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Temporary structures as part of the constructive process: a centering system proposal for the oval dome of San Carlo alle Quattro Fontane

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Abstract: During the constructive process of some domes, it will be necessar the utilization of temporary structures to withstand the materials and guarantee their stability. Furthermore, in the case of oval domes, some of these structures, such as centering systems, become essential, which not only will have a structural function but will also guide the geometry of the construction and define the outline to be followed by the laying of the rows of bricks. When considering the volumetric conformation of these domes, the inherent geometry of the centering structure could be therefore considered the unequivocal link between the graphic design and the real construction.

In the specific case study of the oval dome of San Carlo alle Quattro Fontane, whose architect, Francesco Borromini, was aware of some stability principles, the thickness of the masonry, as well as the opposition of forces along the directions in which them are distributed, were also used to add stability to the whole. Thus, this knowledge of load distribution and static configuration would have been essential to design, place and size the different elements of the centering system probably used for the construction of the dome.

Based on these geometric and structural considerations, a surveyed digital copy of the real construction has been analyzed to propose a feasible centering system used during the construction of this dome.

Introduction

The plan of the church of San Carlo alle Quattro Fontane has an irregular octagonal perimeter with curved chapels aligned according to the central axes and oblique walls between the chapels. The space is covered by a 'cross' dome, set on arches and spandrels organized on the octagon. Nevertheless, the plan projection of it responds to a polycentric oval geometric construction.

Although the church does not have an oval but a mixtilinear plan, it paradoxically contains the greatest number of different ovals that can be contemplated in any building. A series of geometric/constructive reasoning leading to its construction were assumed to underlie this theoretical scheme. Besides, the freedom that the use of the oval gives to his designs leads Borromini to the superimposition of several designs relating to different levels of the church that share features and elements.

The oval form is the instrument through which Borromini succeeds in enclosing in the smallest possible space the characteristics of the longitudinal linear space typical of Latin cross churches, without losing the potential of the space of those churches with a central layout. For Borromini, geometry is an objective of design, not a presupposition (Bellini 2000, 350).

Borromini's interest in the oval form therefore resides in the condition of a polycentric figure that grants freedom in the choice of the position of the centers of curvature and the quantity of them, with the imposition of a single condition between them, that of obtaining perfect tangency between the different curves that make up the layout.

Borromini, therefore, conceived that the process of ideation is not limited to the design phase, but continues unrestrictedly into the construction site, considering the building as a core to be completed and recalibrated, open to any variable, according to unforeseen material contingencies, second thoughts of the client or the skills of the workers. These infinite possibilities can be well associated with the geometric layout of ovals. Moreover, Borromini's technical mastery allowed him to indulge in even unusual constructive solutions, not always congruent with those used and published in the historiography of the time (Bellini 2000)

1. Geometric analysis of the design drawings

From a geometric point of view, it is undeniable that, in most San Carlo alle Quattro Fontane drawings, the construction of the oval forma has a fundamental value as a regulating geometric tracing. However, although at first glance the oval seems to be fundamental in the layout of the church's plan drawings, this polycentric shape is not present in the architecture built at the level of the nave but turns out to correspond with the impost line of the dome above the church, which instead, is never explicitly represented.

A specific analysis of the oval's geometric construction present in some of these drawings can lead us to infer how these constructions may have been directly used for the construction of the dome. In the figure (Fig. 1) we can observe AzRom169, AzRom175, AzRom190 and AzRom192 drawings. In these drawings, the plan layout, conforms the

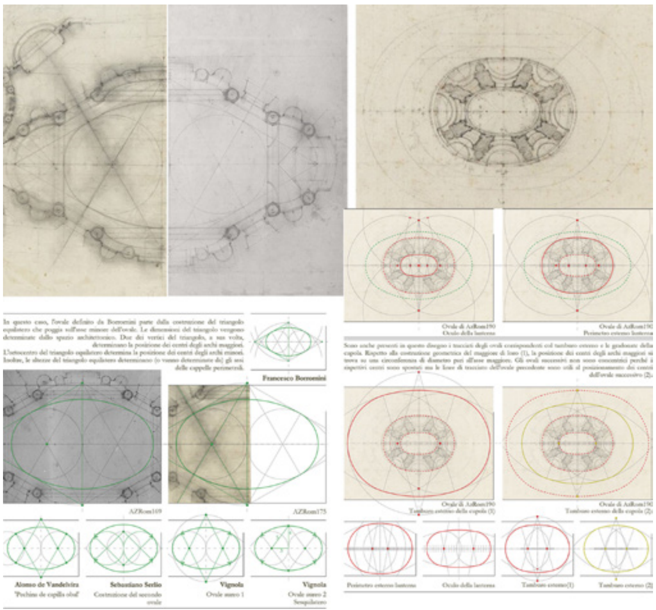

Figure 1. Geometric construction of the oval found in Borromini's drawings AzRom169, AzRom175 and AzRom190. Comparison with other known ovals of similar geometric construction. Image and drawings by the author.

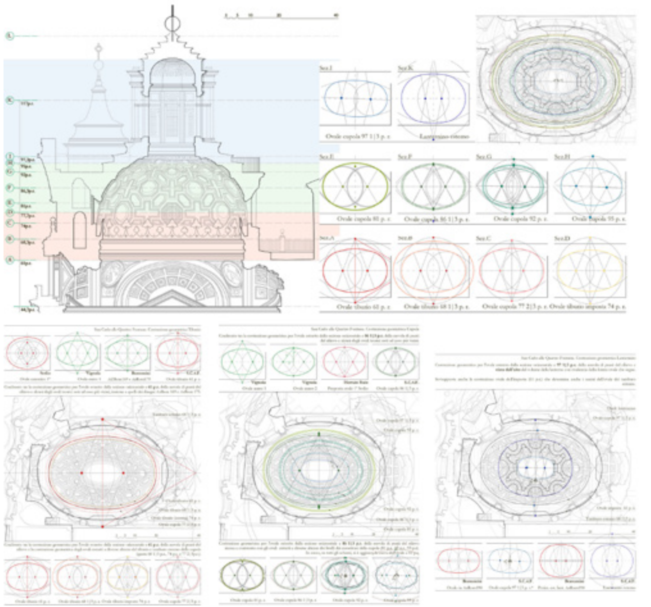

Figure 2. Horizontal sections considered for the study of the geometry of the constructed dome. Ovals related to the different extracted sections. The colors correspond with the three types of geometric constructions identified. Image and drawings by the author.

geometric construction of the oval, according to a direct relationship of correspondences and alignments between some known points. The construction of the central oval starts from the equilateral triangle whose vertices are fixed according to the dimensions of the architectural space. Two of the vertices of the triangle also determine the position of the centers of the major arcs of the oval. The side of the triangle containing these two points rests on the minor axis of the oval and determines the transverse axis of the church. The other two sides of the triangle, arranged at 60º, are parallel to the two inclined walls (diagonal chapel access openings) arranged between the columns of the church; the axes of the openings on these walls are coincident with the directions determined by the heights of the triangle. These drawings have very close proportions to the ones found on the built reality, and AzRom175 is indeed quite faithful to the actual dimensions. The two drawings AZRom190 and AZRom192 cover different aspects of the upper part of the dome, including oculus, lantern, and outer drum. We observe in the first of them the plan of the lantern, with the outer drum profile of the dome and that of the steps. We can also extract the oval corresponding to the geometry of the lantern oculus and the one related to the outer perimeter of it. Both ovals share the position of the centers of the major arcs. These points, in turn, are the points of intersection between the circumferences, which are useful in tracing the minor arcs of the oval that defines the outer profile of the dome drum. Compared with the previous drawings, the different ovals related to the outer drum and steps are not concentric; the successive centers of curvature are shifted along the major axis.

2. Geometric analysis of the built work

The survey of the constructed building and the subsequent processing of the data, both carried out by the author of this paper with the use of a ZF 3D laser scanner and semi-automatic photogrammetric systems, have led to the production of a dense point cloud model that has been considered as the main source data of the real building, always available during the research.

2.1. Analysis of the horizontal sections

As indicated by Canciani (2015), in order to analyse the oval shape of the built dome, it was deemed useful to extract different horizontal sections at various levels of the church, intercepting those architectural elements that determine such a polycentric shape.

In the figure (Fig. 2) the division by colors highlights the architectural elements into which the dome is divided, in direct relation to the different geometric constructions found: tiburium, dome and lantern. The ovals obtained at each architectural element develop more concentric shapes and the centers of the major and minor arches respectively coincide in their projection in plan. From this synthesis of the geometry of the San Carlino (see also Canciani 2015 and Canciani 2016), it has been observed that only the curve related to the tiburium (Sect.A-Sect.D) of the dome can be associated with that of the canonical oval (and its variants) drawn by Borromini in his project drawings (AzRom169 and AzRom175). Moreover, there may be a certain relationship between the analyzed curves and Vignola's Golden Oval 1: the circumferences of the minor arcs are inscribed in a circumference that determines the position of the centers of the major arcs. Despite that, the geometric construction of the latter is different, having the minor circumferences tangent to each other. Corresponding to Sect.B, we observe the outer drum of the dome and it follows the same geometric construction as the other ovals of the tiburium. The centers of the major arches of this oval correspond with the inner curve of the side chapels of the church below. Nevertheless, in its upper part, the drum's geometry is 'deformed' to fit the geometric curve of the canopy. It does not follow, therefore, the course drawn by Borromini in AzRom190. Up to the height of section Sect. D, it seems to occur that the centers of the minor arcs of the different extracted ovals are coincident with each other; the radius and the position of the tangent points change slightly, varying the radius of the major arcs slightly accordingly.

The cap, on the other hand, in its central part (Sect.E-Sect.H) has an oval that is comparable to Vignola's second golden oval, which, by the way, is also comparable to the shape of an ellipse .This oval has the peculiarity that the relationship between the axes and the relative position of the centers of the arcs maintain a sesquilateral proportion (triangle 3:4:5), and the centers of the major arcs lie on their own oval. At the height of section Sect.E, the position of the centers of the major radii, located within the oval curve, changes dramatically, while the centers of the minor radii remain fixed with respect to the lower sections. This condition results in an abrupt change in the curvature of the dome in the cross section, resulting in the oval at this height being slightly more flattened in its minor axis than those at the lower elevations.

