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Remodelling a Medieval Net Vault Construction

Case Study: The Apse Vault in the Catholic Church of Andocs

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ORIGINAL RESEARCH ARTICLE

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ABSTRACT

In the present study, we analysed the exact, laser-scanned geometry of the apse vault of the catholic church of Andocs. The written sources about this vault are very limited, however, the point cloud-based research could provide new details about the history of the building, along with the formerly used building techniques. For the analysis, we worked based on our three-step analysis process, established for net vaults. During the studying of the rib system, we reconstructed the probable original construction and building method, as well as the temporary supporting structures of the early 16th-century vault. The analysis of the individual ribs led us to conclusions about this vault, in the mirror of the widespread ideas of the topic's technical literature, such as the "Prinzipalbogen" theory (all the ribs of a given net vault have the same curvature), or the principle of the longest route (the cumulated length of the ribs' plan, which led from the impost to the crown with the longest possible route equals to the radius of the ribs' curvature). Regarding the curvilinear rib elements, we presumed a likely fabrication method, based on contemporary research results. Mapping the webbing and the ribs, we concluded their building order, as well as the plausible masonry technique of the webs.

KEYWORDS

Andocs, curvilinear ribs, ribbed net vault, medieval construction method, medieval building technique, geometric analysis, medieval geometry, point cloud analysis, building scanning, laser scanning

1. INTRODUCTION

The construction and building methods of the late medieval net vaults have been in the middle of scientific attention for a long while. Since the 16th century (e.g. Rodrigo Gil de Hontañon's treatise from around 1538, Jakobus Facht von Andernach's treatise from 1593) numerous theo-

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ries evolved about the geometric definition of the rib systems, the characteristics of the ribs, or the building technique of the webbing. However, only in our days, with the application of the 3-dimensional surveying techniques (laser scanning, 3D photogrammetry, etc.) has the opportunity arisen to analyse the exact geometry of the net vaults, to supervise the former theories and to establish new ones.

In the current study, we present the analysis of the apse vault of the catholic church of Andocs, based on its laser-scanned point cloud, and through our systematic analysis method applicable for net vaults. Thus, we define a highly possible construction and building method of the vault, and we give some new observations about the former building periods.

2. METHODOLOGY

In the present case study about the apse vault of Andocs, the research process had two main parts: first, the 3D scanned point cloud of the vault was generated, for which a Leica BLK360 scanner was used *(Fig. 1)*. For the further processing of the point cloud, we worked with Leica Cyclone Register 360 software.

In the second part, the data analysation was worked out mainly with Autodesk AutoCAD software. Our established analysis process has three principal steps:

- the analysis of the rib system, including the studying of the plan's construction and considering the spatial positions of the rib junctions;
- the analysis of the individual rib elements, including the testing of the different "Prinzipalbogen" theories and the possibilities of the ribs' prefabrication;
- the analysis of the webbing, including the studying of the conjunction between the ribs and the webs and that of the presumed technique of the webs' masonry.

Reviewing the technical literature on the topic, we found several studies that applied similar workflows, but the method we used seems quite unique, since along with the analysis of certain net vaults, we also accentuated a systematic approach, which can easily be interpreted in the case of other net vaults (or stellar vaults).

Olaf Huth (Huth 2020) used scanning generated point cloud and analysed the curvature of the vault ribs, as well as the height of the crossing points of the ribs and proved in his case study, that in that vault the latter had the utmost importance during the construction process. R. Maira Vidal (Vidal 2017) also used sexpartite vaults' exact geometry to examine the rib deformations. Paula Fuentes and Santiago Huerta (Fuentes–Huerta 2016. 591) surveyed the crossed-arch vaults of the Mosque of Cordóba by laser total station and laser distance meter and analysed the geometry and the construction method. J. C. Palacios Gonzalo and R. Martín Talaverano (Gonzalo–Talaverano 2012) also used a laser distance meter and laser total station for measuring the ribs of Spanish gothic vaults. Although Alexander Wiesneth (Wiesneth 2011) dealt with the architecture of Balthasar Neumann, his method accented greatly to the importance of the examination of the back of the vaults in the search for their building methods. David Wendland and Frédéric Degenève (Wendland–Degenève 2017) experimented with the methods of practical archaeology to reconstruct the production method of curvilinear ribs. Gonzalo and Talaverano (Gonzalo–Talaverano 2013) also gave theoretic solution to the same problem.

Figure 1. The picture of the apse's inside point cloud

3. A SHORT HISTORY OF THE BUILDING

The catholic church of Andocs in Somogy County, Hungary, is a well-known Franciscan pilgrimage site from the 18th century on. The building nowadays has a polygonal apse, covered by a net vault (the subject of the present paper), which connects to the typical Baroque nave covered by a barrel vault with lunettes.

It got under the control of the Franciscan order only in 1716 (Pethő 1929. 11), after being abandoned for nearly 30 years, since 1686 (Reiszig 1914). Before that, from around 1550, the ruins of the medieval church, originally consecrated to the All Saints, had Jesuit priests (Reiszig 1914).

Today the only remains of this Gothic period are the apse of the church. (The huge baroque nave was finished in 1742 [Reiszig 1914] or 1745 [Pethő 1929. 19].) About this gothic building period, we only know very few factual details. Based on the below-detailed reasons, it is highly possible that the medieval building, as well as the vault of the apse, also had several different building periods.

The present vault of the apse is one of the rare examples of the curvilinear-ribbed net vaults in Hungary (Császár 1987–1988. 411). However, the curvilinear ribs appear only close to the crowning line of the structure, meaning a rather slight curvature in the side view. The exact building date of this vault is not fully defined. According to Ede Reiszig (Reiszig 1914), it dates back to 1520, but no further explanation or reasoning is included. In comparison, Tamás Guzsik (Guzsik 1983. 207) dates it around 1500, giving the analogy of the gothic vault of a nearby village, Törökkoppány. Nevertheless, this latter vault has no curvilinear elements. Besides, we claim that the analogy of the vault pattern is not at all that evident, since the vault of Törökkoppány is a simple, widespread net-vault form[1], whereas the vault of Andocs is a richer, more decorative pattern *(Fig. 2)*. László Császár (Császár 1970. 68.) also dates the vault around the end

Figure 2. The apse vault of the church of Törökkoppány (left) and the vault of the apse in Andocs (right)

[1] The rib systems plan is the following: along the crown line, rhombuses are enumerated, supported by ribs starting from the imposts.

of the 15th or the beginning of the 16th century, based on the fact that in the second half of the 15th century the curvilinear-ribbed vaults appeared nearly exclusively in the region of Austria. Nevertheless, according to Balázs Szőke (Szőke 2009. 113), the form of the vault in Andocs is more evolved, which appears only from the early 16th century.

4. VAULT ANALYSIS

As we detailed above, not many factual details are known about this vault, but by scanning it and analysing its three-dimensional point cloud, we attempted to reconstruct its original construction method, as well as to add some more details to the building history of the church.

4.1. Displaced imposts, buttresses

Regarding the vault structure, its most conspicuous detail is the displacement of the third impost (from the nave) on both sides *(Fig. 3)*. There is no written data known about the origin of this phenomenon. We presume that the slightly displaced impost belonged to an earlier vault system,

