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Vaults, centring, and formwork of the Late Gothic period in Southern Germany

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ABSTRACT: The construction of Gothic rib vaults not only required centring for the ribs, but usually also substantial formwork for the masonry of the vault compartments. In the Late Gothic architecture of southern Germany, characterised by vaults with elaborate networks of ribs and advanced building technology, formwork could be largely reduced. At the same time, the centring for the ribs became more complex. This article presents evidence of such auxiliary constructions from various buildings, including the remains of a 15th-century centring that was discovered reused in the roof of a church. Advantages and implications of the constructions are discussed in order to better understand the reasons for the technological changes.

1 INTRODUCTION

In the course of the 15th century, the construction of Gothic vaults in southern Germany underwent considerable changes. Some innovations in the architectural form of the vaults are evident: the French-style, quadripartite rib vault, which had predominated in German religious architecture of the 13th and 14th centuries, was replaced by vault forms with a more complex network of ribs. Important impulses came from designs that Peter Parler realised in Prague during the second half of the 14th century. Parler varied the traditional scheme by inserting additional ribs (liernes) that subdivide a bay into more and smaller compartments, forming decorative patterns such as rhombic figures. The patterns often extended beyond the borders of the bays and thus began to dissolve the strict order of the vaults in favour of a more unified spatial impression. This paved the way for the development of Late Gothic vaulting in southern Germany. In the 15th and early-16th century, the invention of increasingly complex and sophisticated vault forms with star-shaped and reticulated figures led to magnificent buildings such as the churches in Landshut, Munich, Nördlingen and Ingolstadt.

Less obvious than these changes in the architectural form of the vaults are innovations in their construction. As is generally assumed, 'figurated' vaults of the Late Gothic period – in contrast to the older quadripartite rib vaults – could be built without formwork. The reduced size of their webs undoubtedly facilitated such a technique. However, it is not clear whether there was a direct causal connection between the formal and constructional changes, i.e. whether these developments were interdependent. The motivation for abandoning the use of formwork is also not quite clear. Was it just a matter of saving expenses for the woodwork?

In the following, evidence from various buildings is presented that sheds light on the use of formwork and centring. This will provide a basis for discussing the reasons for the developments described.

2 VAULTING WITH FORMWORK

A well-known example of the construction technique of 13th- and 14th-century vaults is Regensburg Cathedral, where significant traces of the building process have been documented (Schuller 1989, 206-8; Schuller 2016, 473-4). On the intrados of the vaults, imprints of boards demonstrate that the brick masonry of the webs was built on a formwork. The boards were closely spaced so that the bricks could be laid in a bed of mortar. After stripping the formwork, the coarse intrados was covered with a smooth plaster.

In the nave, the lateral vault compartments directed towards the clerestory have a relatively large span of up to 6.4 m at the crown. Here the boards of the formwork had to be supported by additional planks, which rested on the diagonal ribs and the ribs of the clerestory. For this purpose, bedding holes were cut into the upper rims of the ribs at intervals of about 50 cm. The holes were observed only in the upper part of the ribs, where the masonry of the webs is inclined at an angle of less than about 50° and thus needed additional support. Further down, a simple formwork of boards was probably sufficient, whereas the steep parts of the webs at the springing could most likely be built without any formwork at all.

Another important observation in Regensburg, characteristic of vaulting on formwork, is a slightly sagging shape of the webs. As Schuller (2016, 474) convincingly explains, this sagging already occurred during the bricklaying process, when the formwork

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began to bend under the increasing weight of the masonry. Only after the last bricks were inserted and the vault was completed did the structure arrive at a more or less stable state. Interestingly, it is this sag that Fitchen (1961, 115–8) predicted in his discussion on formwork of French Gothic cathedrals and that made him argue for a vertical arrangement of the boards instead of a flat one. Whether the French vaults, which unlike those in southern Germany were executed in stone masonry visible from below, actually have such a sagging form can only be determined by precise measurement.

The vaulting technique attested at Regensburg Cathedral is characterised by a formwork that rested on the stone ribs. Thus, the shape of the vault was primarily defined by the ribs. Even though the webs were built on a formwork, a certain tolerance in their shape had to be accepted due to the flexibility of the boards. The layout of the ribs, on the other hand, was precisely determined by a wooden centring, which in this case has left no traces, but must be assumed with certainty.

