Construction of a Pendentive Grid Crossing Vault

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Historical setting

In the 16th century, Andalusia had a simultaneous development of two different architectures: classic and gothic. As discussed below, the gothic tradition of building vaults with ribs is adapted to the Renaissance aesthetic principles, so that the ribs become the way through which can be carried out the stonecutting in the classic vaults. In the grid *crossings vaults*, the gothic ribbed vaults adapt themselves to a classic reticular pattern, drawing on the surface of the vault a design of coffering in line with the stricter Roman canon. We can say that the *crossing vaults* represent an outstanding example of formal autonomy of the gothic rib work which without letting down its medieval construction principles can adapt itself to Renaissance models.[1]

The *crossing vaults* found a wide space in the treaty of Vandelvira study (1580). In this treaty we can find five different models of *crossing vaults*, the first two show vaults with the *crossings* arranged in an orthogonal grid parallel to the perimeter arcs (Fig. 1), the first has a square ground plan and the second a rectangular ground plan. The remaining three are vaults in which the framework is parallel to the diagonals; in the treaty, these vaults are called *lattice chapels* (Palacios 2003, 302-323). The most interesting aspect of the models developed by Vandelvira is that all *crossing vaults* are *pendentive vaults*, that is spherical ones. This circumstance permits Vandelvira to propose, in the carving of his *crossings*, one geometric design based in the spherical domes stereotomy, i.e. using the template of the interior curve of a *voussoir* obtained through the development of conical surfaces. In Vandelvira's spherical vaults, each *crossing* is part of a template whose shape can be calculated geometrically using the method out-

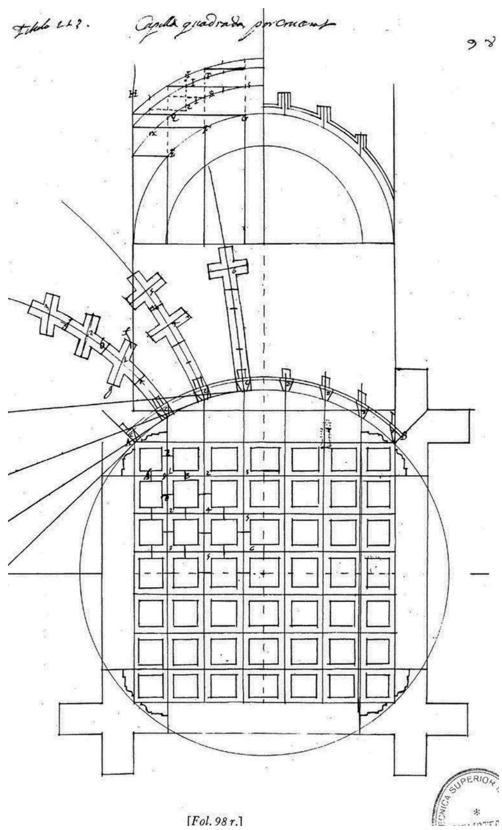

Fig.1: Drawing of the Vandelvira's treaty, *Crossing vault* in square plan.

lined above. This template would allow carving a *voussoir* which would be the intersection of ribs. The sphericity of this piece would be obtained by *bebel.* If the *crossing vault* was spherical, as Vandelvira proposed, all the arcs that form the grid of ribs would have different curvatures. As outlined below, few of the *crossing vaults* that we could study are spherical; often, they are translation surfaces in which a single arc moves towards the two orthogonal directions. The vault that is obtained may appear spherical but its execution is incomparably easier: all their arches are equal. Among them we find the vaults of the Town Hall of Seville, the vaults of the church of Cazalla de la Sierra (Fig. 2), the vaults of the church of the Assumption in Aracena, those of the Rosary parish in Zafra and so on. Within this brief summary we highlight the tremendous vaults of the Cathedral of Merida in Yucatán, Mexico, built in the late 16th century (Fig. 3). The presence of this typology in the viceroyalty of New Spain speaks eloquently of the extraordinary role these vaults represented in the Spanish Renaissance.

