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Research on "cell vaults": analytic and experimental studies on the technology of late-gothic vault construction

Badania „sklepień komórkowych": analityczne i eksperymentalne badania konstrukcji późnogotyckich sklepień

Keywords: Vault Construction, Historical Construction Technique, Survey, Experimental Archaeology, Shape Modelling, Teaching Historical Construction Technique

Słowa kluczowe: konstrukcja sklepień, historyczna technika konstrukcyjna, ekspertyza, archeologia eksperymentalna, modelowanie kształtu, uczenie historycznej techniki konstrukcyjnej

1. INTRODUCTION

In the decades around 1500, builders and patrons all over Europe felt a particularly fascination for the design and construction of vaulted ceilings, searching for ever more challenging, daring, complex and original solutions. In England, the complex rib vaults are developed to fan vaults and further to pendant fan vaults, such as in the Henry VII Chapel in Westminster Abbey. On the continent, the vaults with hanging keystones and "air ribs" first introduced by Peter Parler in St. Vitus Cathedral in Prague became popular. Rib vaults appear with ribs describing double curvature like looping ribbons. These are just some of the many inventions in vaulting of that period.

In this atmosphere, around 1470 the "Cell Vaults" according to common belief were invented first for the construction of the Albrechtsburg, the new palace of the princes of Saxony at Meissen (Germany) [1-3]. These vaults that sometimes have stone ribs but in many cases only sharp groins, are characterized by their folded surface with ridges between the groins (Figure 1), creating ceilings with subtle patterns of light and shadow. The construction material (apart from few exceptions) is brick masonry. Their design basically corresponds to that of late Gothic net vaults, but the pattern of their groins and arches is often much more complex than that in conventional rib vaults. "Cell Vaults" rapidly became popular first in Saxony and then spread all over central-eastern Europe, including Bohemia, Poland, the Baltic, Prussia, and even beyond. During more or less a century hundreds of them were built in palaces, town houses, convents and churches.

From sources and contemporary records, we learn nothing about how these vaults were built, just as little why they were introduced and why they became so popular in such a vast area. We don't even know how these vaults were called – the names we use are of modern origin. Hence, on the motifs we can only guess, but we tend to suppose that they were manifold. Regarding aesthetic motifs, the folded surfaces show some relationship with contemporary sculpture. Further, this type of vaults certainly has great benefits in the task of designing rather low, wide spanned vaulted ceilings, like in the Albrechtsburg. Technological reasons

Fig. 1. Cell vault in the second floor of the Albrechtsburg at Meissen (Germany). The folded surface of such vaults are built in brick masonry (D. Wendland)

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Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

could regard the acoustic qualities and the assumed structural performance. But most scholars since the 19th century believe that the main motif is related to the construction process, which is supposed to be greatly rationalized in this type of vaults, compared to the conventional rib vaults with domed webbings.

This hypothesis, first formulated by G.G. Ungewitter, is based on the assumption that the "Cell Vaults" due to their particular shape could be built free-handed, i.e. without the support of a formwork under the whole surface during construction, in a very straight-forward way, supporting only the groins by centering arches [4]. Ungewitter also believed that by this innovation, the need of cutting bricks ad hoc to the right shape would have been at least greatly reduced.

However, as pointed out, in the sources there is no information whatsoever about the building process and the design criteria of "cell vaults" – hence no contemporary records can be found that could support this hypothesis. Therefore, it is necessary to search other ways in order to find out how five centuries ago the "cell vaults" were, or might have been, actually built.

2. CONSTRUCTION PRINCIPLES OF LATE GOTHIC "CELL VAULTS"

2.1. Problematic of the current technical description

To understand the building process is also necessary for explaining the peculiar appearance of the "Cell Vaults", in particular the curves of its groins and ridges, and the shape of the vault surface. And it certainly is of central interest if we want to gain understanding on the design, and on the communication process which took place between the patrons, architects and craftsmen. Hence, this technical issue gains importance also for the discussion of these artifacts from the point of view of Art History.

