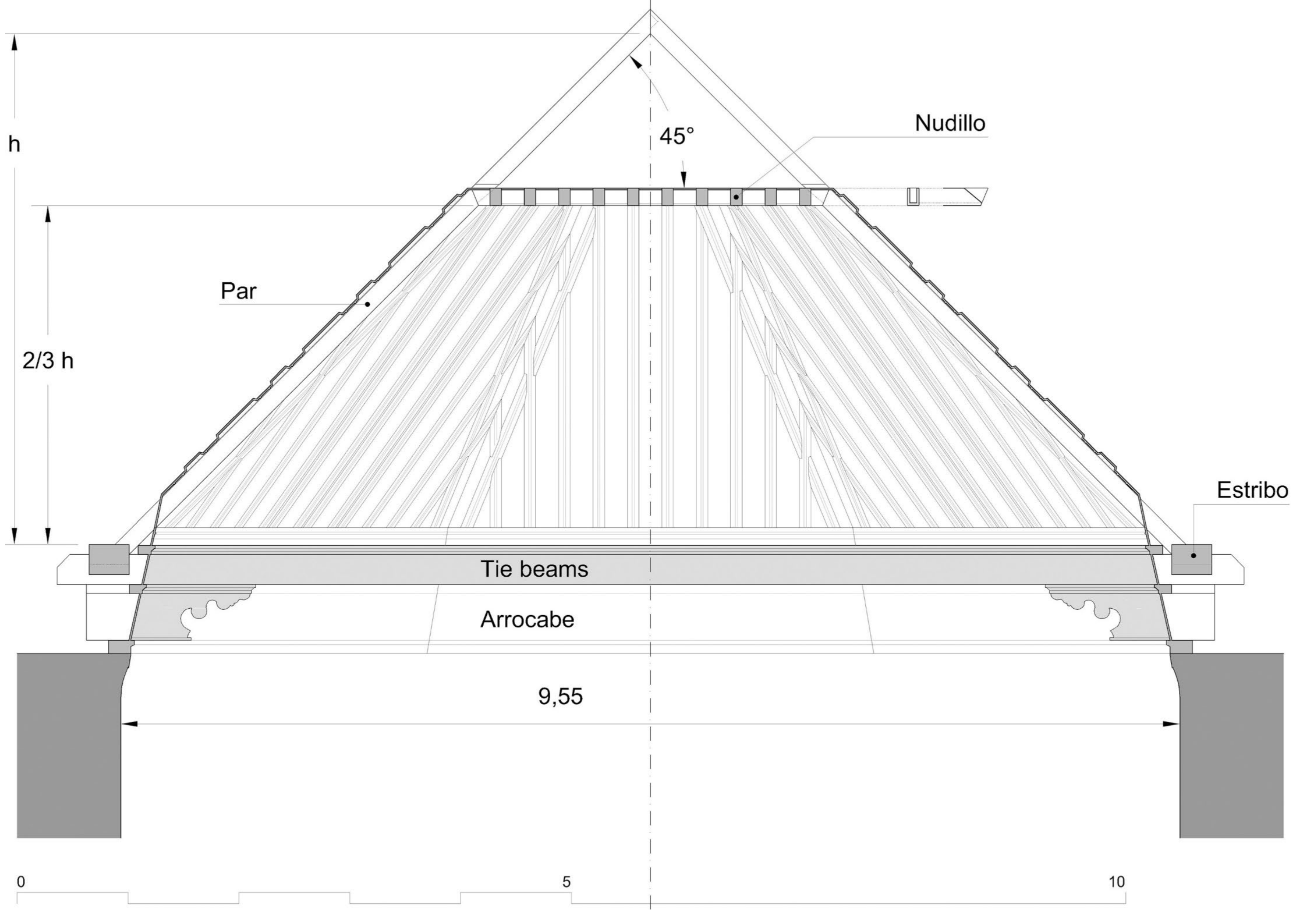


Figure 18: Cross vertical section of the coffered ceiling.