This method of vaulting on a formwork supported by the stone ribs was probably widespread in southern Germany during the 13th and 14th centuries. Evidence of a similar construction method can also be found in Switzerland, for example in the former church of Klingental Monastery in Basel (Figure 1). The vaults of the chancel were probably erected in the late 13th century (Schwinn & Jaggi 1990, 14). Here, the intrados of the webs does not abut exactly on the upper edge of the sandstone ribs, but is rather located a few centimetres above them (Figure 2). The gap between the rib and the intrados, which is filled with plaster, is mostly about 3–4 cm; towards the top of the vault, it increases to about 5–6 cm, while it decreases towards the bottom and disappears completely just above the springing. Evidently, the gap originates from boards that were put on top of the ribs to serve as a formwork. The boards could have rested only on the outer edge of the ribs, leaving a sufficient support for the webs in the middle of the rib.

Dismantling such a formwork may not have been easy. Only after the uppermost boards had been removed in some way or another, could the lower ones be pushed upwards in the resulting groove and then taken out. Finally, after the formwork was dismantled, the remaining groove was closed with mortar and plastered, as was the intrados of the webs.

Figure 1. Klingental Monastery, Basel. Vaults of the former chancel during restoration (photo: author).

Figure 2. Klingental Monastery, Basel. Detail of the vault, the white marks indicating the gap between the rib and the intrados (photo: author).

3 VAULTING WITHOUT FORMWORK

It is commonly accepted that figurated vaults in Germany were built without the use of formwork (Bürger 2007, 322, 348; Nußbaum & Lepsky 1999, 176). This becomes apparent from their shape, which is characterised by a multitude of spherically curved webs, as for example in St George's Church in Nördlingen (Figures 3 and 4). While this is not always easy to perceive from below, a glance at the extrados makes it clear. It would be extremely complicated and inefficient to realise such a shape on a formwork. On the contrary, the slightly dome-shaped form of the webs allows them to be constructed without formwork. In this way, each course of the brickwork forms an arch spanning from one rib to another.

As soon as an arch is completed, it becomes quite stable and can support the subsequent arch.

In southern Germany, Late Gothic vaults were almost exclusively executed in brickwork, with ribs of stone or terracotta elements. The lime mortar used at that time needed considerable time to set, usually a few weeks. However, the freshly prepared mortar instantly had sufficient adhesive strength to allow a smooth vaulting process. To improve adhesion, special bricks for vaulting were produced. Endres Tucher, for example, mentions in his *Baumeisterbuch* from Nuremberg from the years 1464–75 that sawdust was added to the clay for these bricks (Lexer 1862, 95). In

Figure 3. St George's Church, Nördlingen. Vault above the chancel, easternmost bay seen from below (photo: author).

Figure 4. St George's Church, Nördlingen. Vault above the chancel, extrados of the easternmost bay (photo: author).

this way, the porosity and thus the capillary effect of the bricks were increased.

This construction method, which was brought to perfection in the course of the 15th century, made very thin vaults possible. In most cases, the brickwork consists of stretcher courses, and thus the thickness of the shells is equivalent to the width of a brick, i.e. only about 14–18 cm. Because of the relatively light weight of these structures, there was no need for an extensive system of buttresses. This reduced the structural requirements and the costs of vaulting projects at the same time. All this certainly contributed to a veritable boom in vault construction in the late-15th and early-16th centuries, when vaults could now be realised in numerous older buildings that had until then remained without such a covering.

4 COMBINATION OF METHODS

The advantages of vaulting without formwork could lead to the idea that this technique, once it was established, completely replaced vaulting with formwork. An example that this is not the case is provided by the Church of Our Lady in Ingolstadt. This magnificent building, which is almost 90 m long, was vaulted by Hanns Rottaler in just one year, from March 1503 to March 1504 (Hemmeter 2007, 137–8). The vaults above the nave and chancel have a span of about 11 metres. Basically, their shape is that of a barrel vault with pairs of lateral lunette compartments and a rib network creating patterns of large rhombic forms. There is evidence that the individual compartments were built with different construction methods (Voigts 2015, 246–50). In a contour plan of the extrados that was created from a 3D laser scan, the ribs become visible as shallow steps (Figure 5). Some of the webs have a cylindrical, slightly sagging shape, which – as we have seen – is characteristic of vaults built on formwork. Others are slightly dome-shaped and must therefore have been built without formwork. This is also confirmed by the structure of the masonry: in the compartments presumably built on formwork, the bricks are laid in horizontal, radially-inclined stretcher courses typical of this kind of construction. In the dome-shaped sections at the apex of the vaults, by contrast, the brick courses form sloping arches.