In addition, the shape of the following upper sections extracted (Sect.G and Sect.H) clearly differs from the lower ones in which the centers of the major arcs are located close to the oval, if not on their own curve. For this reason, they can be referred to Vignola's 2nd golden oval, although their construction is even closer to that proposed by Hernán Ruiz (ca. 1560) in correspondence with Serlio's first oval.

In relation to what has been described above about the geometric construction represented by Borromini in his autograph drawings, we observe that they do not have many points in common with what has been finally built, except for the position of the centers of the major arches.

It also has to be taken into consideration that it also appears that the ovals extracted from these upper horizontal sections are slightly rotated or crushed in a non-symmetrical manner with respect to the lower ones related to the tiburium, arriving to a 3º rotation.

Regarding the ovals of the oculus and lantern, it is found that the construction of the oval on the section Sect.I, is more elongated and flattened than those on the lower sections (ratio of major to minor axis equal to 5/1), and its geometric construction is totally different from that of the ovals of the dome. This geometric construction seems to echo what drawn by Borromini in AzRom190 (Fig,1, lantern's oculus), although it would seem that the position of the centers of the major arches dialogues with the inner tax line of the dome and not with the outer drum, as seen in the architect's drawing. Subsequent investigation also verified the fact that the position of the lantern columns extracted on section Sect.K dialogues with the position of the columns below (Alonso García 2003, 208). If we therefore observe the oval that can be drawn from the projection from above of the outer cornice of the lantern (Sect. L), we find that it recovers the orientation set at the base of the dome, correcting the deviation suffered by it, confirmed with the analysis of the ovals extracted for the lower sections. It also dialogues with that of the outer drum of the dome: the centers of the major arches are incident in the line of the outer drum. Nevertheless, the geometric relationship that is established between both ovals (Sect.L and Sect.B) does not occur in the way suggested by the AzRom190 drawing.

From a construction point of view, the fact that the curves related to the ovals of the tiburium and the first third of the dome (Sect.A-Sect.D) have a common geometry allows to confirm the identification of construction phases. This portion of the dome was built with a coherent and unified masonry of horizontal rows. It can be said, then, that, for the lower part of the dome, the layout of the oval shape for the construction is determined in plan. The abrupt change between the curvatures of the ovals related to Sect.D and Sect.E sections highlights the gap between construction phases. The gradual transformation of the ovals in correspondence with the successive horizontal rows responds to the progressive change in curvature of the oval defined for the impost and the one for the oculus and directly derives from the construction practice and the execution of the dome. The fact that the outer lantern recovers the original orientation of the layout preestablished, evidence that the rotation undergone by the dome resulted from an inaccuracy in the construction or due to a mechanism triggered during the construction process, or because of some static problem that arose at a later stage. In addition, the partial deformation of the dome in the quadrant where the bell tower approaches it may also be evidence of a possible mechanism triggered punctually. If this hypothesis is confirmed, the position and size of the bell tower, which is of later construction (eighteenth century), may have helped to give stability to the dome.

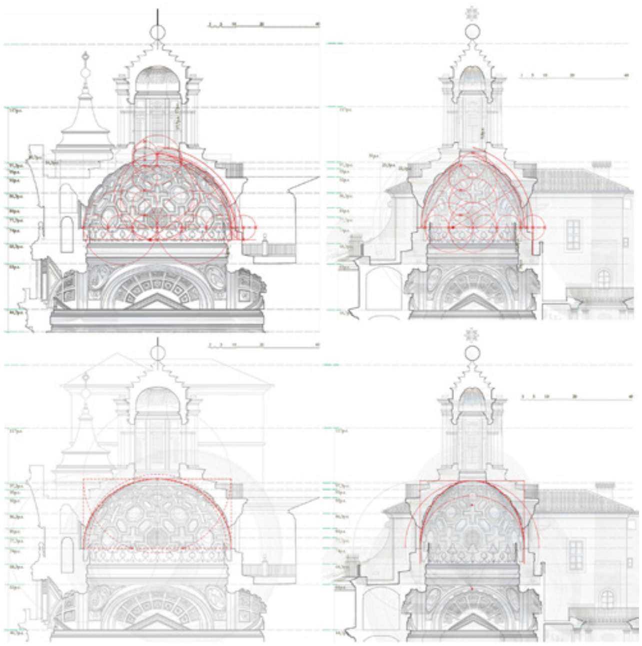

Figure 3. "Division by parts" and "Rope's" systems to trace the geometric layout of the curve defining the arc of longitudinal and transversal sections of St Carlino. Image and drawings by the author.

2.2. *Analysis of the vertical sections*

In elevation, the curve that defines the dome of the San Carlino is variable, determined by a curve similar to the semicircumference in correspondence with the longitudinal section and by an arc of circumference corresponding to the cross section: the relationship between radius and height of the curve on the longitudinal section is slightly above 1 (1.1), while that on the cross section the arc is more acute and the proportion relationship is reduced to 0.75.

In the figure (Fig. 3) we can observe the relationship of proportion established between the plan dimensions and the

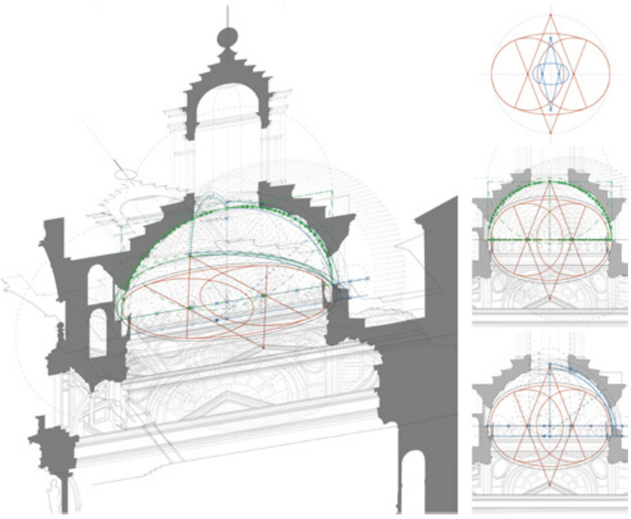

Figure 4. Axonometric diagrams highlighting the oval defined for the impost, at its corresponding height, combined with the different methods possibly used to layout the curvature of the dome's inner surface. Image and drawings by the author.

geometric construction of the sections, with the highlighting of the construction "by parts" for the drawing of the arc related to the intrados and extrados sixths of both sections, longitudinal and transversal. Although the proportional relationships between plan and section are obvious, the question that needs to be asked is whether there is a critical thinking behind these proportional relationships (established by us as part of a theoretical abstraction) and whether they were envisioned, designed and constructed in this way, rather than another. In this regard and due to the absence of specific design documentation on the geometric layout of the vertical sections, it might also be thought that the shape of the sixth, in this case, derives from direct constructive application and execution by concentric rings, as seen in other cases. If so, the shape of the resulting vertical sections would simply be a direct consequence of the system used to execute the dome and, in this way, it would also be possible that the masons of the factory used the rope method for defining the geometry of the ribs needed to shape the dome. In fact, if we try to reproduce the tracing of the curve that conforms the dome by means of the rope method and thus, propose the tracing of an ellipse, the correspondence with the inferred curve of the survey is quite assimilable.

By comparing the plan design drawings of the oval defined for the impost, with this section drawings, several reasonings can be made: from what is shown in the axonometric diagrams in figure (Fig. 4), the relationship between the position of the major arc of the oval defined at the impost and the maximum height of the curve that determines the longitudinal section, whether it is determined by the 'by parts' layout or the 'of the chord' layout seems evident. It can also be seen that the position of the minor centers of the oval defined for the plan and the position of the foci of the ellipse that may have determined the curve of the dome in the longitudinal section are very close. It could be assumed, therefore, that Borromini defined the shape of the oval at the base and later, the centers of the minor arcs were used to fix the nails from which the shape of the vault in this section was then traced by the rope method.

When we refer to the tridimensional construction of this oval dome surface, as stated by Alessandro Sartor

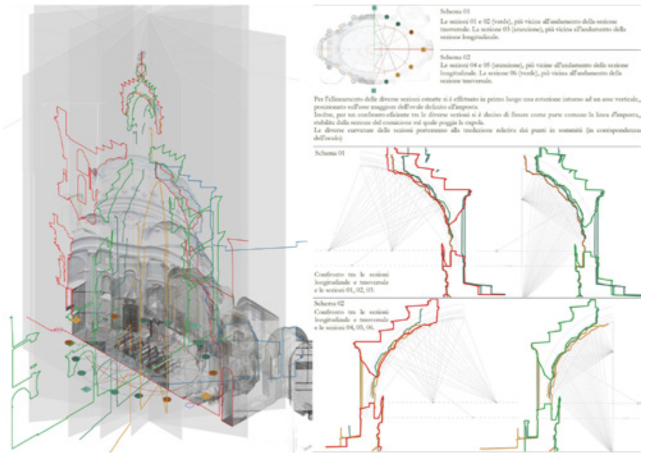

Figure 5. Laying plans of vertical sections analyzed. Image and drawings by the author.

(Sartor 2000), it is not possible to generate it by following a geometric pattern of surface revolution, but it is more likely that it was construction practice that determined the shape of it, furthermore if we consider the brick construction and their usual way of laying them. It would not be enough, then, to study the two main sections to know how the surface of the dome's intrados was actually built. It would be necessary to study other secondary sections, corresponding to vertical planes that pass through singular points of it-such as the geometric centers of the columns below-and that follow alignments related to the geometric layouts in the design drawings. The choice of the laying of these planes will be decisive for the construction of the dome, since these will determine the orientation of the ribs that will give the actual shape of the surface conformed by the laying of the different materials. We must consider, therefore, to an economical and efficient construction system that has allowed for the minimization of resources and material used during construction. In the case of oval domes in which, the curves defining the impost and oculus are not concentric, it would certainly have been necessary to use a system of ribs to define beforehand the shape that the master masons would have to follow with the laying of the bricks. As has already been mentioned, one cannot think of a pattern of geometric construction of revolution for obtaining the surface, but of a system in which the choice of preferred directions roughly guides the resulting form. In this way, geometric choices in two dimensions produce a three-dimensional surface.