The maximum span of the *par-nudillo* system (that is, the distance between the longitudinal walls of the room) is determined not only by the available cross-sections of the *pares**, which were typically a quarter of the standard beam-sawing dimensions, but more critically by the maximum length of the tie beam. The tie beam must be capable of withstanding bending stresses under its own weight. Consequently, the length of the tie beam effectively determined the distance between the walls. The longest spans identified in Spain between the 15th and 17th centuries are found in churches in Segovia, where spans of up to approximately 11m were achieved using pine timber from the Valsaín forests (*Pinus insignis*). However, in most cases, the typical length of tie beams ranges between 6.5m and 7.5m (Fernández, 1991; Fernández, 1997). In the Synagogue of *El Tránsito*, both the distance between the longitudinal walls and the length of the tie beams slightly exceed these average values, measuring approximately 9.5m (Fig. 18).

Double tie beams were more commonly used in coffered ceilings in Al-Andalus, where they formed part of a longer-standing Spanish-Muslim tradition. In Castile, however, double tie beams were typically reserved for projects with greater financial backing, usually associated with noble families of considerable means. The space between the paired tie beams was often used to incorporate decorative elements. The spacing between the pares and the relationship between *calle* and *cuerda* determined the modular system employed in the chosen *lazo* pattern. This implies that certain structural conditions of the *par-nudillo* frameworks (such as the width of the *calle* and the spacing between them, that is, the *cuerda*) were established only after the carpenter had designed the intended *lazo* pattern for decorative purposes. In other words, a carpentry design project had to exist prior to the structural design of the roof framework.

Figure 19: coffered ceiling of the parish church of Almenara de Tormes (Salamanca).

The design of the *lazo* pattern in the *almizate* determines its constructive configuration (that is, both the individual components and their joints). These joints follow the same tenon and mortice system, allowing for the full assembly of the structure (Figs. 23, 24, & 25).

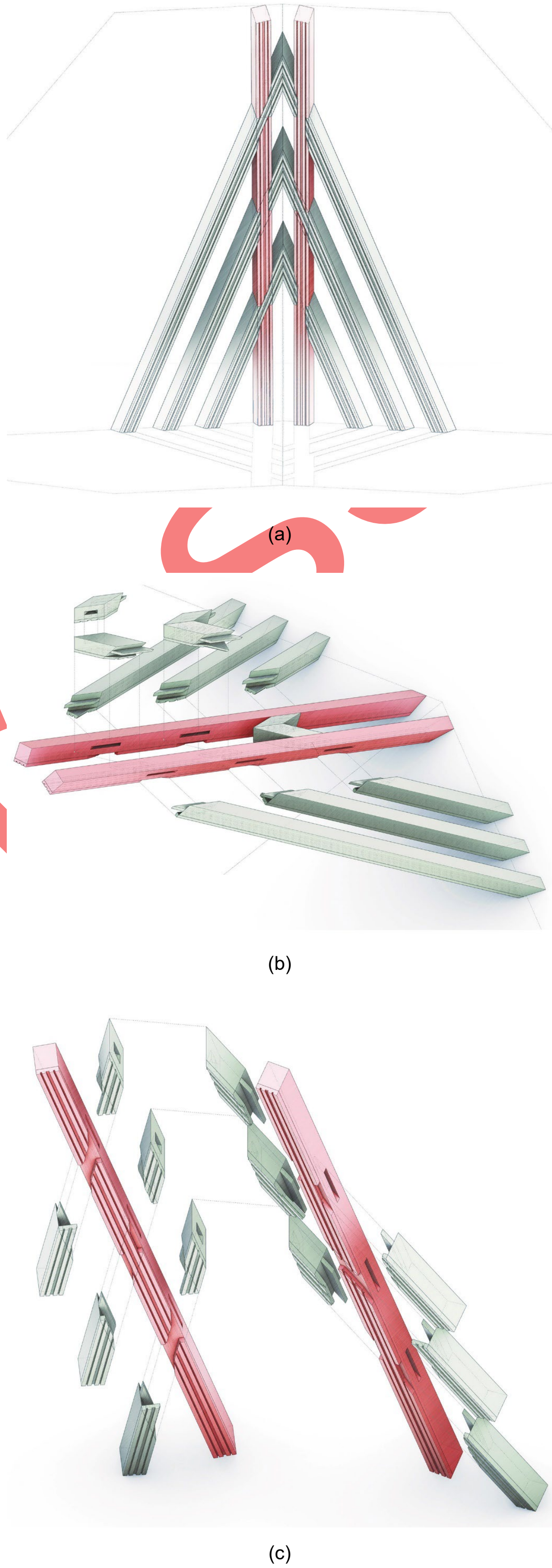


Figure 20: Details of the joints between the *pares* at the junction of two roof skirts: a) Frontal view; b) Extrados view of the parts that form the join view; c) Intrados view of the parts that form the joint.

