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Vaults built without formwork: Comparison of the description of a traditional technique in building manuals with the results of practical observations and experimental studies

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The technique of building half-stone vaults without formwork is at the present not well known, even though this type of vault is dominant in the traditional architecture of central Europe and also very common in the Mediterranean area: standard masonry units (normally bricks in the current format) are placed in a running bond, the resulting thickness of the shell equalling the width of the masonry unit. As we can easily recognize from building manuals, from the available documentation and also from the evidence of the buildings themselves, their construction very commonly occurred free-handed, i.e. without formwork. Nowadays, this technique is known and executed only by very few remaining artisans.

The formulation of a comprehensive technical description of this building technique could help to prevent the loss of this traditional technology, which is to be considered a cultural value. Such a description must allow the reproduction also under the premise that traditional expertise and practical experience may no longer be available.

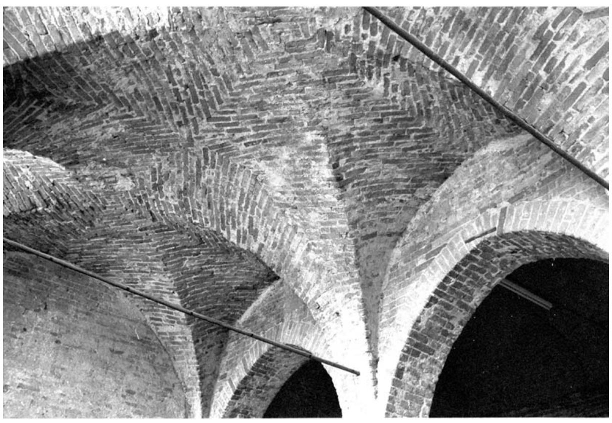


Figure 1. Example of a cross vault with a self supporting masonry apparatus.

As first approach, it appears plausible to develop such a description starting from the great variety of historical technical literature, namely the building manuals published between the end of the 18th and the first decades of the 20th century. Actually these books contain extremely valuable information; however, when attempting to reproduce the technique in practice, serious problems occur which are due to some notorious lacks and even inconsistencies of these descriptions.

Therefore, it has become evident that the acquisition of information from these sources, as in the case of any historical written source, is only possible by a critical review of these texts, evaluating their reliability and practical relevance. For instance, the function and degree of technical involvement of the author can be clarified, and to whom the publication in question is addressed (e.g. masons, architects, or rather commissioners and amateurs). Moreover, the origin of the information referred in the manuals can be searched by retracing the information flow within this class of literature. Not only can many graphs be found to reappear in different publications as copies or variations, but also passages of the texts, sometimes entire chapters, are taken from previous publications, and the reference to their sources appears to be rather the exception than the rule. In the case that a particular publication contains information which is original, not deriving from previous texts, further analysis may clarify whether it is of practical provenience, and therefore has high practical relevance. On the other hand, the fact that a particular statement is repeated in later publications may indicate that it was considered relevant and valuable enough to form part of the "state of the art".

But above all, it has become evident that this information can be used only as part of a comparative study, which includes also available documentation of constructions, analyses of existing buildings, interviews with remaining artisans, and especially experiments on scale models and prototypes.

Questions regarding the geometry of the masonry fabric, namely the spatial arrangement of the beds and the shape of the caps, could be clarified only by such a comparative study. An experimental reproduction of the vaulting technique proved to be necessary, through scale models and a prototype.

The opportunity for the realization of the prototype arose during the winter term 2003/04 within a seminar at the Faculty of Architecture at the Dresden University of Technology. For the students, besides providing a valuable practical experience, this gave the possibility to study in detail a construction typology which is very typical within traditional and historical structures, and demands a lot of manual dexterity and spatial imagination. Together with the previous studies taken out on small scale models, it turned out to be extremely useful for exploring the relationship between the historical technical literature and the practical reality.

As model for the prototype was taken an existing 13th century church vault in the Mecklenburg region (north-eastern Germany), which is a typical example of the gothic cross-rib vaults with strongly domed caps built entirely in brick, including the ribs. It was built in scale 1:4, its dimensions 2.50 by 2.30 m in plan. The construction of the vault masonry was performed with small bricks and lime mortar in the so-called dovetail pattern, supporting only the arches by wooden centering frames.

Figure 2. Experimental construction of a cross vault without formwork, using the so-called dovetail pattern. Prototype realized at the TU Dresden.

Figure 3. Starting the construction of the prototype vault: the centering frames will support the diagonal groins and the formeret and transversal arches

Figure 4. Preparing the bases for the spandrels of the vault prototype.