Analysis of the vertical sections extracted from the survey following different laying vertical planes show that the variation in curvature of the inner surface of the dome is, in each case, progressive between the curve of the longitudinal section and that of the cross section. (Fig. 5)

3. Construction aspects and structural static considerations

The vertical sections of the dome, however, not only guide the geometric form, but are directly related to constructive questions, the thrusts that the lower part receives and the way in which the vertical loads are translated along the building.

As has already been mentioned, Borromini's training had a purely empirical character so, his design and drawing choices would surely have been directly related to the

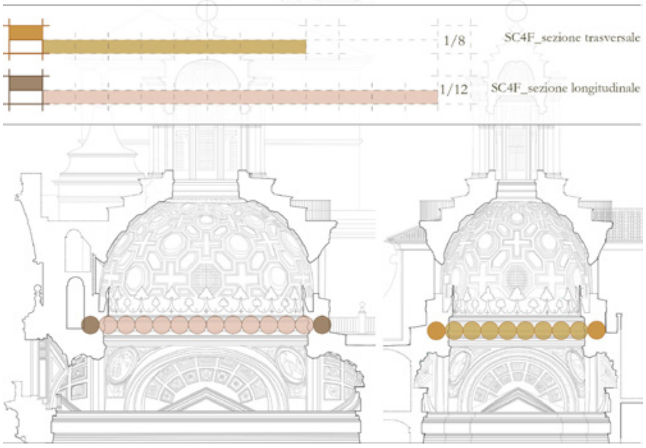

Figure 6. Proportional relation between diameter and thickness of the dome at the height of the impost. Image and drawings by the author.

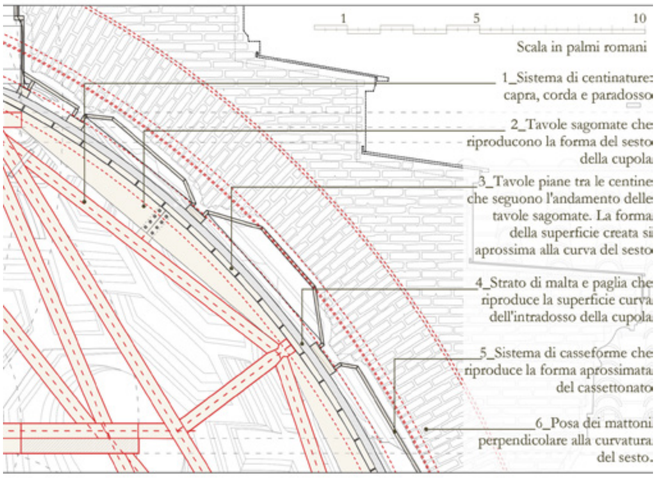

Figure 7. Constructive inner section of San Carlo alle Quattro Fontane. Image and drawings by the author.

constructive considerations applied as customs of the activity of the construction sites. In this regard, in the treatises on architecture and construction practice of the period, when reference was made to the design and sizing of domes, responsibility for construction choices was, in most cases, left to the good intentions of the masters, although it was common to give broad indications (Marconi 1997). For this reason, the comparison of the construction exempla found in the treatises of the time with the data deduced from the survey of San Carlo alle Quattro Fontane was useful to verify that, even in this case, the relationships between the diameter of the dome at the impost and the thickness of the masonry texture at that height are maintained and coincide with the proportions established in the reference texts: in its cross-section, corresponding to the minor axis of the oval in plan, the diameter/thickness relationship is around 1/8 while that of the longitudinal section (major axis) is about 1/12. (Fig. 6)

To further describe the internal masonry composition of the dome, it's been analyzed the specific report present on the last restoration works (Degni 2007, 199–208) that specifies the materials used for the construction of the dome and their arrangement within the wall septum. It has thus been possible to reproduce the inner composition of the dome, associating it with the different construction phases. Corresponding with the first third of the dome, starting from the impost line, the construction process is reduced to the superimposition of horizontal rows of brick, following the course of the horizontal oval curve drawn for this level in the design drawings. Corresponding with the other two-thirds of the dome, which starts from the height of the octagonal window flats of the lower part, and where the laying of the bricks follows a course perpendicular to the curvature of the dome, the surface functions in an 'arch' fashion, and for its construction the need for the use of provisional centering systems can be stated. In this phase the bricks should be placed therefore, of shear. From what was found from the survey investigations, the coffers are also conformed at this stage, using smaller and fragmented bricks together with mortar to adapt the shape to the previously placed formwork.

The outer drum, steps and lantern are also constructed in this phase and the bricks used recover the horizontal course. It is at this stage that the dome acquires its load-bearing capabilities. (Villani 2008). Nevertheless, the final shape of the coffers is completed at a later stage, with the addition of the arriccio from the inside of the dome, to reinforce and adapt the shape where necessary. At the time of placing the formworks around the dome, the surface on which they should be placed is a uniform surface, made of a layer of mortar and straw applied on flat boards, which regularizes the surface of the canopy. (Fig. 7)

The statics of the vaults plays a prominent role in the structural configuration of Borromini's projects, focused on countering not so much the fragility as the "violence of the vaults," as he writes in the Opus Architectonicum, and to preside over the most stressed elements with tools for unloading, contrasting, and distributing loads, mindful of models drawn from the Roman building magisterium and possible exempla from the late antique and Byzantine traditions. The calotte is a brick shell that discharges precisely on the radial structure of the lower body, according to a skeletal pattern derived from the late Gothic tradition.

In the case of the church of San Carlino, although the oval shape is doubly symmetrical and, from this purely geometric point of view, the statics of the vault could be ensured by mutually contrasting vaults and wall masses, from a constructive point of view the dome is made stable by the 'box-like' bodies that enclose and contain it (Bellini 2001). As what is said in (Bellini 2001, 48): "Borromini is convinced that the motion of the upper structures is constrained in different ways and quantities depending on the material and masonry apparatus. So, in the building body, Borromini identifies directions and privileged areas that take charge of holding up the structure". For Borromini, the failures of a vault are related to the kinematics of its shutters, and therefore, he believes that blocking these kinematics (the "*violenza delle volte*") of the arches means ensuring the stability of the vaulted organism (Bellini 2004, 133).

In the case of San Carlino, Borromini chooses to replace the pillars with a shapeless masonry section that runs along the various corridors and chapels. The central space is thus surrounded on the sides by vaulted rooms (except in the facade, where it serves the functions of a counterweight that stiffens the central body, formed by the two overlapping churches (church and 'church below'), making the whole a solid support to sustain the dome, tiburium and lantern.

Borromini is acutely aware of the static weakness of that side and, although it is not represented on his drawings,

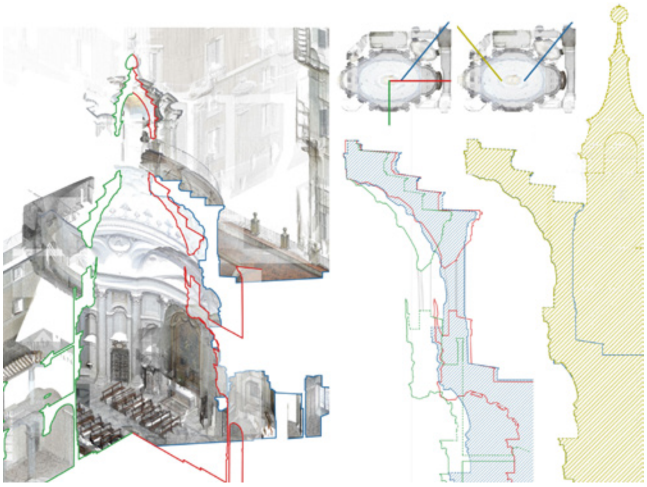

Figure 8. Vertical sections of the dome survey from where Borromini's statics expertise can be analyzed. Image and drawings by the author.

he shifts the church slightly toward the refectory, probably during construction, causing the apse of the high altar to protrude into the rear corridor. This slippage, in the section of its lowest sixth, allows for an increase in the resisting section in the façade side (Bellini 2004, 134). From the analysis of the different survey sections of St. Carlino's survey, the whole system of contrasts just described is more developed in the longitudinal than in the transverse direction. In this respect, therefore, it is evident that Borromini reasoned about more consistent thrusts on the major axis than on the minor axis and, consequently, about the variation of the sixth of the oval dome. (Fig. 7)

However, if we look at the diagonal section of the side of the steeple (north quadrant of the church), the static pattern is different: the wall mass added by the steeple acts like a buttress, adding vertical weight above the vault, thus counteracting the lateral thrust. (Fig. 8).

This situation correlates with the analysis of the horizontal sections, where it was possible to observe the punctual variation in the shape of the geometric oval.

It is known that the present bell tower is the result of a reconstruction after the original one designed by Borromini, carried out by his nephew Bernardo according to his uncle's instructions, given the 'dimensional inadequacy' of the initial one. There is no evidence in the written references of the reasons for this belief/choice.

To verify the deformation mentioned by the analysis of horizontal sections referred to, the dome quadrant relative to the bell tower was compared with that of the opposite (south) quadrant through the alignment of the relative portions of the point cloud. Given the double symmetry condition of the dome, theoretically, the surfaces of both portions should be corresponding and perfectly overlapping. Once the partial point clouds relative to both portions were aligned, three additional vertical sections were extracted, following the pattern of orientations studied previously.

Sticking to what we infer from this analysis, one of the reasons why Borromini might have found necessary to rebuild the belfry might have been to reinforce the corresponding quadrant of the canopy, given the deformation underwent during construction. Such a choice, of modification in progress, would not have been the exception in Borromini's way of acting.

4. The worksite

The construction of the convent of San Carlo alle Quattro Fontane was very gradual, until it included the entire trapezoidal lot defined in Borromini's drawings. It was built in several phases, with partial implementations scattered over a period of time of more than fifty years: a first phase, between 1634 and 1643, a second phase between 1659 and 1667, and a third phase, by Borromini's nephew Bernardo, between 1670 and 1675, as specified in (Bonavia, Francucci, Mezzina 1983). It was not until 1638 that the first work began on the construction of the church. By June 1641 the stucco work had been done and the first mass was celebrated by Cardinal Barberini. In the following years, finishing work was done on the facade, in the sacristy, and in the church "below." In the fall of 1646, the church was consecrated. Between 1656 and 1659 the first bell tower was built, triangular in shape. The architect's death on August 2, 1667, interrupted the construction of the convent's façade on Via del Quirinale, which, begun in 1662, had already surpassed the level of the first cornice and was at the level of the bases of the second order, as evidenced by a drawing by Nicodemus Tessin, datable around 1670 (Portoghesi 2001, 26). In February 1670 it was decided to tear down the bell tower raised in 1656, according to the explicit wishes expressed by the architect before his death, because it was considered dimensionally inadequate. The new, quadrangular plan was quickly built the same year, under the guidance of Bernardo Borromini. In 1675, Bernardo Borromini took on the task of completing the facade. The profile was remodeled and elevated in accordance with the decision for further vertical development, which was not clearly traceable to the architect's original intention. It's not possible to know whether Bernardo decided to make this change from the original design also for reasons of stability, and the elevation of the façade, so prominent, and the connection between the dome drum and it were the result of a consideration of improving the stability conditions not only of the façade, as has been previously mentioned, but also a way of constraining the façade and dome, and making them both more stable. The addition of the vertical weight of the facade, in that part of the dome would, in turn, help counteract the buoyancy of the dome in its longitudinal section.