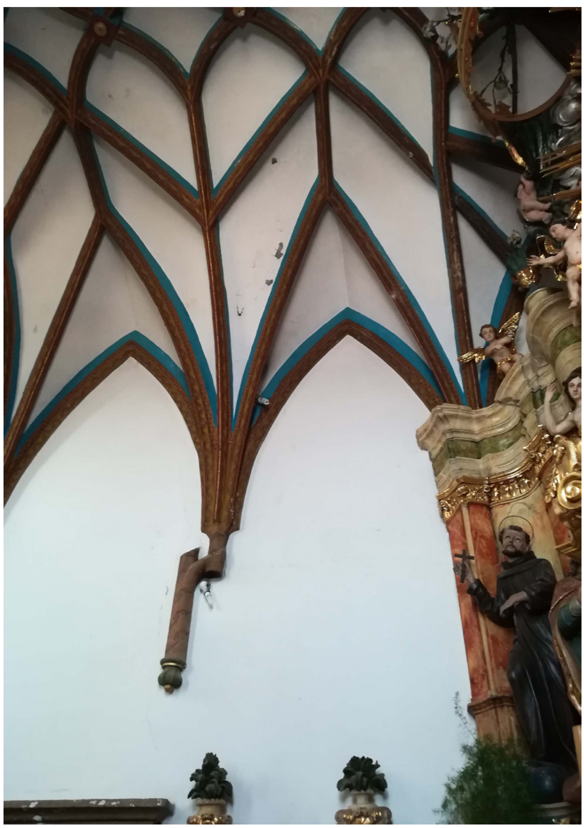

Figure 3. Displaced former impost in the apse of Andocs

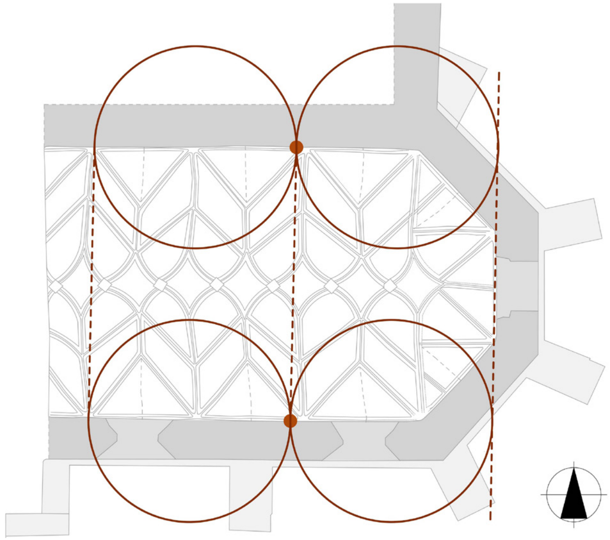

Figure 4. The position of the former imposts

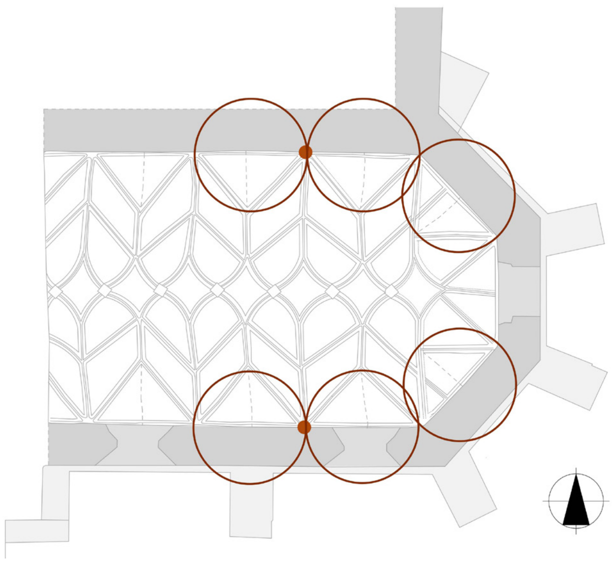

Figure 5. The position of the present imposts

or signifies a change in the conception since the position of the destroyed impost on the plan is exactly at the halfway point between the very end of the apse polygon and the first impost (from the nave) *(Fig. 4)*. The given ratios may belong to a (conceptual) cross-vault, for which the span of the apse is rather big, which could be the cause of the hypothetic conception change. However, the present impost is exactly in the middle between the second impost and the corner of the apse polygon. It is also to be noted that the latter distance is equal to the length of the apse polygon's sides *(Fig. 5)*. That may signify that the present net vault differs in construction from the previous one, and maybe the ending of the apse was also modified at that period.[2] However, even though this hypothesis is in accordance with our further claims about the present vault, without any other remains of this supposed earlier vault, other explanations can also be considered.

As to the previous vaults of this apse, another important detail is that neither the imposts of the present vault nor those of the above-mentioned preceding one adjust to the buttresses of the apse. We assume the buttresses belonged to an even earlier period of the building, potentially with a cross-vault, as deduced from the given vault-compartment ratios, similarly as above.

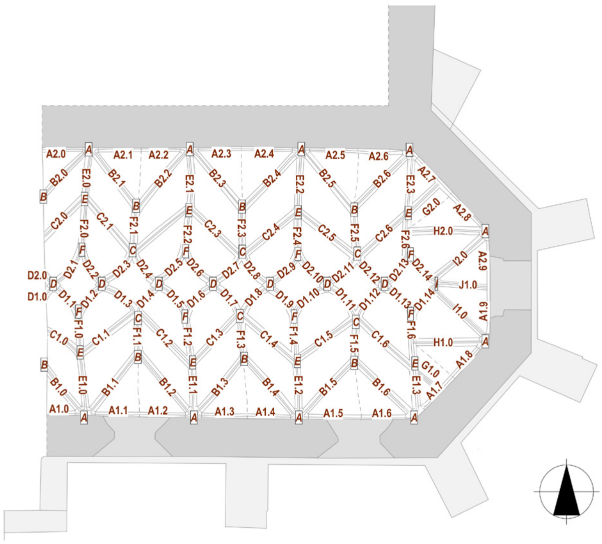

Figure 6. Legend to the ribs and the junction types of the nave vault. The same letter signifies the same function in the rib net. The letter in the rib's sign refers to the upper junction in which the rib ends

4.2. Construction of the rib system's plan

For an easier understanding, we gave a code number for all the ribs and all the junction types (based on the given junction's role in the rib system) in the vault, as shown in *Fig. 6*, as well as gave lettering for five crucial points of the plan's construction, as shown in *Fig. 7.*

After further analysis of the rib system's plan, we attempted to reconstruct the original construction method of the rib net. The method of the net vaults' construction starting from their plan view is the most widely accepted idea in the technical literature. This idea, although with slightly different further steps (as detailed below), is represented from the earliest, 16th-century sources (e.g.Hontañon), through the 17th–18th century (e.g. Ranisch [Ranisch 1695]), up until

2 Our further consideration is that the two tall pointed arched windows of the southern wall of the apse were placed in the same period as the present vault, since the eastern window is nearly at the middle of the wall segment between the corner of the apse polygon and the visibly displaced impost, thus its position would be quite misproportioned with the destroyed impost. In addition, the construction method of the lunettes also leads us to this assumption, as detailed below.

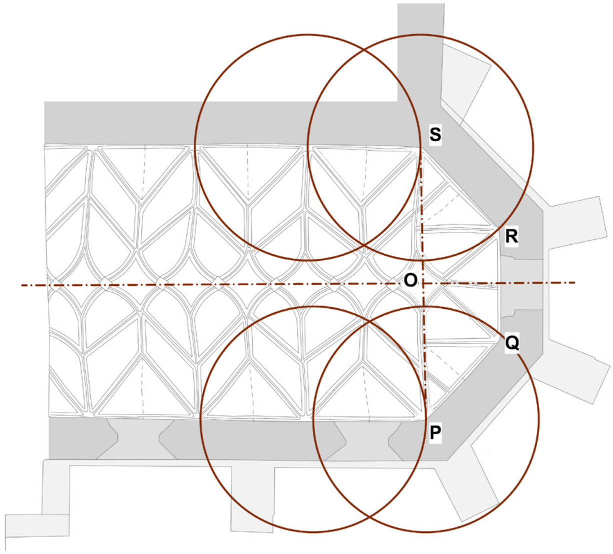

Figure 7. Construction of the rib net's plan, step I

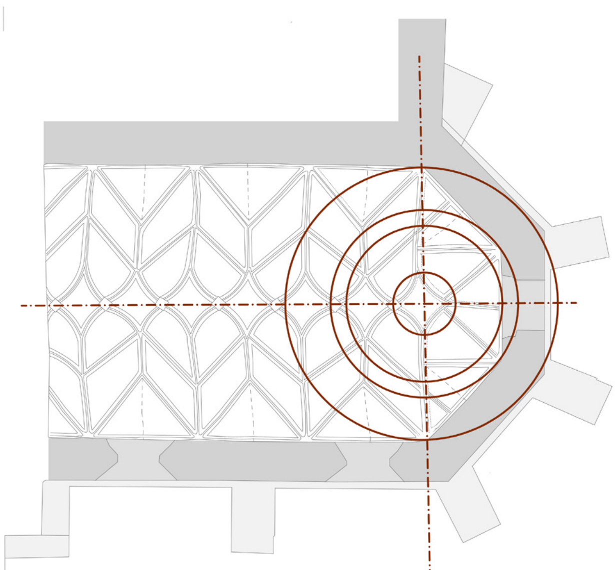

Figure 8. Construction of the rib net's plan, step II

the 19th–20th century's most influential works, which consequently deduce net vaults from rib pattern-plans projected to barrel vault-like surfaces (Warth 1869. 258–260; Ungewitter 1901. 64) or use a construction method based on the ribs, even curvatures for determining the height values (Hoffstadt 1840. XIV A; Warth 1896. 260 Fig. 702).

The foregoing research about how these rib patterns were constructed has, on the one hand, a strong interest in the development and lineage of the pattern (Császár 1983. 44), and, on the

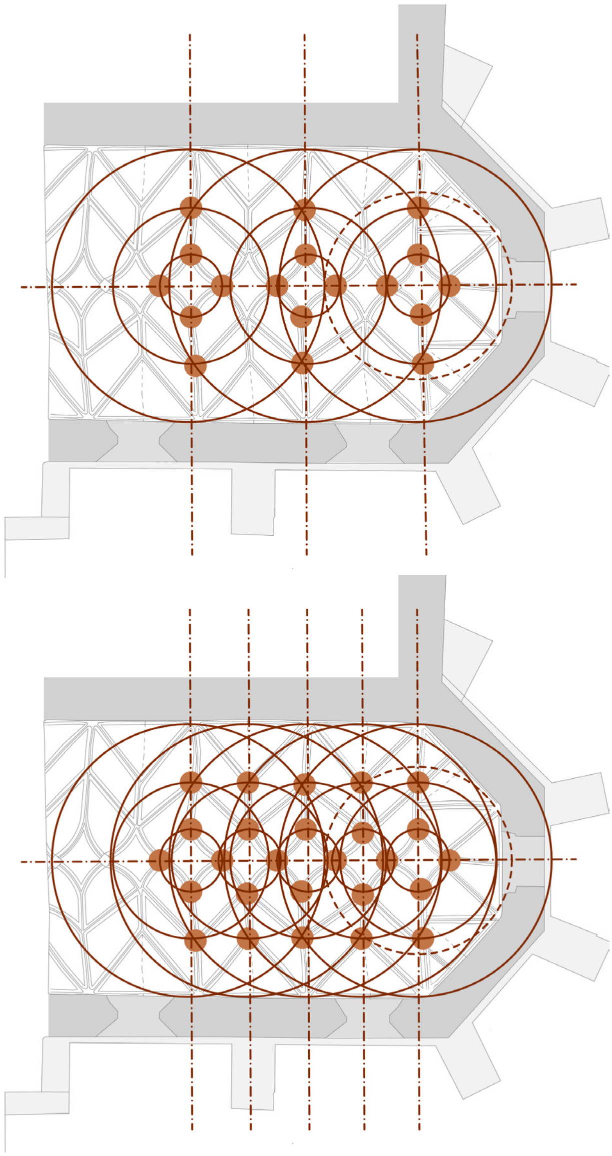

Figure 9. Construction of the rib net's plan, step III

other hand, in the practical aspects, namely that the pattern must have been constructed in real size at the building site (as presented by Wendland and Degenève [Wendland–Degenève 2017. 164]). According to some sources, this latter is often based on the crossing points of a quadrature-net (e.g. Schulze's method, as presented by Müller [Müller 1975. 45]), or (mainly in the case of stellar vaults), on the inscribable (with 45° rotated) quadrats of an original square (e.g. Hoffstadt's XIV. A. board, as described by Müller [Müller 1975. 52]). However, other solutions can also be conceived.

