Structure of baroque church roofs in Bavaria

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ABSTRACT: The authors report results of an extensive survey of baroque timber roof constructions in Bavaria. It turns out that the majority of these roofs lack a tie-beam at their base, because the roofs harbour masonry vaults which rise high into the roof space. In the church roofs analyzed, different historical techniques have been identified for carrying the thrust of the roof and the vault in the case of a missing tie-beam. We analyze these techniques both from a historical point of view (development and spread of technological knowledge by carpentry treatises) and from a structural point of view, including the structural assessment in an exemplary case.

1 AN INTRODUCTORY CASE STUDY

We start from some observations made during an intensive inspection of the southern Bavarian pilgrimage church of Tuntenhausen, some 30 km south-east of Munich. The church was erected in 1628, during the Thirty Years War. It replaced an older, gothic church, of which only the tower in the west is persisting – a strange twin tower, consisting of two towers built wall-to-wall. The church is one of the earliest “baroque” churches in the area. However, its layout resembles very much the layout of a gothic church. The church has three parallel naves with three bays. The main nave is in fact somewhat higher than the aisles, but the whole keeps the general impression of a “hall” church with three naves of roughly equal height (cf. Fig. 1). The main arches of the church are supported by two pairs of slender pillars. In the east, the church features a chancel with an ambulatory, encircling the partly preserved old gothic polygonal apse with the principal altar.

When the authors of the present paper inspected the church, they were confronted with preparations for restauration work, and their opinion concerning wide cracks in the vaults was asked for. It was not clear whether the damage was caused by defects in the roof structure or rather by ongoing settlements. Investigations on the stucco surfaces indicated that the cracks were not new, but had developed with a decreasing rate since the 17th century (Rosenheim 2007).

It turned out that the present state of the structure could not be explained without a thorough understanding of its building process, which could be deciphered from observations in the attic space.

Quite like the church itself, the roof structure resembles gothic constructions very much (cf. Fig. 2).

Figure 1. A view of the vaults of the church at Tuntenhausen.

Figure 2. Section of the roof truss, Tuntenhausen (1628). Shaded beams correspond to the original structure, blank beams are later additions.
The main girders of the roof are constituted by two superimposed trussed frames. The lower one is characterized by two rows of timber columns rising directly above the main arches of the church. This part is well stiffened by various braces rising parallel to the rafters. The upper storey of the roof, by contrast, makes use of a “liegender Stuhl” structure, the most characteristic element of 17th and 18th century roofs in Germany. The roof accommodates the rising barrel vault of the central nave by simply leaving out the tie-beam in the central section.

However, in the intervals between the lunettes of the main vault, projecting beam ends suggest that, originally, the principal transverse trusses of the roof in fact did have continuous tie-beams (cf. Fig. 3). There is no immediately obvious explanation for this feature. However, it turns out that this tiny peculiarity – easily overlooked – is intimately connected to the construction process of the vault and roof, and combines well with the following observations on the vaults, as we shall see:

- The longitudinal barrel vault of the central nave is slightly pointed in cross-section
- The lunettes of the central barrel vault rise considerably (1 m circa) above the capstone of the main arches
- There is no transverse arch, neither in the nave nor in the aisles, neither on the extrados or intrados of the vault
- The vaults of the aisles are rounded transverse barrel vaults, connected to each other by conical lunettes in longitudinal direction
- In cross-section, the profile of the vaults over the aisles is visibly distorted where the adjacent conical lunettes meet each other.

