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A Self-contained Stellar Vault Construction Method. The Vault of the Matthias Oratorio in the Inner City Parish Church of Budapest

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Abstract

In the present study, we analysed the laser-scanned point cloud of the stellar vault of the Inner City Parish Church of Budapest's Matthias oratorio. Our analysis concerned the global geometry of the rib network, as well as the webbing. During the study of the rib system, we reconstructed a probable construction method of the late 15th – early 16th-century vault, which seems to be a self-contained construction system in regard to the rib system's plan, the height of the junction points and the curvature of the individual ribs. We found, that to the latter the widely known "Prinzipalbogen" theory applies, however, the "theory of the longest route", which is often mentioned together with the former, most likely was not used. Mapping the webbing and the ribs allowed us to examine the building technique of the webs too.

Keywords

Matthias oratorio, Inner City Parish Church of Budapest, stellar vault geometric analysis, late medieval construction method, laser scanned point cloud analysis

1 Introduction

The Inner City Parish Church of Budapest has a long and eventful history, starting from the Romanesque era, and the structures of the building reflect the numerous destructions and reconstructions, which happened during these centuries. However, the structures of the Matthias oratorio, above the southern chapel are quite unaffected by these events, so its stellar vault is one of the rare remains of late Gothic architecture in Hungary.

The original construction methods of the late Gothic stellar and net vault systems are a topic, of which numerous ideas exist in the technical literature, however, only a very few of them are sources contemporary to the actual building of such structures (e.g. Rodrigo Gil de Hontañon, Jacob von Andernach), and these are not detailed enough to get the full picture. Nonetheless, the modern survey techniques, based on point clouds (e.g. photogrammetry or laser scanning) allowed the researchers to unfold a newer layer of the question. Examining the exact geometry of these vaults is a great tool for attempts aiming for the reconstruction of the original late Gothic construction strategies.

In the current study, we used a BLK 360 laser scanner to generate the point cloud of the Matthias oratorio, which meant the basis for our further analysis. During our previous works, we made attempts to establish a systematic method for the geometric analysis of net vaults' point clouds (Jobbik, 2022; Jobbik and Krähling, 2022a; 2022b), and in the present study, we applied the same principles to the stellar vault.

Thus, regarding the Matthias oratorio's vault, we concluded a highly presumable original construction method, which seems to be a self-contained construction strategy in this small unit of the parish church.

2 Methodology

As we mentioned above, for generating the point cloud, a Leica BLK 360 laser scanner was used. The processing of the point cloud was carried out by Leica Cyclone Register 360 software. The resulting point cloud is presented on Fig. 1. Afterwards, the analysis of the data happened mainly with AutoCAD software.

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Fig. 1 The picture of the oratorio's point cloud

The above-mentioned systematic analysis method (Fig. 2) has three main steps, out of which the first is the isolation of the structures, which belong to different building periods, followed by the detailed geometric analysis of the global geometry of the rib system. This part can be further divided into the analysis of the rib systems plan, the analysis of the junction points spatial positioning and examining the individual ribs. Lastly, the mapping of the vault structure provides information about the building techniques of the webbing.

Reviewing the technical literature on the topic, we found several studies that applied similar workflows, but none of them accentuated the systematic approach, which can easily be interpreted in the case of other net vaults or stellar vaults, which was one of our main objectives.

Huth (2020) examined the ribs' curvatures, as well as the height of the junction points based on a laser-scanned point cloud. Vidal (2017) analysed the deformations of ribs based on their exact geometry, while Fuentes and Huerta (2016) and Palacios Gonzalo and Martín Talaverano (2013) examined the construction techniques of vaults, based on surveys by laser distance meter and laser total station, which do not provide such a detailed geometry as scanning or photogrammetry do, but they are still more accurate than the traditional techniques.