Geometry

The *crossing vaults* are *pendentive vaults* built with a grid of arches which, in ground plan, intersect themselves orthogonally; so the difference with the gothic vaults is that the rib, instead of springing from the four corners to the central keystone, makes a grid like a net, covering the entire surface of the vault. Their formal aspect is a clearly Renaissance one. However, the technique of construction of these vaults is based on gothic principles. In order to achieve the construction of this vault, we made a detailed geometric study of various existing vaults of this type. This study revealed a considerable number of forms and different strategies to obtain the final volumetry of the vault. In the model to be made in the workshop, we chose the most effective geometry, that which would permit to standardize the vault as completely as possible. The perimeter arches would be oval arches and the grid would be built with the same arch, an arc that would have the same curvature as the top of the perimeter oval. This is the case of the vault of the chapter house to the Town Hall of Seville where the same *segmental arch*, much stretched out, slides in both directions on the oval wall-arch arches. This is an ingenious device that allows greatly simplifying and streamlining the stereotomy of the *crossing vaults*. So, in the vault that we built, the *transverse arches* are oval arches whose central circumference is the same as the one that defines the ribs, while the side curvatures of the ovals are part of the *tas-de-charge* which, as we shall see, greatly facilitates the construction. So the entire vault is constructed with a single arch, the center of the oval. The displacement of this arch generates a translation surface that can be built with one arch. This fact also facilitates the construction of *crossings* because all of them are produced by the intersection of arches of the same curvature.

The analysis of the volumetry adopted by the *crossing vaults* leads us into an interesting topic that goes beyond the purposes of this paper

Fig.2: *Crossing vaults* with parallel grid to the transverse arches and parallel grid to the diagonal line, Cazalla de la Sierra, Seville.

Fig.3: Vaults of Cathedral of San Ildefonso, Yucatán, México. Ribs with distorted section.

(Bravo 2011). The different volumetries of vaults resolved by *crossings*, resulting from the different curvatures of the arches, show a wisdom and a remarkable knowledge of the structural forms, as well as a extreme freedom in the design and construction of any vaulted surface.

Monteas

This term, widely used in the 16th century stone masonry workshops in Spain, refers to the drawings of full size plans of all or part of a work. The vehicle of transmission of the shape and size of a *voussoir* were patterns of its faces whose knowledge was necessary to proceed to its carving. These patterns were produced to natural size and its use was essential in masonry because of the complexity of the carving. The design patterns are obtained by developing the process geometrically in real size, which has the clear advantage, despite being uncomfortable, to obtain patterns without any risk of inaccuracy, since the change of scale was a risky operation that could lead to errors. The design of these full-scale patterns was done on the pavement of the building, or on a flat surface in the *drawing halls*, rooms dedicated to this purpose since the Middle Ages. Giant geometric constructions on the floor or walls would accompany the construction of the various rooms of the Renaissance building.

In the *Gothic building Workshop*, where the *crossing vault* was carried out, the *monteas* were outlined in 1:1 scale on the walls of the classroom (Fig. 4). First, the curvatures were drawn using the same radio of a circumference, following the criteria above mentioned. Later, the cutting-ups were drawn in detail with which the essential parts of the vault were built: *crossings*, *voussoirs* and *tas-de-charge*. During the Middle Ages, this projection system that relates the floor plan of an object to its elevation, known today as dihedral projection system, was developed in the workshops of masonry until the 16th century; the methodology was dominated by master mason that solved complicated abatement of lines and detailed draw-

