Cell Vaults – Research on Construction and Design Principles of a Unique Late-Mediaeval Vault Typology

David Wendland
Technische Universität Dresden, Germany

ABSTRACT: The design and construction principles of a special type of late-gothic vaults are analyzed. The approach of the research is the connection of detailed geometrical analyses of the vault shape and masonry texture, and experiments on models and in full scale. In first place, a critical revision of the current description in the technical literature of the 19th and 20th century is carried out, which is confronted with the archaeological evidence in a survey.
The necessity of a critical analysis of the historical technical literature is underlined, and an approach is presented which combines the geometrical analysis of 3-D-data from the survey with experimental archaeology. For the analysis of constructions with complex geometry, a method is shown using reverse geometric engineering and selective data acquisition on site by means of current measuring equipment.

EXPLORING AN INNOVATION IN LATE GOTHIC VAULTING

The so-called "Zellengewölbe" (a term which is usually translated as "cell vaults" or "diamond vaults") are a particular type of late-Gothic vaults which appears for the first time in the 15th century, in the Albrechtsburg at Meissen (Germany). Subsequently, this type of vault became popular throughout Saxony and extended to Bohemia, Silesia, Poland and Prussia. These vaults in most cases have no ribs, but sharp groins, and are characterized by re-entrant groins in the webs, creating a folded surface (Fig. 1). The construction material is current serial masonry units, usually bricks.
While the historical and geographical development is well-known, about the motivation for the creation of this new type of vaulted ceilings we can only guess. Aesthetic reasons have been seen in the relation to some motives in contemporary sculpture (Meuche 1958); moreover, we assume a significant benefit for the acoustic quality. And the assumption of technical reasons appears to be plausible: The idea that this innovation could be essentially connected to the construction principles of the contemporary late-Gothic vaults, as consequence of the free-handed construction of the vault masonry, has been formulated by Ungewitter (1859) and shared by most scholars (e.g. Meuche 1958). However, there are no historical sources on the construction

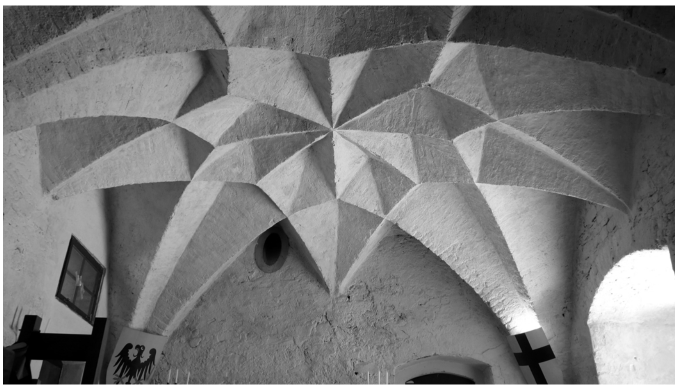

Figure 1: Example of a "cell vault" at Trebsen (Germany), early 16th century.

Figure 2: Experimental reconstruction of a cell vault at Trebsen, 2005. The centering of the re-entrant groins is subject to discussion, as it is conflicts with the preliminary analysis (Förderverein für Handwerk und Denkmalpflege e.V. – Schloss Trebsen).

process that could support this hypothesis. Moreover, no detailed analyses of the shape geometry, the construction details and the masonry texture of such vaults are available that could provide a reliable basis for any hypothesis on the construction process. The same is true for the design principles of these vaults: while the patterns in plan appear to be related to the patterns of contemporary rib vaults, for a closer view on the geometrical definition of the arches, no surveys are available.

According to the general belief that the typology and shape of cell vaults are essentially determined by the building process, it has been attempted to reproduce them in practical experiments (Fig. 2). In particular, such efforts have taken place in seminars on restoration and historical craftsmanship at Trebsen (Germany), where also some original cell vaults are at hand for direct comparison. On the background of these trials in full scale, and of our previous research on vaults built without formwork (Wendland 2007, 2008), a research project has been conceived with the approach of combining further experiments and modelling with detailed analyses of the shape and the masonry textures of cell vaults, aiming to determine the construction principles and also to clarify the design schemes of such vaults. In the following, some preliminary studies for this project will be outlined, starting with a critical review of the existing descriptions of the construction principles of cell vaults.