All these observations can be accommodated in the following hypothetical account of the vault erection: First, the outer walls of the church and the two arcaded walls separating the naves were built. At this point, there was no intermediate transverse connection or stiffening between the free-standing, slender arcades and the outer walls. Next, the roof was erected. The roof made use of continuous tie-beams as anchoring beams in the main trusses. This ensured temporal stabilization of the free-standing, very slender masonry structures (even the outer walls are very slender structures, exhibiting huge windows, but no external or internal buttresses). After roof erection, the vaulting was started with the transverse barrel vaults of the aisles, the anchoring beams of the roof still being in place. After completion of the transverse barrel vaults, the builders obviously trusted them to carry the thrust of both the roof truss and the central barrel vault, and dared to cut the anchoring beams. Then, finally, the central barrel vault was built. One might speculate whether the unusual shape of the pointed vault (unique in 17th century Bavarian architecture) was already a reaction to immediate damage or not. However, it is sure that considerable deformation set in immediately after the completion of the construction. This is testified by the deformed shapes of the aisle vaults, the outward tilt of the circumferential walls, as well as a mess of historical rehabilitation structures above the vault (cf. Figs 2 and 3). These include scissor braces intended to carry the thrust of the roof, as well as another pair of scissors anchored to the circumferential walls, obviously meant to carry the vault thrust. From a modern point of view, it is obvious that the slowly hardening historical mortar would have prevented the aisle vaults from performing their intended function as abutments, and that movements would slowly come to a standstill only as the mortar reached its final stiffness. Most of the thrust is now carried by the conical lunettes. On the other hand, the scissor braces presumably did not do a great service towards stopping the process of deformation.

Anyhow, a large percentage of the present-day deformation must have occurred immediately after completion, since the stucco work of the vault already

Figure 3. Roof structure, Tuntenhausen. Arrow indicates location of originally continuous tie-beam cut away prior to vault erection in the nave.
takes account of the deformed vault shapes, and is also fastened to the vault in such a way as to effectively hide already existing cracks. Therefore, the authors felt entitled to conclude that the present-day cracks present no hazard for the structural stability of the church, even though some of the cracks are up to 10 mm wide.

As a remark concluding the case study, we would like to note that the timber columns of the roof are all tilted. However, this effect seems to be mostly independent from the problems with the vaults. Rather, the upper storey of the roof, the “liegender Stuhl”, leans towards the east due to a lack of stiffening. The stiff construction of the lower storey prevented the upper part from toppling, even though the construction of the hip roof over the ambulatory is very defective. Furthermore, it is worth noting that the horizontal beam at mid-elevation of the lower storey of the roof (cf. figure 2) cannot be considered as a raised tie-beam, being connected to the columns only by tenon-and-mortise connections.

2 CHALLENGES OF THE BAROQUE ROOF

The roof of Tuntenhausen is just one of the starting points of the development of the baroque roof in Bavaria. Obviously, it did not work quite as well as it should have. The reasons for the failure of the structural concept at Tuntenhausen and the challenge of similar situations elsewhere are quite obvious: Baroque roofs in southern Germany typically exhibit a pitch of around 45°. Contemporary carpenter’s treatises call this pitch the “German” pitch. It is a pitch that is considerably lower than the 60° pitch of typical gothic roofs. The low pitch aggravates problems with thrust, particularly in situations where continuous tie-beams are not feasible, and the traditional carpentry techniques that had been developed over the centuries in the area north of the Alps for the high-pitch gothic roofs were ill adapted to the new challenge of low-pitch roofs, as evidenced by many 17th century roofs, including the one of the Hofkirche at Neuburg on the Danube (1615), the lowest of the Bavarian roofs of the time.

Furthermore, brick barrel vaults with small lunettes became the standard vaulting solution in Bavarian baroque architecture. Unlike the adjacent regions in southwestern Germany, Bavarian baroque builders used timber “lattice” vaults only with reluctance, with only very few exceptions, mostly cupolas. In addition, virtually all the brick vaults of south-eastern Bavarian baroque churches rise high enough into the attic space to prevent continuous tie-beams.

At the same time, even minor church buildings of the 17th and 18th century easily reach the 16.50 m span which is a typical upper threshold on late gothic church nave widths (Augsburg, St. Ulrich, 1499).

Technically even more demanding is the church type developed in Bavaria during the 18th century, namely, churches which embed an octogon for the congregation in a rectangular outer shape, the vault being a cupola which is hidden beneath an ordinary ridge roof. These cupolas easily reach 20 m spans (e.g., parish church of Murnau, see below), pushing the required roof span to the limit of traditional carpentry.