(a)

(b)

(c)

Figure 21: Coffered ceiling at the church of *Santa Úrsula*: a) Joints of the *pares*; b) Extrados of the roof skirt; c) Internal side of the coffered ceiling with double tie beams.

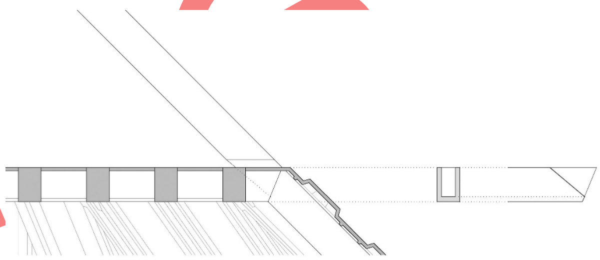
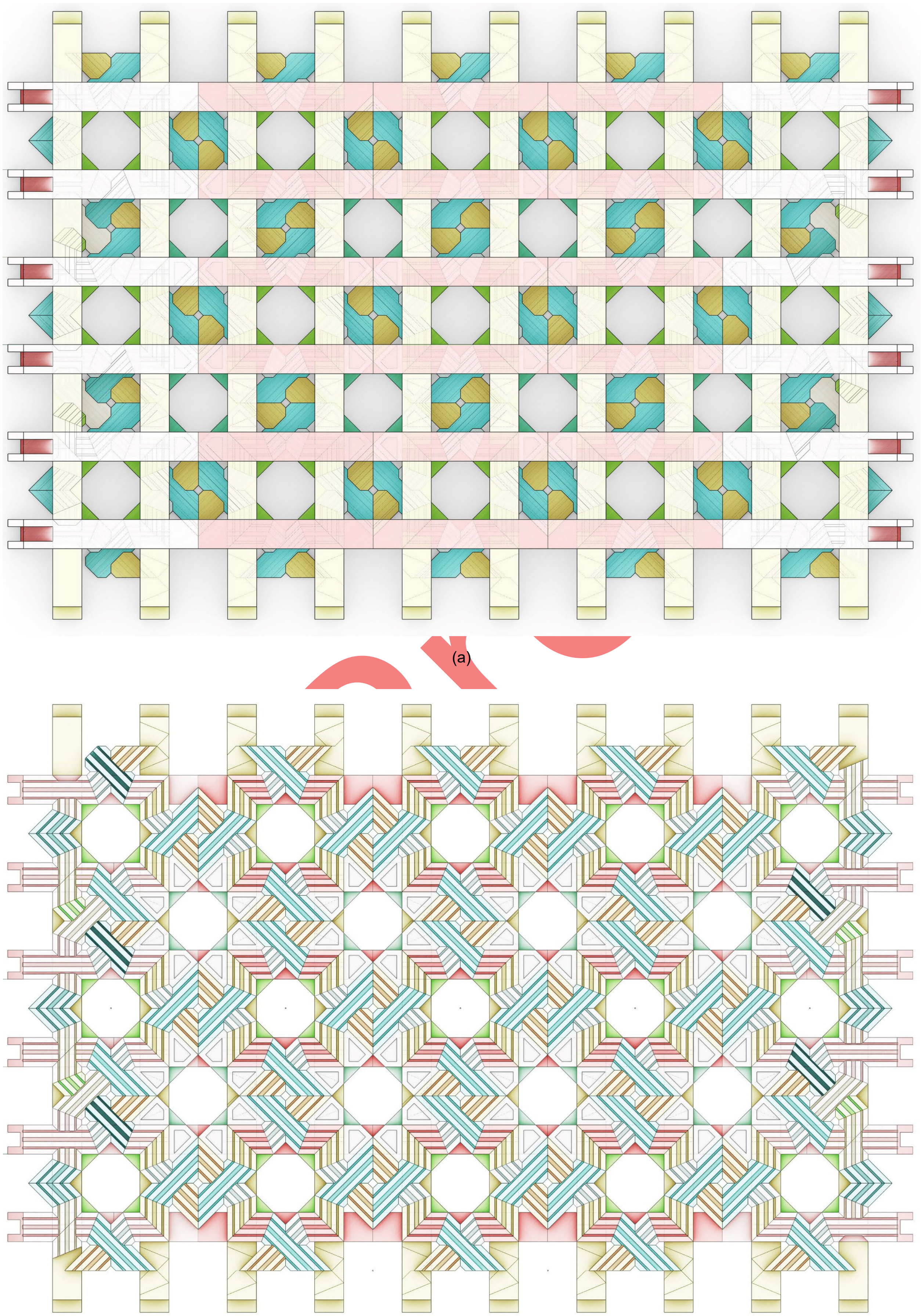