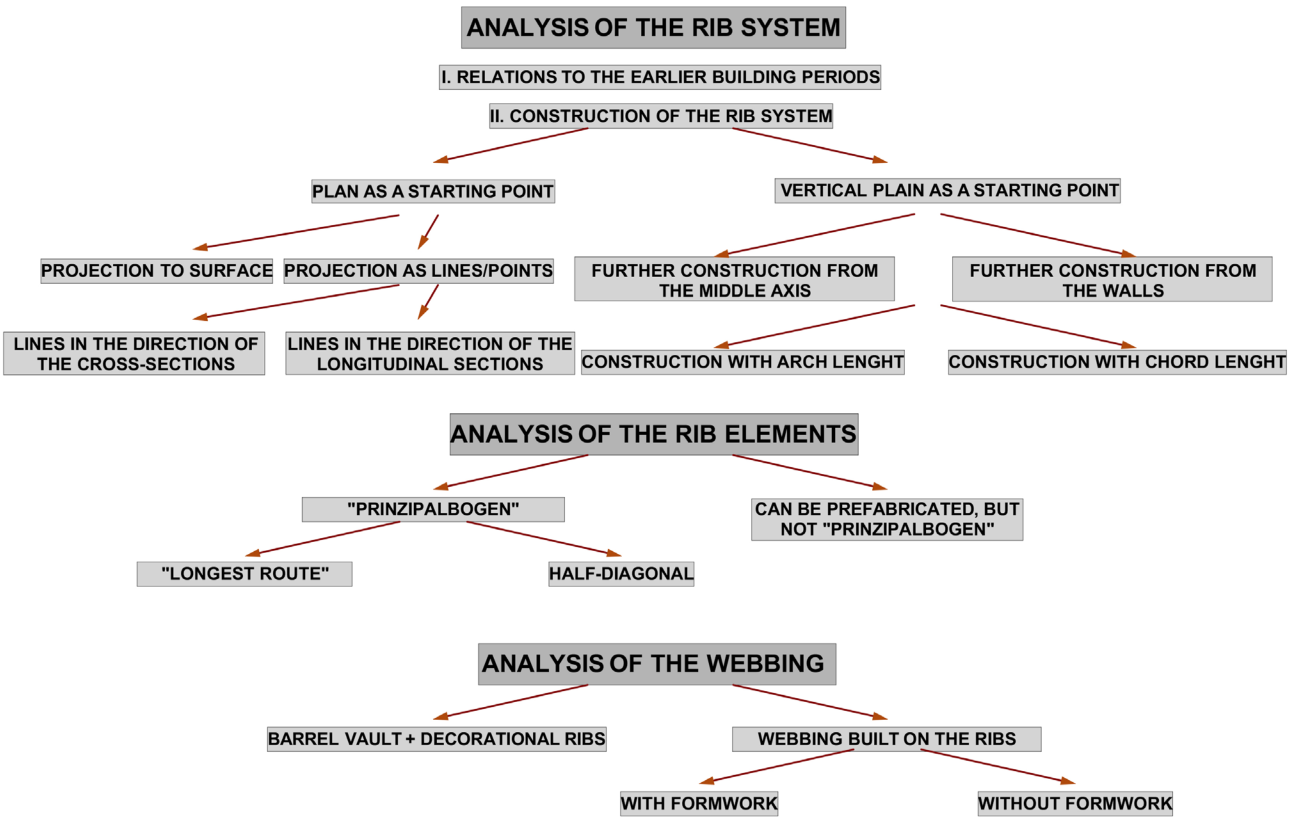

Fig. 2 The mind map of our analysis method for net and stellar vaults' point clouds

3 Short building history of the oratorio

The Inner City Parish Church of Budapest has Romanesque origins and there were two major Gothic reconstructions too (Horogszegi, 2010). The southern chapel of the church (Fig. 3) dates back to the first Gothic period during the reign of Sigismund (1398-1413) (Horogszegi, 2010) or, according to other opinions to the second quarter of the 14th century (Kovács, 2016), thus it was built at the same time as the apsis (Papp, 2005). The Matthias oratorio was built as a second storey on this chapel during the second Gothic period (Gerő, 1956; Horogszegi 2010; Lux, 1933; Papp, 2005), between 1470-80 (Feuerné Tóth, 1958) or between 1490-1507 (Papp, 2005).

After the Medieval period, the church suffered several destructions and reconstructions, however, the oratorio, which is the subject of the present paper was not affected by them in its structure (Horogszegi, 2010). Thus, its stellar vault (Fig. 4) is one of the rare remains of our late 15th – early 16th-century heritage.

4 Vault analysis

Szőke (2010) described the space covering structure of the oratorio as a vault, which has a plan based on an enumerated rhombus net based on a simple 45° network. As Papp (2005)

Fig. 3 The southern chapel

Fig. 4 The vault of the oratorio

pointed out, this plan pattern is the same as the simplest net vault ending solutions in the case of a polygonal apsis.

However, based on the information from the laser-scanned point cloud, more detailed information can be gathered. This information is the base for our above-detailed method, from which the analysis of the vault was concluded.

4.1 Previous building periods

The Matthias oratorio was added as a second story to the early 15th-century southern chapel of the church during the second Gothic construction at the very end of the 15th century (Gerő, 1956; Horogszegi 2010; Lux, 1933; Papp, 2005). As shown on Fig. 5, the new addition follows the outer,

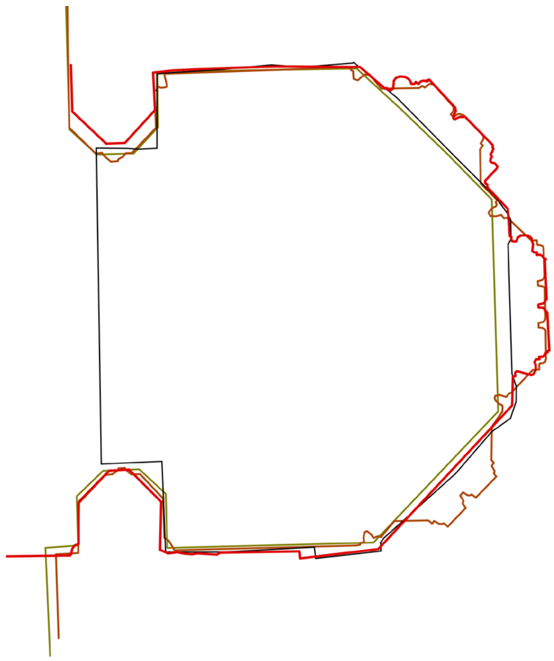

Fig. 5 The outlines of the inner walls of the chapel and the oratorio projected together. (The chapel's wall at floor level: green; the chapel's wall at the level of the imposts: brown; the oratorio's wall at floor level: black; the oratorio's wall at the level of the imposts: red.)

as well as the inner contours of the previous building part, therefore these boundaries were given, and the vault of the new oratorio was determined by them.

4.2 The construction of the ribs' plan

Although the idea that the most important factor of the stellar- and net vaults' building process was the three-dimensional positioning of the junction points appeared in the earlier technical literature by implication[1], it only got accentuated in the 20th century. Some researchers claim that the widespread "Prinzipalbogen"-idea also serves only this purpose (Huth, 2020; Müller, 1975). With the modern survey methods' application, the first data confirming this theory already became known (e.g. Wendland (2010) in connection with cell vaults). According to Wendland (2010), although we only have limited data about the exact geometry of the late medieval stellar and net vaults, possibly a widespread practice was to start the building process by positioning the junctions.

Following the steps of the above-detailed analysis method, we analysed the plan of the ribs. For a simpler understanding, the junction points were given a code, as shown on Fig. 6. It is to be noted, that the ribs of the oratorio are neither too loose nor visibly accumulated, which indicates, that the movements of the vault during the centuries were not of high account, so the analysis of their present geometry can give us clues about their original construction.

In regard to the technical literature on stellar vaults, it is clear, that the initial move is supposedly always to draw out the real-scale plan of the vault (e.g. Hontañon, as quoted by Huerta (2012); Ranisch, 1695; Ungewitter, 1901; Warth, 1896).[2] As for the construction principles, the leading theories are the construction based on a quadrate-net (e.g. Schulze's method, as presented by Müller (1975)) or on smaller quadrates inscribed into an original square, rotated by 45° (e.g. Hoffstadt (1840) as described by Müller (1975)).

Since in the case of the Matthias oratorio the truncated octagonal plan was given by the chapel on its ground floor, the rib network was accommodated to it. To find the original construction method, the plan of the ribs could be analysed. Since the main principle during our analysis is always to find the regular in the irregularity, as we stated above, several standard cases can be checked.