In the following will be briefly described the construction process as it has been performed on the prototype, as well as the results that have been obtained.

The construction of a cross vault with self-supporting courses in the manuals and on the prototype

The possibility of building half-stone vaults without formwork depends basically on the direction of the courses, hence, their masonry apparatus. The basic principle has been formulated for the first time by the German architect J. C. von Lassaulx, whose essay (1829) had a considerable influence to the development of the topic in the technical literature (Wendland 2003). The principle consists in building the vault with self-supporting courses that are stable by their shape by forming arches. Every new course of the vault's masonry must be held in place by the adhesion of the mortar only until it is closed; once the course is complete, it is stable by having the form of an arch and it offers reliable stability for the units of the next course to be laid on top of it.

In cross vaults, these arch-wise curved courses can be spanned conveniently between the centering frames which must be placed under the arches and groins (or their respective ribs). The curvature of the courses necessary for their stability can be obtained by providing a double curvature to the caps ("domed" caps), by tilting the planes of the bed joints, or both in combination.

The caps can be built up independently without any continuity of the masonry fabric between them, connecting the single caps over the diagonal ribs with a mortar joint. In this way, in every single portion the best curvature is obtained by a modest doming and some tilting of the bed joint planes. Their spatial inclination can be corrected if necessary to optimize course curvature. This has been the common solution in such cases where the groins were provided with stone ribs set on the centering before constructing the caps.

The most frequent masonry apparatus in cross vaults, however, is the dovetail pattern (Figure 5). It consists in arranging the courses on diagonally tilted planes perpendicular to the groins. Hence, the masonry fabric is continuous through the neighbouring caps over the groin, avoiding the joint behind the groin rib. The diagonally tilted courses are seamed in the ridge of every cap. The continuity over the groins is beneficial in those vaults which have no ribs or those where the groin ribs consist of small units within the masonry fabric of the caps.

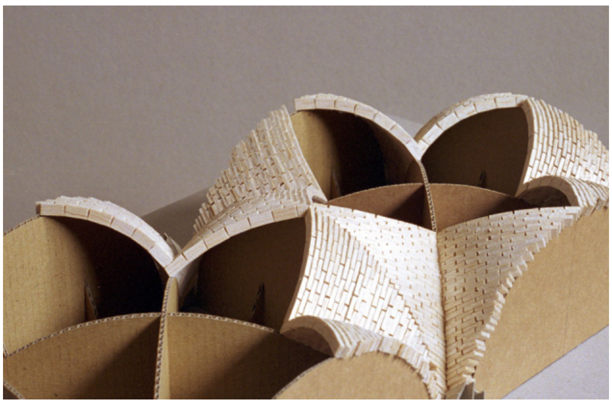


Figure 5. Model of a cross vault built in the dovetail pattern: the courses are stabilized by their curvature, and the masonry fabric is continuous over the diagonal groin.

Figure 6. The same in the prototype: the courses run in continuous planes across the diagonal arch.

The vault masonry is constructed starting from the four spandrels, building the courses across the diagonal arch. The bed joints describe planes which must be gradually tilted to the inside of the vault. It turned out to be very advantageous to create an as much as possible regular masonry apparatus, as this would not only guarantee the stability of the unfinished structure, but also allows an efficient control of the shape.

Figure 7. The beginning of one spandrel. The first courses are horizontal, the following must be tilted inwards.

Figure 8. In this stage, the beds can be easily built tilted in radial direction.

Figure 9. Working on the opposite spandrel.

Figure 10. View of the centering and one spandrel.

Figure 11. The vault masonry is growing towards the center: the position of every course is guided by the diagonal and confining arches.

In principle, the bed joint planes are lying perpendicular to the diagonal arch. According to what is generally stated in the building manuals after the middle of the 19^{th} century, in every quarter of the vault they should be arranged normal to the curve of the diagonal arch, and therefore inclined in radial direction. This description was introduced first by Ungewitter (1859: 104-114) (Figure 12), and, although this author already admits that it could be debatable, generally repeated in the later building manuals (for instance Breymann/Warth 1903, Körner 1901 and Opderbecke 1910). However, such radial inclination leads to an angular deviation between the bed joint planes, as this is visible in Ungewitter's graphic (Figure 12). This is highly problematic, as the local distance of the vault masonry from the turning axis of two subsequent bed joint planes is not constant, calling for a non-uniform height of the courses (Figure 13). Such variations in the height of the courses can be achieved only by increasing the thickness of the mortar joints in some portions of the masonry.

