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The Vault with Curvilinear Ribs in the "Hall of Arms" in the Albrechtsburg Meissen: Studies on the Concept, Design and Construction of a Complex Late Gothic Rib Vault

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During the 14th and 15th centuries, the challenge of creating vaulted ceilings lead to ever more complex solutions in late Gothic architecture. These ambitious, astonishing and sometimes daring constructions rank amongst the finest masterpieces of architecture – extremely demanding from the structural point of view and particularly challenging in their geometric design. Their builders managed to overcome the difficulties of planning the complicated meshes of ribs soaring along spatial curves, providing instructions for the production of their single components and their assembly on the building site, and achieving a curved vault surface which corresponds to the equilibrium condition of shell structures.

The discussion on how the design and planning of these structures was performed and how their construction process was organized, has been so far largely based on sources (some of them dating from long after late Gothic architecture was practised), and in particular on their interpretation as established in the 19th century. However, this current state of research can be shown to be in contrast with the evidence of many of the actual built objects.

At this point, it appears necessary to formulate hypotheses on the design directly from the built artefact, and on this basis attempt a re-interpretation of the known drawings and treatises.[1] For this approach it is also necessary to deal with the methodological challenges of using the building as source. One of the objects analyzed in this on-going research is the vault with curvilinear ribs (Fig. 1) in the Albrechtsburg at Meissen (Germany), which is presented here as work in progress.[2]

The vault is located in the second floor of the north wing of the great palace of the Electors of Saxony, which had been under construction since 1471. While the walls and roofs were completed in the 1480's, part of the internal structure including some of the vaulted ceilings at first remained unfinished, until only decades later the construction works resumed and the vaulted ceiling in the room which is now called "Hall of Arms" was built. It can be dated to shortly after 1521 both by documentary sources[3] and archaeological evidence.[4] The room has a square plan with four annexes, which are carved in the volume of the perimeter walls and separated by profiled stone arches. These pre-existing arches were integrated as *formerets* into the design of the new vault, as well as the diagonal walls that crop the corners of the square plan and contain the springers of the main vault.[5]

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[1] D. Wendland, "Design Principles in Late-Gothic Vault Construction – A New Approach Based on Surveys, Reverse Geometric Engineering and Reinterpretation of the Sources", 2011, research project ERC Starting Grant n° 284373.

[2] A first campaign of geometric survey and analysis was performed by D. Wendland in 2009/2010. The current surveys are carried out by M. Aranda Alonso, A. Kobe, C. Mai, K. Schröck and D. Wendland.

[3] Sächs. Hauptstaatsarchiv Dresden, Kopial 137, Schellenbergisch Copial, 1521-1527: fol. 4 (alt) / 12 (neu) and fol. 48 (alt) / 57 (neu), containing instructions from Duke George. Analysis and transcription by C. Mai.

[4] E. Grotegut, Report on the archaeological investigations in the Albrechtsburg, 3rd floor, during May and September-December 2007, Archive of the Landesamt für Denkmalpflege Sachsen, Dresden.

[5] The remains of the discarded springers belonging to the originally planned vault are still visible.

Fig. 1: The vault in the "Hall of Arms" in the Albrechtsburg at Meissen (M.J. Ventas Sierra / D. Wendland)

Most of the ribs in the vault, in addition to their curvature in elevation, are curved also in plan, thus describing three-dimensional curves. The design is attributed to Jakob Heilmann, a master mason working in Saxony and Bohemia whose major works were built in the first decades of the 16th century and who in that time was working on St-Anne's Church at Annaberg where he built the remarkable vaults with curvilinear ribs.[6] It is supposed that Heilmann was pupil of Benedikt Ried at Prague, who built the first vault with curvilinear ribs on monumental scale in Vladislav's great hall in Prague Castle, completed in 1502. This vault, together with the adjacent "Knights' Stairway", led to a whole series of vaults with curvilinear ribs. Initially, the invention of the double-curved rib is associated with the master masons Madern Gerthener in Frankfurt and Hans von Burghausen in Landshut in the beginning of the 15th century.[7] These early examples incorporate only short segments of double-curved ribs within a grid of the usual single curved ribs, while double–curved ribs that dominate the entire figurations became more frequent only after the middle of the century.[8]

[6] In 1515 Heilmann took over the direction of the lodge at St. Annen in Annaberg and was appointed in 1517 to build the parish church in Most. Before 1515 he apparently worked under the direction of Benedikt Ried at St. Barbara in Kutná Hora. Despite the lack of written sources in relation to his previous domains and apprenticeship, the close formal relationship between his works and the architecture of the Hradchin palace in Prague is generally recognized. Cf. G. Fehr, *Benedikt Ried. Ein deutscher Baumeister zwischen Gotik und Renaissance*, München: Callwey, 1961; E. M. Kavaler, *Renaissance Gothic. Architecture and the arts in northern Europe, 1470 - 1540*, New Haven, Conn. etc.: Yale Univ. Press 2012, p. 141.