On one hand, from a construction point of view, the building site was a very complex replacement site, with partial sewing and unsewing in its various parts. On the other hand, most of the workers present in the first phase of the San Carlino building site (convent and church interior), had been former companions of Borromini's Madernian apprenticeship. He knew masters and master builders, frequently his own countrymen, and he also knew their way of working, their exceptional mastery of execution and mastery in the workmanship and use of machines and provisional apparatus (Marconi 2001, 115). This situation led to the presence of numerous highly specialized workers on the site (Tabarrini 2001).

4.1. The 'Fabrica' books

The book of the 'Fabrica di San Carlo alle Quattro Fontane, Ms. 77a (convent archive catalog collection numbering), Fabrica della Chiesa (1650–1655), was written by the then Procurator General of the Convent of the Order of the Spanish Discalced Trinitarians, Fra Juan de San Buenaventura. This manuscript describes in detail the construction phases of the Convent building and is the only contemporary documentary evidence of the architectural work.

Accompanying the main text on the fabbrica there is a second manuscript volume, referred to in the bibliography as Numero Primo, which likewise contains notes on the building site, receipts, accounts and pacts of different kinds with the workers, and reports on the costs and payments for the construction of the different parts of the convent complex.

Of particular interest in this regard are a few pages with descriptions of the material supplied to the master masons and carpenters, in which information is given on the date, type of element supplied, approximate dimensions, and prices.

As also reported in (Degni 2007, 104), one of the pages of the latter document (pages 163–164), presented as an annotation for master Nicolò Scala, describes the supply of timber to master Donato, carpenter, for the construction of different parts of the complex, differentiated into: church below, church, "*porteria", "stantia"* and capellate. The wood used is, in cases where specified, chestnut, the types of board used are beams, rafters, flats and "*legno per palario*" (palarium wood). The summary dimensions of the elements are also specified in most cases. On this page, the intended use of the material delivered to the carpenter is not made explicit, but in two of the entries, there is a generic indication of the use of the lumber: for reinforcement (*"per armar"*) and for shoring („*per apuntalar*"). In addition, on other pages of the manuscript there is a direct reference to the encasement work for the reinforcement of the vaulted structures. They were carried out at the expense of the master Murator Tommaso, who was also responsible for the procurement of some of the materials and labor: on the aforementioned page, in addition to the wood for the incasing, several beams for the roof of the library, bricks and tiles, tiles and palette are mentioned, and on the page (Nº Primo, 158) direct reference is made to the encasing for the snail staircase and the wolfs mouths of the church below. From this fact it can be inferred that, even in this factory, reinforcing and centering work was a specific task of master masons. Although no direct correspondence between the listed pieces and the elements of the centering system could be found, the dimensions and quantities could be assimilated to that construction phase.

5. Proposed centering system for the dome

As already said, Borromini is aware, thanks to the study and analysis of the scientia operativa practiced in the construction sites he frequented and applied in the works he had as a direct reference, of certain principles of stability of domed organisms. He is in favor of the use of counterweights to stop the kinematics inherent in domes and to ensure their stability. He is aware, therefore, of the functioning of the domed organism as a whole, starting from the eventual lantern and reaching up to the foundations. While this organism is not complete, therefore, it will need auxiliary and provisional structures to ensure its stability.

Therefore, among other reasons, it could be confirmed that for the construction of the dome of San Carlo alle Quattro Fontane, a system of ribs was used to support the dome

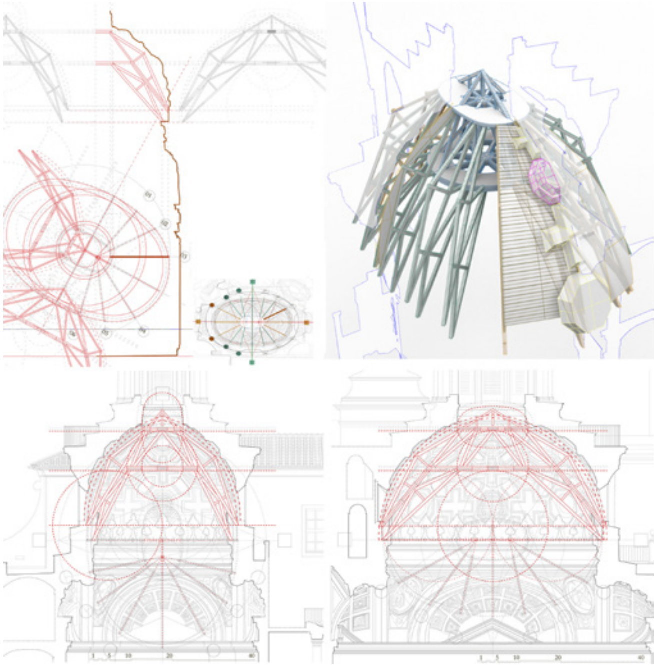

Figure 9. Centering system proposed for the construction of the dome of San Carlo alle Quattro Fontane. Main and secondary ribs. Image and drawings by the author.

from its intrados during the construction process, before the complete execution of the dome and the masonry that conforms the tiburium, which adds stability to the organism.

It has also been said that in addition to holding the materials until the completion of the construction, the centering system guides the geometry of the construction and defines the course to be followed by the master masons as they lay the rows of bricks.

From a strictly practical point of view, the system that would need the least assembly between the elements and thus, the one most easily executed system would be the chosen one.

On the basis of these considerations, taken from the geometric rules in the design drawings and the actual form of the work, deduced from the surveys carried out, comparing them with the reference drawings studied on the construction of domes and with those on centering systems represented in the treatises of the time, a provisional centering system was hypothesized, in which the proportion relationships between the longitudinal and transverse sections allowed the use of a common central structure where the two ribs related to the main sections also fit together.

The height of the first level of the two into which the structure is divided is determined directly by the major diameter of the dome, being half of it and therefore, also corresponds with the length of the semi-major axis of the oval defined at the impost. The diameter of the circular platform arranged on the first level corresponds with the major axis of the oval defined at the oculus. The height of the second level of the structure, relative to the first, is also determined by the dimensions of the oval of the oculus, being equivalent to its semi-major axis. The dimensions of the second platform relate directly to the dimensions of the oculus.

The construction of the two main ribs followed the scheme of division by parts, in which, once the starting point (at the impost) and the ending point (at the oculus) are defined, the main elements (chord, goat and paradox) are placed.

The grafting of the different secondary ribs onto the main structure will then be supported by the geometric arrangement of the different meridian ovals defined in the design and the corresponding vertical section. The relative position of each secondary rib would respond to the curves of the oculus and the impost and would be placed at their relative heights. The remaining elements should be defined accordingly, having as a direct reference model the one defined for the transverse and longitudinal main sections. (Fig. 9).

Conclusion

This research, focused on drawing as an investigative tool for the knowledge of architectural heritage, is directly related to the use of the oval shape for the construction of domed organisms. The analysis of the different ways of drawing the oval shape, allowed some comparisons regarding how and under what circumstances the oval shape was applied in the construction of architecture. The application of this methodology turns to be really appropriated as it considers the geometry of the centering systems as the direct nexus between design (theory) and construction (application).

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Vaulting Techniques in Romanesque Burgundy: Advanced Large-span Groin Vaults at Sainte-Trinité in Anzy-le-Duc (1001–1120)

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Abstract: After antiquity, large span vaults disappeared from Christian Western Europe. It was not until the eleventh century that they returned, and it was in this and the following century that various techniques of vaulting can be found in Burgundy. Sainte-Trinité in Anzy-le-Duc (1001–1120) with its various vaults exemplifies many of these techniques. Beyond that, the geometrically complex groin vaults spanning the nave of the church, a rather big achievement for the period, show a culmination of Romanesque vaulting techniques.
To investigate these vaults through Building Archaeology, high-precision surveys using structure-from-motion (SfM) were employed to capture the still original building fabric with all its details. Further, detailed geometric analyses were used to reveal formwork traces and deformations. By reconstructing centerings and formwork, the construction process and design principles were uncovered. It became clear, that Romanesque builders were capable of building large-span groin vaults by employing intermediate centerings.
To show the broader construction history of Romanesque vaults, comparisons to other significant churches of the era and region, such as Saint-Philibert in Tournus (1008–1120) which was analyzed in a previous publication, give insight into the development of vaulting techniques throughout the eleventh and twelfth centuries.

Introduction

The history of vault construction dates back to the Neolithic, but wide-span vaulting really emerged in the first century CE when the Romans built spans up to 24 m, like in the Basilica of Maxentius in Rome, using innovative techniques and materials like *opus caementicium*, brick, and voussoirs (Lancaster 2005, 138; 2015, 2–18). Yet, after the decline of the Roman Empire, large-span vaulting disappeared from Western Europe until the mid-tenth century, when domes with up to 8 m span were built in the Great Mosque of Córdoba (Fuentes 2019). These however differ significantly from ancient Roman vaults and medieval ones in Western Europe. In Christian architecture, vaults of similar spans reappeared in the eleventh century, for instance in Burgundy at Saint-Philibert in Tournus (1008–1120).