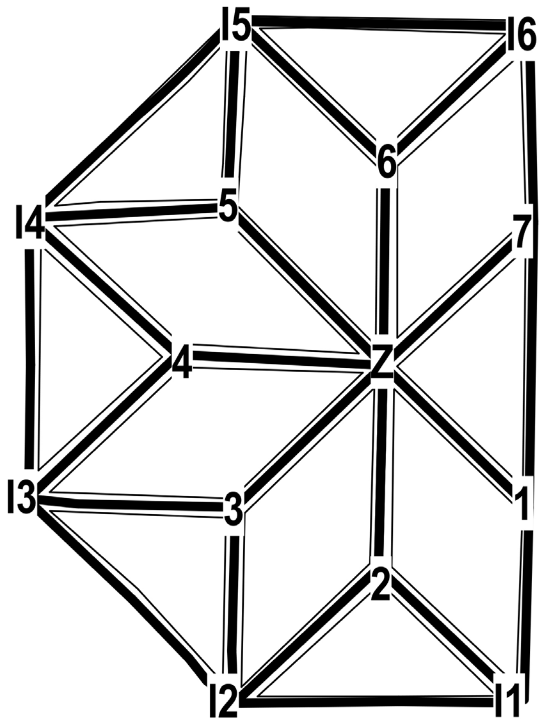

Fig. 6 Legend to the signs of the ribs' junction points

First, we drew all the diagonals running between the vertices of the truncated octagon. As Fig. 7 shows, two of the junction points do not fall onto these lines, so it is likely that this was not the initial method. As a next step, the lines running between the midpoints of the polygon's sides were checked (Fig. 8). Again, two junction points (only one of them is the same as in the previous case) cannot be based on this idea. After that, the distance of the junction points from the crown point was examined (Fig. 9), and one point seems to differ from the others in this sense. The ribs' projected length to the plan was also measured (Fig. 10), and the "I5-5" and "5-Z" ribs' values diverge from the other ribs of the same role in the rib system.[3] The distance between the projected picture of the junctions, in between which there is no rib element was compared too (Fig. 11), but they do not seem reassuringly even either. Finally, the circles which can be drawn on the sides of the polygon all crossed the correspondent junction points (Fig. 12), so these, combined with lines, which went through the same junctions could mean the basis of the original construction.

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1 E.g., in the case of the idea that the junctions are projected to a hemispheric or cylindrical surface, detailed in Section 4.3.

2 An example of this real-scale construction was presented by Wendland and Degenève (2017) during their experimental research.

3 It is also to be noted that the differences between the octagon's side length values are within 7 cm. Thus, the reason behind the misplacement of junction point "5" cannot be simply the fact that it belongs to the "shortest" side of the polygon. The junctions "3" and "4" are perfectly at the same distance from the crown point, and the ribs ending in them have values in accordance with the other values of the same rib types, although the length of the octagon's side belonging to them differs only with 2 cm from the one belonging to junction "5".

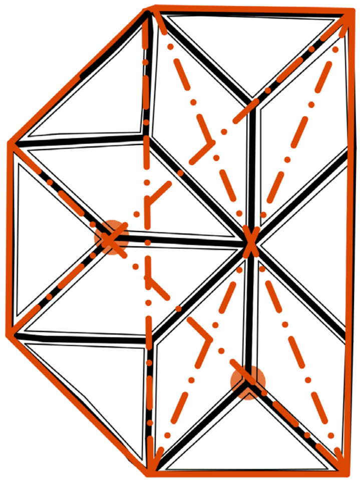

Fig. 7 The diagonals of the rib system's plan. The dots sign the junctions not in accordance with the constructed lines.

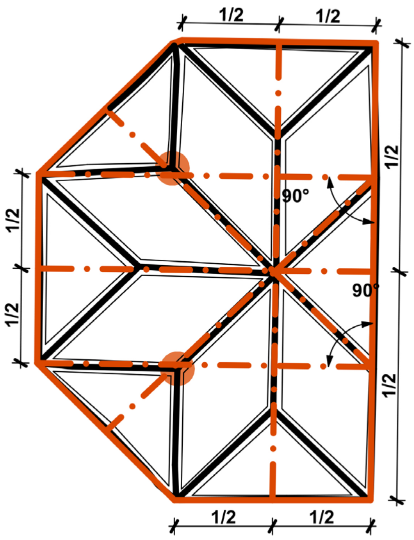

Fig. 8 The lines running between the plan polygon's sides. The dots sign the junctions not in accordance with the constructed lines.

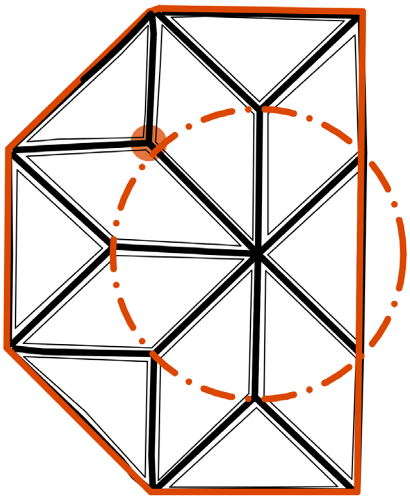

Fig. 9 The distance of the junctions from the crown point. The dots sign the junctions not in accordance with the constructed lines.

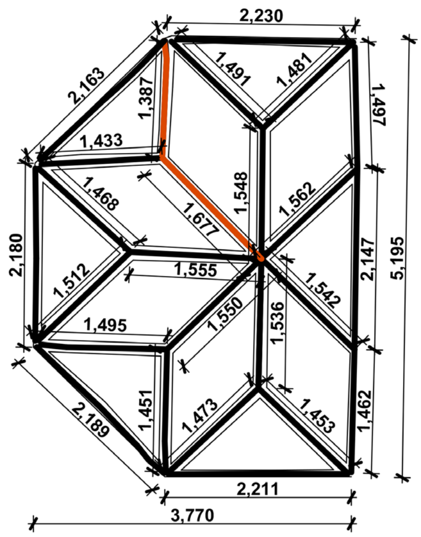

Fig. 10 The distance between the junction points. The coloured lines sign those ribs, whose projected length to the plan is not in accordance with the others of the same kind.