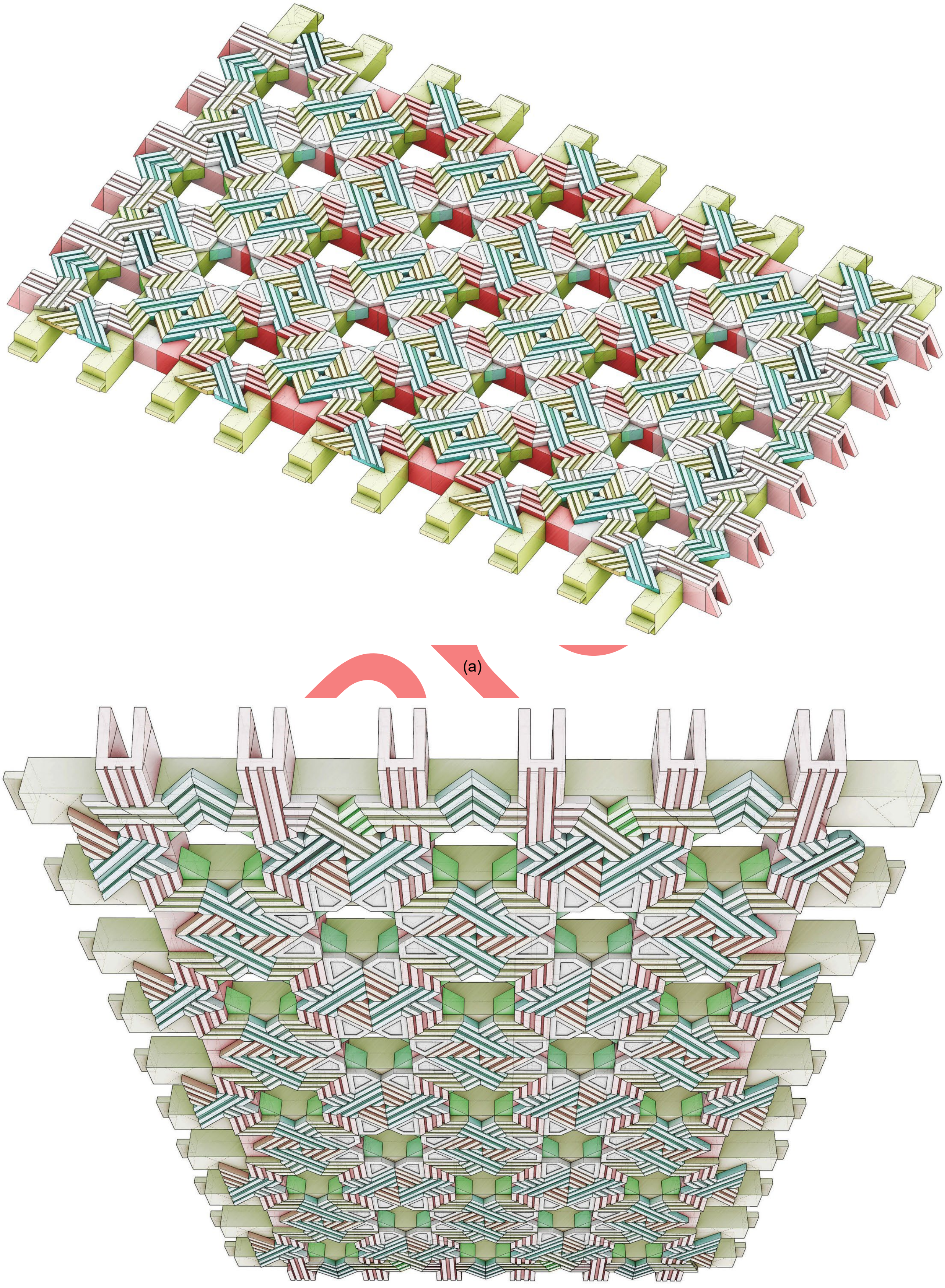
Figure 22: Detail of the joint between the pares and the *nudillos* using a *garganta y quijera* joint.