The authors of the present paper have conducted, during the last two years, an extensive survey of baroque roofs in southeastern Germany (Bavaria), with the goal of identifying typical solution strategies followed by carpenters in that region to cope with the problem of large span and the challenges of fairly low pitch and missing tie-beam. Around 40 church roofs have been inspected, covering the entire period from 1600 to 1800. Our study complements the survey conducted by Sachse in the region directly adjacent to our area in the west (Sachse 1975). The full results of the survey will be published in a dedicated monograph (Holzer & Köck 2008). In the remainder of the present paper, we present typical constructive strategies encountered during the survey, and we address the question how much information the contemporary carpenters could possibly have gained from the comparatively rich production of carpenter’s treatises published in German language. Also, we discuss issues of the mechanical behaviour of the typical structures encountered.

As late as 1814 (!) Franz Sax, of Vienna, Austria, published a section of a barrel-vaulted church with a roof truss in his treatise on Bau-Technologie und Bau-Oekonomie (Sax 1814, cf. Figure 4). The lower storey of the roof structure is constituted by a high “liegender Stuhl”. The only precaution taken to carry the thrust of the roof is a raised tie-beam, connected to the braces of the “liegender Stuhl” by means of iron clamps.

![Figure 4. Design of a church roof accommodating a masonry barrel vault, from Franz Sax, Bau-Technologie, 1814 (detail from plate V). A raised tie-beam is secured by iron clamps.](image-url)
Figure 5. View below the raised tie-beam in the roof of the church at Altenerding (1721). The long tie-beam in the middle of the picture is not a continuous one, but also stops at the extrados of the masonry vault (covered by thermal insulation).

From a modern perspective, it seems unlikely that someone would rely on such a construction. However, a roof corresponding exactly to Franz Sax’ layout was completed in 1721 in Altenerding (Fig. 5). As opposed to the roof depicted by Franz Sax, the carpenter at Altenerding opted for a tenon-and-mortise connection of the raised tie-beam. The tenon traverses the entire rafter and is connected to its outer face by a long iron strap nailed to the top of the tie-beam. The vault at Altenerding is a very shallow, basket-handle shaped barrel vault.

Quite obviously, this system could not be expected to perform well, particularly with a view to the total absence of outer abutments, side chapels, or any other structure capable of carrying the outward thrust of the vault. As a consequence, the roof has undergone very heavy restoration work in the 20th century, modifying the entire structure into a modern truss by members added between the raised tie-beam and the collar beam.

Franz Sax also illustrated a different setup for roofs with discontinuous tie-beam (cf. Fig. 6). Here, two diagonal braces meet at a king post. The details of the joinery at this critical point remain unclear. Roofs of a similar construction were actually built in Bavaria as early as the last decade of the 17th century. One example is given by the former Augustinian abbey church of Weyarn, within 15 km from Tuttenhausen (cf. Fig. 7). The church is a typical example of the Bavarian “wall-pillar church”, i.e. a church with a nave vaulted by a longitudinal barrel vault, accompanied on either side by chapels with transverse barrel vaults. In such a church, the transverse barrel vaults typically spring at the same level as the main barrel vault, but their rise is much lower than that of the longitudinal vault due to the larger span of the latter. The difference is accommodated by rising, conical lunettes. Provided the side chapels are deep enough, the scheme provides optimal abutment to the thrust of the main vault and thus leaves only the problem of roof thrust unaddressed. At Weyarn, the diagonal braces appear in combination with a low first story of the roof truss, whereas the main “liegender Stuhl” of the roof rises on top of some kind of elevated tie-beam. Therefore, the diagonal ties only have to carry the thrust of the lower portion of the roof. Nevertheless, the joint between the king post and the diagonal ties turns out to be the most critical part of the whole structure. In Weyarn, these joints are lap joints secured by a wooden pin. The pins have failed, but nevertheless the structure still stands largely undamaged, probably due to the fact that the thrust of the roof could be transmitted to the abutments through the rudimentary tie-beams by friction. In this respect, the actual design at Weyarn is much better suited to the problem than the one published by Sax, where the lower storey of the roof is also constituted by a “liegender Stuhl”.

