

Geometric design and construction of a Late Baroque brick vault:

Kilian Ignaz Dientzenhofer's Benedictine Church of the Holy Cross and St. Hedwig at Legnickie Pole

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Abstract

This paper investigates the case study of Kilian Ignaz Dientzenhofer's church of St. Hedwig in the Polish region of Silesia. The building, a popular pilgrimage church, is known in the history of art and architecture as a Late Baroque jewel with a curious design and famous frescoes. While the shape of the building and its vault has led to different interpretations in the past, its geometry has not yet been analysed on a reliable basis. Moreover, the construction of the brick vault has not yet been subject to scientific research. In order to investigate these aspects, a 3D laser scan of the vault's extrados and intrados was utilised as the primary source. The 3D model generated from the scan not only enabled the detailed description of structural ribs, brick patterns and construction details on the extrados, but also made a geometrical analysis using reverse geometric engineering possible. The results show a geometric design of the vault surfaces as well as double-curved arches based on simple plane circle segments. This clear geometric definition of the vault is associated with a remarkable simplicity of construction method and centering. In the context of other vault designs by members of the Dientzenhofer professional circle of master builders and architects, the vault of St. Hedwig can be seen as both a continuation and an improvement in terms of geometric design and construction details.

St. Hedwig at Legnickie Pole

The former Benedictine church of the Holy Cross and St. Hedwig is located in the heart of a monastery complex at Legnickie Pole in the Polish region of Silesia (Fig. 01). The building is a Late Baroque *Gesamtkunstwerk*, consisting of architecture, sculpture and painting of the highest artistic standard [1]. The project, which was intended to support the re-Catholicisation of the region, was initiated by Othmar Zinke (1663–1738), the resourceful abbot of Břevnov, a Benedictine archabbey on the outskirts of Prague with supervision over several other monasteries. The abbot hired a group of Bohemian craftsmen he had worked with before, making St. Hedwig's a Bohemian work on Silesian soil [2]. The architect Zinke chose for his monastery project was Kilian Ignaz Dientzenhofer (1689–1751), the son of Christoph Dientzenhofer (1655–1722), who had built two other monasteries for Zinke but had died a year earlier. The design for St. Hedwig bears many similarities to the works of the father Christoph, and uncles Johann and Georg, who were also successful architects and builders but worked in Germany. The Dientzenhofers' designs, especially their vaults, are known for their complex geometries and free-moving forms, which were often associated with the Italian Baroque designs of Borromini and Guarini. The design of the young Kilian Ignaz was in no way inferior to that of his older relatives, making St. Hedwig an early major work of the architect, whose artistic legacy would later surpass even that of his relatives.



Fig. 01: The façade of St. Hedwig

Building history

In 1703 abbot Zinke acquired the land in Legnickie Pole with the intention of building a monastery, but construction of the monastery buildings could not begin until twenty years later, in 1723 [3]. Work on the church then began in 1727 and the consecration took place in 1731. The frescoes were completed in 1733 by the famous Bavarian artist Cosmas Damian Asam (1686–1739) [4]. Only a few years later, in 1740, Silesia became part of Prussia and the connection with the Bohemian Benedictines was severed. While the monastery buildings were converted for different uses in the following centuries, the church retained its function and appearance. Restorations were carried out in 1932/33, in the mid-1980s [5], and recently in the course of the church's designation as a Basilica Minor in 2014. Today, the building is a popular pilgrimage church and tourist destination.

Description

The church is symmetrically situated between the two wings of the monastery; only the front façade with its two towers is visible from the street. The interior consists of several spaces lined up along a longitudinal axis (Figs 02, 04–05). The curved walls and the vault above give the impression of a series of intersecting ovals. The first oval is the entrance under the organ gallery, located longitudinally between the two towers. The high and wide nave has an oval shape, resembling an elongated hexagon aligned along the main axis. There are four chapels in a lenticular shape on the concave sides at the diagonal points of the hexagon. The chapels are separated from each other by wall pillars. Another transverse oval follows before the axis ends in the rounded choir.

The interior is spanned by a domed vault that picks up on the oval shapes of the ground plan. The different regions of the vault are separated by double-curved arches. The large central vault, convex on a longitudinal plan, rests together with the arches on the six wall pillars. This baldachin system of a vault on pillars, seemingly detached from the walls, was also used by Christoph Dientzenhofer for his most important works. The vault is covered with frescoes painted by Asam, which together with sculptures, paintings and the architecture form a *Gesamtkunstwerk* with a complex iconography [6].



Fig. 02: Inside view of St. Hedwig

Previous research

For a long time, St Hedwig was not sufficiently appreciated by architectural research and was only briefly mentioned in relevant publications, a situation that has only changed in recent decades. While aspects of the vault construction have not been mentioned at all and the vault's geometric design was not specifically mentioned, the geometric basis of the design of the church as a whole has been discussed by many authors. In addition to the complex shape of the building, the inconsistency and obvious errors of the available plans [7], as well as the loss of the original building plans during the Second World War [8], may also have been reasons for this debate.

It has been suggested that the design of the building's nave was simply based on a hexagon with concave sides [9]. Jan Wrabec, to whom we owe most publications about the building [10], initially described the design as being based on ellipses [11]. Christian Norberg-Schulz, in contrast, proposed a graphical analysis of the design of St. Hedwig, concluding that the nave is formed by the interpenetration of two circles along one axis, with the architect generally using ovals as auxiliary structures [12].