[7] Cf. N. Nußbaum, S. Lepsky, *Das gotische Gewölbe. Eine Geschichte seiner Form und Konstruktion*, Darmstadt: WB 1999, pp. 259-268. Kavaler (Note 5), pp. 140-146.

[8] Kavaler (Note 5), p. 140. Some examples are the main nave at St. Stephan Cathedral in Vienna (1446-1459), the choir at St. Jakob in Wasserburg (1445-1448) by Stephan Krumenauer, and the looping vault in the cloister of Basel Minster supposedly designed by Jodok Dotzinger around 1465.

The design and geometric concept of the rib system

The vault spans c. 9.40 m in transversal and 11.30 m in diagonal, the height at the summit is 6.72 m and the fleche of the diagonal arch 3.12 m. The ribs, keystones, members of the *tas-de-charge* and the boss in the summit are made of sandstone from the Elbe valley. While the rib voussoirs generally remain underneath the vault surface, as far as it could be observed, the keystones penetrate through the whole thickness of the shell – their plane horizontal upper surfaces in some cases show engraved marks.[9] The main structural feature of the vault is the shell[10] built in brick masonry, which is 30 cm thick and has reinforcing ribs on the extrados. Four additional barrel vaults, only 15 cm thick, support the upper floor in the area of the spandrels, providing empty spaces instead of the usual filling (Fig. 2). This is surely motivated by the aim of reducing the weight of the structure, considering the enormous vertical height of c. 30 m between the foundation level and the springing of the vault.

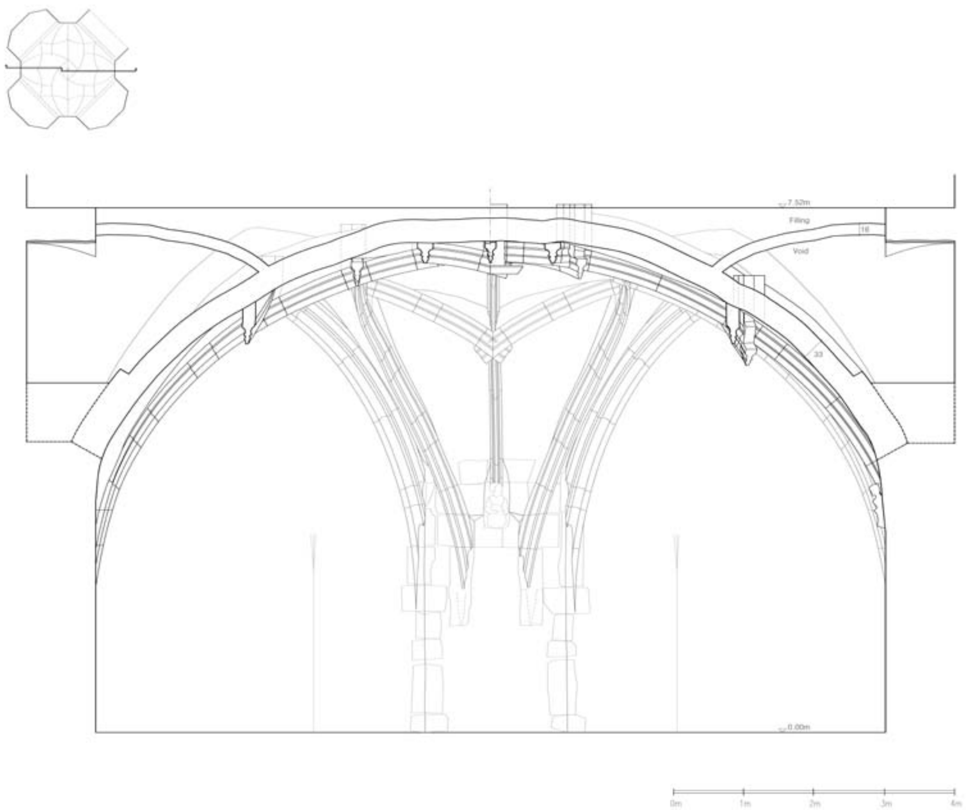

Fig. 2: Diagonal cross section of the vault in the "Hall of Arms": over the main shell of the vault four additional thin vaults support the floor, leaving void spaces in the spandrels (CAD M. Aranda Alonso).