As a matter of fact, all technical descriptions provided in the scientific literature can be drawn back to Ungewitter's hypothesis, hence, have no documental base in the period when the building of "Cell Vaults" was practiced [4]. Moreover, critical revision shows that it is also poorly based on archaeological evidence. Most of the graphical representations in the literature are idealized, especially regarding the curves of the ridges, replacing the actual state with the ideas molded by the reception of the description model founded by Ungewitter. Detailed surveys describing the geometry and the details of these vaults with fidelity are lacking. And even the modern attempts to reproduce these vaults, instead of the archaeological evidence are based on the modern description model – a situation with an enormous risk of circular reasoning.

2.2. The new research approach: Experimental archaeology correlated with detailed surveys and analyses of the archaeological evidence

However, in order to formulate hypotheses on the construction process that is not otherwise documented, its reproduction according to the method of experimental archaeology is the most promising. In the current research on the construction of "cell vaults", experiments were carried out that were closely linked with detailed surveys of original

Fig. 2. "Cell Vault" in Trebsen (Germany), where the curves, surfaces and also the masonry textures could be surveyed and analyzed (D. Wendland)

Fig. 3. Detail of the analyzed vault, showing the geometric complexity of the curve described by the inward fold, and the continuity of the masonry texture; both in contrast to the current description model (D. Wendland)

vaults – in particular one vault where in large portions the masonry texture was visible (Figure 2, 3). The curves, surfaces and single courses in the masonry texture were subject of 3-D-surveys and geometric analyses that were carried out by means of a software tool for Reverse Geometric Engineering. By these analyses the construction process could be characterized, principle statements on the temporary auxiliary structures needed for the building could be made, and construction principles based on the archaeological evidence formulated. The methodology of such analyses has been developed in earlier research by the author [5, 6].

By putting these hypotheses in practice in the experiments carried out in full scale, they could be evaluated and refined, and on the other hand, the practical experiences also lead to further observations on the object.

2.3. Analyzing the construction principles of "Cell Vaults"

From the geometric features of the curves, surface form and masonry texture, it is possible to learn about the building process and the principle features of the centering system. First of all, the geometry of the groins shows that during construction these must have been supported by single centering arches, not by a continuous formwork. Their curves can be described in simple geometric terms, in contrast to the shape

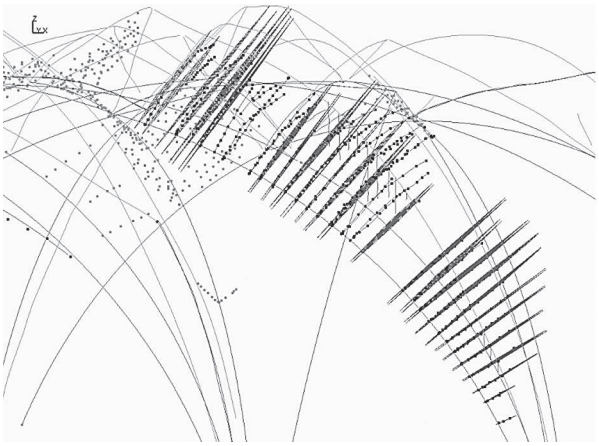

Fig. 4. Geometrical analysis of the masonry texture in the vault: the single courses are inscribed in tilted planes that over great portions are parallel, as usual in free-handed vaulting (D. Wendland)

of the vault surfaces. All arches describe circle segments in vertical planes with discontinuities at the intersection points, which also gives some indication on the whole system of centering arches. Such layout of the arches is common also in the contemporary rib vaults, and it corresponds to what we know about the geometric design of late Gothic vaults [4, 5, 7-8].

The ridges or inward folded groins, in contrast, describe curves with a complex geometry: the three-dimensional curves show variations in the direction and radius of curvature, and also abrupt changes of direction. From this we can conclude that they were not guided by centering, but resulted spontaneously in the process of the construction of the vault surfaces, which therefore must have taken place free-handed.