In our case, the longitudinal axis of the apse, together with the rib pattern, is the line connecting the midpoints of the triumphal arch and of the polygonal ending. The crossing of this axis and the line between the western turning points ("P" and "S") of the polygon is the starting point of the reconstructed construction, as shown in *Fig. 7*. (This point is referred to as "O" further on.) "O" is the middle point of the circles determining the crossing points of the plan.

The small circle's radius, signing the corner points of the arched quadrangles on the longitudinal axis is a third of the distance between "O" and "R" or "S". The big circle's middle point is also "O", and it is tangential to the "RS" wall (*Fig. 8*).

Distributing these two circles and the "PS" line along the longitudinal axis according to the half-distance of the eastern imposts will give the approximate placement of the rib crossings, as shown in *Fig. 9.* It is to be noted that the cross-axis between the western imposts is not orderly in this system. Although the length of the apse would allow finishing the construction according to the above-detailed rules, we suppose that finishing the vault of the apse as if cutting an enumerated pattern rather than shaping an impost in the apse' corner and modifying the rib-system accordingly, was a geometrically simpler solution. Based on some sources, the main characteristic of a net vault is exactly the rib pattern, which "cannot be finished", meaning that regarding any cross-section, there are rib endings not enclosed with the other rib-loops (Császár 1987–1988. 96).

4.3. Temporary working level

If a vault was constructed by projecting up the plan of the rib system, this plan must have been drawn in real scale at the construction site. Usually, this happened on an elevated temporary wooden level, which served as a working platform during the construction work. This idea is visible on Hontañon's drawing too, where this level is placed in the height of the "tas-de-charge", as explained by Huerta (Huerta 2012. 173).

Analysing the cross-sections of the vault allowed us to guess the vertical position of this level.

The main cross-sections[3] (*Fig. 10*) can be constructed according to a regular triangle with a side of the apse's span, and the lower vertexes situated on the lower points of the imposts' floating columns, as shown in *Fig. 11*. The half-points of this triangle's heights determine the heights of the ribs' imposts, as well as supposedly the position of the elevated working level (referred to as "base-line" in the geometrical description below), as the starting points of constructing all the further height values fall on this line (as detailed below).

4.4. Spacial positioning of the junction points (main cross-sections)

The next step according to this plan-based method (also shown on Hontañon's drawing [Huerta 2012. 173]) is to determine the vertical position of the junctions. Presumably, this step happens linearly, as opposed to the earlier theories (Ranisch 1695; Warth 1869. 258–260; Ungewitter 1901. 64), which use the analogies of projecting up a plan to an even surface – a hemisphere in

[3] By "main cross-section", we mean the cross-sections which have continuous ribs from the impost to the crown point, so the cross-sections through the imposts; whereas "secondary cross-sections" are those where the ribs seen in the side view start from the upper junction of the lunettes.

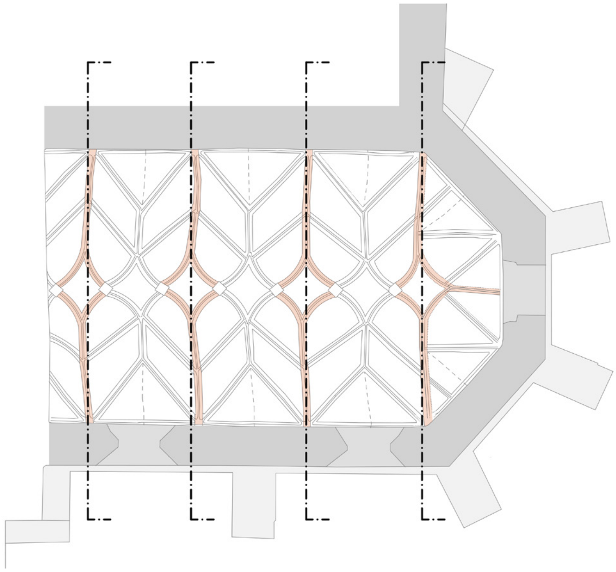

Figure 10. Main cross-sections

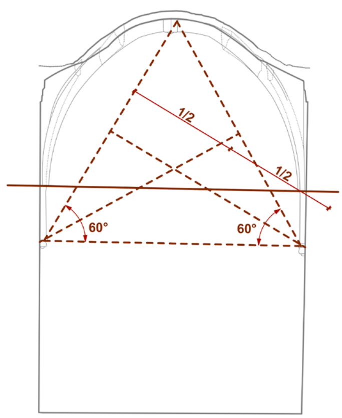

Figure 11. The construction of the temporary working level's position

the case of stellar vaults, and a barrel-vault surface in the case of net vaults. Regarding practical considerations, using surface structures as temporary supporting structures would be beneficial neither economically, nor workload-wise.

The idea that during the construction process the three-dimensional positioning of the rib crossings had the utmost importance dates back to the 20th century. According to some researchers (e.g. Müller 1975), the well-known and widespread "Prinzipalbogen"-theory (see details below) only served this purpose (Huth 2020. 27). Thus, though indirectly, the importance of the vertical positioning of the crossing points of the ribs already appeared in the ideas where the junctions were fitted on a hemisphere or a hemicylinder surface (Ranisch 1695; Warth 1896. 258–259; Ungewitter 1901. 64).

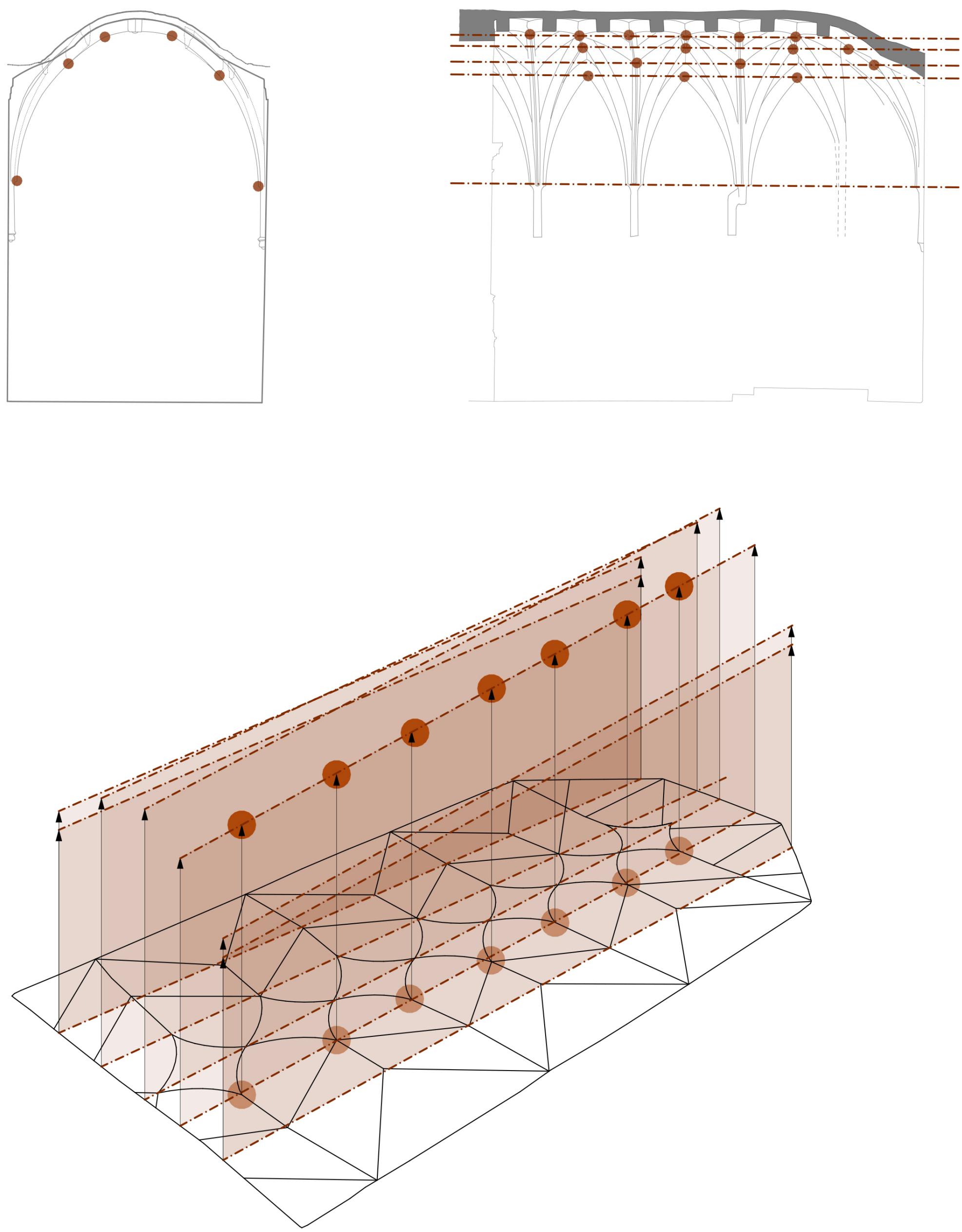

Figure 12. The junctions' position in relation to each other on the southern and northern side of the vault, cross-section (upper left); the junctions' position on the longitudinal section (upper right); the theoretical method of projecting up the junctions' position from their plan, based on longitudinal lines