The large differences in the geometry of early Burgundian Romanesque vaults and the geometrically complex domes of Córdoba make a direct link unlikely. Indeed, the somewhat clumsy early Romanesque vaulting attempts, visible in the crypt of Saint-Philibert, suggest a fresh discovery of techniques. The details of ancient Roman cross vault construction are debated (Lancaster 2005, 34–39; Rasch 2009), however their geometry is usually based on two intersecting semicircular barrels. Some Romanesque cross vaults show a similar geometry and were demonstrably constructed with a principal barrel to which lunettes were added. This could be considered a "false" cross vault, as it is based on a main barrel with secondary lunettes. However, diagonal centerings were introduced early, as exemplified in the galilee of Saint-Philibert from 1030 (Pfister, Holzer, and Vandenabeele 2023). There, the geometry is defined by two diagonal centerings and four more along the boundaries, creating what could be considered a "true" cross vault.

In the first half of the eleventh century, groin vaults spanning more than 2 m started to reappear. However, only in the early twelfth century did they also appear over central naves. A group of churches characterized by such vaults, a rarity in Romanesque churches, has been identified already by Jean Virey (Virey 1892). They are sometimes called *Martinian churches* after Saint-Martin in Autun, which is the suspected and no longer existing "mother-church" of the group. Many theories on the existence of this grouping have been posed without definitive conclusions. (Oursel 1928; Vallery-Radot 1929; Sunderland 1957). Matthias Hamann regarded this grouping as noteworthy, but of secondary importance, as there are also many differentiating characteristics among it (Hamann 2000). Regardless of the coherence of the group, their groin vaults over naves stand out. Not all the vaults of these *Martinian churches* are dated exactly, but some of the oldest remaining ones can be seen at Sainte-Trinité (Sainte-Trinité, la Sainte-Croix et la Sainte-Marie) in Anzy-le-Duc (1001–1120).

This contribution focusses on the rich collection of vaults built between 1001 and 1120 at Sainte-Trinité in Anzy-le-Duc, to highlight the variety and development of Romanesque vaulting techniques over 100 years. Based on on-site observations and digital surveys, new insights were obtained into the challenging design and construction of these structures. The vaults of the crypt, of the aisles, and of the nave display at least three different building techniques that were studied based on geometrical analyses and the detection of traces of original formworks. Sainte-Trinité is an important testimony not only to Romanesque architecture, but also to understanding the emergence of Gothic architecture just 20 years later at Saint-Martin-des-Champs in Paris in 1140, after which, intriguingly, cross vaults over naves albeit with ribs became widespread.

Description of the church

Connected to a basilical nave is a transept, on which a crossing tower stands, followed by staggered choirs and apses above a crypt. (Fig. 1)

The latter consists of three spaces connected by arched openings. The centerpiece is a hall divided into three naves of three bays by four columns. Those are the only difference to the otherwise identical choirs above. The central nave ends in an axial chapel and is covered with groin vaults. The aisles on each side are only half as wide and covered with only half groin vaults, which meet the wall at their highest points. The two adjacent rooms are covered with a single groin vault each. From the northern side room, a staircase leads up to the northern arm of the transept.

Above the hall of the crypt is the main choir with an apse and axial chapel. (Fig. 1) To the north and south, above the respective side rooms of the crypt, are side choirs, each with an apse. All choirs connect to the transept, which also has an apse at the extremity of each arm. The crossing is covered with an octagonal dome on corner squinches, the apses with half domes, the transept and main choir with barrel vaults, and the side choirs with groin vaults.

Extending from the crossing is a nave of five bays with two side aisles. Both the side aisles and central nave are covered with groin vaults. While the transept and choir were built mostly with *petit appareil* and ashlars were only used for pillars and corners, the walls of the central nave were built entirely in ashlar. The aisles also show more ashlars, although the outer walls are built from *petit appareil*, but with larger formats than the eastern half.

State of the art

Dating Romanesque architecture, especially crypts, often proves challenging. Large beams for dendrochronological dating are hardly ever present, and radiocarbon dating of small pieces of wood is imprecise and might not relate exactly to the time of construction. Consequently, dating relies heavily on the style of sculpture, the floor plan layout and possibly stone working, all of which are not entirely accurate. Additionally, archival material might be available but is not always reliable.

In the case of Sainte-Trinité, a comprehensive description of its foundation can be found in a translation by François Cucherat (1812–1887), art historian and archaeologist (Cucherat 1862), of a Latin text by Mabillon (Mabillon 1668). Mabillon in turn relies on the *Vita Hugonis*, which was written in Saint-Martin in Autun around 1040. It describes the story of the foundation of the priory in Anzy-le-Duc in 913 and of Hugues of Poitiers who was venerated there after his death around 930. Further, the existence of a first church was mentioned, whose exact location remains unknown. In addition, it recounts, how, after a "double miracle" in April

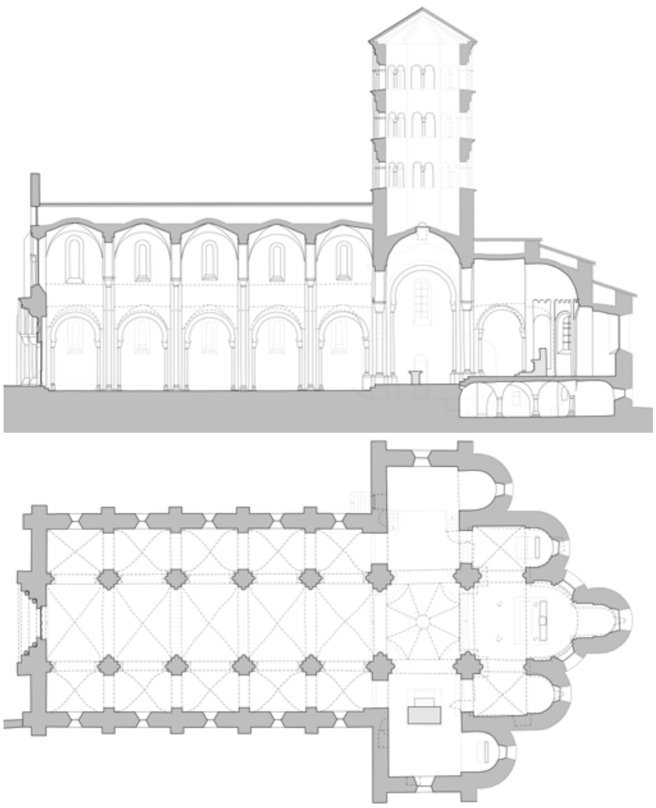

Figure 1. Longitudinal section and floor plan (M. Pfister).

1000, the monks decided to move the relics to a "more befitting tomb", presumably the crypt as it still exists today. Also recorded was the translation of the relics in December 1001, by when the new tomb must have been finished.

A detailed archaeological investigation was carried out in 1989 by Christian Sapin, who excavated the northern staircase to the crypt which was previously only accessible from the exterior (Sapin 1991). During the excavation, an identical blocked staircase to the southern arm of the transept was also located. Sapin further noted that the construction of the crypt, staircases and *chevet* appears coherent. Indeed, the strange layout of the vaults of the crypt hall with only half groin vaults suggests that the floor plan of the crypt was chosen not for its own vaults but rather for what came above, as is often the case (Sapin and Amelot 2014, 124, 241). The same layout of choir and transept was excavated in the slightly older church Charlieu III, dedicated to Saint-Fortunat in 1094 and probably begun under Abbot Odilo before 1049 (Sunderland 1957). A similar layout has also been reconstructed for Cluny II (963–981) (Conant 1954). The conception of the crypt, choir, and transept as one ensemble at the start of the eleventh century seems therefore plausible.

To a similar conclusion came Matthias Hamann, who dates the crypt to 1000–1030, based on the translation of the relics in 1001, the layout as a transition from Carolingian corridor crypts to hall crypts, and the sculpture style of the capitals (Hamann 2000). He too noted that the layout of the choir and transept, which must have already been decided while building the crypt, is very similar to Cluny II.

The choir and transept are generally dated to the end of the eleventh century. Hamann divided it into two phases, with the second one being around the crossing, which had to be adapted to the nave that followed. He dated both phases to around 1090 (Hamann 2000). How the crossing looked before, and whether it might have been built against the nave of the previous church, is unknown. Further, as the crypt was built with a choir and transept in mind, but the current version of those parts is dated around 90 years younger than the crypt, an unexplained gap remains. Either the construction was halted soon after the completion of the crypt and only taken up again at the end of the century, or a previous but almost identical choir and transept existed and were replaced.

Hamann divided the nave into two phases as well, since in the upper parts of the first two bays from the West, mason's marks start to appear, and the masonry shows some different characteristics (Hamann 2000). He dates the eastern phase of the nave to the 1100s, the western one to the 1110s, mostly based on the sculpture. Other researchers generally came to the same conclusion (Pendergast 1976; Vergnolle 1978). The building was finished with the addition of the crossing tower.

Overall, the existing research agrees on the phases, although the gap between the first and second phase remains unexplained. The main phases can be summed up as follows:

- crypt, 1001
- choir and transept, ca. 1090
- nave, 1100–1120

Methodology

To investigate the vaults in question, a highly detailed survey using structure-from-motion (SfM) was carried out. The vault extrados was not surveyed due to inaccessibility. The correct scale was provided by single point laser measurements. The resulting meshes were analyzed in two steps.

Initially, the meshes are processed to highlight small surface deviations such as imprints of formwork boards. Additionally, profiles of the web are extracted along important lines such as the web boundaries and diagonals. These are compared to best-fitting circles, and the deviations shown graphically. Then, this information was used to reconstruct the design principles, meaning the centerings including their positions, radii, center points and angle measures, as well as how the formwork was added to them.