CELL VAULTS IN THE TECHNICAL LITERATURE OF THE 19TH AND 20TH CENTURY

According to common belief, cell vaults have been constructed free-handed, supporting the groins with centering arches (Meuche 1958); about whether such support was used also along the re-entrant groins, there are different opinions.

Descriptions of the construction principles of cell vaults can be found in the technical literature from the 19th and early 20th century. Due to the lack of sources on the construction process, these descriptions are founded in first place on the archaeological evidence, i.e. the interpretation of the shape and the masonry pattern. But for the most part, they are derived from the description models of the elementary vault typologies, namely that of the cross-vault. This is explicitly the case in Ungewitter's description of cell vaults, which has been determinant for the technical literature on the subject and further developed and adopted by later authors.

Ungewitter's description of the construction principles of cell vaults

In his Lehrbuch der gothischen Constructionen (1859-64), Ungewitter describes the construction of cell vaults in close relation to the development of Gothic vaulting in general and to the most common types of vaults. For a detailed critical analysis of the chapters on vault construction and their position in the development of the technical literature, we may refer to our previous studies (Wendland 2008). In short, starting from the fundamental distinction between "Roman" and "Gothic vaulting which he adopts from previous authors, Ungewitter conceives the Gothic vault as essentially determined in it shape and detailing by the construction process (an approach emblematic for the Neo-Gothic movement), emphasizing the tracing of the arches with vertical circle segments, which greatly simplifies the centering device, and the free-handed construction of the vault masonry between the arches and groins, which had been described by J.C. v. Lassaulx to whom Ungewitter refers. On this background, he develops geometric models of the masonry texture which are very detailed and rather complicated (possibly inspired by the classical treatises on stereotomy), but using geometric tools which turn out to be inappropriate for the purpose, with schematisms even causing contradictions to the basic approach.

Ungewitter's model of the constructive and geometrical features of the cross-vault is well-known as it has been adopted by the entire technical literature on the topic. Its basic assumptions are that the courses (which run continuously across the diagonal arches and are sewn along the ridge lines of the caps) are inscribed in planes, and that the spatial position of these planes is radial, i.e. always normal to the intersecting diagonal arch. Because of the angle between the successive bed-joint planes, the problem arises that along the courses the distance from one bed to the next is not constant and therefore the height of the same course varies, which is in obvious contrast to the principles of masonry. While this problem is usually ignored throughout the technical literature, it is recognized by Ungewitter himself (who even proposes an alternative model with parallel masonry courses which is inconsistent due to a geometrical error). In any case, the masonry texture of such vaults is to be described basically with courses in parallel planes, as we could show (Wendland 2007, 2008).

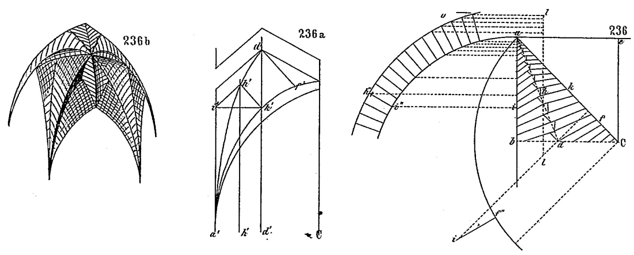

Figure 3: Masonry pattern in cell vaults and the geometric construction of the single courses, according to Ungewitter (1859).

On the base of his model of cross-vaults with radial bed joint planes, Ungewitter develops his description of cell vaults, which he believes to be an organic development caused by the transfer of the construction principles of cross vaults to more complex figures of groins, together with the attempt of rationalizing the building process. As principal improvement he points out the reduced need of cutting bricks to a required angle: at the groins the courses are intersecting orthogonally, and also in the re-entrant groins they need only to be cut ad hoc to length. Hence, Ungewitter traces the radial beds on the groin arch (Fig. 3, right; the position of the outer curve is arbitrary), and performs the construction of the courses assuming them to be symmetrical at the groins: As the angle is 90°, that between the plane of the groin and the course on every side is supposed to be 45°. With help of the auxiliary outer parallel circle segment, the direction of the courses can be drawn in plan, and in consequence in the cross-section the construction of single points along the re-entrant groin is demonstrated, determining the highest points in the vault surface. Concluding his description, Ungewitter once more points out the problem of the "angular deviation", caused by the fact that the planes inscribing the courses are radial and not parallel. He assumes this to be the reason why the construction of cell vaults was abandoned after a certain period in favour of net-vaults with rather small surfaces between the ribs which could be easily built free-handed and where the problem of varying course heights was irrelevant.