The analysis of the masonry texture proves that the analyzed vault was actually built free-handed. This is on one hand clear from the spatial position of the masonry courses, which, over great portions, are inscribed in tilted planes which are parallel (Figure 4) – a typical feature of the masonry texture of vaults built without formwork [5, 6]. Of particular interest are some corrections in the direction of the courses that can be observed (Figure 5): they were carried out where curvature had occurred in the beds that compromised the stability of the fresh course. By inserting bricks cut ad hoc in the shape of wedges, once more tilted plane courses were achieved that allowed to continue the building of the vault surfaces without support also above that point.

While all this confirms Ungewitter's basic hypothesis on the free-handed execution of "Cell Vaults", it is important to point out the fundamental differences that emerge between the analyzed vault and the description model formulated by Ungewitter and generally adopted in the following [4]. First of all, the masonry texture in principle consists of parallel instead of radial courses. Then, the vault surfaces don't correspond to the geometrically defined surfaces supposed by Ungewitter, but must be described as free form surfaces. Consequently, the ridges or inward folded groins differ from the smooth intersection curves of regular surfaces (Figure 6). And finally, the masonry texture in these folds is fundamentally different from Ungewitter's description, as, in spite of what in modern terms we would claim to be a regular bond pattern, usually the courses run continuously across them (Figures 3, 8).

Therefore, the rules for the masonry texture used by the builders of the "Cell Vaults" (and in late Gothic vault masonry in general) must be revised. As fundamental motif we must consider the continuity of the surfaces flow from the springing to the summit and the continuity in the masonry texture. The practical side of this could be clarified in the experiments.

2.4. Experimental reconstruction of late Gothic "Cell Vaults"

The experiments were carried out in collaboration with an academy of historical craftsmanship, reproducing two vaults in full scale with bricks and mortar according to the original. The used bricks have the same large format as the original, and are produced in the traditional manner – their porosity is of benefit for free-handed vaulting, and they can be easily cut to shape with an axe. The mortar has been reproduced according to the analysis of the original mortar.

In these experiments, the hypotheses on the construction principles as developed from the surveys turned out to be practicable, confirming the observations made above. The geometric problems in the masonry texture due to the curvature of the vault surface, have occurred in the experiments in the same manner as observed in the analyzed vault. Modern masons due to their training tend to turn the bed joint planes to a radial

Fig. 5. Corrections in the direction of the courses carried out ad hoc by cutting bricks, indicate that the vault was constructed without formwork D. Wendland)

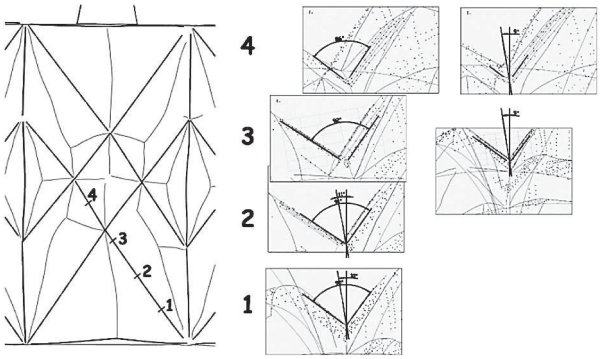

Fig. 6. Left, plan of the vault, showing the groins (black) and the negative edges (grey) in their geometric complexity (survey). Right, analysis showing the angle in the groin normal to the course and of the angle between the bisector and the plane of the groin. While in the cases shown here, the groins are approximately perpendicular, the angle to the plane of the groin arch systematically differs from 45°, contradicting the current description model (D. Wendland)