An almost identical roof can be found in the church of Perlach (today part of Munich). It dates to 1728.
As opposed to Weyarn, the builders at Perlach one generation later would not rely on traditional joinery to carry the load in the diagonal braces, but introduced iron straps fastened to the king post by a bolt with an iron wedge (Fig. 8).

Surprisingly, none of the roofs discussed so far made use of a roof truss element that was already well known in the 15th century, namely, scissor braces. During the 15th century, scissor braces became something like a standard solution for roofs where continuous tie-beams were not feasible because of a wooden barrel vault. Medieval wooden barrel vaults are not frequently encountered today in Germany, but traces prove that this kind of construction was once quite popular, not only in town halls, but also in churches (cf., e.g., Cramer & Eissing 1996). In what is today Munich, the church of Ramersdorf (first quarter of the 15th century, see Fig. 9), is an example of such a structure. The roof with its 60° pitch once accommodated a trefoil-shaped wooden barrel vault, as is evidenced by traces of stucco at the gable ends of the roof (see Fig. 9, background; cf. also Hösch 1996).

In Ramersdorf, the wooden vault was soon replaced by a masonry one with a much lower rise. The roof shows scissor ties connecting all pairs of rafters.

A roof of very similar structure is also depicted in Johann Wilhelms carpentry treatise, *Architectura Civilis*, first published in 1649 (Wilhelm 1649, cf. Fig. 10), the earliest dedicated carpentry treatise to appear in German language. However, it needs to be noted that Wilhelm’s roof is stiffened by a *liegender Stuhl* frame, which collects the loads of the rafters in transversal frames, and only these frames are equipped with the scissor ties, rather than every pair of rafters as in the medieval roof. Wilhelm’s treatise sparked a rich production of further German carpentry treatises, including the *Architectura Civilis* published by Caspar Walter, of Augsburg, in 1704 (Walter 1704). Each of these treatises until the end of the 18th century presented at least one example of a roof truss with missing tie-beam, in combination with a wooden or lattice barrel vault (e.g., plates 18–21 in Walter 1704). Also, several examples prove that the technique was well known to contemporary carpenters and actually employed in building practice. The roofs of the 17th and early 18th century protestant churches of Augsburg (St. Ulrich, constructed by Caspar Walter in 1710) and Regensburg (Trinity church) make use of scissor braces.

Under these circumstances, it seems somewhat odd that the scheme was only reluctantly introduced into roofs which had a brick vault rather than a wooden vault. In the case of the brick vault, the added weight causes greatly increased thrusts, so that proper precautions to carry the thrust become a must. Nevertheless, carpenters adhered longtime to traditional structural forms and did not readily transfer solutions from one problem class to another.

A roof equipped with scissor braces between every pair of rafters (not just in the principal trusses) can be
found in the church of Murnau (1717–21). However, this church was a completely singular structure at the time of its building. The “nave” of the church is constituted by a Bavarian variant of the Roman Pantheon, namely, an octagonal space with a diameter of 20 m. A perfect sphere is inscribed into the nave, the principal corniche coinciding with the equator of the sphere. Strangely, the huge hemispherical cupola (one of the largest baroque cupolas in Germany, surpassing the one at Weingarten, Swabia, cf. Kutnyi & Wiesneth 2007, with a diameter of 15 m, and approaching the cupolas at Ettal and Dresden, both with a diameter of approximately 25 m) is not visible from the outside, but hidden under an ordinary ridge roof. Accommodating such a large cupola in the attic posed an unprecedented challenge to the carpenter.

In Murnau, the carpenter resorted to scissor braces connecting all pairs of rafters to each other in the area where the cupola protrudes into the roof space (see Fig. 11). Also, he added a bridge-like truss in the plane of the rafters to carry the load from the “open” part of the roof to the parts with continuous tie-beams. Last not least, both the brick cupola and the “hole” cut into the base of the roof are reinforced by closed rings of tie-beams at various levels. The Murnau roof is one of the most remarkable feats of Bavarian baroque carpentry and would deserve a monographical study in which we cannot give here.