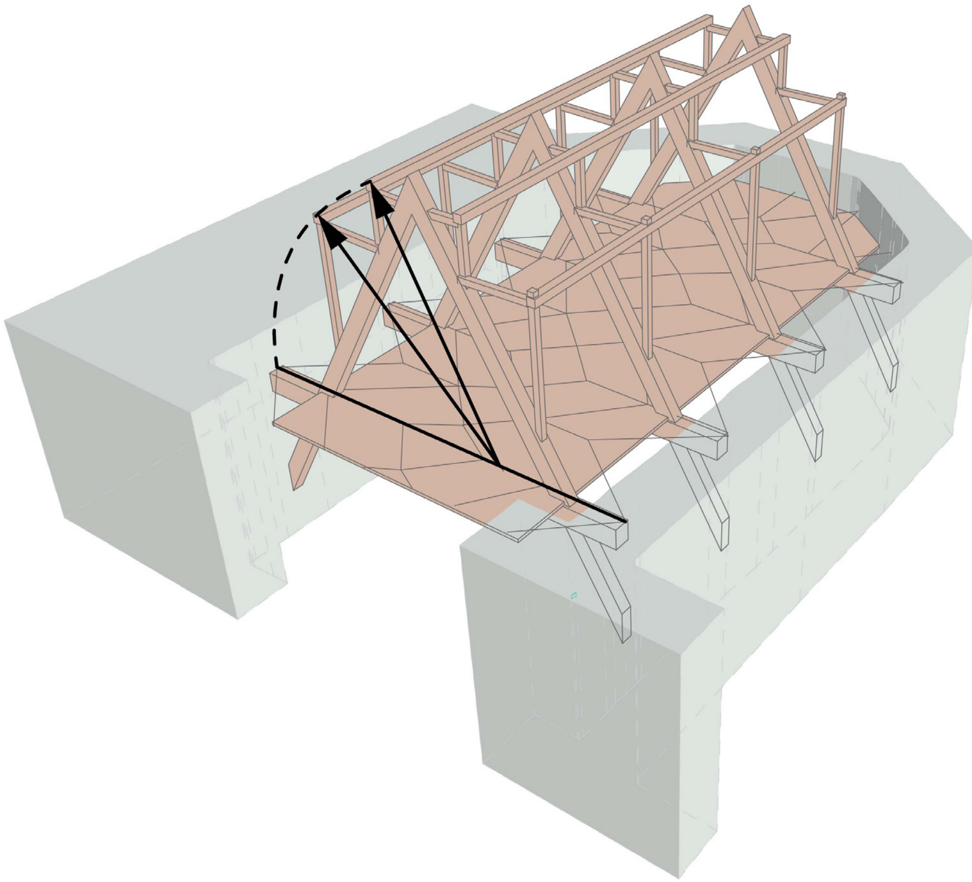

Figure 13. The main cross-sections' construction method's appearance as temporary supporting structures

Wendland (Wendland 2010. 30) proved that in the case of the cell vaults of the castle of Trebsen, the curvature of the groins was not uniform, however, the positioning of their crossings showed the highest precision.

Further significance of this positioning is that the imprecise shaping of the junctions reaks the way of the vault's weight transmission (Huth 2020. 58).

According to Wendland (Wendland 2010. 30–31), although we only have limited data about the exact geometry of the late medieval stellar and net vaults, possibly starting the building process by positioning the junctions was a widespread practice.

In our case, the spatial locations of the junctions seem to prove the point of the linear projection method[4] directly. Analysing the cross-sections, we found that the junctions between the likewise positioned elements are not at the same height on the northern and southern sides of

4 By "linear projection method" we mean the method during which the height coordinate is given to the junctions' position on the plan by projecting them up to a line, which falls on the vertical plane determined by the line, on which the junctions' plan pictures are *(Fig. 12)*.

the vaults. However, on the longitudinal sections, the equivalent junctions are on the same straight lines. Thus, the crossing points determined on the plan view were projected up according to longitudinal lines, and the rib system as a whole cannot be described by a regular barrel vault form (*Fig. 12*).

Nonetheless, the exact height of the longitudinal lines was constructed "on the main cross-section view" – or rather with the help of its realization as a temporary supporting structure, as shown in *Fig. 13*. Using the quarter-point of the base-line's line segment, which falls into the rectangle, as the central point, and its distance from the rectangle's upper vertex as a radius, an arch can be drawn. The vertical projection of the plan's crossing points falls on these arches without exception, on every main cross-section, on both sides (*Fig. 14*). However, as we noted

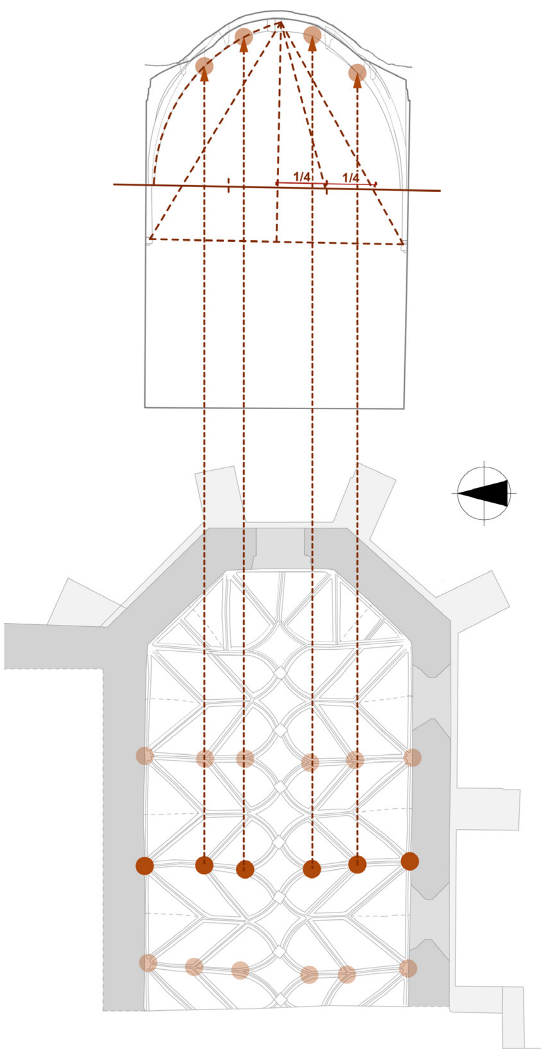

Figure 14. The main cross-sections' construction method

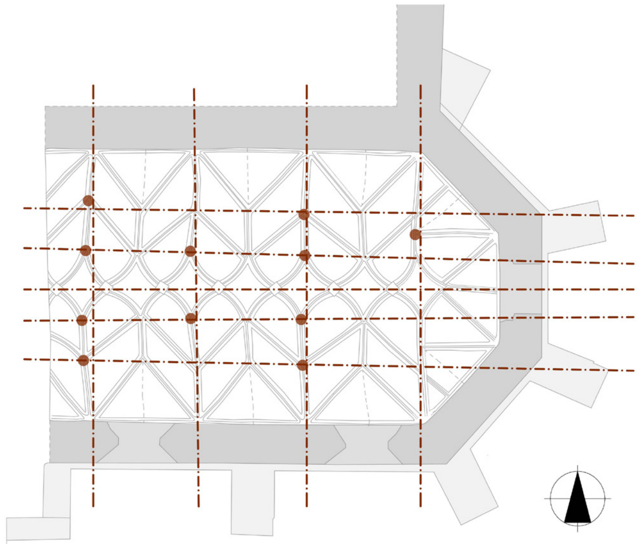

Figure 15. Longitudinally displaced junction points on the plan

earlier, the main sections' crossing points on the plan view have a slight disposition longitudinally (*Fig. 15*). The reason for this phenomenon is most likely the fact that the premade, rigid junction and rib elements must fit together, since carving new stone elements is expensive and time-consuming. So the only flexibility of this rib system is the possibility to slip the junctions slightly sideways as it is needed for fitting in the ribs.[5] Regarding these dispositions and the height relations (detailed above), the simplest conclusion is that the longitudinal lines also meant physical (wooden) temporary structures, on which these alignments could be carried out.

It is also to be noted that the ribs, which have a sign starting with "B" and "E" have a fracture point in their arch line, in the same height in all the ribs on one side. (However, this height differs on the southern and northern side.) Most likely this fracture signifies an additional support line in the temporary supporting structure. This line is approximately above the junction point of the construction triangle and the temporary work level (*Fig. 16*).

4.5. Construction of the lunettes (secondary cross-sections)

Analysing the cross-sections through the lunettes of the vault, we could draw the same main conclusions as in the case of the main cross-sections, thus the junctions were projected up based on longitudinal lines, and the exact height is constructed in cross-section view. We think it is

5 This sideway disposition is more easily constructed in the main cross-sections, because these cross-sections have more adjoining elements, therefore the system has more flexibility there than in the cross-sections through the lunettes.