The development of geometrically determined descriptions of the shape and masonry texture of cell vaults

A much more detailed description, based on the survey of a cell-vault in Kraków, was published in a short essay by Gustav Bizanz in 1888. This was adopted by many later authors (e.g. Mohrmann in Ungewitter/Mohrmann 1890; Opderbecke 1910; Thunnissen 1950), as being complementary to the description developed by Ungewitter.
This description, in fact, exactly follows the terms of Ungewitter's. Bizanz clarifies that, according to the basic assumptions, the surface of the vault can be described as being composed of sections of cones (the curve of every groin is the directrix of two congruent cones with a common horizontal axis), and the curves of the re-entrant groins can be geometrically constructed as their intersection curves, while the courses correspond to the generating lines of the cones that determine the vault surface (Fig. 4). In the vault described by Bizanz, nearly all re-entrant groins in their projection in plan describe straight lines. The construction also allows to determine the heights of the summits of the vault, which however during construction would result by themselves,

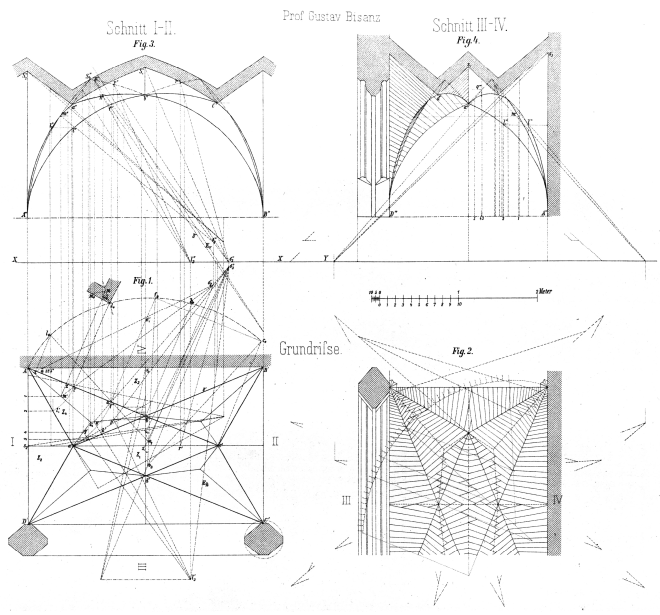

Figure 4: Geometrical construction of the masonry texture and the vault shape of a cell vault by Bizanz (1888), by means of conical surfaces and their intersection.

because only the groins are supported by centering arches.
The development of the technical description of cell vaults is exactly analogous to that of cross vaults: As Ungewitter's description of the masonry fabric and the boundary conditions in simple geometrical patterns could be easily interpreted by the later authors in terms of Euclidean solids, a geometrical model of the vault surface and construction of the curves conceived as intersecting ideal surfaces prevailed in the technical literature. In the case of "Gothic" cross-vaults, the surfaces of the domed caps are conceived as being spherical, but here this concept is inconsistent, not justified by the design and construction process and, above all, not at all corresponding to reality (Wendland 2007, 2008). This, and the problematic assumption of radial bed joint planes, raises serious doubts on the validity of this model for cell vaults.
Another major problem is the lack of foundation on detailed surveys – in Bizanz the relationship between the description and the vault he analyzes is not clarified, and since then no new surveys at all have been introduced to the technical literature. In particular, there is no evidence whether the curves of the re-entrant groins and the shape of the vault surface altogether correspond to the reality. On the other hand, the known modern studies carried out on cell vaults (cf. Radova and Rada 2001) did not seek to assess these descriptions. And finally, in no case the descriptions contained in the technical literature have been connected to the documentation of the construction of such a vault, i.e. the resumed construction process put into practise. Hence, to clarify the situation it is necessary on one hand to analyze in detail the shape and masonry fabric of cell vaults, and on the other hand to carry out experimental reconstructions thoroughly connected with both the surveys and the assumptions on the construction principles. As a matter of fact, the evidence on existing cell vaults, and the preliminary studies taken out so far, raise further doubts on the current technical descriptions, as we shall see in the following.