(a)

(b)

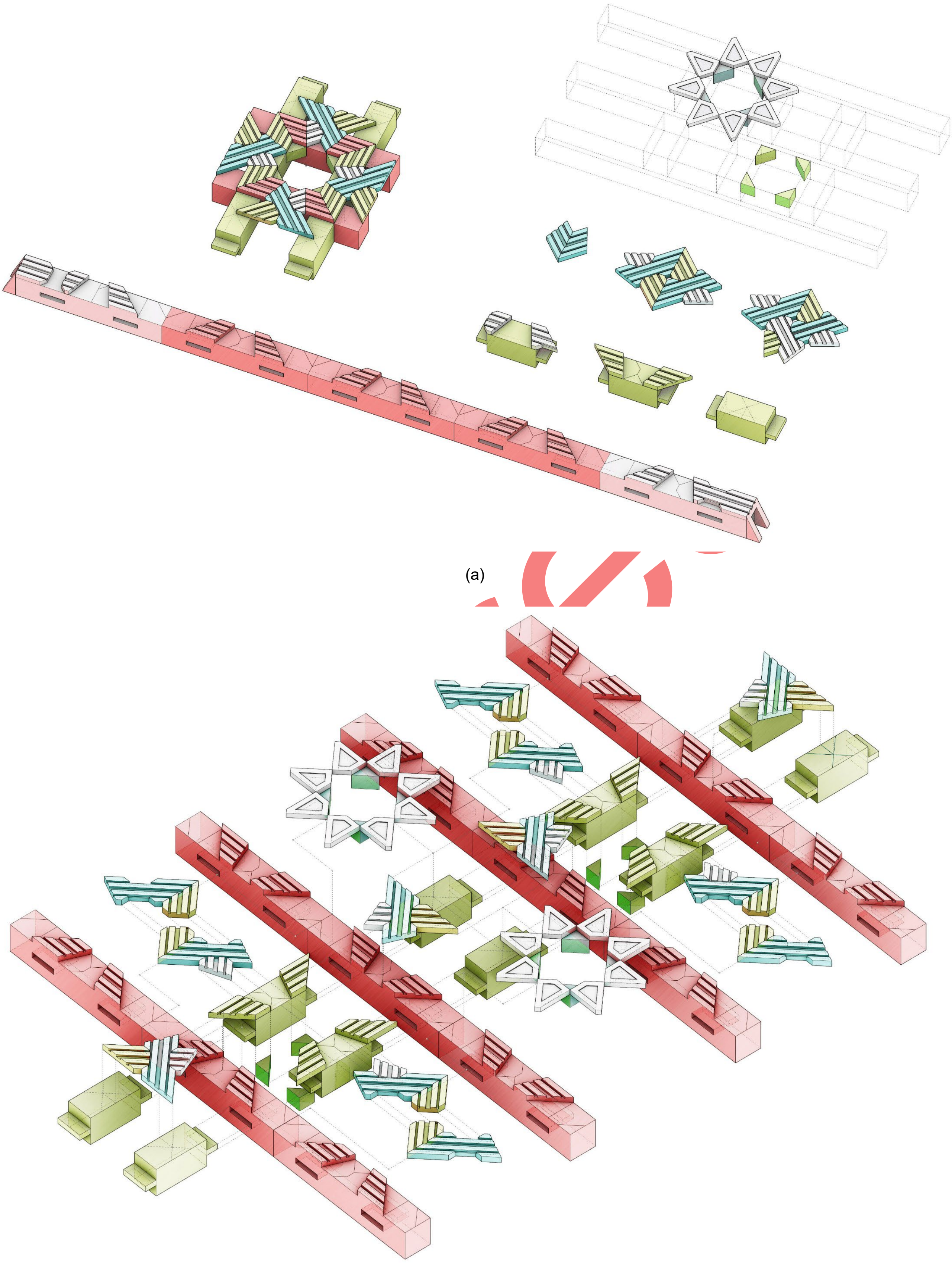
Figure 23: Pieces that form the *almizate*: a) Top view (extrados); b) Bottom view (intrados).