With this methodology, even board traces covered by a thin layer of plaster could be revealed. The analyses are displayed as top views of the vault intrados, with surfaces traces highlighted in color and with the important profiles unfolded on the side showing their deviations too. (Fig. 2)

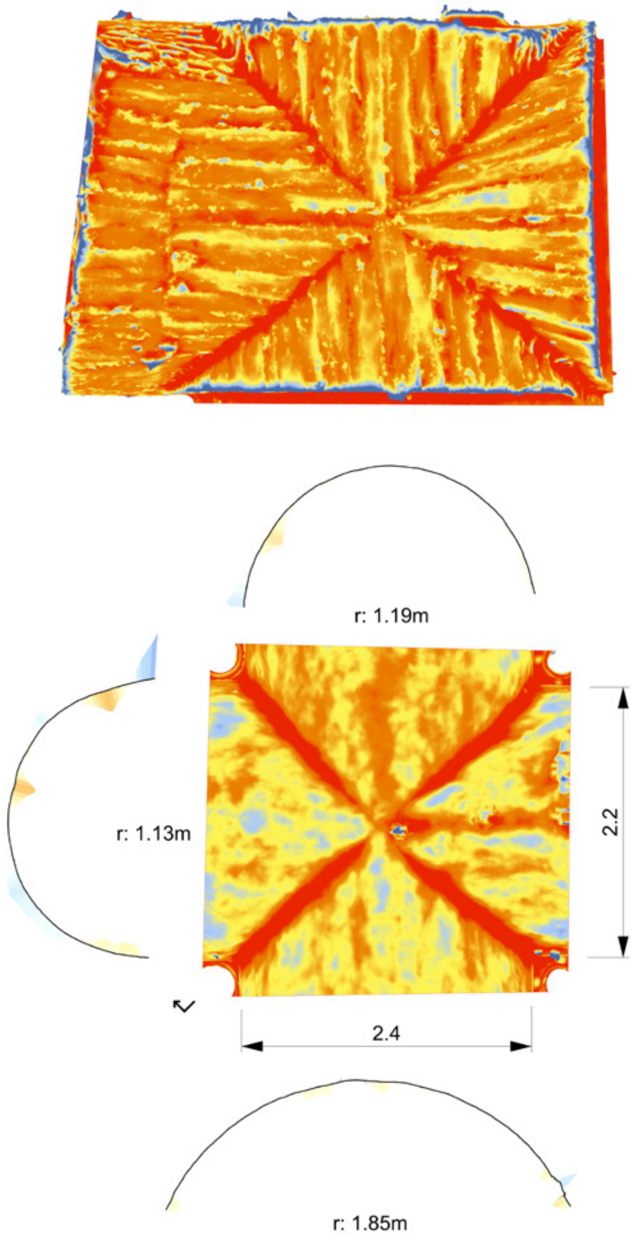

Figure 2. Top views of crypt vaults with highlighted surface traces: the northern side room (above) and the central vault of the hall with unfolded profiles at the boundaries and diagonal with deviations (max 4 cm) (below) (M. Pfister).

1. The introduction of diagonal centerings: The groin vaults of the crypt (1001) and choir (ca. 1090)

The easiest vault to build is probably the barrel vault, which can be created with two or more semicircular centerings, connected with formwork boards of equal length. However, it requires linear supports (walls) on both sides, not allowing for any openings on the level of the vault and creating a strong linear orientation. To overcome this structural and architectural disadvantage, lunettes were added to the main barrel, reducing the necessary supports to the four corners, and allowing openings on all four sides. Such "false" cross vaults based on a principal barrel can be found in early Romanesque vaults, for instance in the crypt of Saint-Philibert in Tournus from 1008 to 1019 (Pfister, Holzer, and Vandenabeele 2023). There, an analysis of the complete formwork imprints revealed that no diagonal centerings were used, but that principal barrels were created with longitudinally overlapping boards. These barrels were used to support the boards of the lunettes. The irregular imprints and general lack of precision suggest an unrefined technique, especially visible at the groins, where the boards of the lunettes were simply laid on top of the main barrel.

To get better control over the geometry, diagonal centerings were introduced, defining the geometry, and enabling a precise fixture of the formwork boards. This is evident in the galilee of Saint-Philibert from ca. 1030 thanks to a detailed geometrical analysis (Pfister, Holzer, and Vandenabeele 2023). The addition of diagonal centerings can be considered a pivotal step in the evolution of early Romanesque vaulting, and their use can be observed in many places like the crypt of San Miniato in Florence from 1018 (Horn 1943) or the ambulatory of the crypt of Saint-Étienne in Auxerre from ca. 1030.

1.1. A standard groin vault

The geometrical analysis of the galilee in Tournus revealed design principles that also exist in the crypt and choir of Sainte-Trinité in Anzy-le-Duc. (Fig. 2) The geometry is characterized by segment arches on the diagonals, i.e., arches with angle measures of less than 180 degrees, and usually stilted arches along the boundaries. This combination of lowering the centre point of diagonals and raising the centre points of the boundary arches creates a vault, where all the highest points, i.e., the ridges of the web, are on the same level. This is particularly crucial where another floor is located above the vault, as is the case for the crypt.

These principles might seem arbitrary but follow a geometric and constructive logic. If the boundary arches are not stilted, the segment arch diagonal will have an even smaller angle measure, which is structurally disadvantageous. More problematically, the diagonals will mostly be below where an intersection of two semicircular barrels would be. This will result in sharp groins, especially toward the spring of the vault. If on the other hand the diagonals are semicircular, the boundaries must be stilted even more to reach the same level. The resulting groins will be even sharper, creating a corner of much less than 90° at the sharpest point. This is difficult to build, particularly with the rubble masonry that is nearly always used for Romanesque vaults.

In summary, diagonal centerings are introduced to define the geometry of groin vaults more precisely. With the requirement of horizontal ridges and no pointed arches, a specific geometry follows logically. It is defined by segment arch diagonals and most likely stilted boundary arches, creating the easiest-to-build geometry, a kind of *standard groin vault*.

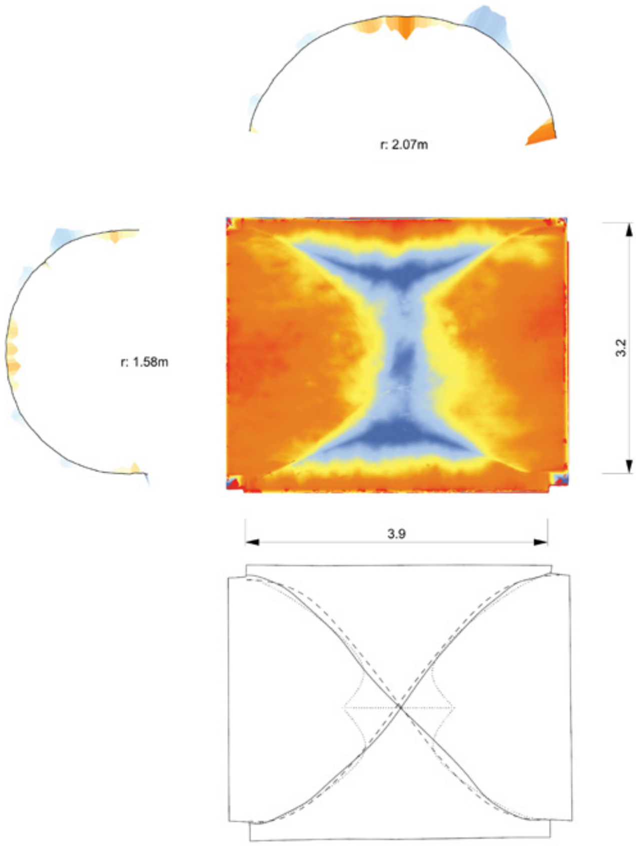

Figure 3. Above: Top view of the barrel vault of the second bay of the northern aisle with highlighted surface traces and unfolded profiles at the boundaries with deviations (max 4 cm); Below: top view of the same vault with lines indicating the intersection of inclined lunettes and a barrel (dots), the geodesic line traced by a rope (dashed), and the actual groins (continuous) (L. Vandenabeele, M. Pfister).

1.2. The dating of the crypt

The geometry described in the last section with a high control over the geometry can be seen in the crypt of Anzy-le-Duc, although with limited spans. Surprisingly, the vaulting shows a higher mastery than the crypt of Saint-Philibert in Tournus, where barrel vaults with lunettes were still built in 1019. The *standard groin vault* was only introduced there starting with the galilee in ca. 1030, but with considerably larger spans of up to 5,8 m. Furthermore, the crypt in Tournus is many times larger than in Anzy-le-Duc and generally a more elaborate construction.

Considering this, the dating of the crypt in Anzy-le-Duc could be questioned. While archival sources point to the year 1001, they are vague, and it is uncertain what exactly was built then. The sculpture points to the first third of the eleventh century, and the floor plan layout is similar both to Charlieu III (before 1049 to 1094) and Cluny II (963–981) (Conant 1954; Sunderland 1957; Hamann 2000). Currently, no expansive analysis of vault geometries has been carried out. Nonetheless, considering only Tournus, a later dating of the crypt in Anzy-le-Duc, perhaps after 1020 could be considered. This would also reduce the gap in construction until the building of the choir and transept, although several decades would still remain.

Alternatively, some other explanations can be considered. The uneven geometry in the crypt in Tournus might not reflect the full abilities of the builders, or the technique was chosen for practical reasons such as lower costs. That the knowledge simply did not reach Tournus at the time seems unlikely, given similar vaults in Italy like at San Miniato in Florence in 1018. To provide definitive explanations, broader investigations are necessary.

2. An alternative way to define the groins: The barrel vaults of the aisles (1110)

2.1. The geometry

Except for the northwestern bay, the groins of the vaults in the aisles exhibit a distinctive pattern that resembles a sinusoidal shape when viewed from above. (Fig. 3) Notably, these non-planar groins indicate the absence of diagonal centerings in the construction of the aisle vaults. Due to the absence of clear board traces, the precise arrangement of the formwork remains enigmatic. Nonetheless, it appears that the design of these vaults is based on a central barrel (with a radius of 1,58 m) aligned with the church's longitudinal axis. In a subsequent step, two inclined lunettes were constructed in the transverse direction, connecting the boundary arches (with radii of 2 and 2,07 m) to the main barrel.

While nine of the ten vaults of the aisle show the geometry described above, the western bay of the northern aisle differs. The groins are very straight in plan and were

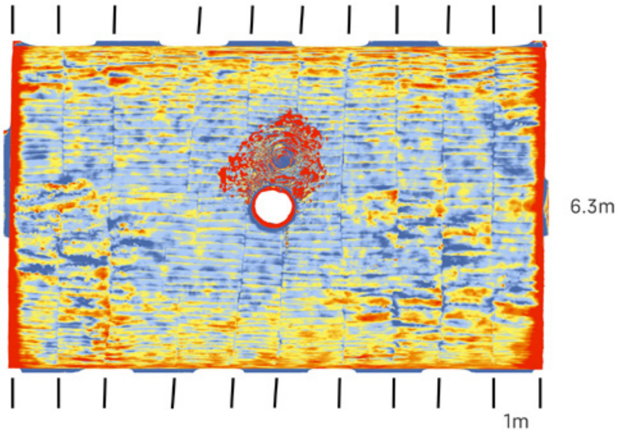

Figure 4. Top view of the barrel vault of the parlor of Saint-Philibert in Tournus with highlighted surface traces and clearly visible imprints of ca. 1 m long formwork boards (M. Pfister, L. Vandenabeele).

most likely supported by diagonal centerings. Evidently, the vault has been replaced, most likely either in the eighteenth or nineteenth century, as it is documented that the roof of the northern aisle was near collapse in 1719, as well as a general lack of restoration measures until the classification as *Monument Historique* in 1851 (Hamann 2000).