PRELIMINARY OBSERVATIONS ON THE CONSTRUCTION PRINCIPLES OF CELL VAULTS: A CASE-STUDY

Some steps towards confronting the existing conceptions with the archaeological evidence and clarifying the design and construction principles of cell vaults have been taken in the preliminary analysis of a vault at Trebsen (Germany), where the masonry texture is visible on the intrados (Fig. 5). With the aim of determining the geometric definition of the vault and drawing possible conclusions on the construction process, a survey was carried out along with simulations on small scale models, as well as the planning of experimental reconstructions in full scale and the interpretation of previous trials (Fig. 2). The vault, built in the 16th century, covers a rectangular room; the normal bays are half as long as wide and the figure of the groins is composed of continuous transversal and intersecting parallel diagonal arches. The masonry fabric is carefully executed, although the intrados originally is likely to be plastered, as usual in cell vaults.
In the vault, the edges in the surface (i.e. the groins, formeret arches and re-entrant groins) were analyzed, as well as the curves of single courses in selected portions of the vault masonry. The analysis was performed with a specialized software tool for reverse geometric engineering on the base of point clouds obtained by selective acquisition of measuring points on the vault.
Already the geometrical features of the surface and its edges can clarify essential aspects of the design and reveal traces of the construction process. First of all, the curves of the groins describe circle segments, within a small range of tolerance (Fig. 6). Among the formeret arches and all the groins, several different radii can be encountered, but the radii of analogous groins or arches are for the most part uniform, as also the level of the intersections. This, of course, well matches to the known principles of Gothic vault design, where the arches are determined a priori as simple curves, instead of describing complex intersecting curves of ideal surfaces. Beyond that, it excludes the possibility (as sometimes suggested) that a cylindrical formwork could have been built. We can surely conclude that the groins were supported by vertical centering arches drawn as circle segment, and suppose that an effective position control of the intersection points was provided.
As regards the curves described by the re-entrant groins, the situation is much more complex (Fig. 11): while some of the transversal ridges could be interpreted as tilted circle segments admitting a high tolerance level (which would not make much sense if centerings were used), most of these curves cannot be reduced to clear geometrical features. It can be recognized that changes in the direction of these curves often occur at

Figure 5: The analyzed cell vault at Trebsen (Germany).

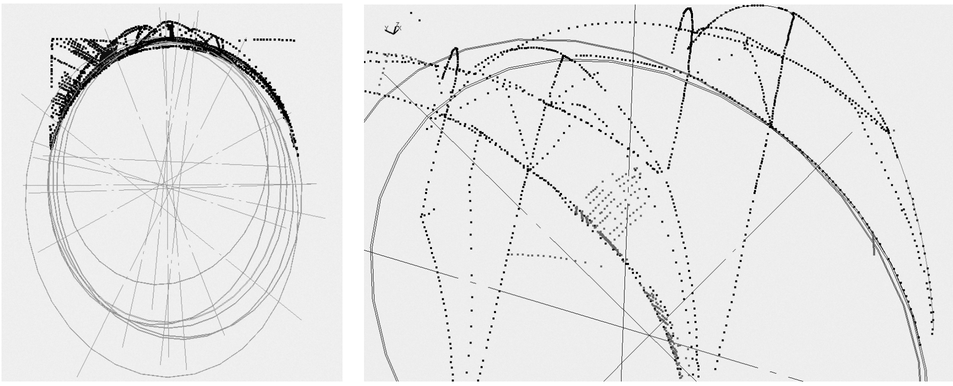

Figure 6: Geometrical analysis of the measuring data of the vault. Left, transversal elevation with radii and tolerance range of the groins. Right, detail showing the radii of subsequent portions of a diagonal groin.