However, these latter sections were probably not built entirely without auxiliary constructions. A few shallow kinks, which are only faintly visible in the contour plan but were also observed when inspecting the intrados from a scaffolding, indicate that some minor supports were used. They must have had the form of segmental arches; probably they were composed of boards. In addition to serving as support, they would also have helped the bricklayer during construction to create a uniform vault shape. The large lateral vault compartments were probably also executed without formwork. This is suggested by the fact that in their lower portions the brick courses are not horizontal, but slope upwards from the lateral wall to the diagonal rib.

A shallow kink in the apex of the compartments indicates that another thin, supporting element might have been positioned there during construction (Figure 5).

The question of how exactly the above-mentioned formwork was constructed cannot be answered with certainty in this case. Very likely, its boards were not placed on the ribs as in the case of Basel, since the profile of the ribs would hardly allow such an arrangement. The upper side of the stone ribs, which was examined in a small sondage opening, is indeed bevelled at its outer edge (Figure 6). However, the resulting space between rib and brickwork, 3–4 cm deep and 2–3 cm high, does not appear to be sufficient as a bedding for the boards. It therefore seems more likely that the formwork was attached to the centring of the rib. The question of how this centring might have been constructed, so that it could possibly have supported the formwork, will be discussed in a moment.

The finding that specific compartments of the vaults in Ingolstadt were built on a formwork is in contrast to the common opinion that figurated vaults were generally erected without such an auxiliary construction. In fact, the way in which both methods were combined

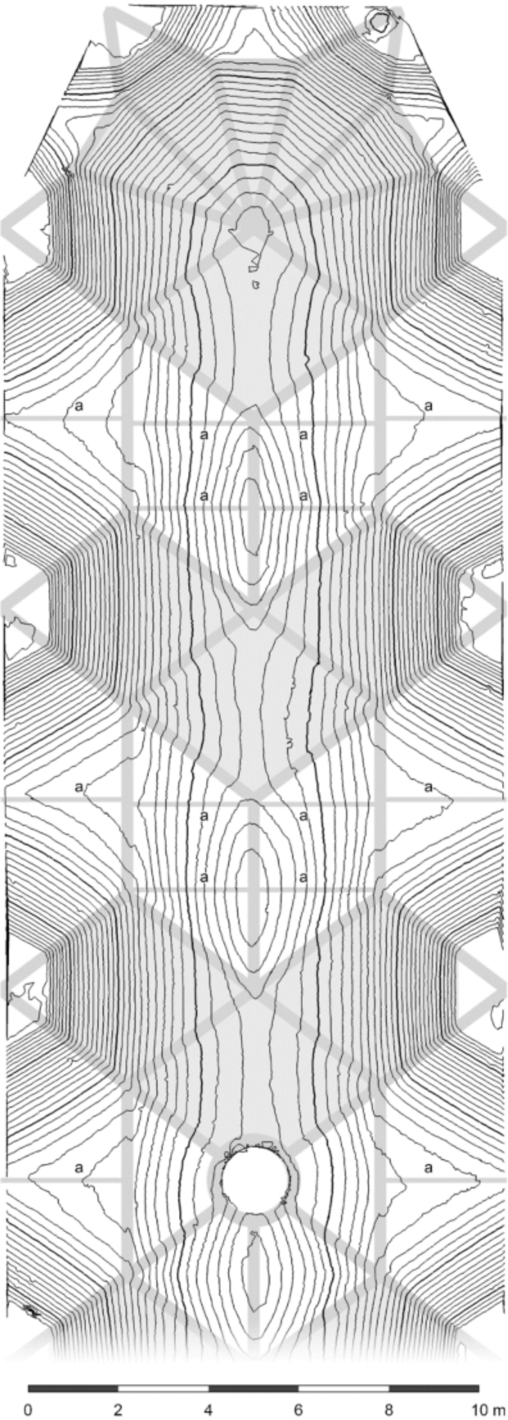

Figure 5. Our Lady's Church, Ingolstadt. Vaults above the chancel, contour plan of extrados, contour interval 0.1 m. Grey lines indicating the centring for the ribs and additional supports (a), light grey areas indicating formwork (graphic: author).