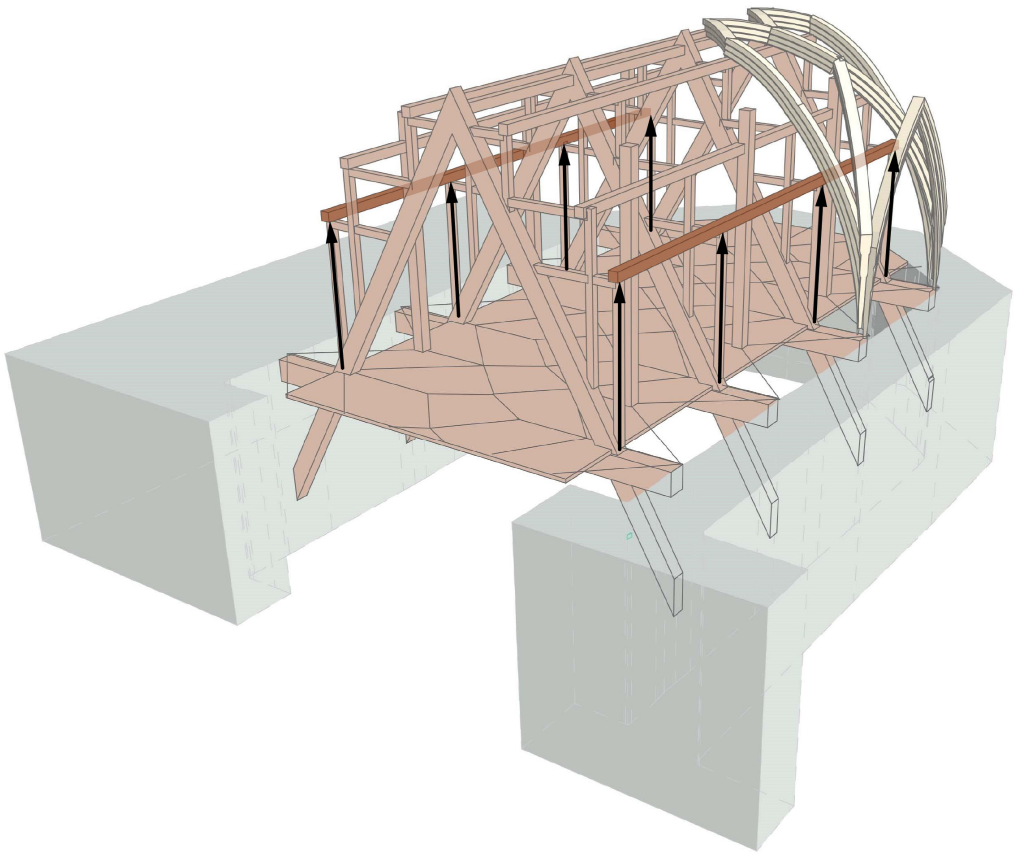

Figure 16. The theoretic reconstruction of the temporary supporting structure

also likely, that contrary to the main cross-sections, the secondary ones did not appear as actual separate supporting structures.

The lower junctions of the curvilinear ribs ("C" points) fall on the same line (and same scaffolding element), as the same junctions of the main cross-sections ("F" points).

The upper junctions of the lunettes are without exception vertically above the lines determining the ending points of the cross-direction ribs starting from the imposts. (On the plan view, it means that this latter line and the line of the lunettes' upper junction are overlapping.) The height of these junctions can be determined by a circle, whose centre is point "O" and the radius is defined by the same sized triangle, which was formerly used for the cross-section construction (as defined in *Fig. 17*). Drawing this circle on the longitudinal section starting from point "O" and sectioning the circle with a vertical line also starting from "O", the height of these points is given *(Fig. 18)*. Thus, in this case, we presume that the junctions were simply projected up to the adequate height.

In addition, with the above-detailed construction on the longitudinal section, rib J1.0 is also given, as well as the height where the top point of the lunettes' pointed arch on the surrounding

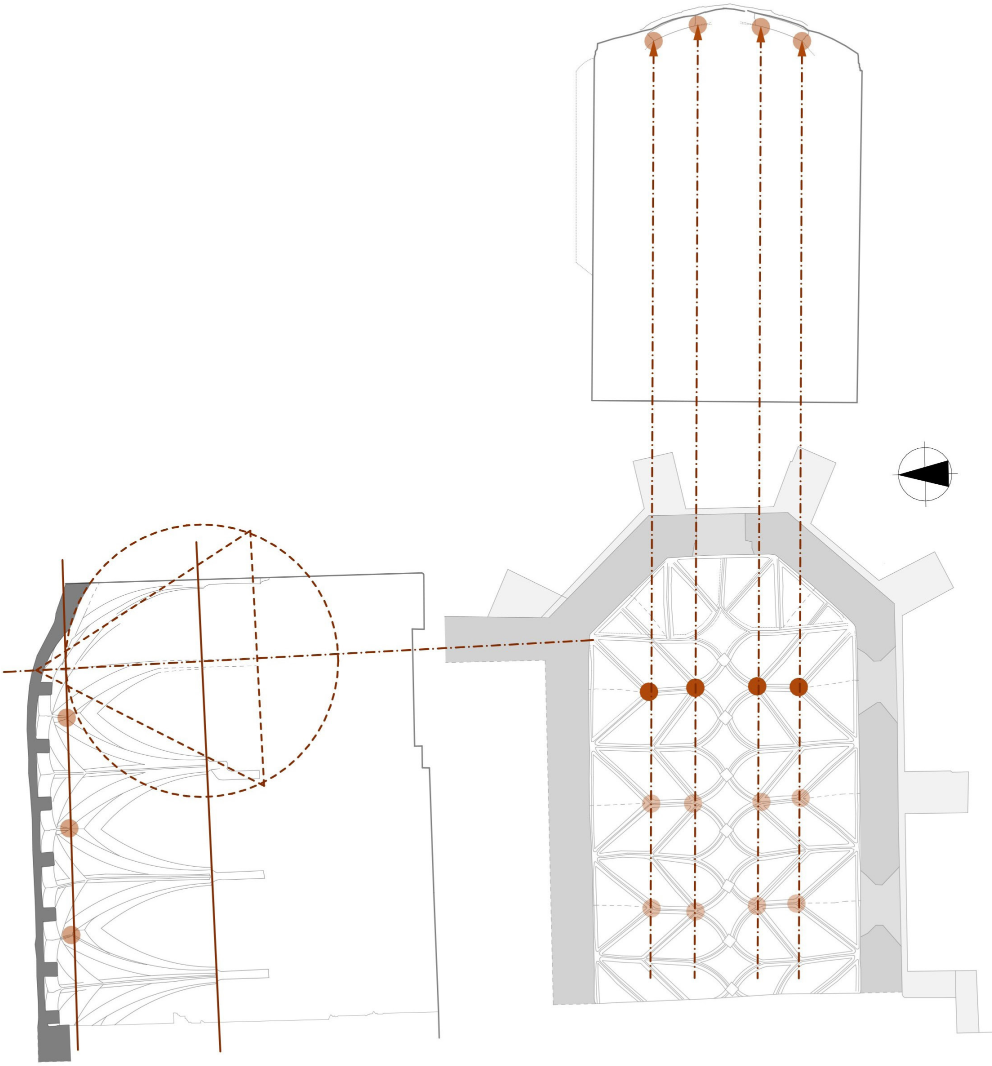

Figure 17. The construction method of the secondary cross-sections

walls, as the section point of the inner wall surface and this circle. However, this latter observation does not apply to the two lunettes of the southern side under which the apse two windows are situated.[6]

According to Huerta (Huerta 2012. 173), Hontañon's drawing also means that the positioning of the junctions elements preceded the positioning of the rib elements. Since in our case the careful positioning of the first, and the way less careful fabrication of the latter (see detailed

6 We have no detailed information about the former gothic church and the surrounding buildings, however, this detail allows the speculation that some edifice existed on its northern side back then too, since the present vault is adjusted to the gothic windows, and this adjustment has no sign on the northern part.

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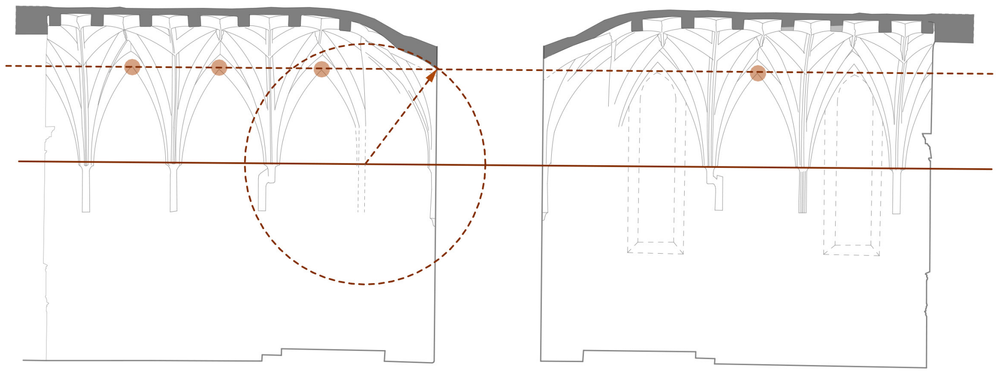

Figure 18. The construction method of the lunettes' wall arches, and their relation to the southern windows

below) in our case is clear, we presume that in the case of Andocs that was the actual building order. All the more so since carving a junction is a more complicated task than making rib elements.

4.6. The construction of the ribs

4.6.1. Ribs with one curvature

Regarding the individual ribs of the net vaults, the most generally accepted idea became the "Prinzipalbogen" theory, meaning that all the ribs of a given vault have the same curvature, which is ideal, since standardization leads to prefabrication, which accelerates the whole building process (Renn–Osthues–Schlimme 2014. 71; Vidal 2017. 1007). The "Prinzipalbogen" idea first appeared in the 16th-century, in the manuscript of Jacob von Andernach (as quoted by Müller [Müller 1974. 65–66]). In the 17th century Ranisch (Ranisch 1695) described numerous examples of it, mainly following the domical vault-like construction. Hoffstadt (Hoffstadt 1840) also presented the idea. The latter two gave the basis of Ungewitter's above detailed, influential writing (Pliego 2012. 218). In the 20th century, among others, Meckel (Meckel 1933. 108), Müller (Müller 1990) and Tomlow (Tomlow 1991) advocated the method. Although the "Prinzipalbogen" idea was opposed by certain researchers from the 19th century (e.g. Lassaulx in 1835 ascribed it to the insufficient knowledge in geometry in the case of Ranisch, as quoted by Wendland [Wendland 2012. 106]), it was the leading theory from the 16th to the 20th century. In the mirror of the recent studies, this theory doubted may be, but there are occasional results to prove its former existence: Voigts (Voigts 2015. 56–57) showed that in the case of the Georgskirche in Augsburg, a combination of the two was applied: the main ribs followed the "Prinzipalbogen" idea, however, their crossing points were carefully positioned, meanwhile the subordinate ribs do not follow the prime construction methods.