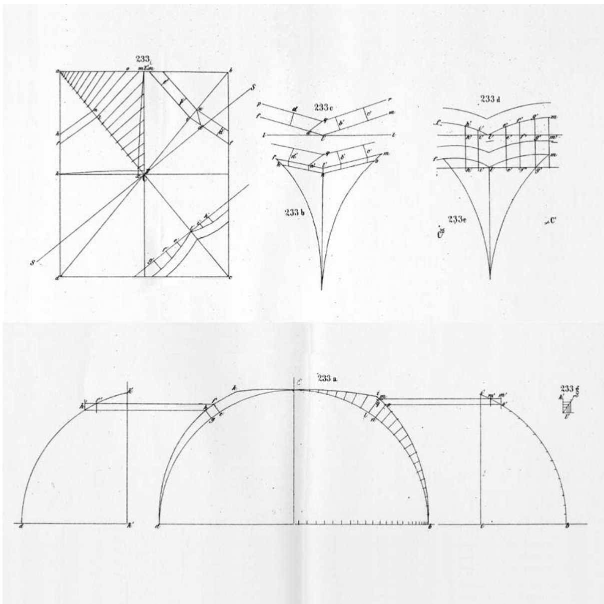


Figure 12. Radial inclination of the bed joint planes according to Ungewitter (1859: detail of pl.8), repeated in many other manuals. Geometric construction of the courses in the vertical projection (above right), normal view of one course and elevation for the spandrel, assuming straight and curved courses (above left), cross-section parallel to the diagonal arch and elevations of the transversal and formeret arches (below).

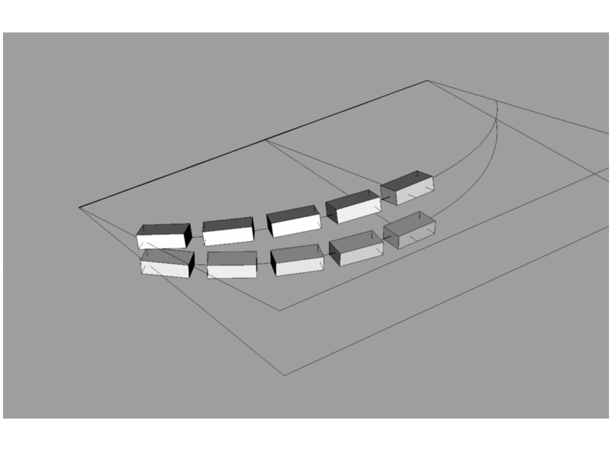
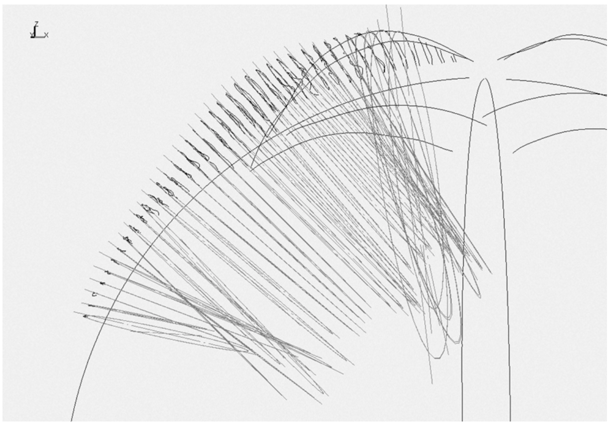


Figure 13. The problem of a varying thickness of the mortar joint caused by the angular deviation of the bed joint planes, as it would occur in their radial inclination.

Figure 14. The analysis of the digital survey of the courses in the prototype, showing the parallel position of the bed joint planes, and the nearly constant radii of curvature throughout the cap.



The construction of the prototype made evident that, contrary to what is stated in the historical technical literature, the bed joint planes must be parallel throughout most of the cap masonry. This arises also from the analysis of the digital survey of the masonry fabric in the prototype (Figure 14), and is confirmed by the survey of existing historical vaults (Wendland 2003; 2004). In practise, the turning of the bed joint planes is feasible only in the lowest part of the spandrels, where the courses are short enough to allow such corrections within the normal variations of the thickness of the mortar joint. But as soon as the courses reach a certain length, no such angular divergence between subsequent bed joint planes is possible. Therefore, throughout the main part of the cap masonry, the bed joint planes will be parallel and their inclination constant (Figure 14). Accordingly, in some portions the units cannot be placed exactly normal to the vault surface, and the courses must be slightly shifted one above the other.

All in all, the procedure is rather straightforward, the courses spanning from one longitudinal or transversal arch to the diagonal arch, until the summits of the longitudinal and vertical arches are reached. From here on, the courses of the neighbouring half-caps are directly connected in the seams which run in the ridge lines of the caps.