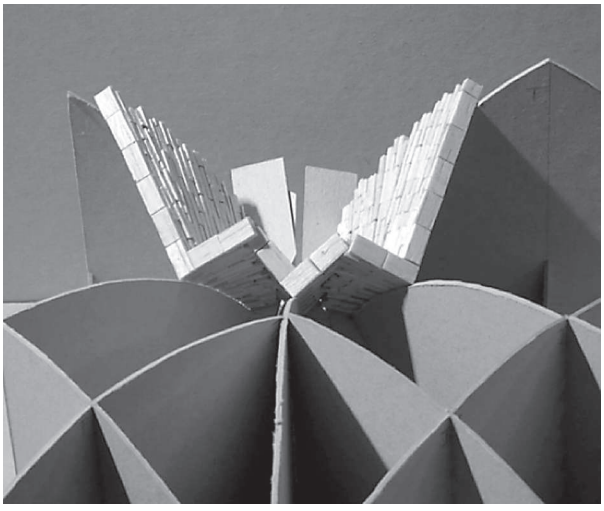

Fig. 7. Model simulation, showing that the angle of the courses at the groin (V-shaped connection in front) is not determined a priori, but depends on the development of the curves of the formeret arches (in the back) (D. Wendland)

Fig. 8. The exposed masonry texture of the analyzed vaults shows the continuity of the courses over large portions, across the discontinuities of the vault surfaces (cf. also Figure 3). This is not conform with modern masonry rules and contradicts the current descriptions models, but in the experiments turned out to be very practical (D. Wendland)

Fig. 9. Due to the continuity of the masonry texture, the courses are not arranged perpendicular to all groins, as usually assumed. Such observations lead us to understand the construction principles and rules applied by late Gothic masons (D. Wendland)

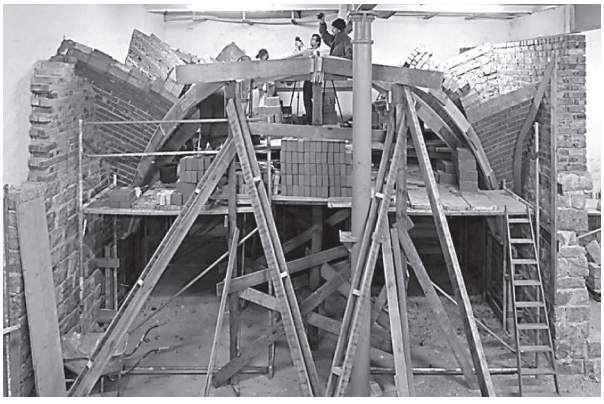

Fig. 10. Experimental reconstruction of the analyzed late Gothic "cell vault" (Figure 2), where the hypotheses on the construction principles and building process could be verified and refined (A. Gosch)

position by augmenting the mortar joints in the portions more distant from the groin. This attempt, however, turned out to be insufficient, apart from not occurring in the original where the thickness of the mortar joint is constant. Consequently, the same "hanging" courses resulted as in the analyzed masonry texture, requiring corrections ad hoc in the direction of the courses.

Also the continuity of the masonry texture over large portions, which we could observed and which we believe to be a principle of late Gothic vault masonry, was even surprisingly easy to reproduce in practice, just by slightly bending the beds and in sometimes cutting the corners of the bricks. The axe

Fig. 11, 12. Details of the experimental reconstruction. The vault masonry is executed without formwork on single centering arches supporting the groins. The thickness of the shell is according to the archaeological evidence. The peculiar masonry texture with the continuity of the courses over the inward folds, as observed on the original vault, turned out to be practical (D. Wendland)

to cut bricks is needed very often in the process (once more contradicting Ungewitter's theory), but the traditional bricks are easily cut as they are rather soft and not brittle.

The main difficulty for everybody was to put apart the modern rules of bond pattern. These rules, although considered "historical" or "traditional", have been formulated only in the course of the 19th century and are not relevant for earlier historical periods. As already pointed out, from the archaeological evidence the construction principles which were used by the masons of the late Gothic vaults could be characterized, and in the experiments could be demonstrated to be very practical in execution. In reality, these principles also make a lot of sense, as with the continuous texture a very good coherence throughout the masonry is obtained. This can be illustrated by the fact that "cell vaults" built in the 19th century with modern criteria often show cracks that almost never occur in the original late Gothic vaults. In conclusion, we can now describe the difference between late Gothic and modern construction rules, and we are capable to reproduce late Gothic vault masonry with high fidelity.