It is also to be noted that using the "Prinzipalbogen" theory in the case of net vaults with a rib pattern, which contains elements, which are not parallel to each other, the uniform rib curvature means that estimating the vaults form with barrel surfaces is not correct.

In our case analysing the curvatures of the ribs one by one gave a quite uneven dataset, with a big dispersion. (See *Table 1*) Big as the dispersion is, the values cannot be classified into clearly

Table 1. Curvatures of the non-curvilinear ribs

Rib's sign according to Fig. 6.	The curvature's radius of the lower part of the rib / The curvature's radius of the ribs without fracture point [m]	The curvature's radius of the upper part of the rib [m]
B1.0	3.51	4.97
B1.1	3.455	4.03
B1.2	3.36	4.24
B1.3	4.23	4.02
B1.4	3.35	4.32
B1.5	3.5	3.37
B1.6	non-measurable	3.25
B2.0	3.14	3.95
B2.1	3.73	4.15
B2.2	3.49	3.73
B2.3	3.58	–
B2.4	3.07	3.88
B2.5	3.15	3.64
B2.6	non-measurable	4.16
E1.0	3.42	3.57
E1.1	3.65	2.6
E1.2	3.81	3.79
E1.3	3.13	3.3
E2.0	3.55	3.81
E2.1	3.42	3.14
E2.2	3.21	3
E2.3	2.87	3.89
A1.0	4.8	3.625
A1.1	4.82	3.215
A1.2	4.57	3.16
A1.3	3.44	2.64
A1.4	3.16	2.675
A1.5	3.235	2.65
A1.6	non-measurable	3.52
A1.7	non-measurable	3.35
A1.8	2.58	2.47
A1.9	3.19	–
A2.0	3.64	3.24
A2.1	3.41	3.18
A2.2	3.82	3.24
A2.3	3.38	–
A2.4	4.43	3.12

Table 1. cont.

Rib's sign according to Fig. 6.	The curvature's radius of the lower part of the rib / The curvature's radius of the ribs without fracture point [m]	The curvature's radius of the upper part of the rib [m]
A2.5	2.54	2.95
A2.6	non-measurable	3.39
A2.7	non-measurable	2.99
A2.8	2.67	2.29
A2.9	2.64	–
C1.0	2.35	–
C1.1	3.9	–
C1.2	4.32	–
C1.3	4.5	–
C1.4	4.35	–
C1.5	4.78	–
C1.6	3.9	–
C2.0	3.4	–
C2.1	3.84	–
C2.2	4.32	–
C2.3	3.9	–
C2.4	3.91	–
C2.5	4.37	–
C2.6	3.875	–
F1.0	3.4	–
F1.1	3.87	–
F1.2	4.19	–
F1.3	4.42	–
F1.4	4.36	–
F1.5	3.59	–
F1.6	4.41	–
F2.0	3.445	–
F2.1	2.89	–
F2.2	4.28	–
F2.3	3.45	–
F2.4	3.46	–
F2.5	3.52	–
F2.6	4.16	–
G1.0	8.31	–
G2.0	3.89	–
H1.0	3.27	3.52
H2.0	3.89	3.3

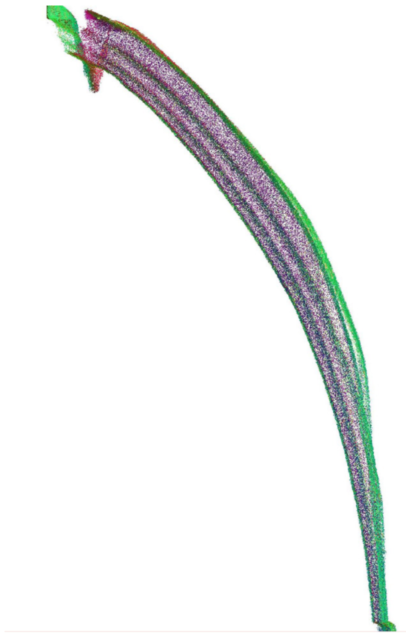

Figure 19. The fractured rib-arch line by the connection of the junction element and the rib element

distinguishable groups based on their curvature, nor is there any clear connection between the curvature of the ribs and their role in the rib system. Based on that, we concluded that although the most widely accepted theory about the ribs of the net vaults is the "Prinzipalbogen" theory, in the case of the apse vault of Andocs it was not the method used.[7]

Furthermore, we found that in most cases, the curvatures of the junction elements' rib startings do not connect evenly with the curvature of the rib elements *(Fig. 19)*. That finding supports our theory about the struggle to place every premade element in place, and its supposed solution that instead of recarving them, they were "forced" to their place, even at the cost of an "imperfect" geometry.

Regarding the junction elements, we must mention that at those points where five ribs are meeting, on the plan view it is clearly visible that the junction of the lower surfaces is not a well-defined point, rather the cross-direction rib and the two curvilinear ribs meet in an orderly way, whereas the two diagonal ribs connect to the sides of the curvilinear elements *(Fig. 20)*. A possible explanation is that these ribs were actually added to the main rib-frame at a later stage of the building process, as secondary elements (see more details below). On the junction seen in *Fig. 20* (F1.3–D1.7–D1.8–C1.3–C1.4 junction), on the lower surface of the C1.3 rib possibly the stonemason's intention to fit the individual rib's profile to the lower surface of the junction element can be discovered. We claim that this is presumably the adjustment of the element to the D1.7 rib after positioning it in its final place. It seems also clear that it is simpler to fit the

[7] We also calculated the value, which would be the radius of the ribs' curvature according to the "theory of the longest route", another widely accepted idea, implementing the "Prinzipalbogen" theory (Hoffstadt 1840. XIV A; Meckel 1933. XXI). The average value is 2.95 m with a disperson of 11 cm, which value shows no clear connections to the measured dataset.

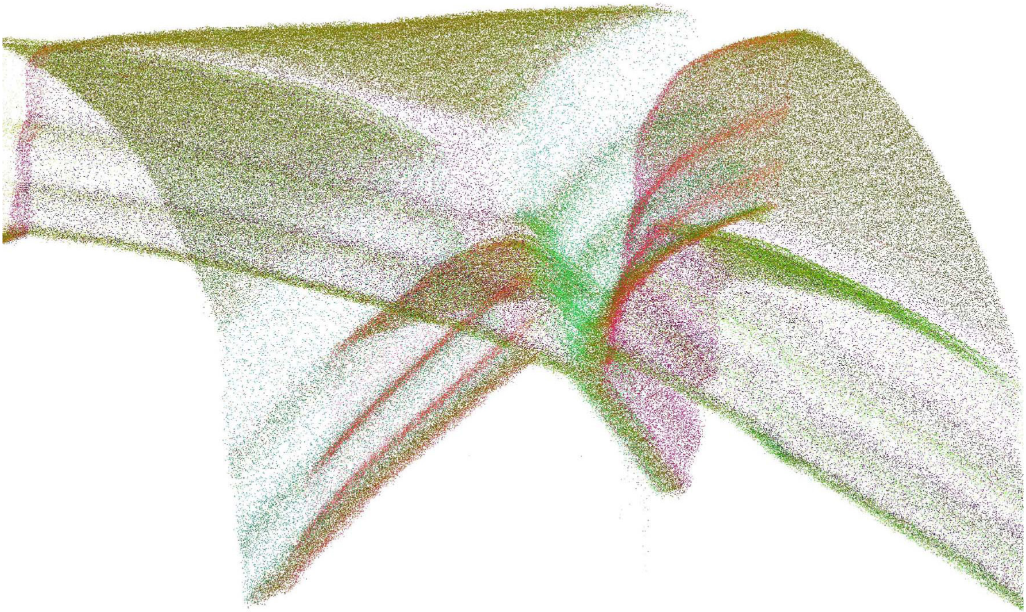

Figure 20. The junction point of five ribs; the posterior correction of the C1.3 rib's lower surface on the point cloud

additional rib to that part, where it must attach to only one other rib, not to the intersection of two ribs.

It is also to be noted that the C1.6–G1.0 and the C2.6–G2.0 ribs' profile is the same as the wall arches (ribs, which have a sign starting with "A") profile, which is visibly smaller than the other ribs' profile. In this crossing these smaller-profiled ribs run at the cross-direction ribs in a way that the lower surfaces of the small ribs are higher than those of the bigger ribs, and the "junction" happens most likely without a junction element – the exact endings of the elements are not visible due to the present dark paint covering of the ribs, however, on the point cloud, there is no sign of fractured arch lines in this case *(Fig. 21* and *Fig. 22)*, as it frequently appears by the junction elements (as detailed above). In addition, the lower junction of the ribs "G1.0" and "G2.0" fall to the ribs "A1.7" and "A2.7" in a non-architectonic point (the middle of an arch). This positioning probably comes from the need to give the required horizontal support for the "C1.6" and "C2.6" ribs' lower endings. The wall behind the wall-arch is obviously enough to support the elements, however visually uncertain this form is. The reason for using the smaller profile for these ribs is undecided, perchance it would have been troublesome to solve the smaller wall-ribs junction to a bigger profile, whereas the smaller profile's connection to the bigger ones, as presented in the given form, is solvable.