Only by the middle of the 18th century, scissor braces had developed into a commonplace solution for the problem of interrupted tie-beams. Regularly, the south-eastern Bavarian architect Johann Alois Mayr (1723–1771) employed scissor-braces whenever there was a need to use discontinuous tie-beams. His church roofs at Baumburg (1756), Marienberg (1764) and Kirchweidach (completed only after Mayr’s death, in 1774) all employ scissor-braces. The case of Baumburg (Fig. 12) is particularly interesting for two reasons. Firstly, Baumburg is a standard “wall-pillar”

3 STRUCTURAL ASSESSMENT OF SCISSOR TRUSSES

Stress analysis of historical roof trusses poses specific problems which are otherwise not common in structural engineering. As opposed to the analysis of modern constructions, the idealization of the structure is not straightforward, in particular because the stiffnesses of the joints and the support conditions are not well defined. On the other hand, these modeling decisions have a decisive influence on the results, as we shall demonstrate by a little example.

In the following, we present some preliminary results from the analysis of a principal girder of the Baumburg roof under symmetric loading. Very similar analyses have also been conducted by Lewandoski & Levin (2003) for historic American scissor trusses. Although these 19th century American trusses are only superficially akin to our baroque trusses, but differ conceptually in many details, our results compare well to those already reported by Lewandoski & Levin (2003).

In the finite element analyses presented, we have considered the “liegender Stuhl” girders as frames with rigid corners. The rafters are in contact with the tilted columns of the “liegender Stuhl”. All traditional timber joints have been considered as perfectly hinged,
quasi pin-jointed connections. By contrast, all connections employing more than one iron bolt have been modeled as rigid because the stiffness of such a connection is much higher than that of a wooden pin and a pair of iron bolts permits transfer of moments.

Firstly, we study the effect of the support conditions. Allowing the supports to slide freely, we obtain what one would probably expect, namely, tensile stresses in the scissor braces (Fig. 13). The computation demonstrates that the king post performs a good job as a tie-rd between what is essentially the upper and lower chords of a triangulated truss, constituted by the rafters and the scissor braces. In this model, the upper portions of the braces act as struts supporting the rafters, but only with minor effect. As a natural consequence of the overall structural response, the lower collar beam is also in tension, which contradicts expectation and will not be permitted by the joinery. However, neglecting the effect of the collar beam will not change the picture much.

By contrast, if we modify the model such that the inner supports of the frame are considered fixed, the stress in the cross-braces reverses sign (Fig. 14); the scissor braces then turn into some kind of an arch supporting the lower collar beam.

This model may be criticized on the grounds that the support will never be perfectly fixed in reality, and it is true that the scissor braces regain their function as tie-beams immediately once one forces even a very small outward displacement on the inner supports.

However, the role of the scissor braces is also strongly dependent on the king-post. If we assume that the king-post is imperfectly fixed to either the ridge of the roof or to the collar beam, the scissor braces are once again transformed into an arch and get compressive stresses (Fig. 15).

In summary, the loads of a scissor-braced truss may either be carried by a simple triangulated, statically determinate truss constituted by the scissor braces and the rafters, with the essential contribution of the king-post, or, alternatively, by some kind of a polygonal arch. The transition between these two distinct and essentially incompatible load-carrying structures depends strongly on local modeling assumptions and stiffness ratios. Somewhat surprisingly, the “liegender Stuhl” frame plays only a secondary role in the overall stress distribution.

The true situation is much more difficult to assess than could be demonstrated in this greatly simplified example. Roofs which do not have a tie-beam are much more sensitive to such modeling assumptions than are roofs with a closed rafter–tie-beam triangle.

Based on experiences similar to the one presented, the authors are currently working on more detailed computational modeling of typical baroque roof trusses which lack tie-beams, including the application of interval arithmetic and fuzzy set theory.

REFERENCES


