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FREE-HANDED VAULT CONSTRUCTION IN THE EUROPEAN BUILDING TRADITION: VAULTING PATTERNS IN HALF-STONE VAULTS

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Abstract

A study on the construction of vaults without formwork is presented, which is based on a critical review of the technical literature and on case studies. The main focus is pointed on the problems of the layout of the vaulting pattern and on the geometry of the caps; current vaulting patterns for different vaulting typologies are described.

Key Words

Vaults, construction history, traditional structures, spatial structures.

1 Introduction

The cupola of Santa Maria del Fiore, one of the most famous vault constructions ever built, is famous also for being built without formwork. In fact, a formwork capable of bearing the weight of the masonry structure spanning 43 meters to be installed way above the church nave would have hardly been feasible.

The advantage of doing without full formwork in vault construction, using only some centering frames if at all, is relevant also for less prominent and even for ordinary building tasks. This is particularly the case for vaults with complex geometry and those built in difficult situations like those built in the height or in narrow spaces. Moreover, considerable material consumption can be avoided. However, although apparently widely practised in the past, today the art of free-handed vaulting is practised only by few specialists. The problems that have to be solved during the construction of these vaults regard the stability of the growing vault masonry, and its geometrical control, i.e. the "navigation" of the curved and tilted wall in space while it is being built.

The vaulting technique most commonly associated with free-handed vaulting is that of laying flat tiles in fast-setting mortar, known as 'timbrel vault' or by the Spanish term 'bóveda tabicada'. This technology is well-known, its historical development has been studied and modern technical descriptions are available (cf. González M.-N. 1999, Gulli and Mochi 1995).

The present study deals exclusively with half-stone vaults. This is the masonry typology common in central Europe for medium and wide spans, where the thickness of the

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vault is that of half a masonry unit, and the caps are executed in a running bond. Half-stone vaults can also be constructed without formwork, without the necessity of special fast-binding mortar.
The execution of this kind of vaults, as practised in historical and traditional construction, is mentioned in the historical technical literature, where some technical information can be extracted through a critical analysis. Moreover it can also be observed in practice, either through the documentation of vaults constructed in modern times or in the very few contemporary cases of vault construction. Regarding structures from earlier periods, detailed documentation of the construction methods is lacking so that any information must be deduced from observations on the buildings themselves, that in many cases present the characteristics of free-handed vaulting.
The possibility of constructing half-stone vaults without formwork is mentioned in the technical literature since the late 17th century (e.g. Gilly), but an exact description of the principle was given only in 1829 by the German architect J.C. von Lassaulx, whose essay had a considerable impact on the development of the topic in the building manuals. This text, which was brought to attention already by Fitchen (1961), and its significance have been discussed elsewhere (Wendland 2003).

2 Half-stone vault with self-supporting courses

The basic principle, as described by Lassaulx, is that the single courses of a vault to be built without formwork must be stable in themselves by having the form of an arch. The units of every new course to be laid are held in place temporarily through the adhesion of the fresh mortar until the course is completed – the adhesion of current mortar, e.g. lime mortar, is fully sufficient if it has the right consistence. As soon as the course is closed, it is stable by its form and no longer by the adhesion of the mortar; it is therefore reliably self-supporting and allows the units of the next course to be laid on top of it.
As the stability of the single course is due to the fact that it forms an arch, it needs sufficient abutment at its ends and must present the necessary curvature. In domes, if the courses are laid horizontally as closed rings they are stable as such. In other types of vaults, e.g. barrel vaults, cloister vaults, cross vaults, the courses must be supported at their ends. Additionally, their sufficient curvature must be provided either by moulding the form of the caps, or by disposing the courses on tilted planes instead of horizontal ones – for example, in a cylindrical cap the courses are curved as soon as they are situated on tilted or vertical planes, i.e. planes that intersect the cylinder else than parallel to its axis. Some attention must also be paid to the length of the courses: in long courses difficulties arise from their possible buckling and from the fact that the phase when the stability is due to the mortar adhesion is longer.
Therefore, the possibility of constructing a half-stone vault without formwork depends from the layout of the courses within the caps, hence, from the vault masonry pattern.