As to summarize the latter two points, we think it is quite likely that the rib elements whose names begin with "C" are of secondary importance regarding the global rib geometry, and they presumably were built to their place as the last elements of the rib system. The main reason for that is the fact that these elements do not have a primary role in getting from the imposts to the crown. Their visibly secondary join to the junction elements and the decision to modify their profile according to the requirements of the whole rib system support our claim.

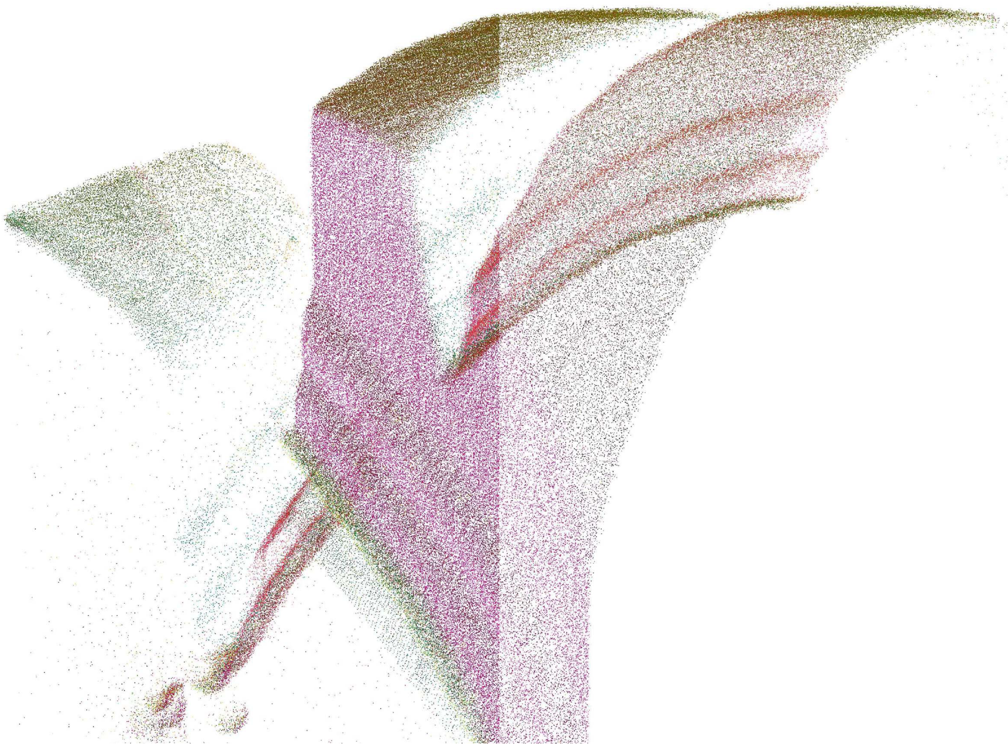

Figure 21. The connection of the E1.3 element (big profile) and the C1.6–G1.0 elements (small profile) on the point cloud

To conclude this part, we want to accentuate that the curvature of the ribs is not easy to measure, and a slight difference in the arch superposed on the side view of the rib's point cloud results in a rather big difference in the value. However, in the case of other similar analyses (e.g. our previous research on the nave vault of the church of Szászbogács [Jobbik–Krähling 2022]), our measurement proved to be precise enough to find the correlations between the values and draw a conclusion.

We claim that in this case, since the overall construction method of the rib system is not based on values closely related to the curvature of the ribs (e.g. the curvature itself, the arc length, the chord length), in Andocs, in the case of the non-curvilinear ribs, the elements were carved less precisely, with only roughly the same curvatures. The above-detailed discrepancy between the junction elements' rib startings and the actual rib elements also supports our conclusion that in the case of this vault, the ribs themselves were less crucial factors in the construction process.

Figure 22. The connection of the E1.3 element (big profile) and the C1.6–G1.0 elements (small profile) in photo

4.6.2. Curvilinear ribs

According to Wendland and Degenève (Wendland–Degenève 2017. 160), there is no known record of the production of gothic curvilinear ribs. However, they reconstructed a possible way by a practical experiment, using metal templates, which determine those two views of the rib which has a simple circular curvature (Wendland–Degenève 2017. 164–165). Mozo, Rabasa and Rodriguez (Mozo–Rabasa–Rodriguez 2020. 248) gave a slightly different solution to the same problem: according to them, the flexible template goes to the side of a cylinder. (Geometrically these two mean the same.) In both cases, the circular curvatures are necessary, however, as opposed to the statement of Mozo, Rabasa and Rodriguez (Mozo–Rabasa–Rodriguez 2020. 248), it is not necessarily connected with the "Prinzipalbogen" theory – the circular curvature's radius is not bounded in this sense. Another theory is to describe the curvilinear rib vaults' plan view with straight lines and construct their curvatures with circumference lines. Afterwards, based on the projection to the straight line, the height of any point can be constructed. (Gonzalo–Talaverano 2013. 195)

In the case of Andocs, the presumed construction process gives the required information about the two ending points of each curvilinear rib on the plan view, as well as in three dimen-

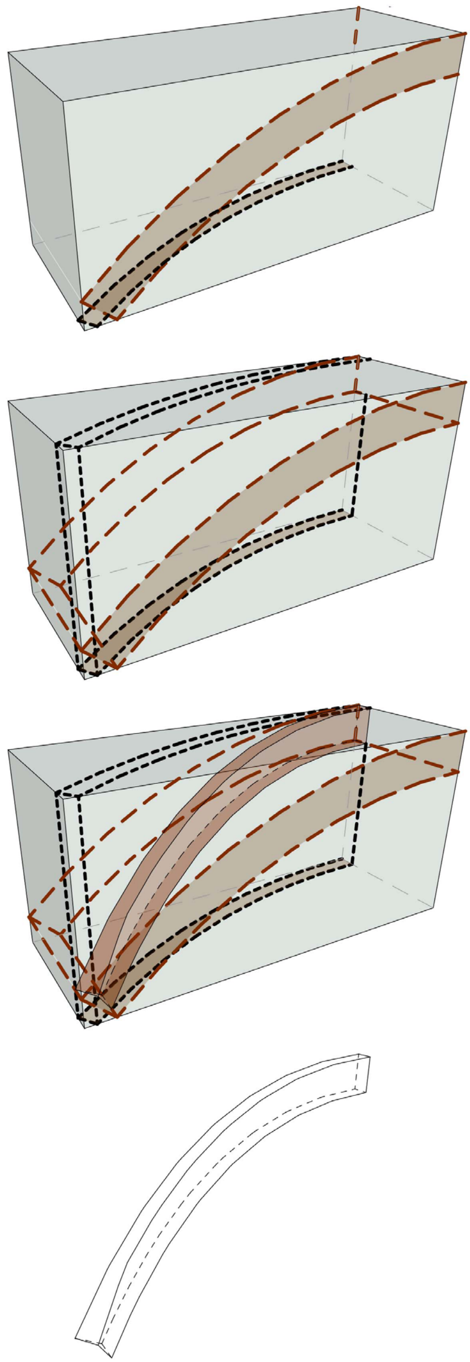

Figure 23. The theoretic reconstruction of the curvilinear ribs' fabrication, based on Wendland–Degenève 2017

sions. We concluded that even though the present paint-covered surface of the ribs does not allow the visual observation of the connection points of the individual rib modules, the length of these ribs implies that they are carved out of one single piece of stone per rib.

Analysing the curvatures of these ribs on the plan, we found that their curvature is with a good approximation the same. (The average of the measured curvature values is 97.5 cm, with a dispersion of 10.9 cm.) It was also possible to find the direction of the side view, which presumably was used for the construction, based on the above-detailed idea of Wendland and Degenève. In our case, it is the view parallel to the line connecting the two endpoints of the middle line of the curvilinear rib's plan *(Fig. 23* and *Fig. 24)*. This assumption is quite likely since this method results in the need for the smallest block stone to start with. However, the curvatures measured on the side view are not the same for every rib, but three different curvature groups can clearly be distinguished, for which the reason is not quite clear, since it does not come from the geometrical restrictions *(Table 2)*.

Figure 24. The theoretic overall dimensions of a curvilinear rib, represented in the photo of the vault. (Naturally, the carving of the ribs happened before they were built in, the figure only means to picture the supposed dimensions.)

Table 2. Curvatures of the non-curvilinear ribs

Rib's sign according to Fig. 6.	The curvature's radius of the ribs on plan view [m]	The curvature's radius of the ribs on the side view, as defined in the text [m]
D1.0	non-measurable (too short line segment)	non-measurable (too short line segment)
D1.1	1.09	2.39
D1.2	0.945	3.72
D1.3	0.85	6.795
D1.4	0.68	3.79
D1.5	0.92	3.7
D1.6	0.826	3.71
D1.7	1.08	6.44
D1.8	0.93	6.7
D1.9	0.81	3.725
D1.10	0.88	3.69
D1.11	1	3.79
D1.12	0.92	2.4
D1.13	0.87	3.72
D1.14	1.26	2.3
D2.0	non-measurable (too short line segment)	non-measurable (too short line segment)
D2.1	1.11	2.29
D2.2	1.01	3.75
D2.3	1.09	3.72
D2.4	1.14	7.05
D2.5	1	3.67
D2.6	0.83	6.95
D2.7	0.95	3.74
D2.8	0.965	7.02
D2.9	0.97	3.775
D2.10	0.98	3.81
D2.11	0.9	3.63
D2.12	1.01	3.71
D2.13	0.72	2.44
D2.14	0.98	2.11

It is also to be noted that the C1.0 element is curvilinear, whereas all the other elements which have a sign starting with "C" have only one (side view) curvature. The side curvature of this element can be categorized into the above-mentioned three curvature groups, however, its plan curvature is significantly bigger than that of the other curvilinear elements. This difference from the other parts of the vault, which does not even match the rib's symmetrical pair, is hard to explain. On the one hand, they perhaps used a superfluous curvilinear element out of necessity to finish the vault, or the rib can be a spoilt crown element, which could not be used for that part, because of its plan curvature. On the other hand, this curvilinear element can be the remnant of another conception for this vault, which eventually was simplified for an unknown reason.