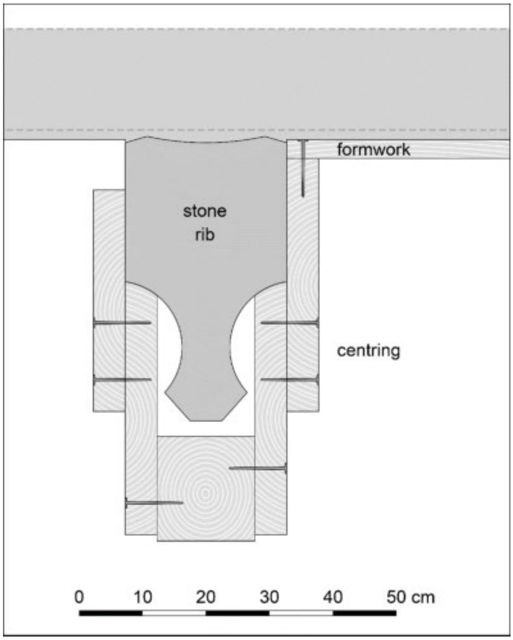

Figure 6. Our Lady's Church, Ingolstadt. Vaults above nave and chancel, hypothetical reconstruction of centring and formwork (drawing: author).

here suggests a careful planning, which aimed at an efficient and safe construction process and a saving of material at the same time. It becomes tangible how the master builder took into account the workflow on the construction site and the costs when he designed this building. Artistic and technological considerations were coordinated and brought into harmony with each other.

5 CENTRING

Our idea of what medieval centring might have looked like is strongly influenced by Fitchen (1961). Based on the broad rib profiles of French cathedrals, Fitchen proposed a pair of arches made of squared timber as support for each rib. Such massive centring was certainly not necessary for the figurated vaults of the Late Gothic period in Germany. Here, the spans of the centring and its wooden arches were much shorter, since usually a support by a vertical post can be assumed for each rib intersection. This is because the construction of the centring intersections could hardly have been accomplished in any other way. Furthermore, the existence of such vertical supports is suggested by measurements of vaults, which showed that the intersections systematically have a more precise height definition than the rest of the ribs (Müller 1990, 161–2; Wendland 2015, 77–8; Wendland 2019, 14–5). As a consequence, depending on the density of the rib network, the centring often had to span only about 2–3 m from one post to the next, especially in the central sections close to the crown of the vault.

Another aspect relevant to the centring is that the ribs of the 15th century generally have a profile that tapers significantly towards its bottom, where it ends in a narrow bar or even a sharp edge. For such ribs, a centring with a U-shaped cross-section would be preferable, so that the rib elements could be set into a channel.

All these general considerations would suggest that the centring for Late Gothic vaults consisted of arches that were composed of boards rather than squared timber. Two or three layers of boards nailed together with staggered joints could form a very stable girder. This could easily be constructed in the shape of an arch with an intended radius. As already proposed by Kotrba (1961, 211), two such arches made of boards together with some wooden spacers in the middle would have provided a very efficient centring (cf. Figure 6). Structures of this kind were actually realised as is shown by the large quantities of boards and iron nails explicitly listed for the construction of centrings in building accounts of the 15th and early-16th centuries (Mai 2014, 161–3).

In any case, the economic and technical prerequisites for such constructions were given in the 15th century: boards, which until the 12th and 13th centuries had to be manufactured with great effort either by splitting or sawing by hand, could increasingly be produced in water-powered sawmills in the Late Middle Ages. In Augsburg, for example, it is documented that several sawmills existed as early as the 14th century (Finsterbusch & Thiele 1987, 105). In consequence, boards became the more and more inexpensive building material that we know them as today.