[9] S. Bürger and G. Donath, "Zeugnisse werkmeisterlicher Betätigung – Die Werksteine des Jakob Heilmann im Wappensaal der Albrechtsburg" pp. 232-243 in S. Bürger, B. Klein and K. Schröck, (Eds), *Werkmeister der Spätgotik: Personen, Amt und Image*, Darmstadt: WB, 2010, Similar evidence is also found on other late Gothic vaults and was first described by R. Willis, "On the construction of the vaults in the middle-ages", *Transactions of the Royal Institute of British Architects*, Vol.1, 1842, pp. 1-69.

[10] D. Wendland and M.J. Ventas Sierra, "Designing a Masonry Shell in the Reconstructed Vault of the Palace Chapel at Dresden – an Attempt to Recover the Forgotten Art of Late Gothic Vault Construction", *Informes de la Construcción*, vol.65, Nº extra-2, 2013, pp. 49-63.

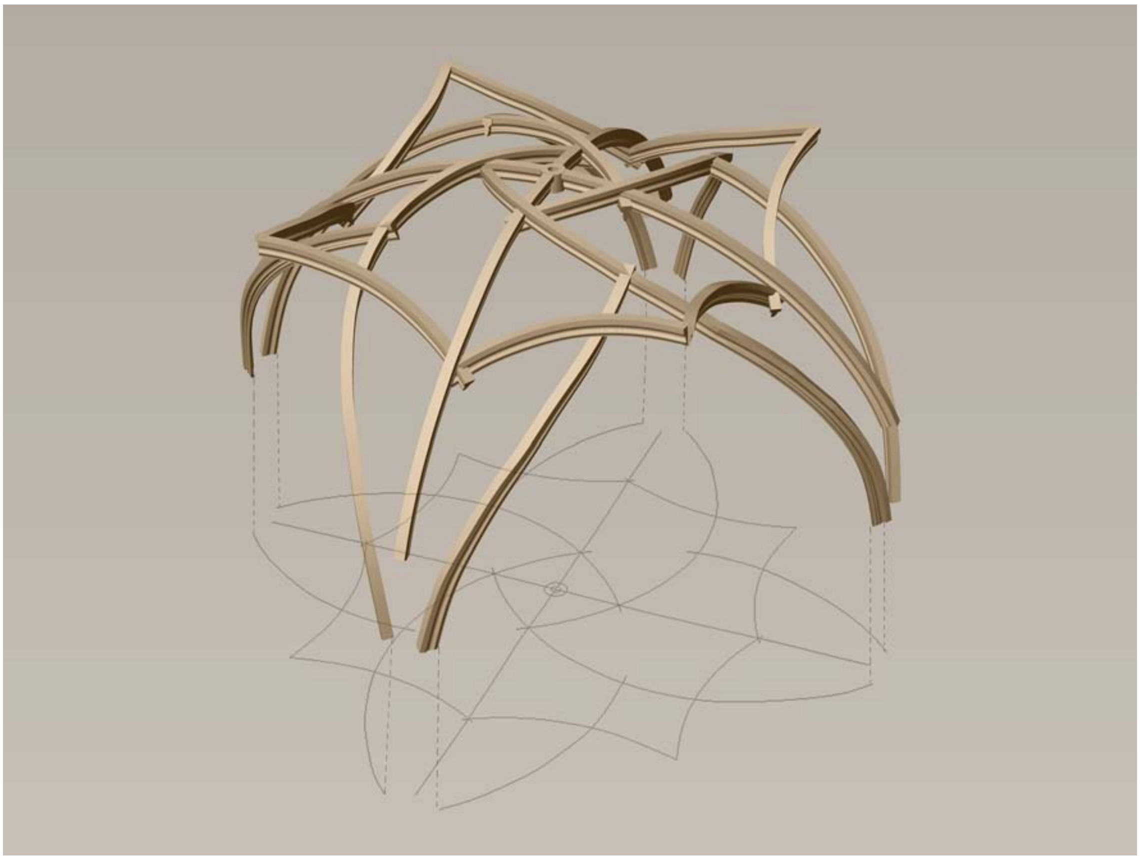

Fig. 3: CAD model of the spatial system of the ribs, showing only the profiled parts (CAD M. Aranda Alonso)