In the following, course patterns related to free-handed vault construction and their application in different vault typologies will be presented and discussed.

2.1 Barrel vaults

Barrel vaults can be built with self-supporting courses by turning the planes of the bed joints in vertical or nearly vertical position, perpendicular to the axis of the vault. The first course to be laid is leaning against the end wall of the room to be covered, or against an arch constructed previously at the extremity of the barrel vault. The following courses are leaning against the preceding courses, and ring by ring the vault is being completed. This typology, known as "Nubian vault", is known to be used already in ancient Egypt and Mesopotamia. As the courses are rather long, in the Middle-Eastern

building tradition their stability is improved by optimizing their form by applying to them the shape of the catenary.

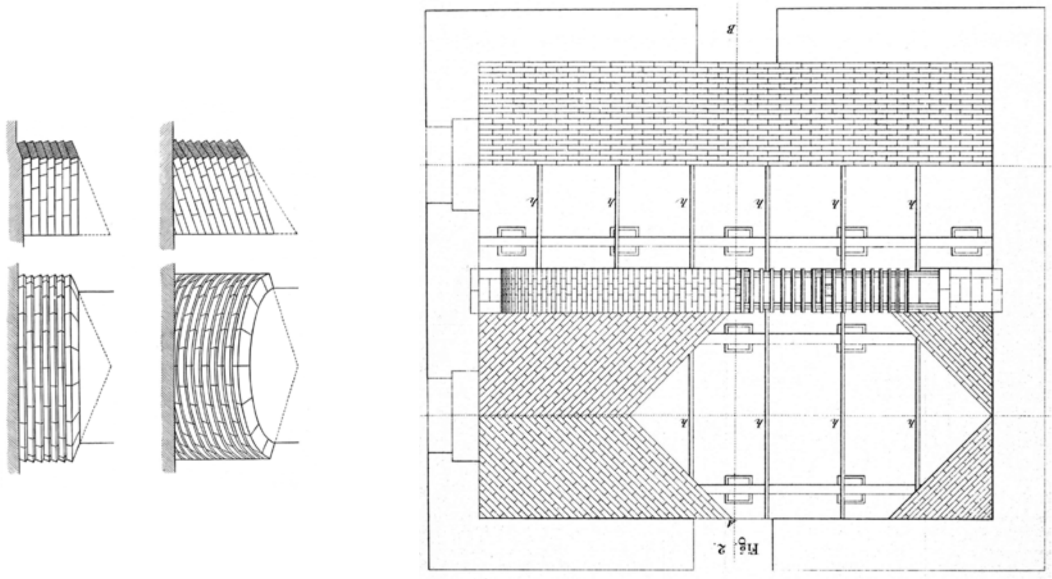


Figure 1 Vaulting patterns in barrel vaults (after Breymann and Gilly): upright standing arched courses, courses running parallel to the springing line, dovetail pattern.

In a cylindrical vault, arch-wise curved courses can also be obtained by laying the bed joints on tilted planes. This "dovetail pattern" with courses departing diagonally from the springing line and seamed in the summit is often used in surbased cylindrical caps.
Wherever the courses are running parallel to the springing line of the vault, they are straight and can therefore be laid without centering only on a small length, as long as the thrust line remains within the thickness of the course.