Method

In 1991 Wrabec wrote that a final confirmation of the theories about the underlying geometry of St. Hedwig's design could only come from an "ideal survey, but this is difficult to imagine" [13]. Thirty years later, a method using millions of single measurements comes close to such an ideal and is already common practice: 3D laser scanning.

In November 2021, a Leica RTC360 LT was used to scan the interior of the church and the roof. The data obtained was not only used to draw accurate plans of the entire building (Figs 04–05), but also to learn more about the geometric design and construction of the vault. The analysis of the shape of the intrados of the vault as it was executed was possible with reverse geometric engineering. To do this, the triangulated mesh model (Fig. 03) was divided into its individual regions, and geometrically defined curves and surfaces were fitted to these regions as accurately as possible. These hypotheses were then verified by analysing the deviation between the scanned model and the ideal curves and surfaces. The deviation between measured and modelled surfaces was visualised by colour coding and the deviation between measured and modelled curves by needle diagrams (Figs 07–08, 10–11).

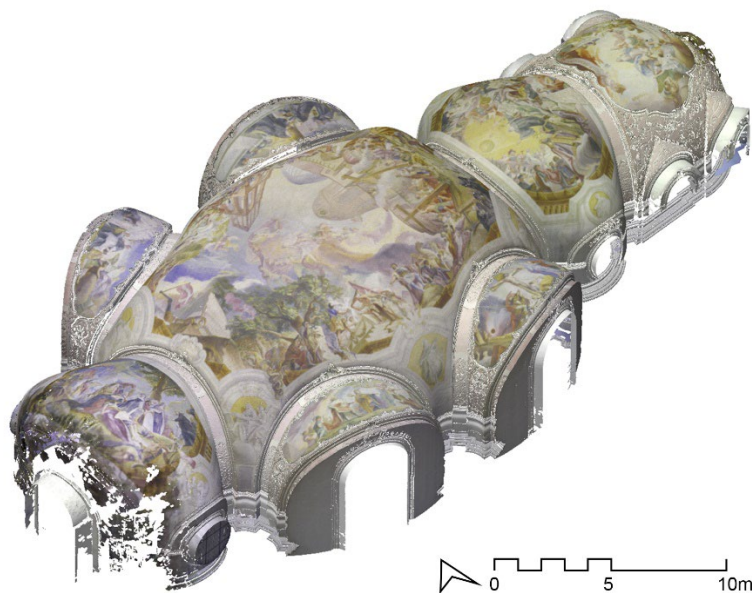


Fig. 03: The intrados as a triangulated mesh model (isometric top view)

A vault's deviation analysis is always influenced by factors other than the original building design. Typical vault deformations such as a slight sagging of the apex, deviations during the construction process, and slight changes of the intrados' surface due to repainting and restoration have to be taken into account as well as error tolerances in the measurement (in this case 2.9 millimetres at 20 metres). For these reasons, the results must be discussed, put into context, and presented in a disprovable way [14].

Construction and geometric design

The vault of St Hedwig (Figs 04–05) has a total length of 41.7 metres. The cornice ends 10.8 metres above the floor, above which follows a 1.86 metre high vertical wall section with plaster decoration before the actual springing of the vault. The maximum internal vault height from this point is 7.75 metres. While the lower half of the vault merges into the outer wall, the upper half extends into the roof. This upper half reveals the construction of the vault on the extrados (Fig. 06). The vault is accurately built of bricks of uniform size (30 x 15 x 7.5 centimetres). The mortar joints have a thickness of 1–2 centimetres. The thickness of the masonry shell is about 34 centimetres, corresponding to the length of a brick plus 1 centimetre of plaster on the extrados and 3 centimetres on the intrados. Apart from the main vault, the rest of the vault is covered by a layer of mortar. The masonry shell has structural ribs on the extrados. During a repair in the twentieth century, a concrete ring beam was inserted around the main vault, as well as several tie rods anchoring it to the outer wall.

The geometric design of the building, based on circular arches (with a radius of about 9.8 metres) combined into oval shapes arranged along a longitudinal axis, is evident in the plans (Figs 04–05) [15]. The design of the vault translates these two-dimensional forms into three-dimensional bodies separated by double-curved arches. The horizontal and vertical (longitudinal and transversal) sections and projections of these shapes provide an initial insight into the form, which is refined by subsequent modelling and deviation analyses. Together with the observation of construction details, these analyses also enable hypotheses about the construction process of the vault.