The spatial system of ribs that intersect on different levels consists of four plane diagonal arches meeting at the central keystone and several groups of curvilinear ribs (Fig. 3). Two sets of curvilinear ribs start from each of the four springers located in the corners of the room: one of them loops around the summit, running through two of the four triple intersections in the central part of the vault and then ending with a clean cut, while the course of the other is interrupted much earlier, again with a clean cut, just above the intersection with its long counterpart. Further, from the vertex of each of the four *formeret* arches a pair of double-curved ribs descends towards the corners of the hall, crossing the course of the long double-curved ribs and ending just after the intersection with the diagonal arches. Apart from the pre-existing *formerets*, all ribs have a uniform profile.

Especially eye-catching are the cut-off ribs that are suddenly truncated and virtually resting in the void. In particular, the way the lower ends of the arches descending from the *formerets* are attached underneath the profile of the continuing diagonal rib frankly contradicts the idea of tectonics. Likewise, a portion of rib is literally cut out between each long curvilinear rib that rises from the springer and the shorter one that comes from the next corner of the hall. In consequence, the figure of the ribs becomes rotation-symmetric.

As we know, generally in late Gothic vault design the curves of the ribs are not derived from the vault surface, but on the contrary, pre-determined: they are the primary feature of the vault, forming a spatial system of curves to which the surface is adapted.[11] Therefore, the phenomenon of ribs

[11] This has been largely discussed since the early 19th century, in particular Willis (Note 8). Cf. W. Müller, N. Quien, *Virtuelle Steinmetzkunst der österreichischen und böhmisch-sächsischen Spätgotik: Die Gewölbeentwürfe des Codex Miniatus 3 der Österreichischen Nationalbibliothek in Wien*, Petersberg: Imhof,

intersecting on different levels and springing on different heights is usually explained by the geometric definition of the ribs as autonomous curves. Often it is considered to be a consequence of a supposed design routine that is based on the use of one singular radius for all ribs, determined according to certain rules, called “principal arch” (*Prinzipalbogen*).[12]

While there is no doubt on the characterization of the ribs as autonomous curves and that they are a primary feature of the vault design in late Gothic, the validity of the “principal arch” concept turns out to be questionable. The term is definitely not associated with the late Gothic building practice;[13] the characterization of the design process as “algorithm” is doubtful;[14] moreover, the evidence on the built vaults (as far as geometric information is available) does not confirm the use of uniform arch radii to have been general practice.[15] This is also the case in the vault in the “Hall of Arms”, where already the initial design, as we can reconstruct it from the survey, is based on two different main radii for the arches (Fig. 4).