4.7. The construction of the webbing

The connection between the rib system and the webbing of the net vaults is a point at issue in the technical literature. The more commonly accepted idea is that the rib systems were built first, and the webs afterwards, on the ribs as their formwork as described first by Saunders in 1814 and specified later by Willis in 1842 (as quoted by Wendland [Wendland 2007. 342]). Ungewitter (Ungewitter 1901. 37) also accents this as the main difference between the barrel and net vaults.

The opposing idea is that the webbing of the net vaults with complicated rib patterns is in fact built as a simple barrel vault, under which the ribs were applicated later. (In some works, this supposed feature of the vault appears in consequence of its material, e.g. ceramic-ribbed net vaults, as described by Fabini [Fabini 1999], but the theory appears in connection with the Szeged-Alsóváros church's nave vault too, where only the ribs are made of ceramic, but the junctions are of stone [Harsányi 2001. 302]).

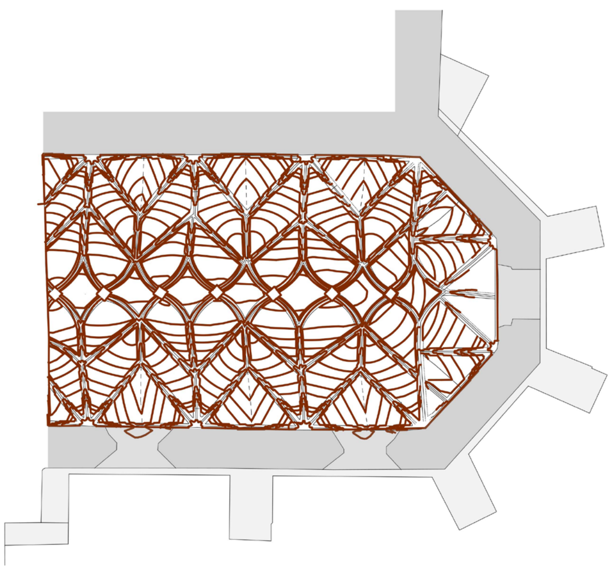

Figure 25. The mapping of the vault
(The mapping was executed on the point cloud of the inside of the apse.)

Scanning a vault can provide the answer to this question in any given case. In our case, for the analysis, we “sliced up” the vault horizontally, both in the case of the point cloud of the apse and the point cloud of the back of the vault. “Mapping” for presenting the conjunction between the ribs and the webbing in drawing can be seen among others by Choisy (Choisy 1883. 54 Fig. 60.), as quoted by Javier (Javier 2012. 201). This “empiric method” to describe surfaces (Wendland 2007. 345) was also used by Rave in 1955 (as quoted by Wendland [Wendland 2007. 345]), and by Voigts (Voigts 2014. 247; Voigts 2021. 81). The mapping of a vault based on its point cloud also can show the slight deformations of the webs, which can lead to conclusions about using of formwork, as presented by Voigts (Voigts 2014. 248).

The result of this mapping process in our case, as shown in *Fig. 25*, clearly indicates the three masonry types applied to the webbing. This differentiation in the direction of the courses makes it clear that the webbing was not built as a simple barrel vault, but it was built web by web, on the ribs.

As for the building process, after completing the rib system, supposedly the wooden structure and the ribs’ supporting structures did not get removed until the webbing was also finished. This way the ribs were additionally supported during the building process, when e.g. one-sided loading and other complementary impacts could occur (Fitchen 1961. 262).

The direction of the courses in the case of the lunettes indicates that it was built from freehand, clearly choosing the shortest course directions possible between the surrounding ribs. The same can be concluded in the case of the lower part of the vault (under the ribs, which have a sign starting with “C”). (As opposed to the building method using formworks of the webs, which can be usually identified by the flat surface of the webs [Wendland 2007. 342]). In addition, the masonry pattern of the latter two indicates that they were built at the same time, so the lateral forces acting on the ribs are neutralised. However, the upper part of the vault (above the ribs, which have a sign starting with “C”) shows a different pattern. Here the courses are approximately parallel to the walls of the apse. A slight alinement to the ribs is still visible, but the masonry rather resembles that of a barrel vault. All the more so since the webs between the curvilinear ribs at the crown line have also only this barrel-like curvature in perfect concordance with the webs underneath them, instead of their own “bumps”, as in the case of other net vault examples. In addition, from the backside of the vault we know that here the bricks of the courses are also parallel to the walls. (That is the part of the vault which is freely visible from above since the charging of the imposts does not cover it.) At the same time, it is also to be noted that the span between the ribs is quite small, so it is still possible to build the vault from freehand. (This small span, as the possibility of free-hand web building, is one of the important characteristics of late gothic vault design [Lassaulx 1829. 324; Wendland 2007. 311]). Nonetheless, since the lower parts of the webbing were clearly built on the ribs, considering the stability of the structure during the building process, as well as the assumed construction method of the ribs system, it seems highly probable that the upper part of the webbing was also built on the ribs, and not the other way round.[8]

Recognising these diverse patterns in the webbing of a single vault is important since it shows how the former builders always aimed for the most practical solutions.

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8 This conclusion also refers to the barrel vault theory of the net vaults, because one of the main reasons for it is the lack of these “bumps” on the back of the vault. However, just as in the case of Andocs, it is conceivable that the charging hides the “bumps” of the lower part of the webbing. Analysis with a space scanner can provide new data to consider in these questions at issue.

5. CONCLUSION[9]

The primary result of our research is the highly plausible reconstruction of the original early 16th-century construction and building method of the Andocs catholic church's apse vault.

We found that the construction method was based on circles and parallel shiftings on the plan view, while the heights of the junctions were constructed on the cross-section view primarily based on a regular triangle and circles. These findings are basically in accordance with the relevant technical literature, complemented with the case-specific details and inner rules of the construction system.

Additionally, we presume that the geometric construction process was in close connection with the temporary supporting structures, and at some points, the temporary structures also served as a tool for the construction.

Furthermore, we claim that the slight sideways excursions of the main cross-sections' junctions are due to the efforts to fit the premade rib elements to their places, between the premade junction elements.

We also found that the widespread idea of the "Prinzipalbogen" theory cannot be applied to this vault. As for the reason of this phenomenon, we assume that in this specific case the spatial positioning of the junction points had the utmost importance during the construction, therefore less attention was paid to the individual rib elements' accurate fabrication.

Regarding the curvilinear elements, we concluded a possible fabrication method, based on their exact geometry and the technical literature on the topic.

Moreover, we claim that the webbing was built on the rib system (as opposed to the decorated barrel vault theory). In addition, the webs were built one by one, from free hand in the lower parts of the vault, whereas in the upper part it was built more like a barrel vault, however, the geometric connection between the ribs and the webs can be detected there too.

Reconstructing the construction method of different late medieval vaults can provide further details about the supposed connections (especially regarding the builders) of certain building groups, and may complement other considerations of the research.

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9 We would like to emphasize, that although the question of load distribution between the ribs and the webbing is often discussed together with the questions of the building methods, as stated by the newest research, the masonry structures have multiple equilibrium states (Heyman 1995. 20–22; Huerta 2012. 183). According to the latest computer models, the loads distribute between the two elements, holding a dynamic equilibrium, so they rearrange even due to the slightest displacement of the supports (Lengyel–Bagi 2015. 58). The real load distribution is hard to remodel; even the results of finite element and discrete element software must be compared to the real cracking pattern of the vault to verify them (Bruggi–Lógó–Deák 2021). Thus, the construction and building method of the vault and its building order concluded from its exact geometry do not determine its load-bearing characteristics. Therefore, in the present study, we do not attempt to make statements about this question.

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Középkori hálóboltozat szerkesztés újramodellezve

Az andocsi templom szentélyboltozata

ÖSSZEFOGLALÓ

Jelen tanulmányban az andocsi katolikus templom szentélyboltozatának térszkennerrel felmért, pontos geometriáját elemeztük. Noha a boltozatról kevés írott forrást ismerünk, a pontfelhő alapú kutatás által új részletekre derült fény az épület építéstörténetéről, csakúgy, mint a késő középkor boltozatépítési technikáiról. Az elemzéshez azt a három lépésből álló elemzési módszert alkalmaztuk, amit hálóboltozatok pontfelhőjének értelmezésére fejlesztettünk ki. A bordaháló vizsgálata során rekonstruáltuk a valószínűsíthető eredeti szerkesztési és építési módszert, valamint a kora 16. századi boltozat ideiglenes építés közbeni tartószerkezeteit is. Az egyes bordák elemzése által a boltozatot a téma szakirodalmának széles körben ismert elméletei – mint a vezérgörbe elv (adott hálóboltozat minden bordájának azonos a görbületi sugara), vagy a leghosszabb út elve (a bordaháló alaprajzon a vállától a záradékig vezető leghosszabb bordaút teljes hossza adja a bordák görbületi sugarát) – tükrébe tudtuk helyezni. A térgörbe bordák tekintetében a legújabb kutatási eredmények alapján bemutattuk e bordák feltételezhető készítési módját. A süvegrendszer és a bordarendszer vízszintes síkokkal való „felszeletelése” által megállapítottuk az építési sorrendet, valamint a süvegek valószínűsíthető építési módját.

KULCSSZAVAK

Andocs, térgörbe bordás boltozat, bordás hálóboltozat, középkori szerkesztési módszer, középkori építéstechnika, geometriai elemzés, középkori geometria, pontfelhő elemzés, épület szkennelés, lézerszkennelés