2.2 Cross vaults

Cross vaults with vertical courses, analogous to the first pattern described for the barrel vault, are not common in Central Europe, although they can often be found Persia, the Middle East and also in the Extremadura region in Spain (Ger 1869).
Wherever the courses are running parallel to the springing of the vault, the curvature is obtained by doming the caps, i.e. providing them a double curvature.
In many cases it is useful to tilt the courses in order to obtain a sufficient curvature of the courses. In combination with a modest doming of the caps their construction with self-supporting arch-wise curved courses is quite easy without formwork, supporting only the groins with centering frames.
If the dovetail pattern is used, the courses lie on diagonally tilted planes perpendicular to the planes of the groin arches. A great advantage of this vaulting pattern is the continuity of the masonry fabric of every two neighbouring caps over the groin, avoiding the joint behind the groin rib. Therefore, it is normally used in cross vaults without ribs or those where the ribs are made with bricks laid within the masonry fabric of the caps.

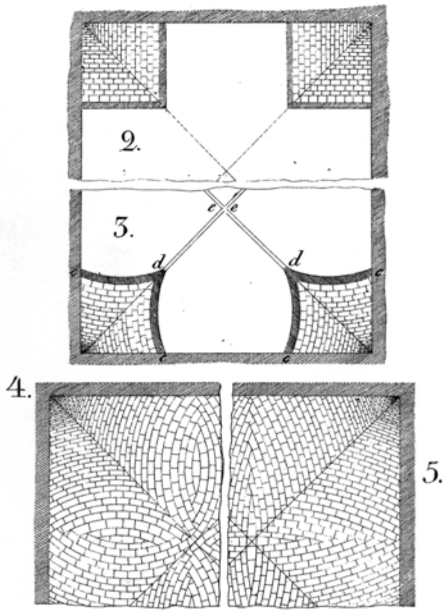
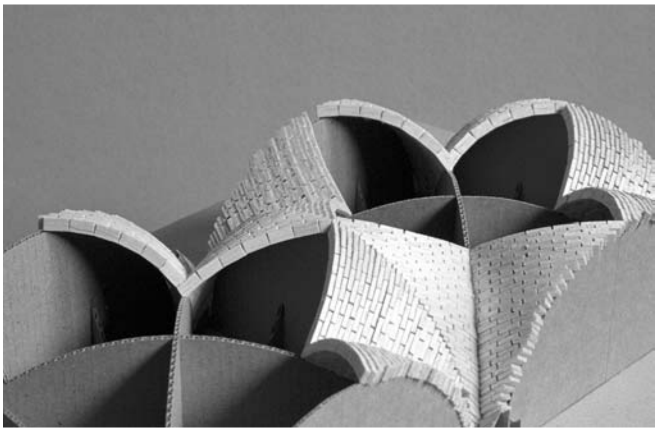


Figure 2, 3, left: Cross vault with self-supporting courses (Lassaulx 1829): Domed caps with horizontal courses (nos. 3, 4), and tilted courses (no. 5). Right, caps being built independently with tilted self-supporting courses in the reconstruction of a gothic vault in Schneeberg, Germany, 1979.

Respect to working the caps independently with the possibility of adjusting the inclination of the course locally where necessary, however, the dovetail pattern demands high precision in maintaining both a uniform shape in the caps and a uniform inclination of the courses all around the four spandrels. In fact, already in a rather early stage of the construction process the spandrels meet at the summit of the confining arches, and in the following they are seamed in the four ridges; hence, they must be brought up together and any change of the courses inclination would affect the masonry pattern of the entire vault.