2.5. Some conclusions regarding the building organization and the general design principles in late Gothic vaulting

Finally, the practical experience also gives way to statements regarding the building process on the whole and its organization, which are relevant not only for the construction of "Cell Vaults", but for late Gothic vault construction in general.

First of all, this regards the centering device. Except from very few fragments, no centering of late Gothic rib vaults or

"Cell Vaults" is preserved. However, a principle characterization of the temporary support construction that served also for the geometric control of these complex structures could be obtained by correlating the geometric analysis of the surveyed vault (and also survey data from rib vaults), with a source describing the construction of rib vaults in the 16th century [8] and information contained in the building accounts [9]. These considerations were also evaluated and further developed in the experiments, leading to a hypothesis about how the centering devices of late Gothic vaults must have looked like (Figure 15).

Another consideration relevant for late Gothic vault constructions in general regards the organization of the building process. As a matter of fact, it would not have been possible to build the analyzed "Cell Vault" by construction one bay after the other because, as pointed out, the masonry texture is continuous over the whole squinch. Therefore, starting from the springer, single portions must be have been built up contiguously reaching from one formeret arch to the next, which reached out into the two neighboring bays. Above the summits of the formerets, the whole vault masonry must then be built up together (this may be achieved by a small group of masons moving around). Such building procedure "springer by springer" instead of "bay by bay" must have been common to the vault constructions in the succession of Peter Parler's vault designs, hence, in most of the late Gothic vaults in the German speaking area. In fact, already the vault of the High Choir in St. Vitus Cathedral could be brought up only "springer by springer" until the summits of the formerets, and then in continuity over the full length. Current research is expected to bring more clarity on the design principles of these challenging constructions.

3. CONCLUSIONS

In the presented study, a methodology of analyzing historical construction is proposed, which enables to formulate statements on construction processes and design criteria in historical structures that lack documentation. This may be relevant in conservation or restoration by providing better knowledge of complex structures, as well as in basic research on construction history. The approach combines 3-D-surveying with geometric analysis on one hand, and experimental archaeology on the other hand.

Regarding the "Cell Vaults", which represent a peculiar, yet wide spread type of late Gotic vault construction, in any case emblematic for the complexity of vaulted ceilings from that period, the construction procedure could be clarified. The hypotheses developed upon detailed analyses from the archaeological evidence are verified in practice in the full scale experiments that were carried out. Further, information on the geometric features and on the construction details is provided in a new quality. This is a necessary precondition for the conservation of these structures.

The improved knowledge of the construction principles and details illuminates the original construction principles of late Gothic vault construction, which until now have been perceived through the optics of modern interpretation as established in the 19th century. Finally, through the collaboration with an academy of historical craftsmanship, this knowledge is disseminated to the technicians and craftsmen operating in the practice of restoration.

Fig. 13. Also in the higher portions the continuity over the whole squinch can easily maintained. Over the transversal cap, the courses are seamed (D. Wendland)

Fig. 14. At the intersection points in the groins, the direction of the masonry courses change. Never-theless, the continuity of the texture is maintained (D. Wendland)

Fig. 15. Reconstruction of the centering used for building late Gothic "Cell Vaults", developed from surveys in correlation with sources and the experience of the experimental reconstruction (D. Wendland)