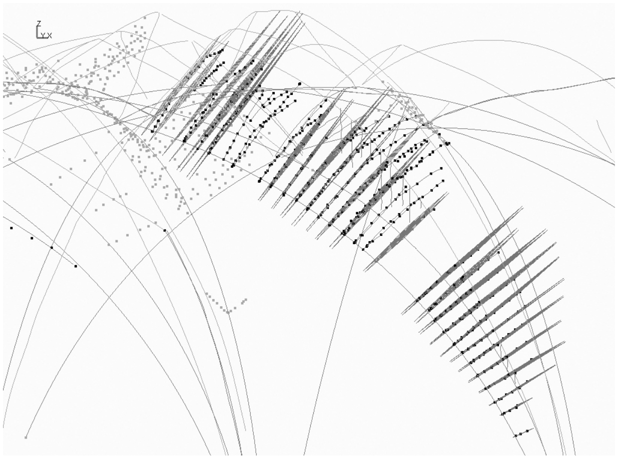

Figure 7: in some places, the position of the bed joint planes was corrected towards a radial inclination, by interrupting the continuous masonry fabric inserting bricks cut ad hoc. This is because in principle the bed joint planes are parallel, as it becomes visible also in the measuring data.
Figure 8: points along the visible bed joints in the vault, and inscribing planes, showing that the bed-joint.

the courses which have their origin in a discontinuity of the groins, i.e. an intersection point (Fig. 5, left). All this makes it likely that these curves resulted ad hoc from the intersection of the courses built starting from the groins, and were neither supported by centering nor guided by any form control. This confirms the opinion of Ungewitter and Bizanz that the vault surface was built free-handed, supporting only the groins and formeret arches with centering. But at least in this case it contradicts the idea of intersecting conical surfaces (cf. Fig. 4).
Further information on the construction principles and the building process can be obtained analyzing the geometric properties of the courses in the vault masonry. The courses in many cases are straight instead of describing arches (as usual in vaults built free-handed), but in no case they are sagging downwards, which would indicate the use of formwork. Beyond that, some typical features of free-handed vaulting could be encountered. As far as the spatial position of the bed-joint planes could be determined in the analyzed portions of the masonry texture, these planes are principally parallel, as it is the typical case (Fig. 8), instead of being radial, as supposed by Ungewitter. But in some places corrections in the direction of the courses are visible, by inserting wedge-shaped bricks cut ad hoc (Fig. 7). The problem which was overcome here apparently was caused by the divergence of the radial direction and the direction of the courses according to the parallel planes; in the groins the bricks had to be laid in radial direction in order to enable the continuity of the course on both sides of the groin, but then a curvature resulted in the course that would have caused an overhanging of every new course, making it instable during construction. Parallel bed-joint planes in the masonry texture and such corrections in the direction of the courses are typical for vaults built without formwork (Wendland 2007, 2008).
Of particular interest is the relation of the spatial position of the courses and the planes inscribing them to the groins, as this is a core issue in the description models discussed above. According to the survey, systematically the courses are not symmetrical to the plane of the groin, i.e. the angle is not 45° and even varies throughout the development of the same groin. Also deviations from the principally perpendicular intersection at the groins are possible, although they rarely occur. While in the lower parts the bed-joint planes are perpendicular to the groins, in the upper portion they are sometimes not perpendicular at all (Fig. 9). As it appears, the direction and spatial position of the courses is in first place determined by the edges of the vault surface, i.e. the formeret arches, instead of the angle they come to meet the groins, and, beyond that, by the continuity of the vault surface and masonry texture. This is especially the case in the groins of the central portion where the deviation of the 45°-angle cannot be explained by the boundary condition of the formerets, but by the continuity of the surface, and the deviation of the perpendicular position respect to the groin plane is definitely due

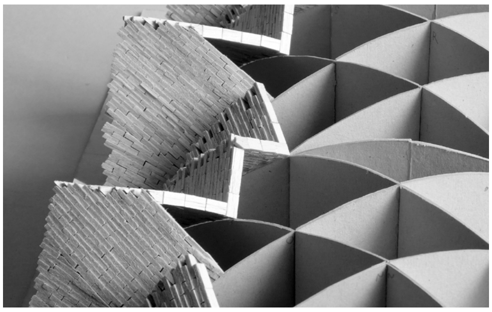

Figure 9: Here the position of the planes of the courses is not perpendicular to the groin, but tilted to it, in contrast to the current description. This is due to the continuity of the masonry fabric from below;
Figure 10: The building of the portion at the lateral intersection in a model simulation.