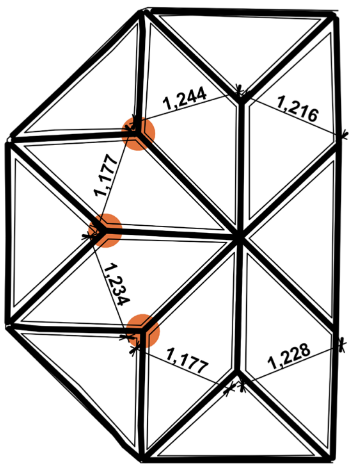

Fig. 11 The distance between those junction points, in between which there is no rib. The dots sign the junctions not in accordance with the majority of the values.

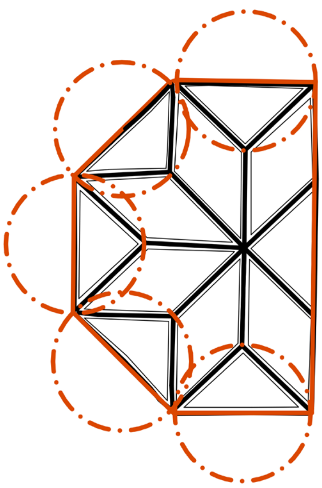

Fig. 12 The circles drawn on the sides of the polygon

Based on the information gathered above, the following hypothetic construction order can be suggested: In the first step, the lines between the imposts "I2" and "I5", and between the midpoints of the "I3-I4" and "I1-I6" sides, as well as the diagonals between "I1" and "I5", and "I2" and "I6". This step also resulted in finding the "Z" crown point (Fig. 13). Following that, the circles can be drawn to the sides of the polygon, and the crossing of these and the lines from the previous step give the junction points (Fig. 14). Finally, the distance of the "6" point from the "I6" impost, and the "2" point and the "I1" impost can be measured from the imposts to the longest side of the polygon, resulting in junction "1" and "7" (Fig. 15).

This fairly simple geometric pattern could be reached through several similar ways but as a result of the precise geometry known from the laser-scanned point cloud, an attempt to discover the original track of thought of the builders can be made.

4.3 The construction of the height coordinate of the junctions

After constructing the plan of the ribs, various sources give various solutions for the further steps resulting in the height data of the junction points of stellar vaults. Some of them present the step as the projection of the junction points' plan to a semi-spherical surface[4] (Ungewitter, 1901; Warth, 1896), or regard them as forms deductible from cross-vaults (Ungewitter, 1901; Warth, 1896). Another idea is to determine the height values by ribs with even curvatures (also known as "Prinzipalbogen" theory - in detail see below) (Hoffstadt, 1840; Warth, 1896). A more practicality-driven approach appears in the famous drawing of Hontañon, where the junctions are supported in their spatial position during the construction by wooden poles, in the height determined by the diagonal of the initial square of the vault (Huerta, 2012).

During the analysis of the Matthias oratorio's vault, we found that the height of the junction points is presumably based on a triangular construction.[5] The height of the

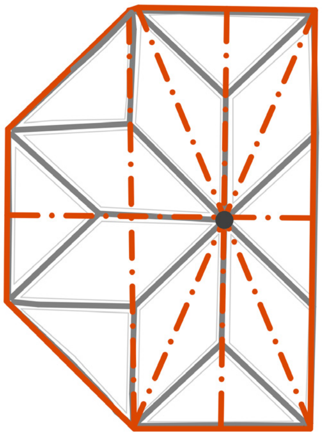

Fig. 13 The first step of the construction of the rib system's plan

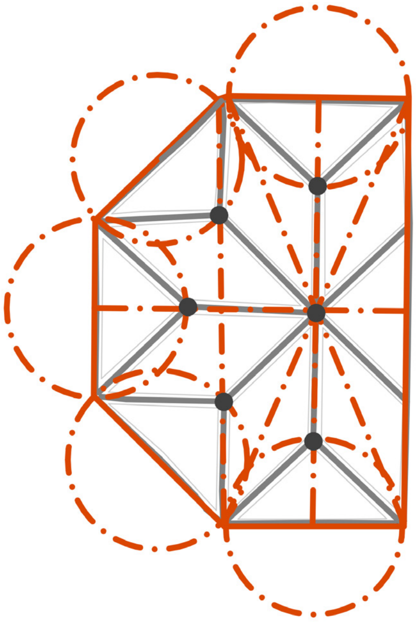

Fig. 14 The second step of the construction of the rib system's plan

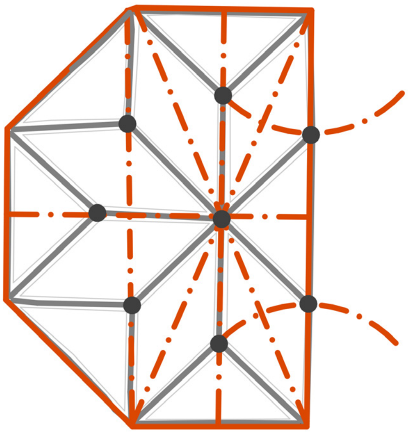

Fig. 15 The final step of the construction of the rib system's plan

4 However, it is important to note, that using surface structures as temporary supports during the building process is an unnecessarily expensive solution and requires a lot of supplementary work. Thus this semi-sphere approach is most likely to be seen as an abstraction, not a practical solution.

5 During our examination regarding the junction point's height positions, we always worked with the lower surface of the ribs, since the temporary structures supporting the vault during the construction most likely worked as supports from underneath, therefore they must be positioned accordingly.

imposts from the floor is equal to the height of an equilateral triangle with the side length equal to those of a square in which the basis octagon can be inscribed (Fig. 16). From here, a smaller equilateral triangle with a side length equal to that of the basis octagon's corresponding side can be drawn to each side, and the apices of these triangles give the height of the wall arches.[6] From the height of the imposts, the apex of another equilateral triangle with its sides equal to the distance between the imposts and the crown point on the plan gives the height of the crown point (Fig. 17). The height of the other junction points is determined by the centre point of the equilateral triangle which has a height equal to the height differences of the latter two triangles (Fig. 18). The junction points "1" and "7" are slightly higher positioned, as the junctions "2"-"6". This height is approximately in the middle between the height of the crown point and that of the wall arches (Fig. 19).