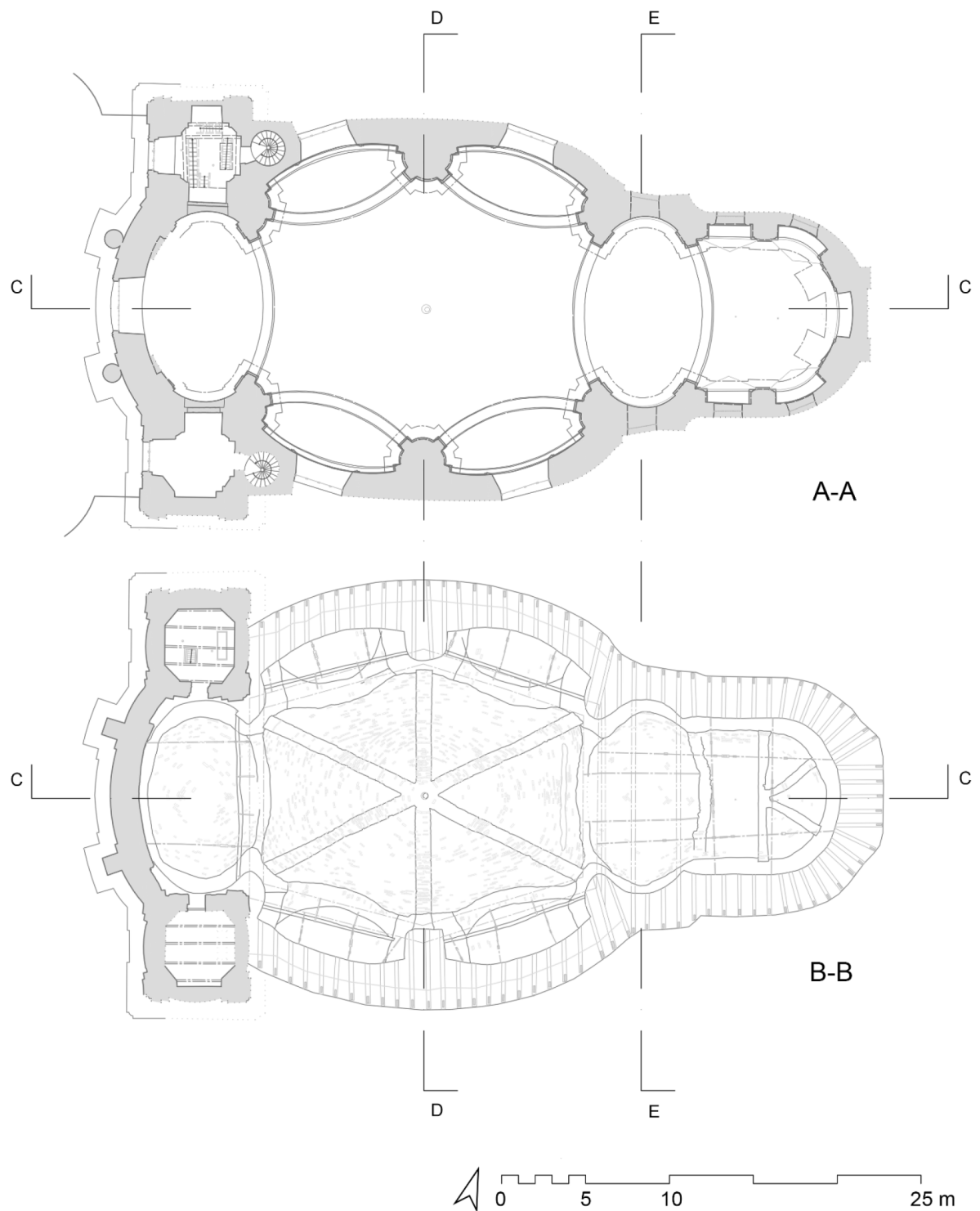


Fig. 04: Horizontal sections of the vault: intrados (A–A, view from below) and extrados (B–B, view from top)

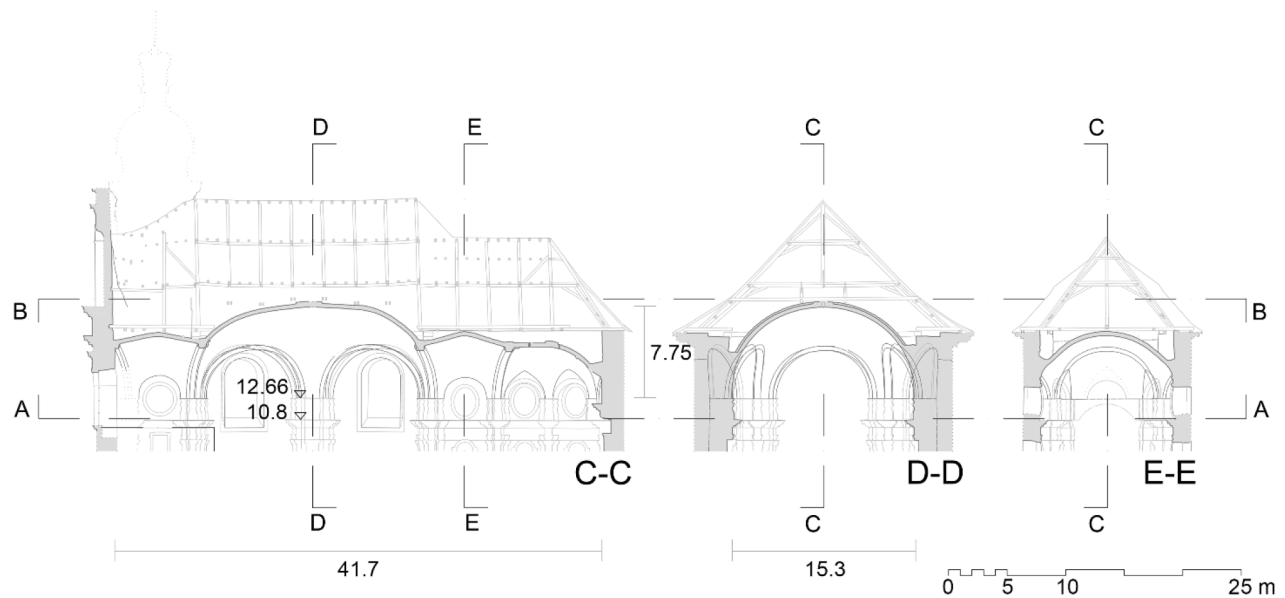


Fig. 05: Longitudinal section (C–C), cross section through main vault (D–D) and choir vault (E–E)