2.2. Non-planar groins

The construction of the formwork for the lunettes is particularly intriguing due to the intricate geometric complexity and the remarkable skills involved in replicating the exact same pattern in both aisles. In theory, the intersection could have been achieved by intersecting two inclined barrels (lunettes) with the primary one. In practice, this would have necessitated placing a series of boards spanning from the transverse arches to the main barrel with the same inclination of 20°. However, the challenge of inclining and shaping each board forming the lunettes with such precision raises questions about whether an alternative method was employed to define this geometry. One hypothetical strategy could involve using a tensioned rope connecting opposite corners of the main barrel, which would provide a geodesic path on the formwork. This straightforward technique would have offered a repeatable and adaptable method for creating groin vaults based on a main barrel, using boards to connect the boundary arches to the path of the rope.

Both reconstruction hypotheses closely align with the observed geometry of the vaults in the aisles. (Fig. 3) It is therefore evident that a distinct construction technique was employed for the aisle vaults, differing from that in the crypt or the northwestern bay. This technique, avoiding diagonal centerings in favour of barrel-shaped formworks, results in the characteristic non-planar intersections between the webs.

2.3. A systematic approach

Although these vaults share a fundamental similarity with those in the crypt of Tournus, their larger scale (3,2 x 3,9 m), exceptional workmanship with higher precision groins, and consistent patterning in all nine vaults of this kind strongly suggest that a well-thought-out approach was used to define the groin profiles. The exact reasons for favouring this method remain unclear and seem even more puzzling considering the use of diagonal centerings in the crypt and choir. Perhaps once the new technique for barrel vault intersections was known, building those turned out to be simpler since the boards for the main barrel did not have to be cut individually to fit to the diagonals. Hopefully, analyses of more vaults will shed some light on this topic.

The aisles show that groin vaults were not built exclusively with diagonal centerings even after they were introduced, and that the technique for building barrel vaults with lunettes was also improved. Evidently vaulting did not evolve wholly sequentially with one method replacing another, but rather several techniques were known and developed in parallel.

3. The challenge of larger spans: The complex groin vaults of the nave (ca. 1110)

To build a large span barrel vault, the span of the centerings can be increased by using larger beams, possibly supported from below. To increase the length of the vault, the number of centerings can be increased. Remaining unaffected are the formwork boards, usually consisting of short boards of about 1 m length as can be seen in the transept or in Tournus (Pfister, Holzer, and Vandenabeele 2023). (Fig. 4)

For a groin vault with diagonal centerings however, increasing the span will also affect the formwork boards. The longest ones are placed at the top, spanning half the size of the vault in either direction. Therefore, to span the nave of Sainte-Trinité boards of up to 3 m length would be necessary, not even considering the inclination of the web. Such boards were not only hard to make but would have required a thickness approaching that of a beam to support the vault masonry. As a result, building *standard groin vaults* is nearly impossible in naves spanning more than ca. 5 m.

The formwork aside, building groin vaults over naves poses some other constructive challenges. Those vaults have to be built in one of the highest and most exposed places of the church, increasing the difficulty for formworks and scaffolding. Furthermore, there is a lack of support for the transversal thrust of the vaults. That support is further reduced by one of the main reasons to build groin vaults in the first place, that is to add clerestory windows to the upper walls of the central nave. Interestingly, longitudinal barrel vaults on naves were much more common at that time but create a lot of transversal thrust as well. Perhaps the even spreading of the force on the entire wall by a barrel vault is advantageous compared to the more local loads of cross vaults, considering also the relatively small size of buttresses in the Romanesque period. Later on, this would lead to the addition of flying buttresses in the Gothic period when cross vaults over naves became widespread.

In Anzy-le-Duc, the groin vaults spanning the nave, built around 1110, are one of the most distinguishing features of the building especially considering their early dating. (Fig. 5) Spanning 6 m, they are among the largest Romanesque groin vaults. Moreover, groin vaults on naves are a rarity in Burgundian Romanesque architecture, with the abbey Sainte-Marie-Madeleine in Vézelay (1120–1150) being one of the few other examples. There the construction was finished with groin vaults spanning a nave of approximately 9,5 m in around 1150 (Büttner 2016), likely the largest Romanesque vaults of this kind still standing in Burgundy.

Figure 5. Photograph of a groin vault over the nave of Sainte-Trinité (M. Pfister).

3.1. The geometry

Different to the groin vaults in the crypt, the ones over the nave do not have horizontal ridges. Instead, the center point is raised by 0,8 m, resulting in an inclination of the ridges of 14° toward the short boundaries and 22° to the long boundaries. The former are aligned with the longitudinal axis of the church and the profiles are semicircular with spans of 4,4 m, radii of 2,15 m and angle measures of ca. 174°. The latter span 6 m across the nave, have a radius of 3,22 m and an angle measure of approximately 130°.

To overcome the challenge of the 6 m span, intermediate centerings were used. This can be seen clearly in the traces of the formwork boards, which shift position or change direction along lines parallel to the short boundaries, which indicates centerings along those lines. (Fig. 6) Consequently, most boards must have had a length of around 1 m (horizontally), The rhythm of one centering approximately every meter could also be observed in the transept and other churches. (Fig. 4) Moreover, the profiles of the web along these suspected centerings are semicircular with radii similar to the short boundary arches, further suggesting the presence of centerings along these lines. In the parts of the web connected to the long boundaries, the board traces are not quite clear enough to determine the presence or absence of intermediate centerings.

A peculiar detail of these vaults is the position of the groins in the corners, where they are slightly curving away from the longitudinal axis of the church when viewed from the top. So rather than connecting opposite corners with a straight line, they consist of a straight middle segment pointing towards the pillars and two curved ends going towards the corners of the vault. In principle, this behavior is similar to the groins in the aisles, but here the middle segment is distinguishable from the curved end segments and both longer and straighter.

Whereas the position of centerings can be gleamed from the board imprints, there are still several possibilities for the complete layout of the formworks. Two options seem particularly likely and are covered in the following sections. One could be considered a derivative of the *standard groin vault*, the other of the barrel vault with lunettes.

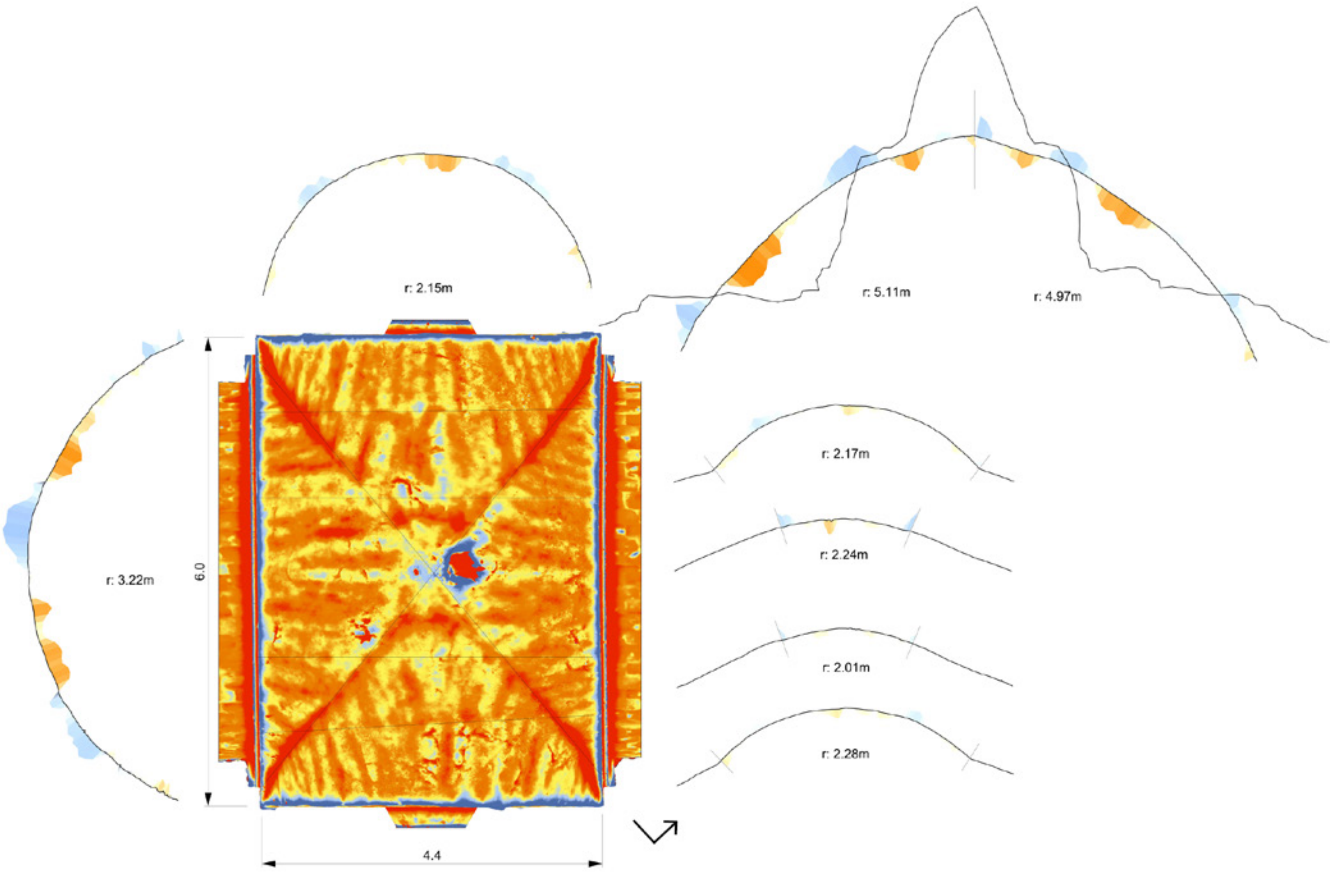

Figure 6. Top view of the groin vault of the fourth bay of the nave with highlighted surface traces, unfolded profiles at the boundaries with deviations (max 4 cm) from a single circle segment, unfolded diagonal profile with deviations (max 4 cm) from two circle segments with an additional line for deviations from single circle segment, and four unfolded intermediate profiles with deviations (M. Pfister).