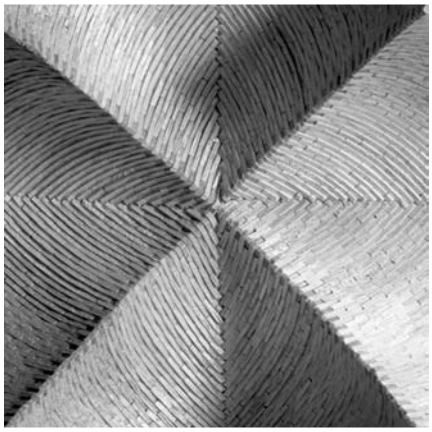
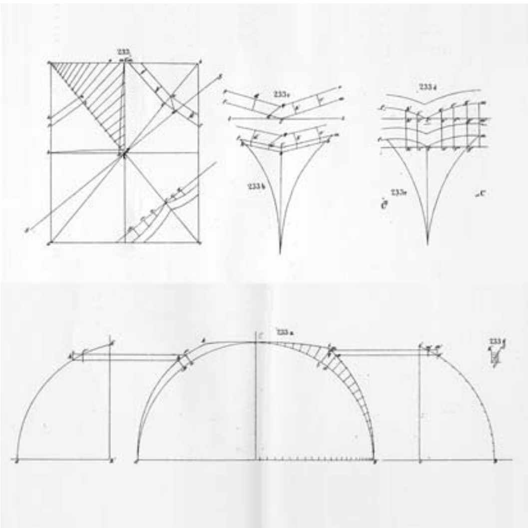
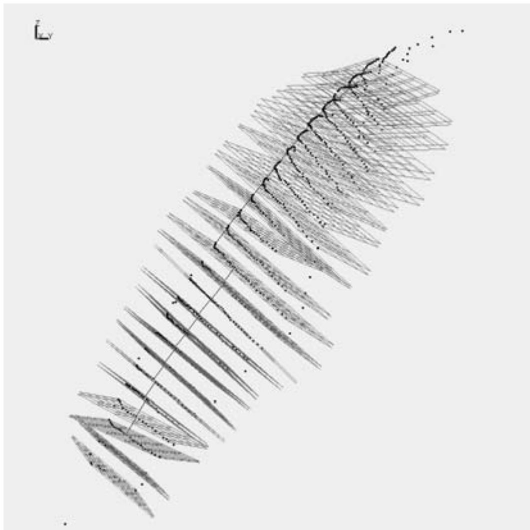


Figure 4, 5, Model of cross vaults built with the dovetail pattern. Note the continuous masonry fabric over the groins and the rather early moment of connecting the spandrels. Right, vertical view of the intrados.

Figure 6, 7, Experimental construction of a cross vault without formwork, using the dovetail pattern, Dresden University of Technology 2003

The spatial position of the planes of the bed joints, according to the technical literature (starting from Ungewitter) could be radial, starting from horizontal at the springing of the spandrels. However, turning the bed joints planes one respect to the other in such manner demands a variation of the thickness of mortar joints due to the variation in distance of the vault masonry from the turning axis. Such an angle between successive courses by applying non-uniform thickness to the mortar joint is feasible in practise only in the first courses of the spandrel because they are rather short. Later on, in the main part of the caps, the bed joint planes must be assumed to be parallel; this is confirmed from case studies and practical experience.

Figures 8, 9, Spatial position of the bed joints' planes: radial, as described by Ungewitter (left), and in parallel planes as it emerges from the measurements in the vaults constructed by Lassaulx at Treis, Germany (Wendland 2003) (right).

A description of the shape of the caps is not at all trivial. Unlike the "archetypical" idea of the cross vault, the caps are not cylindrical (especially if they are domed), and, unlike some statements found in the technical literature, they are not spherical, either. Their shape is geometrically complex and derives from the construction process (cf. Wendland 2003).

Figure 10, Treis, Germany, extrados of the cross vault constructed without formwork: The particular geometry of the cap is due to the construction process.

2.3 Cloister vaults and barrel vaults closed by coves

These two types of vaults can be conceived as being generated by four cylindrical portions along its four sides, intersecting with re-entrant groins at the corners.
In the traditional architecture in Middle-East, two solutions for the construction of cloister vaults and barrel vaults closed by coves with self-supporting courses are common (Besenval 1984). They appear to derive from the "Nubian vault" or barrel vault with upright arched courses, and their courses are also rather long; both can be constructed without any centering at all.
The "voûte à navette" is built starting from two opposite sides, turning the bed joints' planes in the lower portions gradually from horizontal to diagonally tilted, and seaming the two apparatuses in the middle. The "voûte à trompe d'angle" starts from the four corners with diagonally tilted parallel bed joints' planes. In the second, all courses can have the shape of the catenary, reducing the risk of their buckling while the mortar bed is fresh. A considerable advantage is that this second type the demand on the form control is not very high: above the connection of the fours "trompes" the courses are, in fact, set from one seam to the other, excluding any failure of connecting the single portions – no mistake is possible.