The main vault

The main vault, measuring 19.3 x 15.3 metres, covers the nave. The canopy-like vault rests on six wall pillars and is framed by six double-curved arches. As a result of the removal of the mortar covering of the main vault's extrados (presumably during a structural restoration), the header bond pattern of the brick masonry is clearly visible (Fig. 06). The brick courses in the vault are arranged in continuous circumferential courses that adapt to the concave shape, up to a point of about 60° inclination (measured from the springing). From there, in the upper part of the shell, the masonry pattern is adjusted to forming perfectly circular ring courses (Fig. 07). Six ribs on the extrados run radially from the six corners to the peak where they meet. These ribs, which are interlocked with the rest of the masonry and also follow its ring courses, are about 88 centimetres wide and protrude 15 centimetres, or half a brick high, from the surface of the vault. The ribs are bricked alternately in stretcher and header bond courses. At the apex of the vault is a circular opening 30 centimetres in diameter, closed off from above and below (and incorporated into the Asam fresco as a church clock). A patch of mortar in the eastern part of the main vault suggests that a bricked-in wooden beam was removed here, possibly during the repair measure.



Fig. 06: The extrados of the main vault, north-east corner

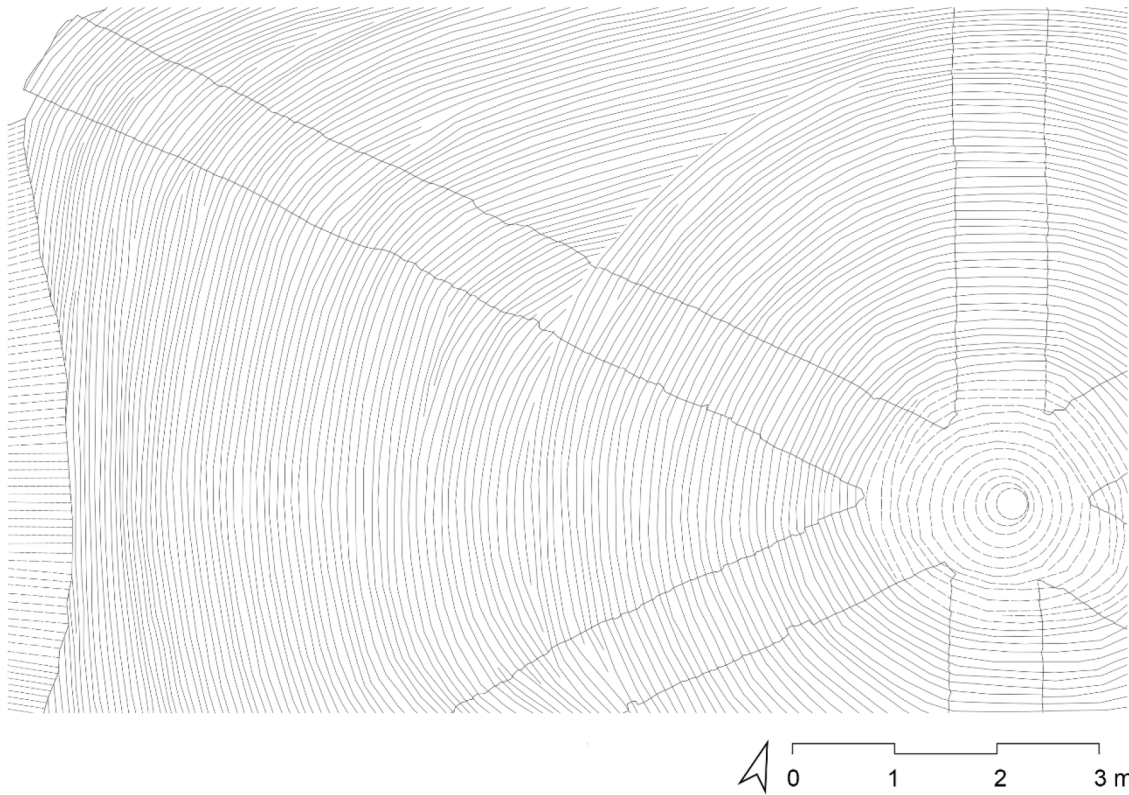


Fig. 07: Horizontal section of the vault (extrados detail): brick courses

To understand the geometric definition of the vault shape and to get clues about the centering, it is necessary to analyse the plane sections and projections of the scan where geometric features can be encountered. The horizontal projection of the main vault (Fig. 08 a) shows the vault edges based on the adjacent double-curved arches. The corners of the hexagonal shape are 27.5° from the transverse line. The cross-section at the widest point (Fig. 08 b) shows a relatively large deviation of 10 centimetres as opposed to a perfect semicircle. The longitudinal section (Fig. 08 c) shows a small deviation (< 2 centimetres) from the circular arcs in the lower area. The upper portion is best described by two lines that rise slightly towards the apex. The transition from arc to line occurs at 60° inclination. Similarly, a diagonal section through the vault (Fig. 08 d) shows almost perfect circular sections up to 60° and lines rising above. Based on circular arcs in the lower part and rising lines in the upper part (Fig. 08 e), the vault can be modelled with a loft command (a surface is spanned between defined curves, Fig. 08 f). This model has a maximum deviation of 10 centimetres for a span of 21.7 metres (Fig. 08 g).

One can imagine the construction process as follows: wooden centering in the shape of circular arcs was placed on these diagonal, longitudinal and transverse lines and the vault was built up to 60° , with the extrados ribs above the centering. The upper part of the vault was vaulted using simple planks that spanned from the centering to a central post. This area was built with a much shallower angle and circular courses.