Thus, the claimed construction method regarding the heights of the junctions can fully be concluded based on triangulation.

A further notion about this question is that of the existence of a temporary working level during the construction, as visible e.g. on Hontañon's drawing, where this level is placed in the height of the "tas-de-charge", as explained by Huerta (2012). On the one hand, a level like that could be of benefit at the height of the imposts, since that way the further construction steps could have been carried out from there. On the other hand, in this small, compact, and independent fraction of the building, where the construction works affected only the oratorio itself at the time (since the chapel underneath was already built), building the scaffolding from the floor level would not have been an unworkable challenge. At present, our merely geometric data is not enough for certainty.[7]

6 It is to be noted that since the previously found line for the imposts refers to their lowest point, and the height for the wall arches junction is also its lowest point, the straight line between these two can serve as a real (wooden) supporting structure, since the ribs' profile on their lowest point does not cross this line, it "sits on it".

7 Another consideration can be that the widespread theories about Medieval architecture claim that the main principle of the Gothic style is geometric division, whereas that of the Romanesque is addition. However, these general principles do not necessarily apply in every single case. For example, in our case, the addition of the oratorio as a new elevation would make it difficult to do the constructions by divisions, since it would require the builders to mark out a bigger initial form than the given outlines. On the other hand, the addition of the triangles can be implemented quite easily.

4.4 The analysis of the ribs

After the analysis of the global geometry of the rib system, the next step is to examine the individual ribs. The most widespread idea about the ribs of stellar and net vaults in the technical literature is the "Prinzipalbogen" principle, which means that each rib in a given vault has the same curvature. This theory's roots can be detected back to the 16th century (the manuscript of Jacob von Andernach, as quoted by Müller (1974), and its popularity did not fade during the following centuries (Hoffstadt, 1840; Meckel, 1933; Müller 1990; Ranisch, 1695; Ther et al., 2010; Tomlow, 1991; Ungewitter, 1901). Albeit there were certain opposing opinions, mainly from the 19th century on (e.g. Lassaulx in 1835 as quoted by Wendland (2010)), it remained the leading theory in the field, and although with the modern, point cloud-based surveying methods it is now proven that there are cases where this principle do not apply (Jobbik and Krähling, 2022a), there are also proofs about its implementation too (e.g. Voigts, 2015).

According to certain sources, the value of the ribs' uniform curvature also can be calculated, usually based on the plan of the rib system. This idea, the "principle of the longest route" means that starting from the impost on the plan of the ribs the longest possible oneway route to the crown point is drawn. This fractioned line is straightened afterwards, and this will be served as the radius of the curvature. (According to some writings, the method is also suitable for calculating the heights of the junction points (Hoffstadt, 1840; Meckel, 1933).)

The measurement of the curvatures' radius for each rib was carried out based on the point cloud.[8] The measured values are presented in Table 1, and the ribs' sign used in the table can be seen on Fig. 20.

Our measurements resulted in a rather consistent dataset. The average of the values is 3.00 meters, with a 0.1 meter standard deviation. We also calculated the "ideal" curvature value based on the "principle of the longest route", which is 3.095 meters (Fig. 21). This value could be interpreted as a close enough number to the ribs' actual curvatures (the discrepancy between the two can

8 However, it must be stated that measuring the curvature of the ribs based on the laser scanner-generated point cloud is not simple, and a slight difference in the established arches can cause a palpable difference in the radius value. On the other hand, based on our previous experience in research with a similar objective (Jobbik and Krähling, 2022a; 2022b), we found that the achievable results are precise enough to have an interpretable conclusion.

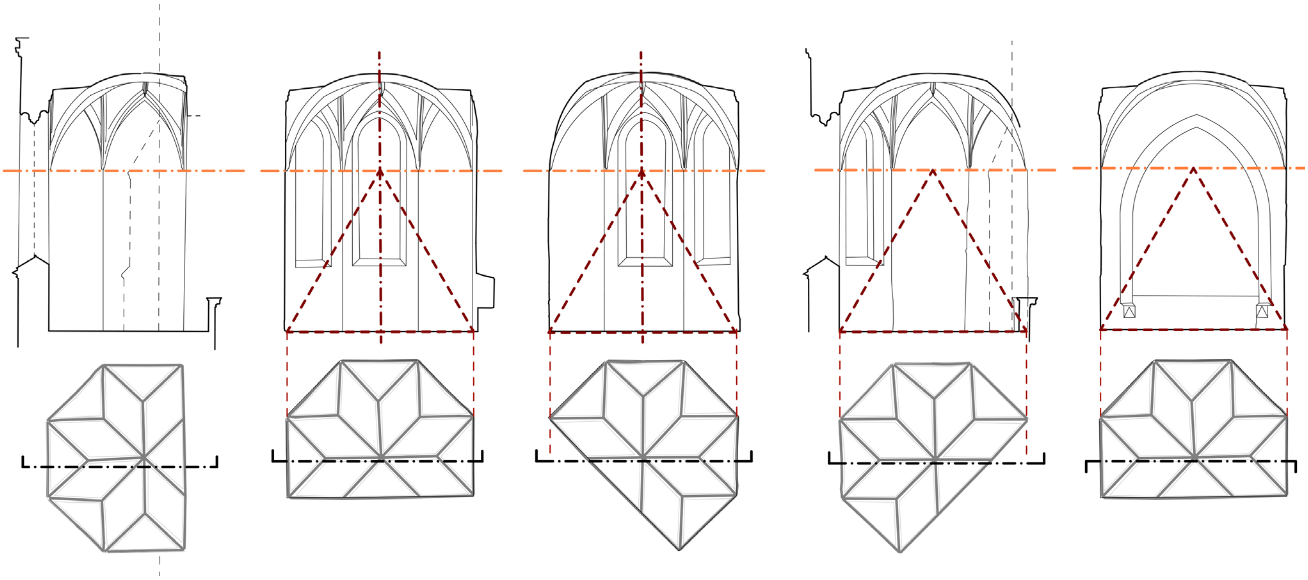

Fig. 16 The construction of the impost's height ("I1"-"I6")