The fact that the centring for figurated vaults usually implied short spans and could be realised with relatively light wooden arches does not necessarily mean a saving of timber. The reduction of material that was possible for the individual arches was most likely cancelled out by the greater number of arches, but above all by the vertical supports that had to be installed at close intervals. Presumably, even the timber saved by omitting the formwork was compensated by these supports – depending on how they were constructed.

6 SUBSTRUCTURES OF CENTRING

In connection with the centring, the building accounts frequently mention a large quantity of undressed timber, which was obviously used for the vertical supports (Mai 2014, 161). As long as the vaults were not particularly high above the ground, these poles could simply be placed on the floor. But at a height of more than about 8–10 m, which was easily reached when vaulting churches, two or more of these poles would have had to be joined together. Such joints are often imagined to have been made simply with rope, similar to those of historic scaffolding. But this would have compromised the stability and precision that the vertical posts were supposed to give to the vault construction.

Figure 7. St Jacob's Church, Wasserburg. Timber reused in the roof above the nave (photo: author).

Figure 8. St Jacob's Church, Wasserburg. Timber reused in the roof above the nave (photo: author).

For this reason, the existence of a working platform at the level of the springing has been postulated, which would have served as a base for the vertical posts of the centring (Wendland 2019, 16–7). Of course, such a platform would have had to be very stable and immovable so that no deformations could occur during the vaulting process. Possibly it could have been supported by the lateral walls; however, relatively strong beams would have been required to span the entire width of the vaults without sagging. Alternatively, a wooden substructure could have supported the platform, but it would have had to be constructed with squared beams and carpentry joints to provide the required stability.

Evidence of a wooden structure meeting the latter criteria was recently found in the roof of St Jacob's Church at Wasserburg (Voigts 2020, 61–2). In the roof above the nave of the church, which dates from 1414 or a little later (Gschwind 2012), a substantial reinforcement was subsequently installed. This secondary structure is partly made of wood that shows obvious traces of reuse (Figures 7 and 8). Empty mortises and sockets of lap joints, some of which still contain wooden pegs, demonstrate that the beams had previously been used in a different context.

At the same time, the form of the joints indicates that the timbers, which are now laid horizontally, were arranged vertically in their first use. Since the beams still have a considerable length of 7.10–7.80 m, they must have originally belonged to a relatively high construction. Particularly interesting is the chronology of their primary and secondary use: dendrochronological dating has revealed that the trees that the beams were made from were felled in the winter of 1449–50 (Gschwind 2012). The reuse in the reinforcement of the roof occurred only three years later, in the spring of 1453, as we learn from building accounts (John & Nadler 2007, 76). Obviously, in the original construction, the beams were in use only for a short time. It therefore seems reasonable to assume that they were parts of some kind of auxiliary construction that was only used during a building process. Strikingly, the dates of the felling and reuse of the timbers coincide quite precisely with the beginning and completion of the vaulting of the chancel of St Jacob's (Voigts 2020, 62). However, the beams are certainly not components of a conventional scaffolding. The careful execution with elaborate carpenter's joints would rather correspond with the idea of a solid working platform described above.

7 CONCLUSION

As we have seen, Gothic rib vaults in southern Germany were usually built on formwork. Vaulting without formwork, which has a long tradition in other regions of Europe, seems to have been introduced here only in the late-14th or early-15th century. The exact circumstances of this development, when and by whom the impulses were given, are not clear at the present state of research.

The reason why vaulting without formwork prevailed in Late Gothic times is probably not that the wood for the formwork could be saved. This advantage was offset by the greater expense of the centring with its dense network of wooden arches and vertical supports. But the thin and relatively light vaults that could be erected with the help of this network did not require massive buttresses. All in all, the lower structural requirements are likely to have made vaulting with this method more efficient.

If we also include the scaffolding for the masons in this consideration, it becomes clear that an enormous amount of timber was necessary for vaulting – regardless of the method. Finally, this is also confirmed by the findings from St. Jacob's Church in Wasserburg, which suggest the existence of a solid working platform carefully constructed by carpenters. Temporary structures of this kind, erected with great precision, were the basis for the construction of the Late Gothic vaults that we still admire today.

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