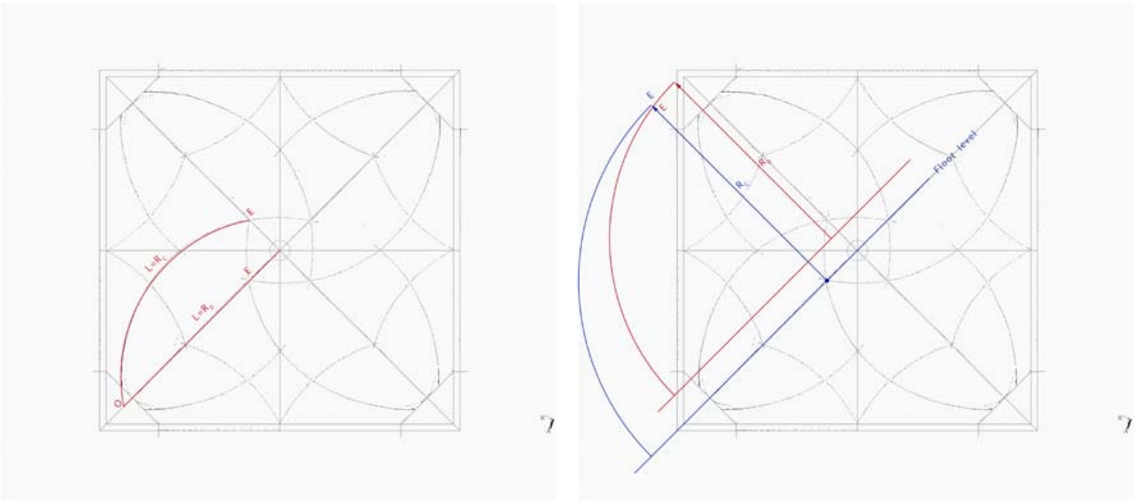

Fig. 4: Reconstruction of the geometric design based on the survey data (D. Wendland). In the initial design, the radii of the diagonal and the curvilinear arch are determined in the plan (left) according to the real lengths in the horizontal plane. In elevation (right), both arches are traced as quarter circles with a common summit level; the centre of the curvilinear arch is located on the floor level, while the centre and springing of the diagonal arch result on a higher level. In the following steps of the design process, the single portions of the arches will be adapted to the exact positioning of the keystones.

2005, and elsewhere. D. Wendland, *Lassaulx und der Gewölbebau mit selbsttragenden Mauerschichten: Neumittelalterliche Architektur um 1825 – 1848*, Petersberg: Imhof, 2008, and elsewhere.

[12] Cf. Müller and Quien, *Virtuelle Steinmetzkunst* (Note 10). Also W. Müller elsewhere.

[13] On the sources and the epistemology of the *Prinzipalbogen*: D. Wendland, “Johann Claudius von Lassaulx’ Gewölbe ‘aus freier Hand’ – Die Wiedererfindung der gotischen Architektur und die Entwicklung der technischen Literatur”, pp. 92-117 in U. Hassler, C. Rauhut and S. Huerta (Eds), *Construction techniques in the age of historicism*, München: Hirmer, 2012. D. Wendland, *Lassaulx* (Note 10).

[14] This view was suggested by Werner Müller. Cf. Müller and Quien, *Virtuelle Steinmetzkunst* (Note 10).

[15] This doubt was put forward by Nussbaum and Lepsky, *Das gotische Gewölbe* (Note 6), p. 180. Our surveys of late Gothic vaults in Saxony in most cases reveal multiple radii. Cf. D. Wendland, “Cell Vaults – Research on Construction and Design Principles of a Unique Late-Mediaeval Vault Typology”, vol.3 pp. 1501-1508 in *Proceedings of the Third International Congress on Construction History*, Cottbus, 2009.

In the particular case discussed here, we find that the superposition of the ribs in the upper part of the vault is not caused by the autonomous development of the curves described by the ribs, but that the intersection on three different levels in the four keystones around the summit is given *a priori* (Fig. 5, left). Each of the four long curvilinear ribs passes through two of these triple crossings: the first time above the diagonal rib, and the second time below, while the diagonal ribs remain in the intermediate level. At least the two curvilinear ribs could intersect straightforwardly in one point, because both their springing and their first intersection occur at the same level. But the arrangement of the intersection in three different levels determines the situation at the gap between the long and the short curvilinear ribs: while in the plan the course of one long and one short curvilinear rib in principle could be inscribed in one single arch (cf. Fig. 3), this is not the case in the spatial development, where the two ends of the ribs clearly miss each other (Fig. 5, right).

Fig. 5: Details of the rib system. Left, keystones with triple intersection near the summit. Right, the gap between the curvilinear ribs, showing that their course is discontinuous in the third dimension (M.J. Ventas Sierra / D. Wendland).