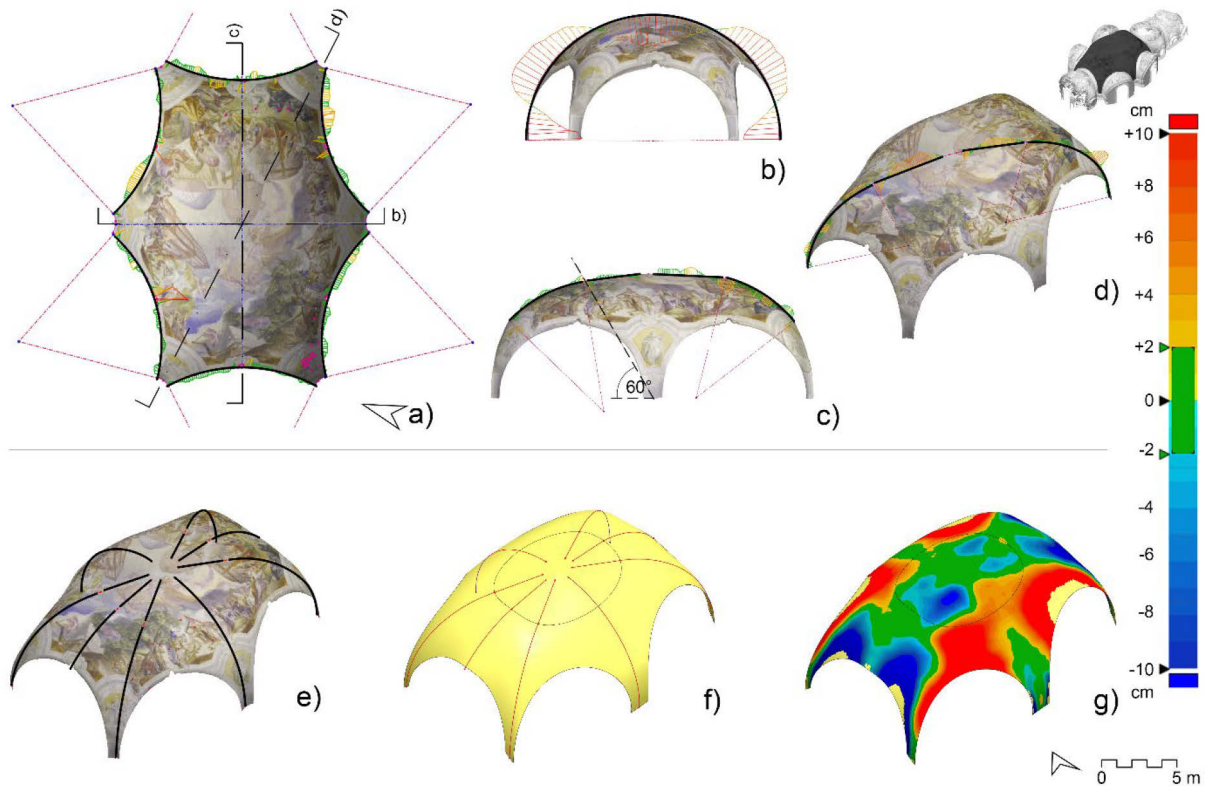


Fig. 08: Geometric design of the main vault: a)–d) horizontal, transverse, longitudinal and diagonal projections; e) curves defining the geometry; f)–g) modelled vault surface and its deviation from the measured surface. The deviation from the measured points is shown in a colour scale.

The vaults with an oval projection

Along the longitudinal axis in the east and west, two vault areas with an oval projection adjoin the main vault. These vaults, above the organ gallery and between the main and choir vault, both measure approximately 11.35 x 7.1 metres. Circular windows cut into the vault in the lower, vertical wall area. Their extrados surfaces are covered with mortar, but the header bond pattern of the bricks is visible at a few places. The bricks are laid in rounded courses with a dovetail seam along the longitudinal axis of the building (the transverse axis of the oval vaults).

The vault between the main and choir vaults shows its oval shape in the horizontal projection (Fig. 09 a). The four ideal circle segments with two different radii that form the oval show a maximum

deviation of 6 centimetres from the measured data. The longitudinal projection (Fig. 09 b) shows curves closely resembling circular arcs for the apex of the vault (maximum deviation 4 cm), only the area around the window openings deviates. The transverse projection (Fig. 09 c) shows that the ridge curve can be described by rising straight lines towards the peak. The vault is delimited by the two double-curved arches on the long side and the two incising window openings on the narrow side, which also follow a double curvature (Fig. 09 d). These arches, together with the arc and the lines of the apex, define the geometry of the vault (Fig. 09 e).

During the construction process, a centering in the shape of a semicircle was probably used for the apex of the vault in the longitudinal direction and simple boards were used in the transverse direction, which were attached to this wooden arch.