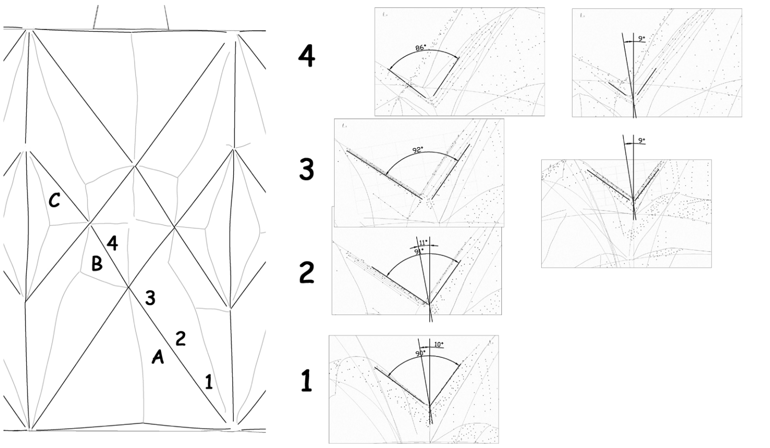

Figure 11: Left, plan of the vault, showing the groins and the negative edges (survey). Note the geometric complexity of the curves of the re-entrant groins, in contrast to Bizanz's description (Fig. 4). Right, analysis showing the angle in the groin normal to the course and of the angle between the bisector and the plane of the groin. While in the cases shown here, the groins are approximately perpendicular, the angle to the plane of the groin arch systematically differs from 45°, contradicting Ungewitter and Bizanz.

to the demand of a continuous masonry texture. In these terms, we can also interpret a peculiarity in the surface flow along the formeret arches, where an undulating movement can be observed, as the vault surfaces sometimes "detaches" from the curve of the arch and shortly above has been forced back to it. This can be explained by the fact that the masonry surface tended to proceed in direction normal to the bed-joint planes, much steeper than the pre-determined curve of the formeret. We could show that this and especially the undulating surface flow are typical features of vaults built without formwork (Wendland 2007, 2008).
Respect to the construction principles formulated in the current description models as developed by Ungewitter and Bizanz, we must conclude that the assumed rule of perpendicular courses is a "soft" rule which can be put aside if necessary, but the postulation of symmetric courses at the groin is definitely not according to the practical reality. Also, the spatial position of the courses in the description model is different from the evidence: the courses are principally inscribed in planes that are parallel instead of radial, and can even intersect the groins in an angle different from perpendicular. Instead of the geometric rules supposed in the description model, we can state that "continuity" is an essential rule in cell vaults, such as in general in half-stone vaults built without formwork. Finally, and in consequence to this, the concept of the vault surface being composed of conical surfaces, or any elementary Euclidean surfaces in general, must be rejected. This is clear from the geometrical character of the curves described by the re-entrant groins, which are clearly not corresponding to the supposed intersection curves constructed by Bizanz, neither to their appearance in his drawing. Therefore, it will be necessary to define which could be more valid construction principles for cell vaults. In this place, only these first ideas could be sketched, leaving the task to future research within the proposed project.

SOME REMARKS ON THE TRACING OF THE ARCHES IN THE CONTEXT OF GOTHIC VAULT DESIGN

As already pointed out, the definition of the groin arches in the analyzed vault well corresponds to the approach to vault design common to Gothic architecture, defining the arches as principal feature as elementary curves. However, it remains to be clarified in which aspects the design schemes of late-Gothic rib vault were also used in the cell vaults. The geometrical description of the arches is crucial for the shape of the vault, and especially the design schemes are generally believed to be strongly influenced by the demands for the production of the stone ribs. In particular, the aim to define all the arches in a vault by one uniform radius, which is well known from sources in the German-speaking area – the so-called "Prinzipalbogen" –, is often associated with the possibility of prefabrication of the rib elements, which is obviously irrelevant in cell vaults.

Figure 12: In the spandrels of some cell vaults at Trebsen (left, center), the transversal arches "immerge" in the vault surface, which indicates the application of design schemes regarding the geometric definition of the arches similar to those in late-Gothic rib vaults in the German-speaking area. The solution for a spandrel in the Albrechtsburg at Meissen (right) is definitely not determined by technical considerations, but by the application of late-Gothic design rules.