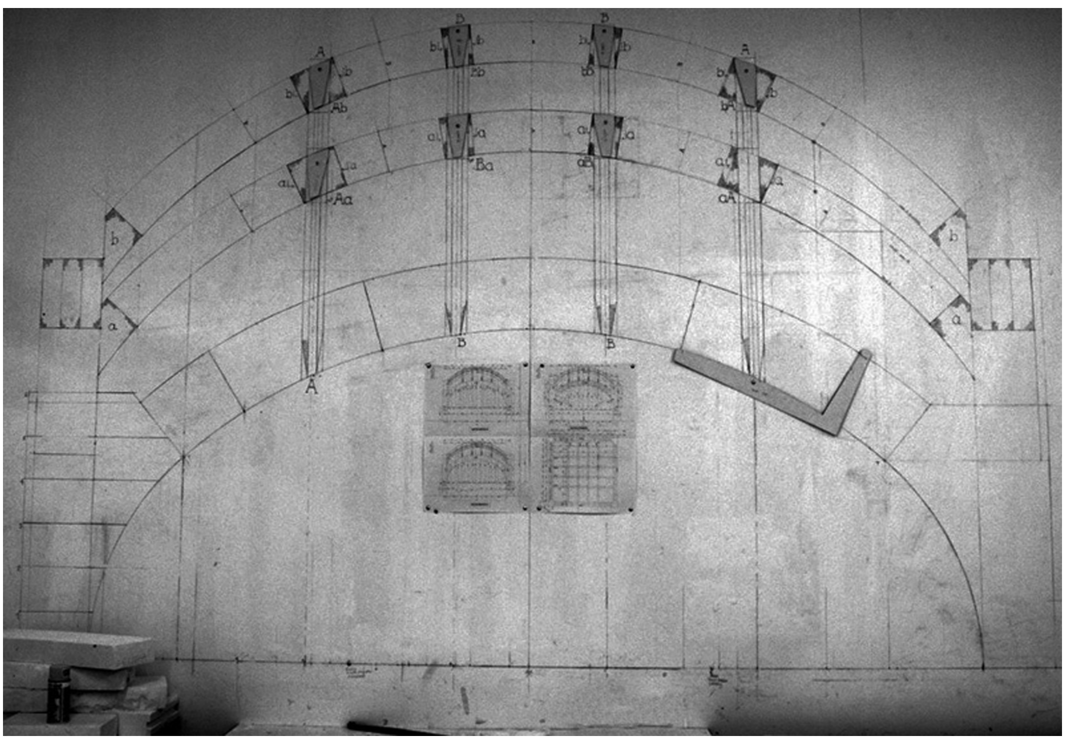

Fig.4: *Montea*. Full size drawing of the vault, showing the different arches and the sections of the ribs

ing of the parts. Vandelvira (1580) in his treaty already warns that this type of vaults can be built with *square section* or *distorted section*. This is a fundamental aspect in the construction of this kind of vault, as the *crossings*, the most complex and important pieces, depend on the combination and position of these *distorted sections* within the volumetry of the vault. The section of *distorted section* ribs, according to the gothic tradition, keeps vertical the axis of its section, whatever the position of this arc in the vault is (right side of Fig. 1). As you can see, this circumstance changes all sections of the arches, from the top of the vault to its perimeter, where the *distorted sections*, i.e. the deformations, are maximal. By contrast, in the arches with *square section*, the section remains unchanged because its axis of symmetry is radial, i.e. it is always oriented toward the center of the vault. The rationale that explains the existence of the *distorted sections* in front of the *square ribs*, common in the Renaissance, is undoubtedly the medieval tradition. We can recall that the gothic rib is always vertical, i.e. it guides its axes according to the vertical of the vault.

The vault we are talking about consists of four oval wall-arches and eight segmental ribs, four in each direction, of the same radius of circumference, which simplifies the sketching because a single *bebel* resolves, as we said before, the curvature of all ribs. The intersection of these eight ribs, generates sixteen *crossings* which can be reduced by symmetry to four different *crossings*. These four *crossings* are produced by intersecting arches of equal curvature, but with different *distorted* sections. The vault we are building has ribs with *distorted molds A* in the extremes and *distorted molds B* on ribs in the center, as shown in Figure 5. The possible combinations of these *distorted* ribs derive in four different *crossing*s: Aa, Ab, Ba, Bb. Carving these *crossings*, as we shall see later, is the most complex task of building the vault.

The construction

The templates that are extracted from the monteas carried out in natural size are drawn on the stone block, to then proceed through the mallet and the chisel, to remove the surplus volumes of this and thus obtain the desired piece. In our case, owing to the easy and speedy carving, we used solid plaster instead of stone. To perform this operation of stonecutting, the fundamental tool was the *bebel*. The *bebel* is an instrument of medieval origin, whose task is to obtain the inner curve of the arches. This is a rigid square with one curved arm, designed with the curvature of the intrados of the arch that defines. The other arm is straight, placed in position of the radio of the arc. Since all the arches that make up this vault have the same curvature, with the same *bebel* the construction of the whole vault can be carried out.