(a)

(b)

Figure 24: Pieces that form the *almizate*: a) 3D axonometric view; b) One-point perspective.



(a)

(b)

Figure 25: Details of the pieces that form the *almizate* and their assembling system: a) Configuration of one module; b) Assembling of several modules.

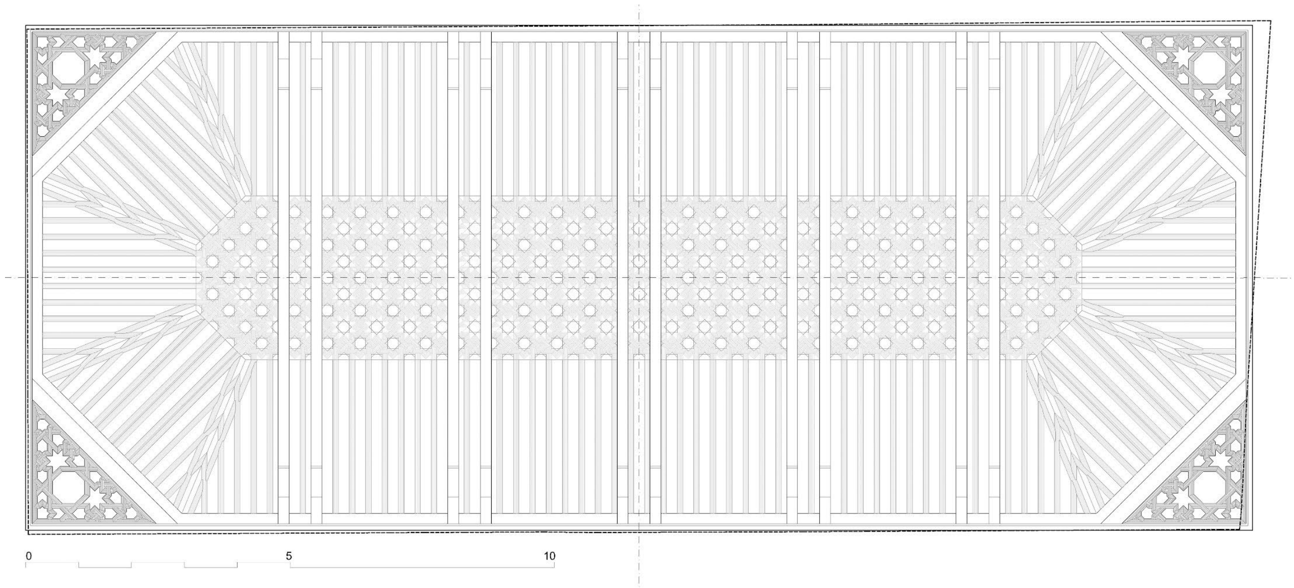


Figure 26: Plan layout of the whole coffered ceiling together with the actual profile of the walls of the room that support it (marked with dashed lines).

3.3. Comparison between the idealised model and the actual structure

Once the idealised design model was developed, it was compared with the actual geometry of both the structure and the room in which it is located. The plan of the idealised structure shows a good alignment with the actual horizontal profile at the level where the roof skirts and the *almizate* begin (Fig. 14, top), and also at the *estribos* level (Fig. 16). However, the greatest discrepancies occur at the *estribos* level in the northern corner (15cm) and in the southern corner (11cm). At the *almizate* level, the maximum deviation is smaller, and it does not exceed 8cm. Given that the total coffered ceiling total dimensions are 23m × 9.2m, the maximum deviations represent approximately 0.6% of the total length. Therefore, the idealised model can be considered to be closely aligned with the actual structure.

However, when comparing the orthogonal perimeter of the idealised structure with the profile of the supporting walls, a notable deviation can be observed on the south-western side (Fig. 26): the coffered ceiling outline diverges from the alignment of this wall of the room, which appears to follow the orientation of the street on which the building is located.

This deviation can also be observed in the actual structure, which is not parallel to the wall on this side of the room. It is thus evident that the coffered ceiling was skilfully executed to accommodate the irregularity of the walls, that are not perpendicular to each other. The result was the construction of a structure that is orthogonal, and thereby facilitating its assembly, while simultaneously creating a transition between the oblique wall and the framework itself (subtly concealed by the cornice), so that the deviation is barely perceptible to the naked eye. Ultimately, the carpenters' expertise enabled them to solve an irregularity in the perimeter of the walls, allowing the roof structure to be constructed with greater simplicity (Fig. 27).