One premise to approach this topic is the creation of a database on the geometric description of the arches in cell vaults – the existing studies focused on the figure in the plan, not analyzing the tracing of the arches. The other problem is that also regarding the actual geometry of comparable rib vaults, such information is still lacking; for instance, the implementation of the "Prinzipalbogen" method could be verified only in very few examples (e.g. Tomlow 2001), in some analyzed net vault it is definitely not applied (cf. Nußbaum and Lepsky 1999, p. 180).
From the existing studies of cell vaults, it is clear that the figures in plan fully correspond to the developments in the contemporary rib vaults (Meuche 1958). Regarding the tracing of the arches, from visual evidence there are some indices for the use of the known late-Gothic design rules. These are, for instance, the springing of the arches at different levels, or the phenomenon of transversal arches "immerging" into the lower portions of the vault surface (Fig. 12). This can be explained by the fact that the transversal arch is much shorter than the diagonal arches and still reaches the common summit level of the vault, and by the choice of a radius of the arch which is not determined by a projective procedure, but a priori, presumably with the "Prinzipalbogen" or a related design scheme.

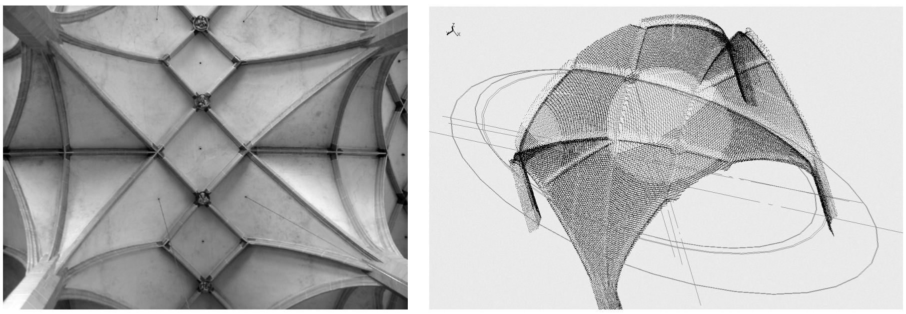

Figure 13: St. Peter's in Bautzen (Germany), vault of the central nave. The geometrical analysis reveals that the vault was not designed with uniform radii, and that the choice of a different radius for one portion of the diagonal arch is comparable with the tracing of the arches in the cell vault at Trebsen (arch B in Fig. 11).

More detailed assertions can be made only in geometrical analyses of cell vaults based on measurements. In the case of the analyzed vault at Trebsen, the diagonal length of the bay in plan seems to play an important role in the definition of the radii. This is according to the variant of the "Prinzipalbogen" method as described by Ranisch (1695) – a post-Gothic source which is in some aspects divergent from the other known sources, while in our case of extreme interest as it partly refers to cell vaults. On the other hand, it turned out that the radii throughout the vault are not at all uniform; in particular, they even differ within the single portions of the diagonal arch. According to the analysis of the measuring data, the radius of the middle portion is systematically different from the other two (Fig. 11, arches A,B,C). The question is therefore, whether the design scheme with uniform radii has been put aside because no ribs had to be produced, or whether such decisions would by possible also within the design schemes actually used by the architects (supposing that these were far more differentiated than the few known sources on the matter), and therefore could occur the same in a rib vault.
For an initial working hypothesis this was verified on the vault of one bay in the parish church of Bautzen (Germany), with data obtained with a 3-D laser scanner. This late-gothic vault roughly fits in the geographical and chronological context of that in Trebsen, and although the figure of the ribs is different of that of the groins in

Trebsen, there is the common problem of a diagonal arch divided in three parts, where the application of a uniform radius could lead to geometrical problems (Fig. 13). In fact, the radii of the ribs are not uniform, and especially the radius of the second portion of the diagonal arch is different from that of the first and third one – not according to the known design schemes, and similar to the cell vault we analyzed. This detail makes it clear that for describing the design principles of cell vaults in the context of contemporary vault design, also further research on those principles as implicated in rib vaults must be carried out, based on detailed surveys. Hence, the current knowledge on the principles of Gothic vault design will have to be critically revised.