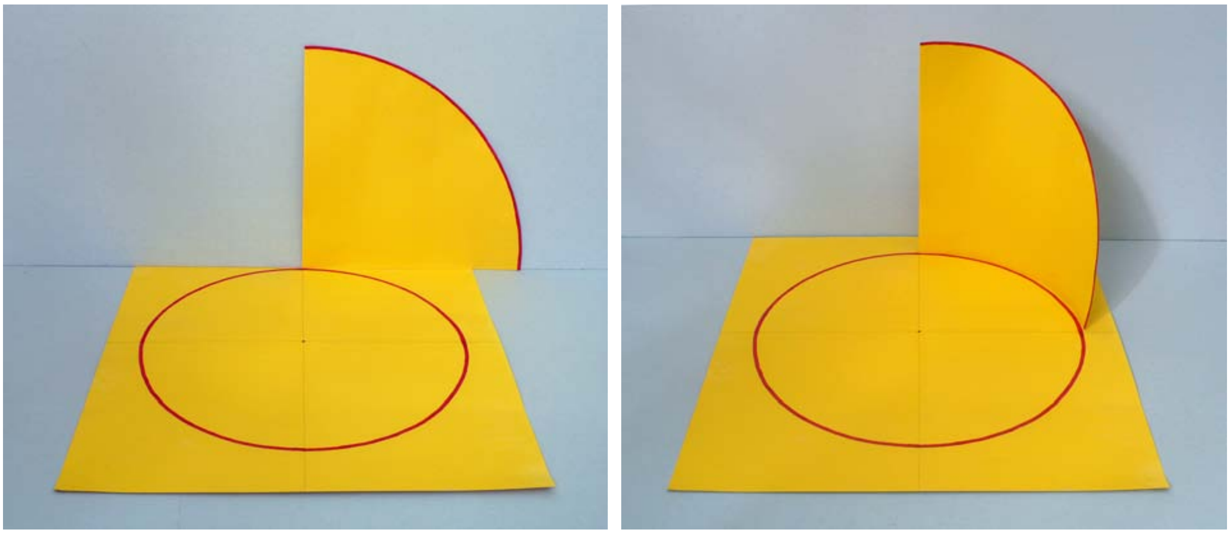

Fig. 6: Visualization of the curve generation for the looping ribs: their development in the third dimension is determined bending a circle segment in the vertical plane according to the circle in the plan (M.J. Ventas Sierra / D. Wendland).

Hence, the asymmetry of the figure in plan is related to the vertical development of the curves – it depends on the choices made in the layout of the four triple intersections where the multi-layer development in the spatial system of curves is deliberately imposed. Another interesting aspect in the spatial arrangement of the ribs can be observed at the intersections of the diagonal rib with two curvilinear ribs descending from the *formerets*, which have two levels: the two curvilinear ribs intersect in one point underneath the diagonal rib. The vertical distance corresponds to the height of the rib profile, suggesting their level at the intersection point to be given *a priori* and not resulting from the development of the curve. Consequently, these ribs are determined by their starting and ending point and by the horizontal tangent at the upper end – in plain contradiction to the "principal arch" concept. This is an interesting parallel to the geometric concepts exposed in the schemes of Gothic vaults in Philibert de L'Orme's Treatise (a source usually not considered relevant for the German speaking area),[16] where the positions of intersection points are determined prior to the curves themselves, and the radii of the rib curves constructed subsequently. In the "Hall of Arms", in principle such type of procedure seems to correlate well with the actual configuration of the vault.

The analysis of the geometric definition of the curves described by the looping ribs clearly confirms the idea of autonomous curves. We exposed elsewhere how the curve geometries can be characterized on the basis of the survey of the built object.[17] In Gothic vaults with plane arches, the curves are generally defined with elementary geometric terms, as circle segments (or composed of more than one circle segment with tangential continuity) inscribed in a vertical plane, the curves of the looping ribs are generated as circle segments "enrolled" according to the curvature in the plan, which is also circular (Fig. 6). In geometric terms, this can be referred to as a spiral, with the vertical development defined by a circle segment.[18] This geometric definition is in complete accordance with what we know about the procedures of constructing curves used by the late Gothic architects, who never constructed curves by projection or intersection of geometrically defined surfaces, but always operated with real lengths.

As a consequence of this curve definition, by principle the single members are not interchangeable – in contrast to ribs in plane arches, in curvilinear ribs every member will fit only exactly in the position for which it was made (Fig. 7). Moreover, the profile of the rib is maintained vertical throughout the course of the spiral curve. This implicates additional difficulties for the geometric design of the single members and for the organization of their production and assembly.

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[16] Philibert de L'Orme / J.-M. Pérouse de Montclos (Ed.), *Traités d'architecture* ('Novelles Invention pour bien bastir et à petits fraiz', 1561, 'Premier Tome de l'Architecture', 1567 / 1648). Paris: Léonce Laget, 1988. W. Müller, "Zum Problem des technologischen Stilvergleichs im deutschen Gewölbebau der Spätgotik", *Architectura*, 1973, pp. 1-12.