ACKNOWLEDGEMENTS

The research on "Cell Vaults" has been carried out within the research project "Form, Konstruktions – und Entwurfsprinzipien von spätgotischen Zellengewölben – 'reverse engineering' und experimentelle Archäologie", B. Klein, D. Wendland, Technische Universität Dresden (Germany), funded by the Deutsche Forschungsgemeinschaft since 2009. The experiments on the construction of "Cell Vaults" are carried out in collaboration with the academy of historical craftsmanship and monumental conservation – Förderverein Handwerk und Denkmalpflege Rittergut Trebsen, Trebsen (Germany) – and are funded by the Saxon castles administration – Staatsbetrieb Schlösser, Burgen und Gärten Sachsen. The current research on the design of late Gothic vaults is

carried out within the research project "Design Principles in Late-Gothic Vault Construction – A New Approach Based on Surveys, Reverse Geometric Engineering and Reinterpretation of the Sources", D. Wendland, awarded with the ERC Starting Grant and funded by the European Research Council in the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 284373. The author wishes to thank C. Mai, scientific collaborator in the research, as well as Prof. B. Klein, U. Bielefeld, H.-A. Gasch, B. Bubnick for their support and advices, and Director C. Striefler, A. Thieme, S. Schellenberger and D. Welich (SGB) for making the experiments possible.

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Abstract

The so-called "Cell Vaults", also called "Diamond Vaults", are a particular type of late Gothic vaults, which appeared for the first time in Saxony and became common in central and eastern Europe during the late 15th and 16th century. They can be found in such prominent buildings as the Albrechtsburg palace in Meissen (Germany) or St. Mary's church at Gdánsk (Poland).

The reason for the invention and the popularity of these vaults is usually seen in the building process, which is believed to have been an improvement respect to usual Gothic rib vaults. However, this hypothesis is difficult to prove, because there is no information about the building process in the sources. In any case, the understanding of the building process and the construction principles is a core issue for explaining the peculiar shape of these vaults.

In the current research, attempts are made to formulate new, well-founded hypotheses on the building process and a better understanding of their construction and design principles. This is done by correlating detailed surveys and geometric analyses of vaults, comprising the curves, surfaces and especially the masonry texture, with experiments on the construction procedure and principles, which are carried out in full scale using realistic materials.

Hence, one focus is the methodology, discussing possible ways to determine the design and construction principles from the existing building, searching "traces" of its making. The other is exploring the particular late mediaeval masonry technique, essentially different from the modern, in practice.

Streszczenie

„Sklepienia komórkowe", znane również jako „sklepienia kryształowe", są szczególnym typem późnogotyckich sklepień, który pojawił się po raz pierwszy w Saksonii, a u schyłku XV i w XVI wieku został rozpowszechniony także w Europie centralnej i wschodniej. Sklepienia te występują w tak ważnych budynkach jak pałac Albrechtsburg w Miśni (Niemcy) czy kościół mariacki w Gdańsku (Polska).

Przyczyną wynalezienia i rozpropagowania tych sklepień jest proces budowlany, znacznie ulepszony w stosunku do zwykłych gotyckich sklepień żebrowych. Jednakże trudno tą hipotezę udowodnić, gdyż brakuje informacji źródłowych dotyczących procesu konstrukcyjnego. W każdym razie, zrozumienie procesu budowlanego i reguł konstrukcyjnych jest podstawą niezbędną do wyjaśnienia niezwykłego kształtu tych sklepień.

W opisanych tu badaniach podjęto próby sformułowania nowych, dobrze uzasadnionych hipotez na temat procesu budowlanego tych sklepień, oraz lepszego zrozumienia zasad ich konstrukcji i projektowania. Osiągnięto to przez skorelowanie szczegółowych ekspertyz i geometrycznych analiz sklepień, obejmujących krzywe, powierzchnie, a zwłaszcza fakturę elementów murowanych, z eksperymentami dotyczącymi procedur i reguł konstrukcyjnych wykonanymi w pełnej skali z wykorzystaniem pierwotnych materiałów.

Stąd też, z jednej strony zwrócono uwagę na metodologię, rozważono możliwe sposoby zidentyfikowania zasad projektowania i konstrukcji na podstawie istniejącego budynku, poszukiwano "śladów" jego konstruowania. Z drugiej zaś, na zgłębiono tę szczególną technikę murarską z okresu późnego średniowiecza, tak zasadniczo różną od stosowanej obecnie.