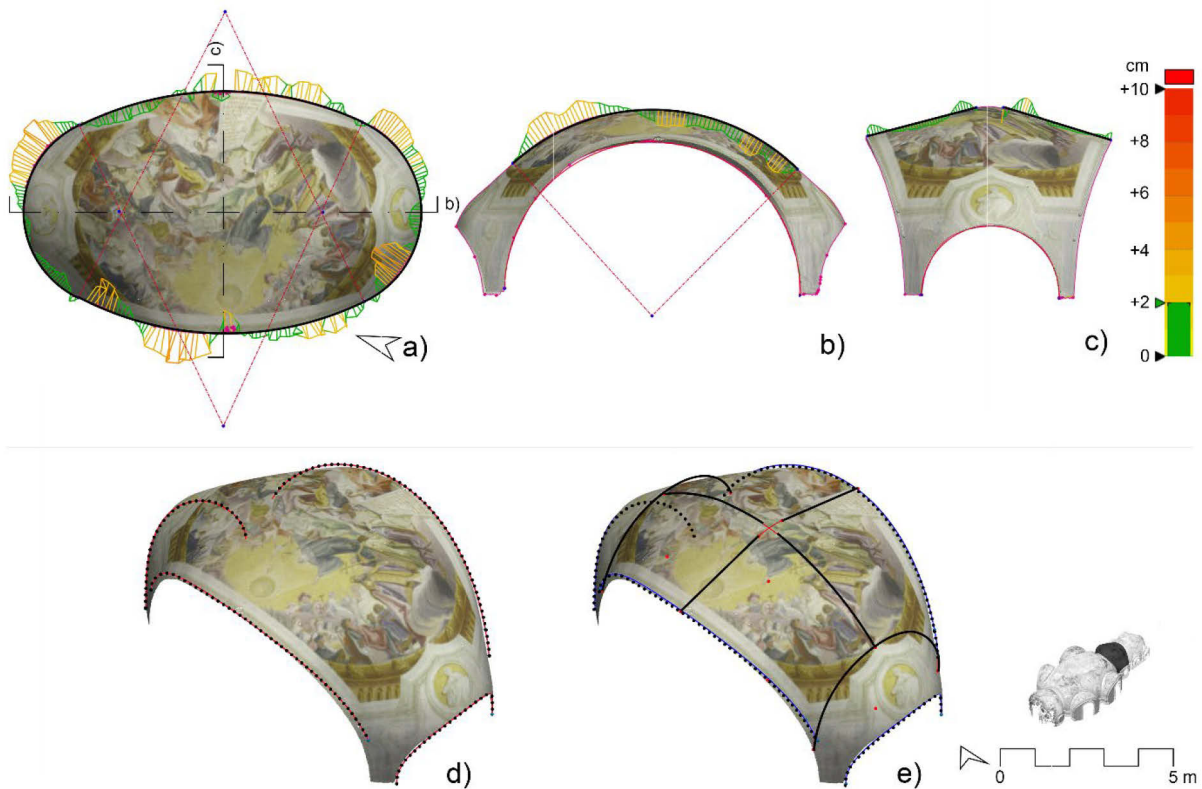


Fig. 09: Geometric design of the vault between main and choir vaults: a)–c) horizontal, transverse and longitudinal projections; d) double curves (dotted lines) defining the edges; e) apex curves defining the geometry. The deviation from the measured points is shown in a colour scale.

The choir vault

The vault above the choir, approx. 7.40 x 9.30 metres, consists of a barrel-shaped area that merges into the flat rounded end of the apse. Five lunettes intersect the vault surface above the circular windows and the niche of the high altar, their edge is highlighted with stucco. At the extrados, the header bond of the bricks and their continuous, seamless ring courses are visible underneath the mortar. The rounded, almost quarter-spherical, part of the choir vault has four extrados ribs, which match the ribs of the main vault but are more irregularly bricked and taper towards the peak (40–60 centimetres width). Two of these ribs, merging at the apex, are placed across the vault where the barrel-shaped section merges into the rounded section. Two others are placed in such a way that they divide the rounding into three equal parts. The geometry of the choir vault is defined by circular arcs for longitudinal- and cross- sections.

The double-curved arches

Seven arches, curved in their horizontal as well as their vertical projections, divide the different regions of the vault from each other. Three of them, with a span of 8.13–8.25 metres, are located in the longitudinal axis of the building, while four arches with a slightly smaller span of 7.91–8.01 metres are located along the outer walls of the central hexagon. All that can be seen of their extrados is that their bricks are laid mostly with a header bond transverse to their direction of span. All the double-curved arches are attached to wooden beams with two iron bands about 5 centimetres wide (Fig. 10). One end of the iron bands is bricked in, the other one nailed to the beam. The double-curved arches are suspended against their bending towards the edge of the vault. The iron bands of the two arches adjacent to the intermediate vault are connected, but this connection seems to have been changed during the repair works.



Fig. 10: Two iron bands attaching the double-curved arch above the organ gallery to a wooden beam.

The double-curved arches of St. Hedwig (in this example, the one next to the choir vault) follow very closely simple circular arcs in their horizontal (Fig. 11 a, maximum deviation less than 2 centimetres) and vertical (Fig. 11 b, maximum deviation 4 centimetres) projections. The particular shape of the arches is defined geometrically by the spatial curves describing their edges. These spatial curves can be modelled by extruding the planar curves from the respective projection plane horizontally and vertically (Fig. 11 c, d), and intersecting the resulting cylinder surfaces (Fig. 11 e). The surface of the arch can be modelled by spanning a surface between the two edges with a loft command (Fig. 11 f). The deviation between the modelled and measured surfaces is about 8 centimetres, indicating a sagging apex (Fig. 11 g).

The iron bands attaching the arches to wooden beams were used during construction to prevent the double-curved arches from tilting inward before the main vault, keeping them in place, had been erected.