(a)

(b)

Figure 27: Two views of the south-western wall of the Prayer Hall with the coffered ceiling in which the deviation between such elements can be noticed: a) View from bottom to top; b) Front view.

4. Discussion of results

The results of the study reveal several issues that help to contextualise the significance of the coffered ceiling of the Synagogue of *El Tránsito* within the frame of Spanish-Muslim and Castilian historic carpentry. This section examines in depth the convergences and divergences with previous research, the unexpected outcomes of the geometric and constructive analysis, and the implications of these findings for the knowledge, conservation, and historical interpretation of the coffered ceiling.

4.1. Relationships with previous research

The analysis carried out aligns closely with previous studies focused on the Spanish-Muslim and Castilian historic carpentry. First, it corroborates the observations made by authors such as Nuere, Fernández, and Franco regarding the strong modularity of the *lazo de 4*, understood as a standardized pattern since the 14th century. The results show that a single module, derived from the side of a square, organizes the whole layout of the coffered ceiling, from the *almizate* to the roof skirts formed with *pares** and *nudillos*. This finding is consistent with previous research, and it demonstrates how modularity facilitated not only geometric coherence, but also the replication and circulation of design templates among different carpentry workshops.

Likewise, the technical continuity observed in the coffered ceiling joint systems corresponds to what was documented in other contemporary structures in Toledo and in the Nasrid context. The presence of tenon and mortice joints, as well as trenched connections between *pares* and *nudillos*, reproduces identical solutions to those identified in the Church of *Santa Úrsula* or in various timber frameworks analysed by Martín, Cabo, and del Blanco (2024, 2022). Thus, it underlines the idea of a shared and well-established tradition of building construction.

Finally, the absence of a ridge beam is an aspect that was already underlined in several studies on *mudejar* coffered ceilings (Fernández, 1997), and it is fully confirmed in the case of the Synagogue of *El Tránsito*. As previously described, the structure relies for its stability on the combined action of the *pares* and *nudillos*, without the need for an upper linear element. This feature, once again, relates this work with the typical structural solutions of Spanish-Muslim carpentry tradition, in which the logic of the framework replaces the use of a ridge beam as the primary organizing axis.

4.2. Unexpected and remarkable outcomes

The results of the study also reveal several unexpected issues that enrich the analysis of the coffered ceiling. One of the most significant is the 45º slope of the roof skirts, an uncommon inclination in Castilian carpentry works after the 15th century, where 30º to 35º angles were more usual. This unusual roof pitch is closer to solutions related to the Nasrid tradition. Thus, it may be concluded that there was a direct influence of the southern constructive tradition (which was still present in the 14th century in Toledo), or it could also be a deliberate aesthetic decision with the aim of enhancing the monumentality of the Prayer Hall by raising the *almizate* and underlining the verticality of the room.

Another noteworthy result is the exceptional geometric precision observed between the idealised model and the actual structure, with deviations not exceeding 0.6%, even in long structural elements. This level of accuracy is rare in 14th century roofs, and it suggests that the carpenters who built the coffered ceiling had a remarkable command of geometry. It likewise strongly points to the existence of detailed and rigorous preliminary design drawings, likely more developed than those commonly documented in medieval Castilian carpentry contracts, where descriptions tend to be more general and less prescriptive in geometric terms.

Finally, the constructive solution adopted to address the irregularity of the building's southwestern wall is another unexpected finding. The coffered ceiling was laid out as a perfect rectangle, despite resting partially on an oblique wall (as shown in figure 27). Rather than deforming the structure to adjust it to the irregular perimeter (a common practice in many medieval coffered ceilings) the carpenters preserved the geometric essence of the ensemble, and they solved the discrepancy through a carefully integrated transition in the *arrocabe*, which visually hides the deviation. This approach underlines the idea that geometric regularity and modular coherence were fundamental priorities in the design, rather than the adaptation to the precise contour of the existing walls.