CONCLUSIONS

In the case of cell vaults, the understanding of the design and construction principles and the building process is of particular interest, in order to interpret the motivation of the appearance of this type of vault and its popularity in a rather large geographic range, as well as for the apprehension of their shape. A better knowledge is also required for their conservation. The preliminary study could confirm the general opinion that these vaults were built free-handed, supporting only the groins and formeret arches by centering. But it also puts in evidence that the current description of the construction principles in detail, as formulated in the 19th century, has to be for the most part refuted. Instead, some indications can be given on the base of new studies on half-stone vaults built without formwork. Further, the studies carried out so far reveal a clear relationship between the procedures of geometric design of cell vaults and that of contemporary rib vaults, although these design rules often are associated with the production conditions of the stone ribs that rarely occur in cell vaults. The studies regarding the design principles of cell vaults therefore must be oriented also to a better understanding of the design rules as they were actually implemented in practise.
In general, the study shows how the detailed analysis of geometrical features both in the vault shape and the masonry textures can reveal the traces of the design and production process, providing knowledge that is missing in the sources and cannot be provided by conventional research methodology, and is apt to strongly enhance the possibilities of experimental archaeology. Finally, the potential of the used methodology in the analysis of constructions with complex geometry is demonstrated, by means of reverse geometric engineering and based on selective data acquisition with current measuring equipment, alternative to 3-D-scanning.

REFERENCES

Bizanz, G., 1888: Studie über ein Zellengewölbe. *Allgemeine Bauzeitung* 53, pp. 30-31.
Bürger, S., 2007: *Figurierte Gewölbe zwischen Saale und Neiße – Spätgotische Wölbkunst von 1400 bis 1600*. Weimar: VDG.
Clasen, K.H., 1958: *Deutsche Gewölbe der Spätgotik*. Berlin: Henschelverlag.
Klein, B.; Wendland, D., 2008: Form, Konstruktions- und Entwurfsprinzipien von spätgotischen Zellengewölben – "reverse engineering" und experimentelle Archäologie. Project application for the DFG. TU Dresden.
Lassaulx, J.C.v., 1847: Gewölbeformen. In: *Bausteine*, Koblenz, pp. 1-8.
Meuche, H., 1958: *Das Zellengewölbe: Wesen, Entstehung und Verbreitung einer spätmittelalterlichen Wölbweise*. Dissertation, Greifswald.
Müller, W., 1973: Zum Problem des technologischen Stilvergleichs im deutschen Gewölbebau der Spätgotik. *Architectura*, pp. 1-12.
Müller, W., 1990: *Grundlagen gotischer Bautechnik*. München: Deutscher Kunstverlag.
Nußbaum, N.; Lepsky, S., 1999: *Das gotische Gewölbe: Eine Geschichte seiner Form und Konstruktion*. Darmstadt: Wissenschaftliche Buchgesellschaft.
Opderbecke, A., 1910: *Der Maurer*. Leipzig: Voigt.
Radová, M.; Rada, O., 2001: *Das Buch von den Zellengewölben*. Prag: Jalna.
Ranisch, B., 1695: *Beschreibung aller Kirchengebäude der Stadt Dantzig*. Danzig: Stolle.
Thunnissen, H.J.W., 1950: *Gewelven: Hun constructie en toepassing in de historische en hedendaagse bouwkunst.* Amsterdam: Ahrend.
Tomlow, J., 2001: Neue Erkenntnisse zur Baugeschichte des Kreuzgangs: Entwurf und Ausführung eines mittelgroßen spätgotischen Gewölbes. In: *Alpirsbach: zur Geschichte von Kloster und Stadt*. Stuttgart: Landesdenkmalamt Baden-Württemberg, Theiss Verl., pp. 427-448.
Ungewitter, G.G., 1859-1864: *Lehrbuch der gothischen Constructionen*. Leipzig: Weigel.
Ungewitter, G.G.; Mohrmann, K., 1890: *Lehrbuch der gothischen Constructionen* (rev. ed.). Leipzig: Weigel.
Wendland, D., 2007: Traditional vault construction without formwork: Masonry pattern and vault shape in the historical technical literature and in experimental studies. *International Journal of Architectural Heritage* 1 (4), pp. 311-365.
Wendland, D., 2008: *Lassaulx und der Gewölbebau mit selbsttragenden Mauerschichten. Neumittelalterliche Architektur um 1825-1848*. Petersberg: Imhof.

ACKNOWLEDGEMENT

The presented study has been carried out in preparation of the research project application "Form, Konstruktions- und Entwurfsprinzipien von spätgotischen Zellengewölben – 'reverse engineering' und experimentelle Archäologie", presented by Prof. Dr. Bruno Klein, in collaboration with the *Förderverein für Handwerk und Denkmalpflege e.V. – Schloss Trebsen*. The author wishes to thank Prof. Klein, Mr. Bielefeld, Mr. Gasch and Mr. Bubnick for their support and advices. Figs. 1, 5 - 13 are by the author.