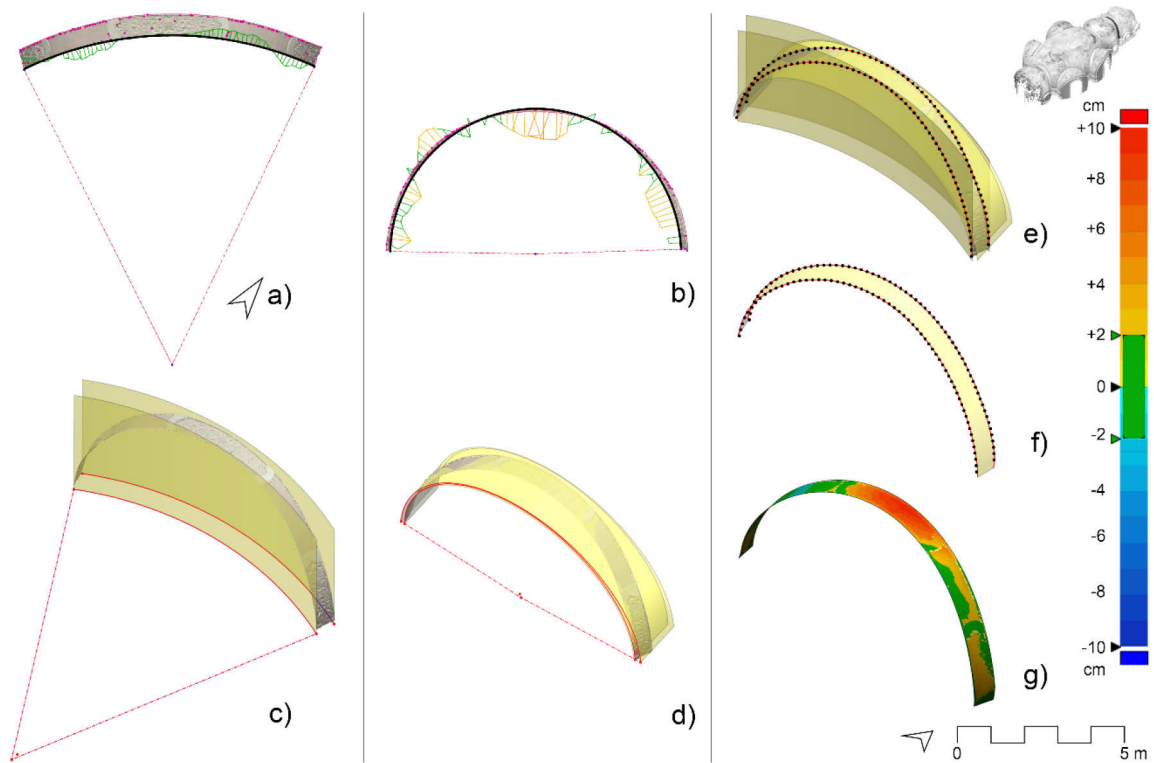


Fig. 11: Geometric design of the double-curved arch (next to the choir vault): a)–b) horizontal and vertical projections; c)–d) surfaces extruded from plane curves; e) intersection curves (dotted lines) of surfaces; f)–g) modelled surface between the intersection curves and its deviation from the measured arch. The deviation from the measured points is shown in a colour scale.

The lunette vaults

The four lunette vaults are defined by the curves of the double-curved arches and the outer wall to which they adjoin. They correspond to rounded barrel vaults with a slightly raised apex. Although their extrados is mostly covered with mortar, it can be seen that they were built with a header bond in courses parallel to their short side, which merge into the courses of the double-curved arches.

Similar to the double-curved arches, the lunette vaults (in this example the south-eastern one) follow circular arcs in their horizontal and vertical projections (Fig. 12 a–b, maximum deviation 5 centimetres). Their shape can be recreated by extruding these circular arcs (Fig. 12 c–d),

intersecting the resulting surfaces (Fig. 12 e) and creating a loft surface between the intersection curves (Fig. 12 f; because of the raised apex area, an additional arc with the same radius but 14 centimeters higher position in between the two curves is required for modelling). The resulting deviation between modelled and measured surfaces is about 4 centimetres (Fig. 12 g).