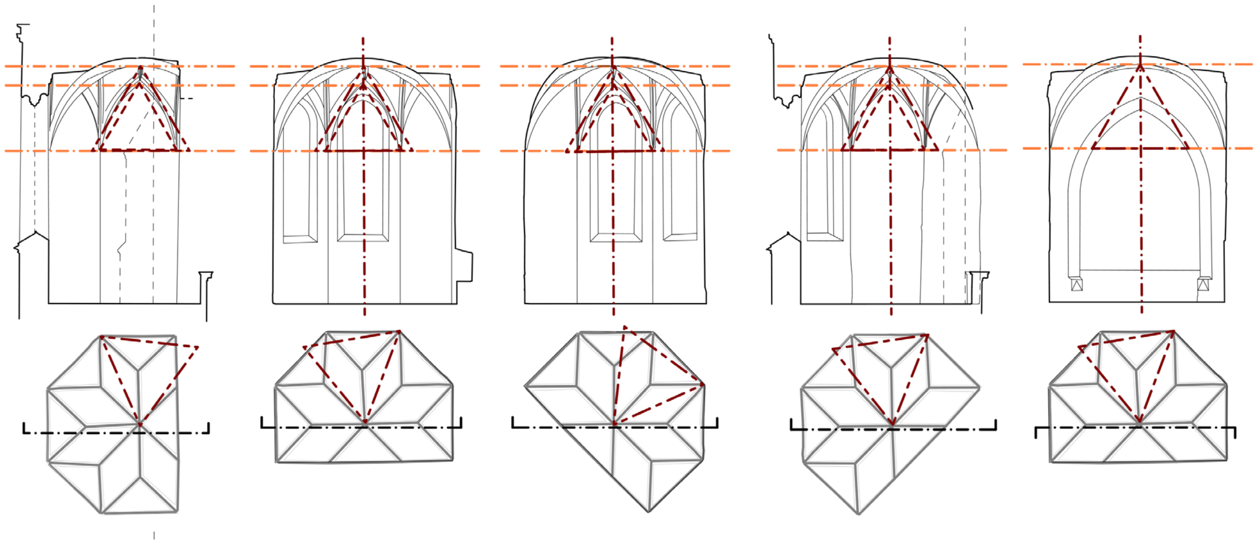

Fig. 17 The construction of the crown point ("Z")

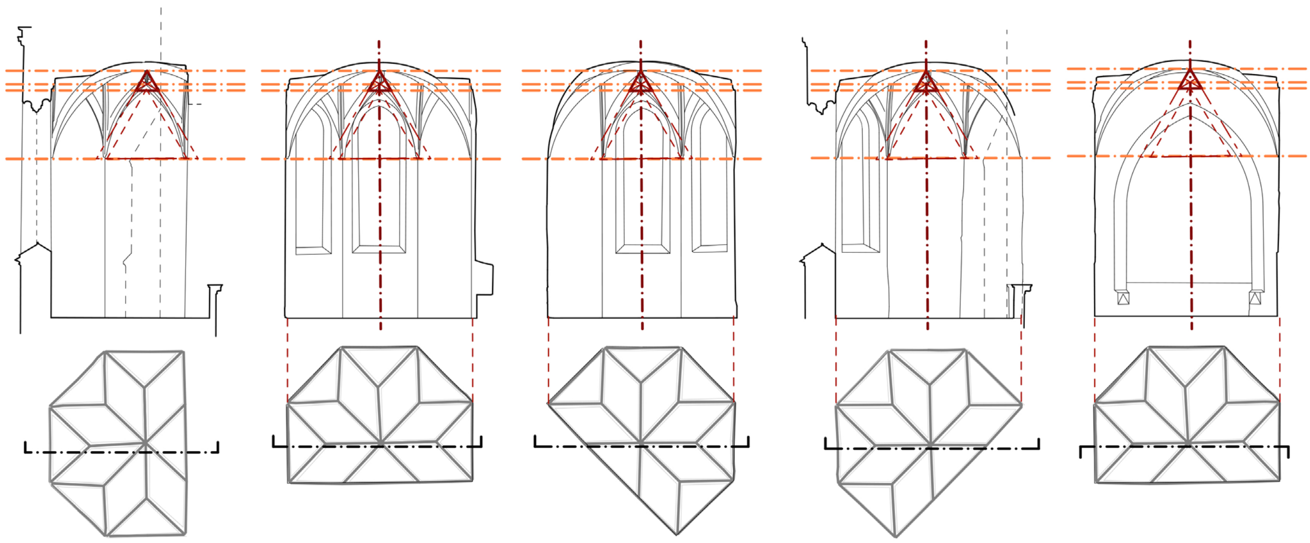

Fig. 18 The construction of the junction elements position ("2"-"6")

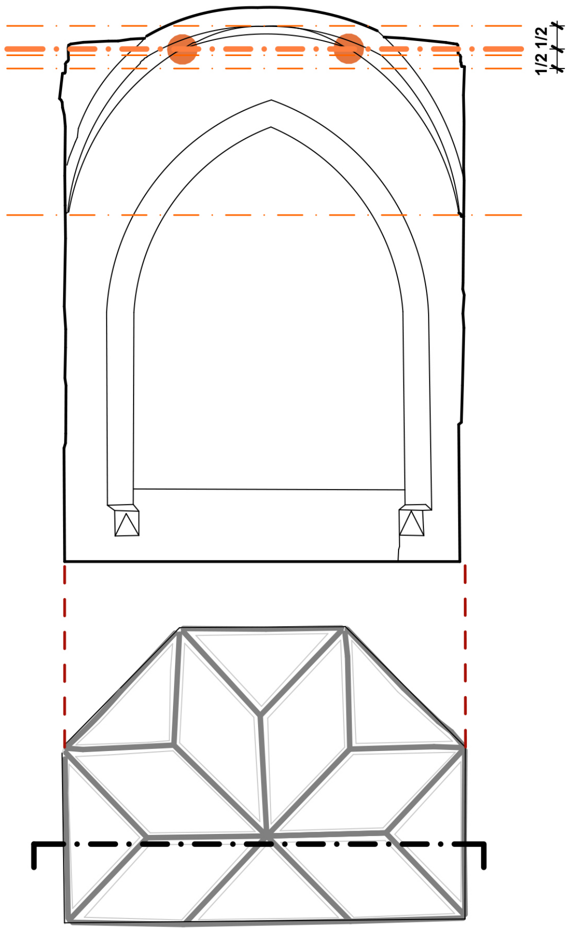

Fig. 19 The construction of the junction points "1" and "7"

also be seen in Table 1), however, the height coordinates of the junction points do not correspond to those, which could have been constructed based on this idea (Fig. 22). Nonetheless, the circle's radius which can be drawn around the biggest equilateral triangle of the above presented quite likely construction method of the height values is perfectly in tune with the 3.00 meter average value of the ribs' curvature[9] (Fig. 23).