[17] D. Wendland, "Arches and Spirals: The Geometrical Concept of the Curvilinear Rib Vault in the Albrechtsburg at Meissen and Some Considerations on the Construction of Late-Gothic Vaults with Double-Curved Ribs", vol.1 pp. 351-357 in R. Carvais et al. (Eds), *Nuts and Bolts of Construction History: Culture, Technology and Society*, Paris: Picard, 2012. The geometric concept of the curves described by late Gothic looping ribs has been first described for the case of the Vladislaw Hall in Prague by J. Muk, "Die Gewölbe des Benedikt Ried", vol.1 pp. 193-205 in J. Tomlow and R. Graefe (Eds), *Geschichte des Konstruierens IV, Wölbkonstruktionen der Gotik*, Stuttgart/Tübingen: SFB 230, 1990.

[18] Muk, *Gewölbe* (Note 16).

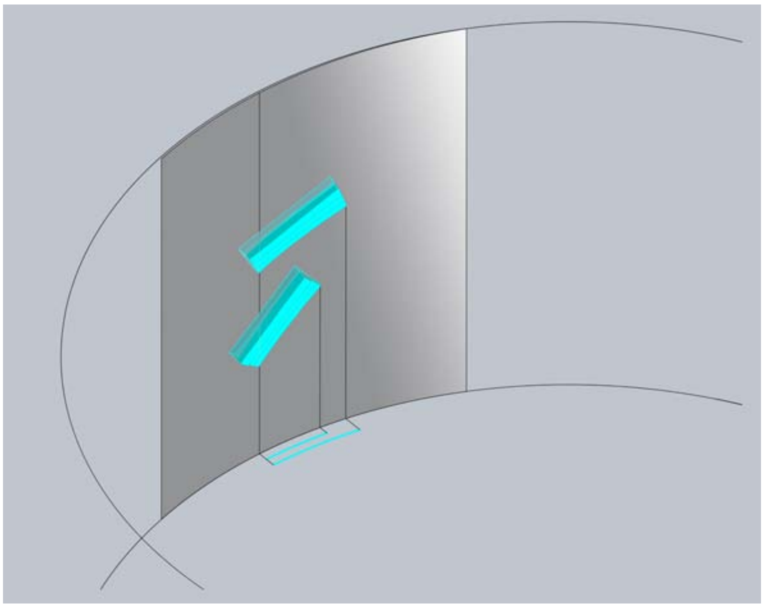

Fig. 7: Two segments of the same rib: The different voussoirs cannot be interchanged, every member fits only in the exact position along the curve for which it was produced (CAD M. Aranda Alonso).

Because the curves of the ribs are not derived from a defined surface, but developed as autonomous curves, by principle they are not inscribed in a continuous surface. Moreover, the multilayer development of the rib system with the intersections in different levels, as shown above, leads to a more complex relation between the curve system of the ribs and the surface of the shell. In consequence, at many positions we can observe considerable vertical distances between the extrados of the rib profile and the shell, which are bridged by vertical diaphragms.

Although the phenomenon of vertical portions above the rib profile has its origins in early Gothic architecture in the Île-de-France, the crucial steps towards the characteristic solutions of the later 15th century were made in the Middle-Rhine region. The master mason Madern Gerthener played a particularly import role in the development in looping ribs, and for the development of these so-called ploughshare webbings (Fig. 8).[19] Until the end of the century, both motifs became dominating elements of German late Gothic vaults, producing dynamic rib figurations and an increasing degree of spatiality of the rib and web structure that required a high degree of rationalization in planning and communication processes to guarantee a perfect realization of the design on the building site.

[19] The first example introducing a discontinuity between vertical and curved portions of the webs which would finally lead to thin vertical membranes, appears in the choir of St. Leonhard in Frankfurt, designed by Gerthener and dedicated 1434. The later development was strongly influenced by the work of Nikolaus Eseler the Elder and his son Nikolaus Eseler the Jounger in Nördlingen, Dinkelsbühl and Rothenburg o.d. Tauber. In Saxony, first examples occur around 1460. On the Eseler: A. Pelizaeus, *Die Eseler von Alzey: Werktätigkeit und Wirkungsstätten einer spätmittelalterlichen Bau- und Werkmeisterfamilie*, Alzey 2010.

Fig. 8: Ploughshare webs in the vault of the cloister in Basel Minster, c. 1465 (A. Kobe).