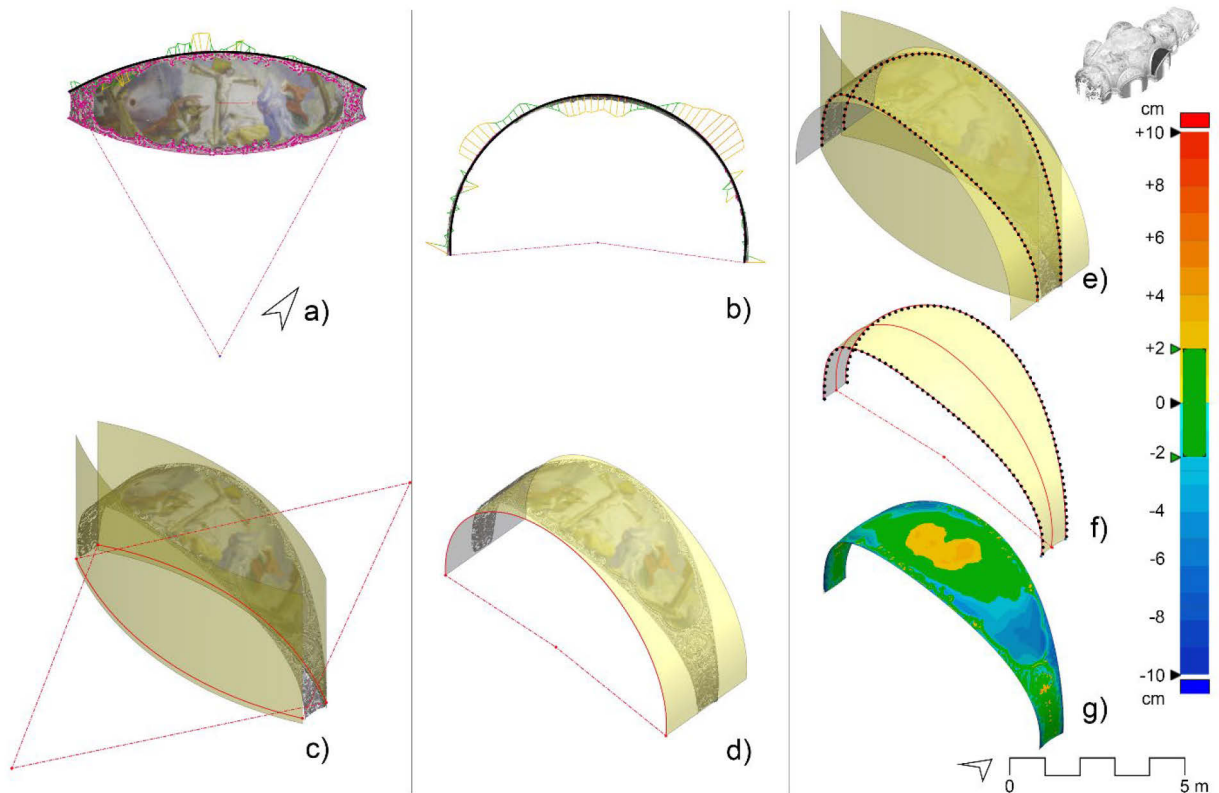


Fig. 12: Geometric design of the (south-eastern) lunette vault: a)–b) horizontal and vertical projections; c)–d) surfaces extruded from plane curves; e) intersection curves (dotted lines) of surfaces; f)–g) modelled surface between the intersection curves and its deviation from the measured arch. The deviation from the measured points is shown in a colour scale.

Theoretical and historical context

The results concerning geometric design of St. Hedwig must be considered in their theoretical and historical context. Looking at the geometry of the vault, the frequent use of double-curved arches is striking. Spatially curved forms were a common feature in Early Modern treatises on architecture

Authors' manuscript, originally published in: Construction History Society (ed.): Timber and Building Construction. The Proceedings of the Ninth Annual Conference of the Construction History Society. Cambridge: Construction History Society, 2022, pp. 143-155.

and stereotomy [16], such as the practical *Le premier tome de l'architecture* by Philibert de l'Orme, (1567) [17], but also the more theoretical *Architettura Civile* by Guarino Guarini (1737) [18]. These spatial curves were also part of a common practice in building crafts, a standard task dating back to Late Gothic design practices and traditions that had not yet died out in Bohemia [19]. Kilian Ignaz Dientzenhofer probably made his design for St. Hedwig under these various influences.

Not only double-curved arches, but also oval shapes in general, were an essential part of the designs of other members of the Dientzenhofer family and of the architects and builders in their professional circle. Johann Dientzenhofer's Banz Abbey Church (1710–18), for example, has a design based on circle and oval arcs for its general shape, but also for its double-curved arches [20]. The same applies to several buildings by Balthasar Neumann, who was in close contact with Johann, for example the pilgrimage church Vierzehnheiligen (1742–72) with its design of oval arcs or the Residence Church in Würzburg (1732–43), with oval and circle arcs [21]. The recourse to these forms, the frequent use of double-curved arches, and construction details such as the extrados ribs all indicate a common knowledge base about geometry and construction in the Dientzenhofer environment. While Kilian Ignaz's designs are generally somewhat simplified, more often using for example circular arcs instead of oval arcs, they are clearly an advance on the concepts already established by this group. This is also in line with the general research opinion that sees Kilian Ignaz's churches as further developments of Guarinesque spatial concepts [22], and as simplifications of the designs of his father Christoph [23].

Conclusion

Kilian Ignaz Dientzenhofer's St. Hedwig's is remarkable not only for its extraordinary architecture and art, but also for the elegant geometric design and well-thought-out construction details of its brick vault. The three-dimensional design of the vault is based entirely on simple planar circle arcs arranged to form elaborate double-curved arches and complex-looking vault surfaces. Uncomplicated two-dimensional shapes are used to maximum effect to create refined forms with simple geometric definition. The laser scanning-based analysis of form and the observation of construction details provide insight into the vault construction process, such as the use of

Authors' manuscript, originally published in: Construction History Society (ed.): Timber and Building Construction. The Proceedings of the Ninth Annual Conference of the Construction History Society. Cambridge: Construction History Society, 2022, pp. 143-155.

straightforward centering based on circular arches and simple planks. Compared to other Dientzenhofer designs, the double-curved arches are not only based on a reduced geometric design of circular arcs, but also have added construction details such as the iron bands, suggesting an intensive examination of possible weaknesses in the traditional design. As a result, St. Hedwig's can be considered not only part of a significant group of sacred architectural works, but possibly even as an improvement in the areas of geometry and construction.

Acknowledgements

This paper is part of the author's doctoral research project, "Vault Architecture of the Dientzenhofer Family and their Professional Circle in the Context of Applied Geometry and Stereotomy", which is underway at the DFG Research Training Group 1913 at Brandenburg University of Technology under supervision by David Wendland.

I wish to acknowledge the kind support of the officials of the church of the Holy Cross and St. Hedwig, who enabled my survey in Legnickie Pole during a week in October 2021: Rev. Dr. Stanisław Szupieńko, Conservator of Monuments of the Bishop's Curia of Legnica, and Rev. Włodzimierz Gucwa, priest of St. Hedwig. I also thank Teresa Lipczyńska for assisting me before, during and after the survey.

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Authors' manuscript, originally published in: Construction History Society (ed.): Timber and Building Construction. The Proceedings of the Ninth Annual Conference of the Construction History Society. Cambridge: Construction History Society, 2022, pp. 143-155.

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