To conclude the analysis of the ribs, it can be stated that the "Prinzipalbogen" principle applies to them. Regarding the actual value of the ribs' curvature, it cannot be stated for sure, which was the original reasoning behind it, but it seems a valid assumption that the main construction principles of this small oratorio quite likely composed a self-contained system. Thus, if our idea about the height values construction is correct, in regards to the ribs' curvature the latter method is the more plausible.

9 It must be stated, that at the time of the oratorio's original construction the metric system did not exist, thus having an integer value in meters is a coincidence.

A supplementary observation apropos of the rib elements can be added: in certain cases, the connection of the junction elements and the rib elements is not fully uninterrupted, and a slight "breakage" can be observed in the arch. This slight geometric anomaly can be interpreted as evidence of the prefabrication of the rib system's elements. Since if our presumption about the priority of the junction elements' placement over the normal rib elements during the building process is valid, it is quite likely that the builders attempted to fit every rib element between the junction elements, even if they were not perfectly aligned, instead of refabricating them (Fig. 24).

4.5 The analysis of the webbing

In the technical literature on the topic, in regards to the building technique of the webbing of a stellar or net vault mainly two different methods were in use. It can be done using a formwork, which means that boarding is constructed between the completed rib network's adjacent elements, and the courses of the webs are built on it (Voigts, 2021). This results in a nearly fully flat web surface (Wendland, 2007), and occasionally they also can bend under (Schuller, 2016). The other method is to build the web "from free hand", that is to build each course as an individual arch, which makes them self-supporting (Voigts, 2021). This can happen with the use of a centre (Ungewitter, 1901; Viollet-le-Duc, 1854-68) or without that (Lassaulx, 1829), the former resulting in a more regular web form than the latter.

To examine the form of the webbing, we "sliced up" the vault's point cloud horizontally, so to say we mapped it (Fig. 25). Describing vault surfaces with this representation method already has a history: it was in use from the 19th century on (e.g. Choisy, 1883; Rave in 1955 as quoted by Wendland (2007)), however using it on a point cloud gives actually accurate data about the structures, and shows even the slight deformations (Voigts, 2021).

The result of the "mapping" shows unequivocally that the webs have a notable curvature, therefore it is likely that they were built "from free hand". Slight irregularities in the form of the mapping lines can also be noted. Since the mapping was projected from that part of the point cloud which belongs to the oratorio's inner space, these anomalies can be indicative of the lack of centre during the building process, however, without further proof, this cannot be seen as certain.

Table 1 The ribs' radius of the curvature and their relation to the calculated "longest route" value

Sign of the rib	Radius of the curvature [m]	Difference between the radius of the curvature as a measured value and the calculated radius, based on the "principle of the longest route" (3.095 m) [m]	Difference between the radius of the curvature as a measured value and the calculated radius, based on the "principle of the longest route" (3.095 m) [%]
A1	3.08	0.015	0.49%
A2	2.94	0.155	5.27%
A3	2.89	0.205	7.09%
A4	3.04	0.055	1.81%
A5	2.97	0.125	4.21%
A6	2.85	0.245	8.60%
A7	2.9	0.195	6.72%
A8	2.89	0.205	7.09%
A9	2.97	0.125	4.21%
A10	3.08	0.015	0.49%
B1	3.05	0.045	1.48%
B2	2.92	0.175	5.99%
B3	3.09	0.005	0.16%
B4	3.08	0.015	0.49%
B5	2.97	0.125	4.21%
B6	2.91	0.185	6.36%
B7	3.12	−0.025	−0.80%
B8	2.94	0.155	5.27%
B9	2.78	0.315	11.33%
B10	3.05	0.045	1.48%
C1	3.16	−0.065	−2.06%
C2	2.99	0.105	3.51%
C3	2.98	0.115	3.86%
C4	3.02	0.075	2.48%
C5	2.94	0.155	5.27%
C6	3.07	0.025	0.81%
C7	3.24	−0.145	−4.48%
D1	2.98	0.115	3.86%
D2	3.09	0.005	0.16%
E1	3.1	−0.005	−0.16%
Average	3.00		
Standard deviation	0.10		

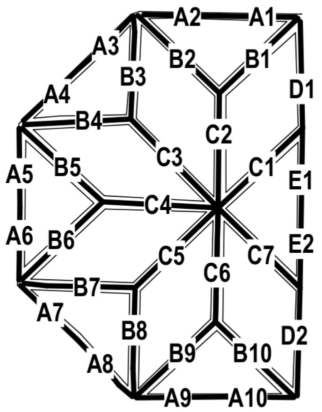

Fig. 20 Legend to the sign of the individual ribs

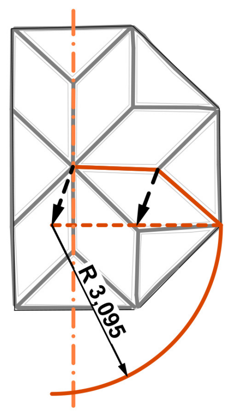

Fig. 21 The construction of the "longest route" for the oratorio's vault

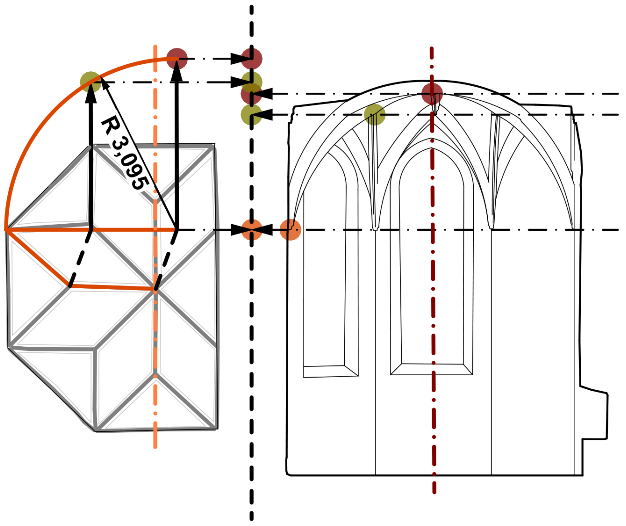

Fig. 22 The junctions' height constructed based on the "principle of the longest route", compared to reality