There are no precise indications about the radius of curvature of the courses. A strong curvature is beneficial as this stabilizes the courses; accordingly, Hörnig's manual (1836) says that less experienced masons will tend to give more curvature to the courses. However, the limit of the possible curvature is given by the vault geometry and can be precisely established in the portion right above to the summits of the formeret and transversal arches. In this area, the longest courses occur which most deserve stability through curvature, and they must be connected to the neighbouring cap masonry. The limit of possible curvature, i.e. the smallest possible radius, is reached if there is a tangential continuity of the course with the surface of the opposite half of the cap, causing a smooth vault surface at the ridge (Figure 15). Less curvature (greater radius) leads to a re-entrant groin in the ridge of the cap, which is common and formally satisfactory, while a greater curvature (smaller radius) would lead to an inverse discontinuity of the vault surface in the ridge that would appear as projecting to the inside, which is not acceptable at all.

The right choice of the curvature must be made in a much earlier stage, as it is difficult to correct the curvature from one course to the next: Only gradual changes can be performed, first of all because of the obvious necessity of laying one course on top of the other, and also because

Figure 15. The vault masonry above the summit of the formeret arch. In this photograph, the tangent continuity of the course on the left with the opposite cap surfaces is visible by the shadow. A smaller radius of curvature of the course would cause the ridge to project inwards, which would not be acceptable.

any discontinuities in the slope of the vault must be avoided for structural reasons. This calls for a good spatial imagination of the masons.

At the summit of the formeret and transversal arches, the question arises of how the procedure can be defined beyond this point, namely in geometric terms: below, the shape of the cap could be conceived as translation surface with the curves of the two confining arches as track curves. Above, only the diagonal arch remains, and there is no clear rule of how to define the height of the starting points of the courses in the seams, and with that the curve described by the ridge line. The solution of this point is critical for the further building procedure and also the vault geometry, with essential implications for the structural behaviour.

In this fundamental problem, the descriptions in the historical technical literature are not helpful at all. Obviously, the solution was left to the experience passed by oral tradition among the craftsmen. Wherever the manuals offer more or less detailed instructions about how to proceed beyond this point, these are derived from general considerations on the vault geometry, which, as we shall see, are highly questionable.

The caps of vaults built without formwork with self-supporting courses usually present a pronounced double curvature, and in consequence the ridge line is also visibly curved. Therefore, it is obvious that their shape cannot be described by assuming cylindrical surfaces, according to the elementary idea of a cross vault.

Lassaulx (1829) already describes this phenomenon, comparing the extradoses of medieval vaults with that of egg-shells, and therefore rejects the idea of generating the vault surface with straight lines. But he avoids any description in geometrical terms, as his description of the vaulting technique is strictly procedural. Ungewitter assumes the curve of the ridge line to be circular (Figure 12), without motivating this: once more, his description is very detailed but at the same time problematic, as the shape of the curve is not derived from the intersection of the opposite portions of the vault surface, but comes in as imposed geometrical pattern. This assumption is also repeated by many other authors (e.g. Breymann/Warth 1903: 264).

Later publications attempt to describe the shape of the caps by Euclidean geometric primitives, assuming that they are composed of spherical surfaces: for instance, Körner (1901) and once more Warth (Breymann/Warth 1903: 266). This assumption is problematic first because it is not consistent: in fact, as soon as some of the vault's arches are stilted, i.e. the arches don't depart on the same springing level, as this is very often the case, it is not applicable.

But it also doesn't correspond to what can be observed in reality, where the curvature of the vault surfaces is almost always non-uniform: the ridges of pointed cross vaults often present a re-entrant groin in some portions, while they are smooth in other portions, and the curve of the ridge line (Figure 16) usually presents a typical shape with a smooth and continuous, but not uniform curvature, and therefore cannot anyhow result from the intersection of spherical surfaces.

Basically, the shape of the vault surface depends exclusively from the construction process, as it is not guided by any kind of mould. Along the ridge line, no centering is necessary, so that its shape results from the intersection of the opposite portions of the vault surface. Therefore, it appears to be more reasonable to describe their shape as consequence of the construction process and its principles, than to characterize it by using imposed geometric patterns.

This matter has been discussed more in detail elsewhere, as also the possibilities of geometrical modelling of the shape of the caps as they result from the construction process (Wendland 2004). Accordingly, the ridge lines of the caps can be defined as the intersection of two surfaces which can be described as translation surfaces generated by shifting a curve on tilted plane which is congruent to the masonry courses. If we assume constant curvature of the courses, the vault surface can be described as being composed of eight intersecting circle-stack surfaces (Figure 17). With this surface model, also the characteristic profile of the ridge line of domed cross vaults, as it is visible in great number of existing vaults, can be reproduced and explained.