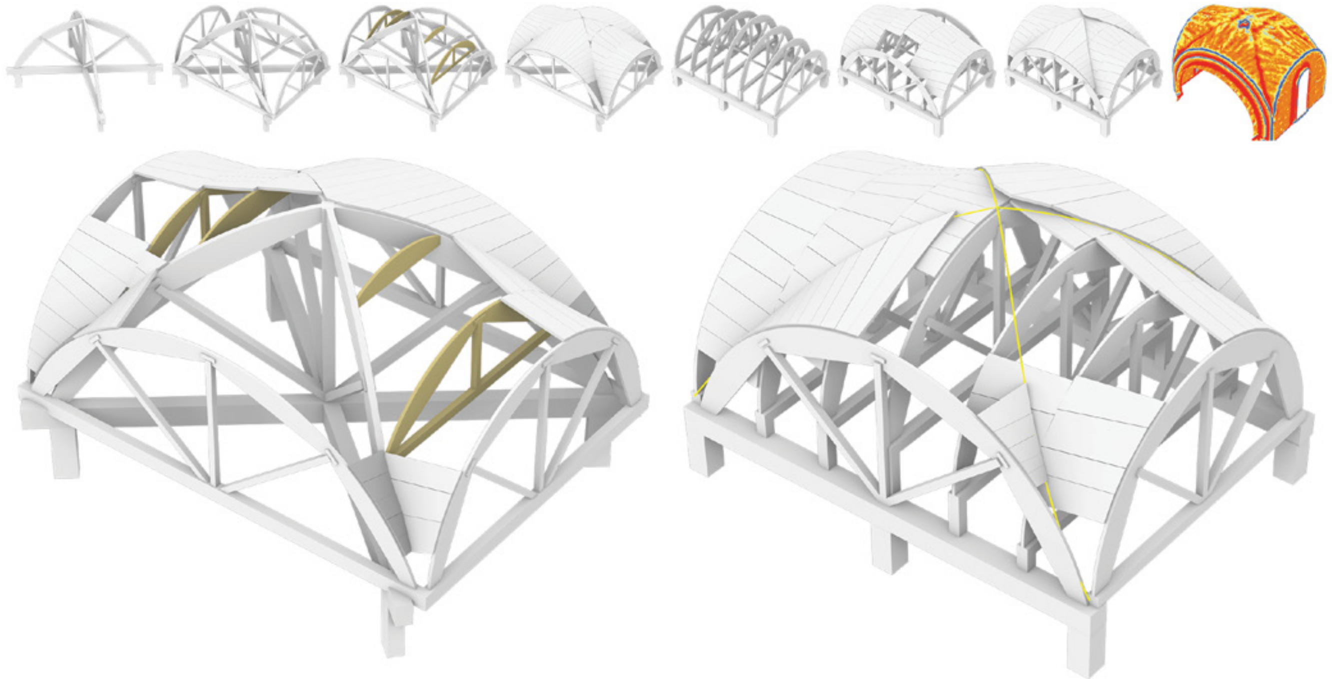

Figure 7. 3D models of formworks and construction process and survey with highlighted surface traces; version A with intermediate centerings in yellow and anomalous boards in the corners in grey (left); version B with geodesic line of tensioned rope in yellow for the addition of the lunettes (right) (M. Pfister).

3.2. Version A: Pointed diagonal centerings

If diagonal centerings were used, they would have been slightly pointed, consisting of two circle segments with radii of about 5,1 m and angle measures of about 55°. (Fig. 7) If a single circle segment is fitted to the diagonals, it would have a radius of around 3,9 m and an angle measure of around 145°. The deviations would be substantially larger, making pointed diagonal centerings more likely. Furthermore, they would not have been perfectly aligned with the corners, but rather oriented towards the pillars. Such a position would match most of the groins, except for the corners.

In a second step after adding centerings along the boundaries, the intermediate centerings would have been placed on the diagonals. The disadvantage of this method is that all intermediate centerings would have to be supported on the diagonals, which is difficult for the construction of the formworks. Then, short boards of about 1 m length would have been added, and placed horizontally where possible, which creates the slightly angled imprints in the top view. In the corners of the vault, boards could have been placed from the springing of the long boundary arch to the barrel of the short boundary arch instead of to the diagonals. (Fig. 7) This would cause the groins to be curved. Alternatively, the spring could simply have been built without formwork. A similar layout with intermediate centerings but with circular diagonals has been suggested by Ulrike Heckner for St. Pantaleon in Cologne, for a vault tentatively dated to the tenth century by radiocarbon dating (Heckner 2022).

3.3. Version B: Barrel with lunettes

Alternatively, a technique without diagonal centerings like what was observed in the aisles could have been used, with some key differences. First, the formwork for the main barrel would have been built. (Fig. 7) Judging by the traces of intermediate supports, the main barrel likely would have spanned the nave. Additionally, the boards of the lunettes would have to span less far that way. Different to the aisles, the main barrel would not have been horizontal, but composed of two rising barrels, meeting in the middle. To avoid long boards, multiple centerings would have been used, their position evident in the board traces. They reveal a total of seven centerings, that would have been placed every meter (horizontally), with a height difference of 0,25 m from one to the next. They could have been supported by two transversal beams next to the pillars.

Then, two rising lunettes were added, as was done in the aisles. The intersection could have been found by tensing a rope from the highest point to each corner of the main barrel, although the actual groins diverge slightly from that line. The difference in radius of the short and long boundary arches as well as the different inclination of the connected webs could certainly cause curved groins. In fact, given these conditions the groins should be more sinusoidal than they are, although using a rope would involve some imprecision. In addition, the springing could have been built without formwork accounting for the curved groins there.

The boards for the lunettes have a maximum horizontal length of half the width of the bay, in this case 2,2 m. To reduce the length, an intermediate centering could have been used, bringing the length and the horizontal spacing of centerings to 1,1 m, similar to the main barrel. However, the board traces in the respective areas are not clear enough to gain further insight. Further, the intermediate centerings would have to be attached to the main barrel, increasing the difficulty of constructing the formwork. Given the span of 2,2 m, using intermediate centerings would not have been necessary for the lunettes.

3.4. Discussion

For the nave it was demonstrated how the challenge of larger spans was met without compromising the vault type. If version A is assumed to be true, the use of intermediate centerings allowed for groin vaults beyond two times the maximum board length. With version B on the other hand, the advanced control over the intersection of the barrels, possibly with a tensioned rope, enabled the complex intersection of an inclined barrel with inclined lunettes. As a result, the main barrel could be erected first with as many centerings as necessary and was not limited in span by the maximum length of the boards.

With the current knowledge of the discussed vaults and vaulting techniques in general, it was not possible to definitively accept or reject either version proposed here. The curved groins in the corners do not fit either theory perfectly, but could have been built without formwork, although their regularity would then be remarkable. Attaching the intermediate centerings to the diagonal ones would be challenging for the construction of the centerings. On the other hand, for version B the boards of the lunettes would have to be fixed to the main barrel well enough to take heavy loads. Furthermore, the use of a rope for the intersection of rising barrels does not fit the groins exactly. Perhaps it could be asked, why all four webs are rising, which is uncommon for barrel vaults with lunettes. One reason could be the structural advantage it provides, although it could also have been done for architectural reasons. Hopefully, investigations into other churches with groin vaults on naves constructed after 1100, such as in Gourdon (ca. 1100–1125), Bragny-en-Charollais (ca. 1110–1130), Toulon-sur-Arroux (ca. 1100), Issy-l'Evêque (ca. 1110–1130), and Vézelay (1120–1150) can shed more light on these subjects. Moreover, curved groins have been observed in the naves of all the churches listed above save Issy-l'Evêque. The latter, however, does feature pointed arches along the diagonals and boundaries, and has therefore very similar design principles to many Gothic vaults, save the ribs.

The use of groin vaults on a nave has clear architectural advantages over barrel vaulted naves, allowing clerestory windows in the walls of the central nave. However, even after the appearance of groin vaults with intermediate centerings, barrel vaulted naves were still built in Romanesque architecture. The development of this vaulting technique was therefore not wholly transformative. Nevertheless, the question of the impact of this development is an important one. Architecturally, the vaults of the nave of Anzy-le-Duc seem like a clear precursor to their Gothic successors that appear only a few decades later, when cross vaults on naves become prevalent, albeit with ribs. Furthermore, if diagonal pointed centerings were used, it would signify another important step for the construction of vaults, being nearly identical to Gothic ones with the only major difference being the use of ribs. Whether Gothic vaulting relied on intermediate centerings is not well researched, although the problem of the maximum span of boards with the use of diagonal centerings is just as valid there as it is in Romanesque vaulting, more even as spans tend to increase. Regardless of what followed this technique shown in Anzy-le-Duc, it stands at the culmination of over 100 years of Romanesque vaults.

Conclusion

Sainte-Trinité in Anzy-le-Duc is without a doubt a significant testimony to Romanesque vaulting techniques, showing a large variety in the three presented vaults. The crypt shows the early mastery over the geometry of groin vaults with stilted semicircular boundary arches and segment arch diagonals. These design principles emerged from the geometric and constructive conditions and created a kind of *standard groin vault*.

In the aisles, an alternative technique for groin vaults has been demonstrated, where lunettes are added to a principal barrel. While it is still unclear whether the vaults of the nave are derived from barrels with lunettes or from groin vaults based on diagonal centerings, the use of intermediate centerings has been established. Furthermore, two possible versions of the formwork have been proposed, and should be investigated through additional geometric analyses.

These discoveries were made thanks to high-precision surveys and new digital analyses, which revealed previously unnoticed traces of boards. With those and the likely position of centerings unearthed through geometric analysis, complete formworks could be reconstructed.

Romanesque vaulting has often been overshadowed by the development of Gothic vaults, and many of the finer details pertaining to the design and construction are still unknown. However, as the connection from vault-less architecture after the fall of the Roman Empire to the flourishing of vaulting in succeeding periods, it is a crucial step in the reemergence of the art.

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