Voussoirs

The construction began with the carving of *voussoirs*. First, from the *monteas,* is made the *bebel*. Then we made templates of the sections, which in this case for the *transversal arches* is square and for the ribs there are two: *distorted section A* and *distorted section B* (Fig. 5). Note that in order to

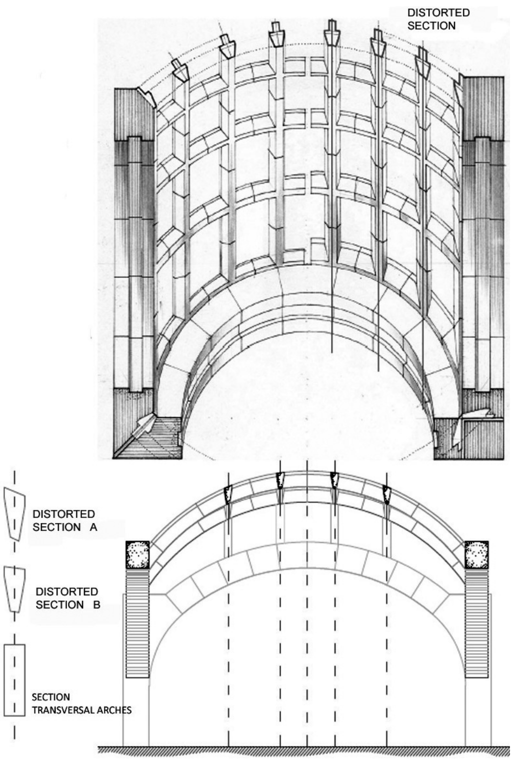

Fig.5: View of the vault section. Ribs with distorted section in the right side, and ribs with *square section* in the left side.

simplify the carving, the templates of the *voussoir* section don´t have any protuberance, that is to say, the projection of the extrados of the arch, so as to be that it is embedded into the *caissons.*[2] Finally, with the *bebel* and template of the corresponding section, the *voussoirs* can be carved. The plaster allowed the use of handsaw, chisel and file in order to rapidly attain the desired shape. The carving of the *voussoirs* is explained in Figure 6. A block of plaster is cut with the help of the *bebel* achieving exactly the curvature of intrados. Subsequently, at the end of the piece, the template of section is drawn with the appropriate *distorted section*. Finally, the shape to each *voussoir* can be given by removing the exceeding material.

Crossings

The *crossings* are the most important and complex pieces of the vault. The stonecutting of these elements tested like no other the capacity of the quarry masters. In the gothic vaults were solved the complicated crosses of arches hiding the difficult encounter with a cylindrical vertical piece: the *keystone*. However, in the Renaissance vaults, the junctions of ribs are resolved through the clean intersection of the arches: the *crossings*.

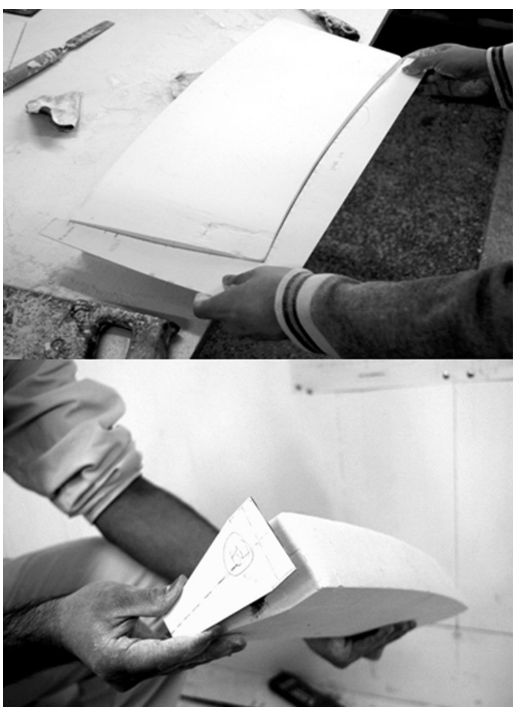

Fig.6: Carving of the vault with the help of *bebel* and template section.

In order to understand the work of carving of these pieces, a careful analysis of several built examples was carried out. In most of the vaults, it was possible to observe how the *crossing* was defined on a long *voussoir* in which are carved the other two arms of the transept, exactly at the junction. This method greatly facilitates the implementation of these parts, because the geometric calculation of a pattern with its two completed arms is a delicate process which can easily lead to mistakes. A simple deviation from the position of the arms would make impossible the closure of the grid. It is therefore safer carving an arm of the transept with its full length: *main direction*, and cut the other arm in its origin: *secondary direction*, in order to prevent mistakes in the angle of intersection.

In the cutting of *crossings* it was essential to maintain a strict nomenclature to avoid confusions when building it. As we specify earlier, in this vault were defined four types of *crossings*:

– *Aa* in whose primary direction it contains the *distorted section A* and the secondary direction will receive the *distorted section A*;

– *Ab* with main direction of *distorted section A* and secondary direction with *distorted section B;*

– *Ba* with main direction of section *B* and secondary direction with section *A*;

– *Bb* with main direction of section *B* and secondary direction with section *B.*

We carved four *crossings* of each type, so the vault is built with 16 *crossings*.