Investigations on the stone cutting of the rib elements

Since the 1980s, scholars have emphasized the rationalization of building procedures as an important precondition and key feature for the development of Gothic architecture.[20] In relation to stonecutting, research has focused especially on the problem of standardization and pre-fabrication of piers, attached shafts and walls in 13th century churches.[21] Surprisingly enough, its importance in relation to the most discussed element of gothic architecture – the rib vault – has not yet been studied in detail. Moreover, captivated by the apparent analogy between aesthetical and technological logic in French *Rayonnant*, for a long time researchers were not interested at all in the role of rational design strategies in its supposedly ´bizarre´, ´decorative´ and ´anti-rational´ late Gothic counterpart.[22] Until now, the strategies and range of possibilities of late medieval masons to organize the stonecutting and joint system in such a multilayered rib vault with ploughshares have not yet been studied and constitute one of the central issues of the project.

In the "Hall of Arms", the survey of the positions of the joints in the ribs (detecting their actual position under the modern paint on a scaffolding and measuring with a full station) reveals that the members of all double-curved ribs have a regular sequence of long and short pieces, with only slight differences between the lengths of the corresponding members of the different ribs. This suggests fixed lengths for the members in every rib type of the vault (except for the plane diagonal ribs). Given

[20] See especially the studies of Dieter Kimpel. For a summary: D. Kimpel and R. Suckale, *Die gotische Architektur in Frankreich 1130-1270*, München: Hirmer, 1985.

[21] E.g. A. Hartmann-Virnich, "Préfabrication, module et 'standardisation' dans l'architecture de pierre de taille médiévale. Quelques exemples du Sud-Est de la France (XIIe – XIVe siècles)", pp. 187-204 in *Terres et hommes du Sud, 126e congrès national des sociétés historiques et scientifiques, Toulouse, 9-14 Avril 2001*, Paris 2004.

[22] However see recently: M. Hurx, Architect en aannemer. De opkomst van de bouwmarkt in de Nederlanden (1350 - 1530), Diss. Phil., Nijmegen 2012.

Fig. 9: Detail of the stone members of the vault in the "Hall of Arms". For clarity, the stone surfaces are highlighted, plastered portions marked as hatched areas, and the joints retraced (A. Kobe).

that the position of the single parts of the double curved ribs is unchangeable, as pointed out, such an establishment of consistent joint systems for every type of rib must not only have facilitated the prefabrication of the stone members, but also helped to provide structured design information, assuring the correct transfer of information during the process of planning, carving and assembly of the single elements of the vault.

In relation to the stonecutting, the thin membrane-like elements or ploughshares pose similar problems that extend to the question to which degree the shape of the shell in such late-medieval vaults has been planned in advance. With regard to the design of the joint system, in the "Hall of Arms" the approach is essentially different from that in the earlier examples, like for instance in the western wing of the big cloister in Basel Minster (circa 1465). At the springers of the vault in Basel (Fig. 8), these portions are treated as thin walls made of dressed stones with horizontal beds, sitting on the rib voussoir that comprises only the rib profile and is separated by a continuous joint along its extrados.

In Meissen, on the contrary, at least in the lower parts the stone members of the ribs clearly comprise both the rib profile and the diaphragm reaching to the vault surface: they are worked in single pieces with radial joints that extend all the way up to the shell (Fig. 8, far left, shows the upper end of such an element). As the intrados and the extrados of these voussoirs follow different curves (that of the rib and that of the shell intrados), which are not parallel but have variable distances, the shape and size of these stone members are subject to constant change all along the course of the rib. Again, in respect to the design for the joint system we underline the challenge of creating voussoirs which are not interchangeable due to the double curvature of the ribs and the unity of rib and ploughshares.

Finally, this design of the rib members also implicates the shape of the shell of the vault to be determined in the design process, i.e. together with the tracing of the stone elements. We can show that at least under some aspects and in some portions the shape of the vault surface was anticipated in the design. This contrasts to the current belief that the masonry of late Gothic vaults was built ad hoc. However, also the principle requirements of shell structures, stable by their form, suggest that there must have been at least some sort of a strategy for the development of the surface. Therefore we assume that the brick masonry structure of the shell is not only well executed, but also carefully designed.[23]

[23] Wendland, *Arches and Spirals* (Note 16); Wendland and Ventas, *Designing a Masonry Shell* (Note 9).

Acknowledgements

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