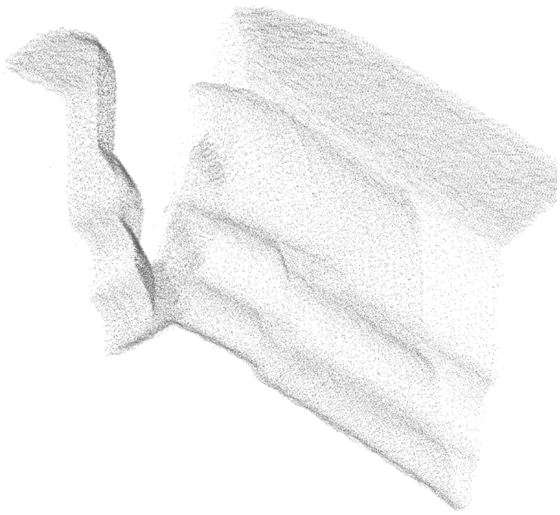

Fig. 24 Example of the non-perfect connection of the rib elements and the junction elements (rib "B1")

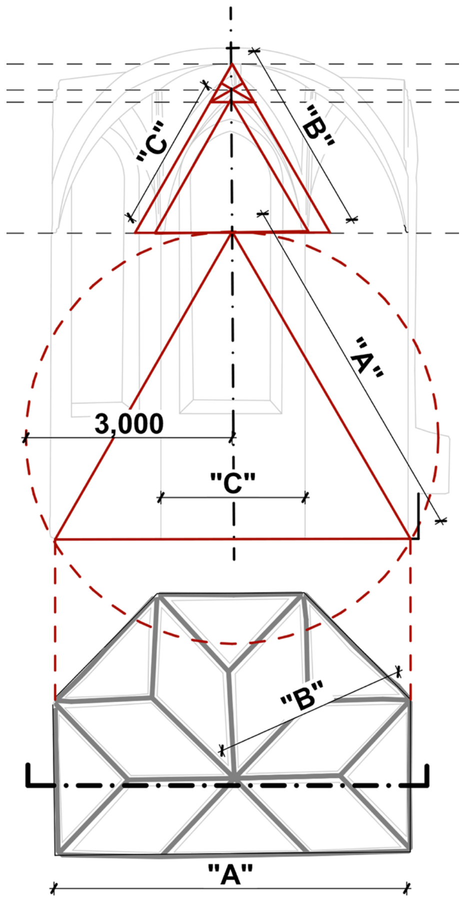

Fig. 23 The geometric connection between the positioning of the junctions and the geometry of the individual ribs

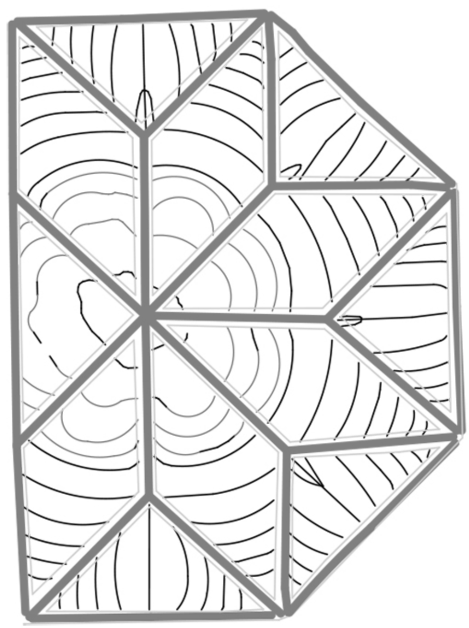

Fig. 25 The mapping of the vault

5 Conclusion

As a result of our presented research, we established a highly probable construction method regarding the late 15th – early 16th-century stellar vault of the Matthias oratorio in the Inner City Parish Church of Budapest.

During the analysis of the vault's geometry, we applied our method, which gives a logical concatenation of steps to find the original construction and building techniques of stellar and net vaults with a high probability.

We concluded that the webbing of the vault was built "from free hand", probably without the application of a centre, which is not at all an unusual method for a late Gothic cellar vault.

Furthermore, we described the possible construction strategies of the rib system's plan pattern, and based on the vault's exact geometry, known as a laser-scanned point cloud, we deduced which ideas were most likely used during the actual process. Beyond the new information about this given value, if this kind of analysis will happen in numerous other cases throughout Europe, the data gathered this way can be valuable complementary information and a strong basis for comparison to the medieval constructions known from sketchbooks and tractates (e.g. the sketchbook of Villard de Honnecourt).

Moreover, we also found some geometric rules, based on equilateral triangles, which describe the rib system's junction points' height positions. The size of the triangles' sides came from lengths determined on the plan of the ribs.[10] What is more, we also realised, that the radius of the individual ribs' curvature, which follows the "Prinzipalbogen" principle, can also be deduced from this system. Although these latter two claims cannot be proven without all doubts, they are still exceedingly probable. This means that the construction of this small oratorio was an exceptionally well-coordinated effort, resulting in a self-contained construction system, where all the ratios describing the vault's global geometry have a connection to each other.

Getting to know the late Gothic vaults in so particular detail is of benefit not only regarding the given case study but if the opportunity is given for analysing several examples of a certain region or era, it also grants more comprehensive knowledge about the connections of the buildings to each other and the different construction strategies of the individual builders or building lodges.

10 Since the connection between the sidelength of these triangles is the plan of the vault, meaning that it is not possible to get all the values from one single section view, it is likely that the descriptive geometric method of rotation to get other views of the same 3-dimensional system was used. This maybe indicates that a building lodge of sophisticated knowledge carried out the construction, which is plausible, given the important status of the church.

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