The carving of a *crossing* in its main direction is produced by a process similar to that of the carving of *voussoirs* described previously. In this case, once you have obtained the solid capable of containing the *crossing*, the vertical axis of the *distorted section* of the secondary direction is transferred from the vertical *montea* to the stone. The prism which will contain this *distorted section* is drawn, and later we continue the carving of the main direction as it was described previously for the *voussoirs*, respecting the delineated prism. Once the main direction has the suitable form, the secondary direction is carved in the central prism; for that purpose the sections of the arches which compete in this *crossing*, will be cut with the proper inclination so that this one fits in correctly. To carry out this cut we need to know the arrival angles of these arches, angles that must be obtained of the vertical *montea* of the vault, by a compass or *saltarregla.*[3] These arrival angles are decided in relation with the top horizontal plane or bottom plane of the prism. The angle moves to the stone and allows to give the precise cut to the sections of every arch.

In order to complete the complex issue of the *crossings,* we will point out that, in the main direction, a full arch is formed putting together *crossing* after *crossing*. On the other hand, in the secondary direction, a *crossing* followed by a *voussoir* is placed in the assembling of the vault (Fig. 7).

Tas-de-charge [springing-stones]

In a gothic vault the *tas-de-charge* is the start all the ribs that form the vault. In the case of a *crossing vault,* the ribs load on the *transverse arch* and these arches in turn discharge into the *tas-de-charge*, so that, in this case, the *tas-de-charge* is only the springing of the *transverse arches*. The *tas-de-charges* are elements of the utmost importance to the stability of the vault, as they contribute in a significant way to fit the vault in the walls or columns that hold the cover. As previously mentioned, the *transverse arches* are oval arches, which means an arch that consists of three curves: the central curve and two smaller ones in its ends. These small arches determine the *tas-de-charge*, i.e. the tangential point between the arches of the oval is the maximum level that the *tas-de-charge* should reach. The ends of the oval are not therefore autonomous arches but part of the solid start of the vault that must be constructed by horizontal layers. This is a very effective resource that, on the one hand, facilitates the carving of the *transverse arches* and, on the other it simplifies the vault since it has only one curvature.

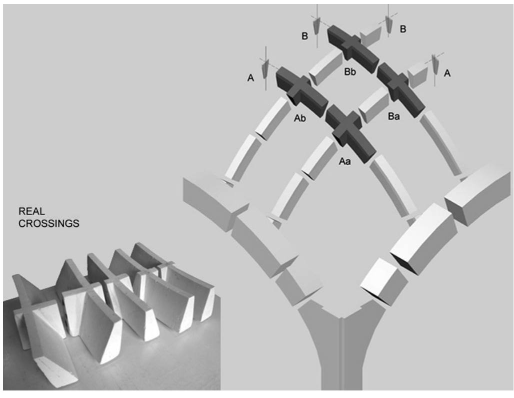

Fig.7: The cross pieces in the main direction.

For the construction of the *taps-de-charge* we resort again to the *Moneta*: the drawings of the horizontal layers that the *tas-de-charge* form in the elevation and in ground plan. With these drawings are prepared a series of templates that allow to carve every layer. The lower layer is traced in the lower plane of the ashlar, and the top layer on the top face. Then we proceed to the stonecutting connecting a face with another. As the last *tas-de-charge* receives the transverse arches, we need to carve it with adequate inclination to come into contact with the first *voussoir*; this information is extracted from the *montea* in elevation. Thus, the *transverse arch* works as an arch above the level of *tas-de-charge.*

Centering

Once the *voussoirs*, the *crossings* and the *tas-de-charge* are carved, we proceed to the construction of the vault by putting the *tas-de.charge* in its precise place. On this occasion, in order to counteract the inevitable horizontal thrusts, were envisaged a strong buttresses embracing the *tas-de-charge*. At this moment became necessary the concurrency of the woodwork to assemble for preparation of the centering. The design of the centering is important because it will receive the weight of the ribs and later will have to be removed with ease. Please note that this type of vaults as benefiting from gothic knowledge also in the construction of the centering. A coffered Roman vault built with lime and little stones masonry or with *voussoirs*, would have required a complete wooden structure capable of supporting all the weight of the vault. However, being built by ribs, the centering should only support the weight of each arch while being built. It is important to notice that, once each arch is finished, is this arch that receive, instead the centering, all the corresponding weight of the vault; therefore the wood centering can be much more economic and lighter.