4.3. Implications of the findings

The results of the study allow pointing out several issues relevant to the technical, cultural, and historic understanding of the coffered ceiling. First, the strong modularity that was detected suggests that the carpenters worked from an exceptionally elaborated preliminary layout. The geometric consistency of the system indicates the existence of an initial design plan based on the *palmo* as the basic dimensional unit, which served for setting a square-based module. Then, several variations were developed to create a whole set of "geometric pieces" which formed a pattern that not only organized the coffered ceiling but may even have conditioned the position and proportions of the room's walls themselves. This planning level leads us to reconsider the role of the medieval carpenter, who appears not merely as an executing craftsman, but as a highly trained technician that was capable of conceiving structures through geometric abstract procedures.

The combination of the identified elements (such as the Castilian dimensional units, the *lazo de 4*-based pattern which was typical of the Christian context, the roof inclination characteristic of Nasrid traditions, and the joints that belong to the *mudejar* technique) confirms that the coffered ceiling at the Synagogue of *El Tránsito* is an extraordinary example of cultural and technological synthesis materialized in a single masterpiece. The harmonious interaction of such components drawn from Christian, Muslim and Jewish traditions reflects the 14th century cultural context in Toledo and underlines this structure as an exceptional testimony to technical and aesthetic exchange.

From the point of view of the coffered ceiling, the idealised model demonstrates that the structure follows a rational, repetitive, and fully replicable system that can be reproduced using digital tools. The correspondence between the ideal design and the coffered ceiling's current status enables highly precise comparisons between both of them, facilitating the detection of deformations relative to the original layout. This allows developing monitoring and preventive restoration strategies (such as periodic comparisons between point clouds and parametric models), the identification of deformations associated with long-term loads, as well as structural assessment through precise geometry-based simulations.

Finally, the fact that the structure remains perfectly orthogonal despite resting on an oblique wall (and consequently, that the walls were adapted to the carpentry layout rather than the other way around) has significant historiographic implications. This suggests that the roof occupied a central position within the architectural project and that the carpenters participated in early phases of the building's design. The coffered ceiling thus seems to be conceived from the beginning as a prominent feature of the building. This is aligned with the cultural and symbolic program promoted by Samuel ha-Leví: beyond being a mere structural solution to cover the Prayer Hall, it was a key component of the meaning and identity of the ensemble.

5. Conclusions

This research about the coffered ceiling of the Synagogue of *El Tránsito* allows understanding this structure as a work of remarkable technical coherence and refined planning. The study demonstrates that the entire system is organised around a single module (derived from the side of the square and equivalent to the *palmo*) which rigorously governs the layout of the *almizate*, the roof skirts with the *pares* and the *nudillos*, and the overall proportions of the work. This modularity not only confirms what was described in previous research regarding the standardisation of the *lazo de 4* but also reveals an accuracy degree which was unusual in 14th century structures, with deviations between the idealised model and the actual structure not exceeding 0.6%. Such accuracy underlines the exceptional geometric mastery of the carpenters who executed the work.

The comparative study between the idealised model and the point cloud geometry highlights the builders' ability to maintain the orthogonality of the coffered ceiling, even when the supporting walls have irregularities, as it happens in the case of the southwestern façade. The solution adopted (that is, to preserve the geometric regularity of the coffered ceiling and to hide the deviation within the *arrocabe*) demonstrates a clear attempt to prioritise the formal and modular essence of the design rather than a direct adjustment to the building's pre-existing geometry.

Furthermore, the integration of elements from Christian, Muslim and Jewish traditions makes this structure an exceptional example of cultural and technical synthesis. The roof is not only a result derived from a rational and standardized system but also stands as tangible evidence of the artistic and constructive exchange which was usual in Toledo in the 14th century.

Finally, the point cloud and the idealised reconstruction of the coffered ceiling have not only enabled a deeper understanding of its original design but also opens new possibilities for the monument's conservation and dissemination. Periodic comparison between the idealised model and the current state of the structure could facilitate the early detection of deformations and the implementation of preventive restoration strategies. Besides, the 3D digital models of the wooden pieces help the understanding of a complex construction system that is barely recognisable to the naked eye. In conclusion, the results of this study contribute significantly to the knowledge of Spanish-Muslim and *mudejar* historic carpentry, and they underline the artistic, technical and cultural value of the coffered ceiling at the Prayer Hall of the Synagogue of *El Tránsito*.

Acknowledgements

The authors wish to express their gratitude to the *Museo Sefardí* of Toledo (*Ministerio de Cultura*, *Gobierno de España*) for allowing the use of the graphic products obtained during the architectural survey of the Prayer Hall of the Synagogue of *El Tránsito*.

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