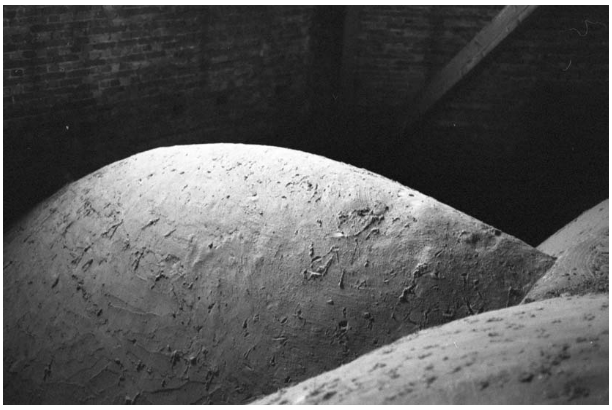


Figure 16. Example of the characteristic profile of the curve of the ridge line, visible on the extrados of a vault.

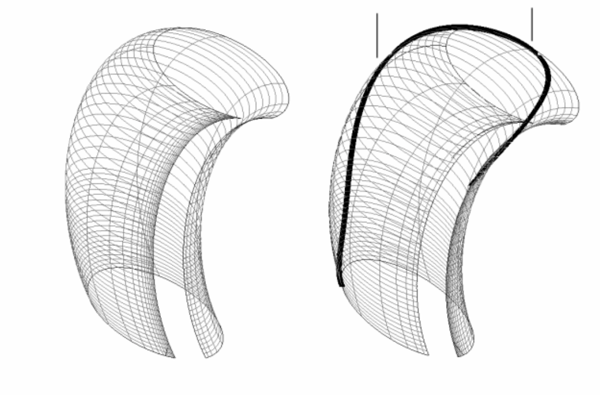


Figure 17. The ridge line profile can be reproduced by means of a translation surface which is comparable to the development of the surface of the cap (Wendland 2004). The surface is generated by parallel translation of a plane circular curve on an elliptical track, and intersected with a vertical plane (right), showing the portion of the intersection curve that corresponds to the ridge line in Figure 16.

The practical procedure above the summits of the formeret and transversal arches can be best understood by emphasizing the continuity of the vault surface normal to the beds. In fact, a drastic turning outwards would be prohibitive both for formal and structural reasons. Also any change of direction inwards, apart from its structural disadvantages, would be hardly feasible as the inclination of the beds cannot be changed, and as according the basic principle of masonry the courses must by superposing to a high degree.

Therefore, in this portion around the summits of the longitudinal and transversal arches, the slope of the vault's surface can be very gently curved or even straight. The correct height of the seaming points in the ridge line is consequently found by keeping a continuous slope in the cap masonry.

Building the very last part of the cap near the keystone of the vault is not very difficult, as the courses in this area are rather short. Therefore, the slope of the cap can easily be bent to the inside by shifting the courses, by inclining the bed joint plane and even by allowing some double curvature in the bed joint. Also the curvature of the courses can be easily reduced at one's convenience.

This improved knowledge acquired from the construction of the models and the prototype is also useful to better understanding the contents of the historical technical literature, thus making them accessible as historical source. For instance, it is remarkable that the detailed description of vault construction, as it develops in the technical literature of the 19th century, is provided by

Figure 18. View of the extrados of the finished prototype vault.

Figure 19. The vault prototype from inside.

authors who are connected to the neogothic movement, as it is the case for Lassaulx, Viollet-le-Duc and Ungewitter. The contributions by J. C. von Lassaulx (1829 and 1846) and G. G. Ungewitter (1859-1864) are decisive for the technical description of vault construction in the German building manuals, including such wide-spread publications as Breymann's "Baukonstruktionslehre" (1849 and following editions). The approaches of these authors, and also their problematic aspects, can be understood in the context of this architectural movement, and can at the same time throw new light on its understanding. But for this, one precondition is that the information is retraced to its original sources, and the other, that the contents can be discussed on the base of detailed knowledge of the processes which are described.

Building in large scale with real materials in a construction laboratory was highly motivating for the students, as they felt that the task had practical relevance, and as the result was a visible real structure. Besides that, it proved to be a good way not only to bring more practical sense into the teaching activity, but also to treat extremely complex matters that literally become tangible, and, finally, to link together research and teaching.

Note

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