A wooden platform was constructed at a height of the *tas-de-charge* height. In the points where the *crossings* were placed, wooden pillars were located with the suitable height, again the *montea,* to place in its correct position each of them. Between these wooden pillars the centering of the arches were placed, holding with each other and stabilizing the whole structure.[4]

Assembling the vault

Once the centering is finished, we continue with the placement of the *transverse arches*, then the *voussoirs* and the *crossings* of the main direction. Finally, the grid is completed with the placement of the *voussoirs* of the secondary direction. It is in the process of placement of the pieces on the centering system where we must pay attention to the joints. To get a correct alignment of the *voussoirs* that form an arch requires placing them separated from each other, so that the errors of the carving are not transferred between them. The joints should be filled with a mortar of plastic consistency. Once the grid of the vault is completed, we get on by filling the *caissons* to obtain the complete surface of the vault. In this teaching experience we made the decision not to implement the *caissons* so that the grid of ribs is perceived more clearly; you can see how thanks to the *distorted sections* of the arches and *crossings,* in the extrados you get a completely smooth surface that allows to place correctly the vaulted shell (Fig. 8).

Removing the centering

The vault is not fully complete until the wooden centering has not been removed. Only then the vault reveals all the beauty of its geometry. The removed of the centering of the vault was filmed by the service of tele-education of the Universidad Politécnica de Madrid and is visible in the web page: www.youtube.com/watch?v=qPdMUnOAbSk

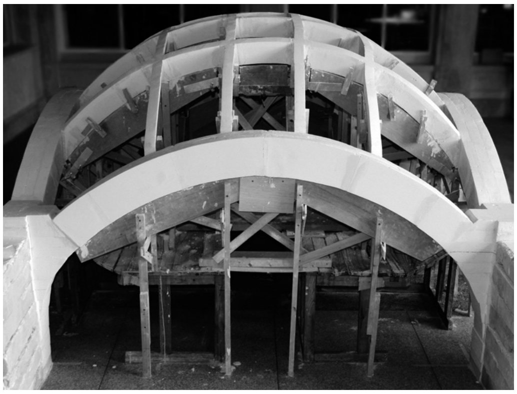

Fig.8: The *crossing vault* all ready built with the centering.

As previously stated, participating in the construction of a *crossing vault* leads us to discover how, in the 16th century, the gothic art of building, of important medieval origins, blends with Renaissance designs. First of all, we saw how a strictly classical vault could be studied from a gothic perspective, which enriches and facilitates its construction. Secondly, already in the Workshop of stonework, we saw how in order to carve the *voussoirs*, the *tas-de-charge* and the *crossings,* we can apply medieval methods of carving and stonecutting whereby the geometry of the arches and the volumetry of the more complex pieces were transferred to the stone.

Without the knowledge of construction, as an indissoluble part of the architecture, any approach to the creative process of architecture will remained unexplained; as shows the experience we bring to your attention. Without a constructive definition of the *crossing vaults,* it is impossible to understand this important chapter of the architectural work of the 16th century in Spain.

On the other hand, participating in the construction of a vault is an extraordinary educational experience. Students live the excitement of translating into practice the empirical knowledge. The history of architecture, the discovery of the medieval geometric principles; the carving, the stone cutting tools, the stone masonry, the emergence of the stereotomy principles, the centerings, the assembling work and, finally, the principles of stability appear along the construction of the vault. Thus, the greatest achievement of this experience was linking theory with practice, giving meaning to the theory through the real experience of the construction.

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Notes

1. Gómez (1999) attributed to Siloé and the stonework of the Jerónimos' Monastery of Granada the use of the *caisson* vaults made with crossings. An Andalusian stonework school was founded in which this type of vaults appears with remarkable frequency.

2. We can say that the *caissons* are the vaulted shell of this type of vaults. The gaps between the ribs that form the grid are covered with a *voussoir* carved in the manner of a vault by square layers. In the Workshop we could not carry out these *caissons*, that's why their carving process was not described in this text.

3. The *saltarregla* is a kind of compass with straight arms to transport angles. This tool was already used since the Middle Ages.

4. Hontañón's (1540) recommendations were followed for the construction of the centering.

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