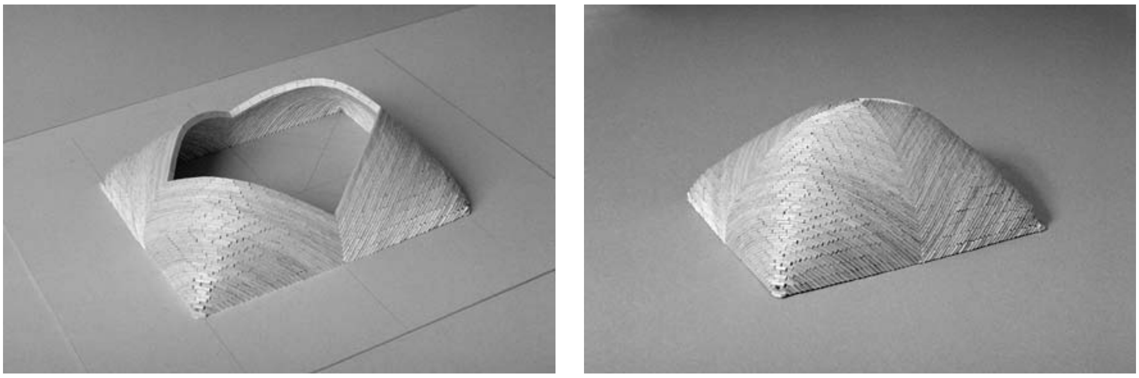
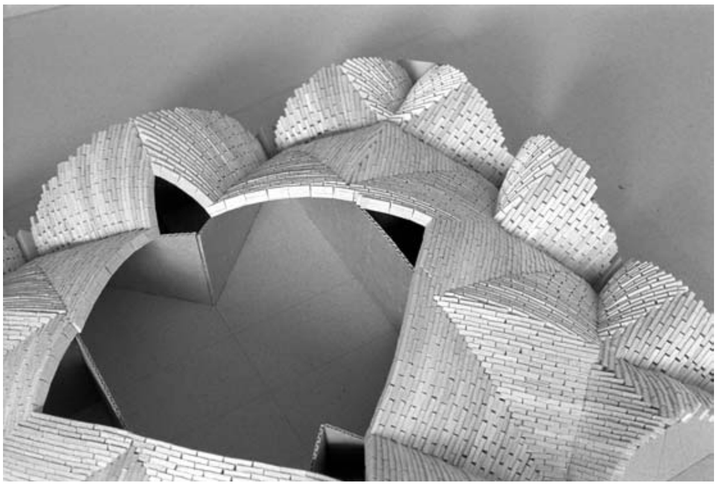


Figure 11, 12, Model of a "voûte à trompe d'angle" during construction and after completion; note the long courses with catenary shape and the absence of centering.

In the European tradition, vaults of this shape are normally intersected with lunettes, giving better possibilities to arrange openings in the room and a more pleasant lighting.

In this case, they can be built with the dovetail pattern, dividing the surfaces of the vault in several portions and setting the bed joints' planes normal to the groins resulting from the intersection with the lunettes; in the central portion, the apparatuses are brought up from the four corners like in a surbased cylindrical cap. If this solution is adopted, it is advisable to erect centering arches under all groins to support the beginnings of the courses, and also in transversal direction. In some cases the centering of the groins can be omitted; however, in this last case the geometrical control of the groins and their spandrels is extremely difficult.



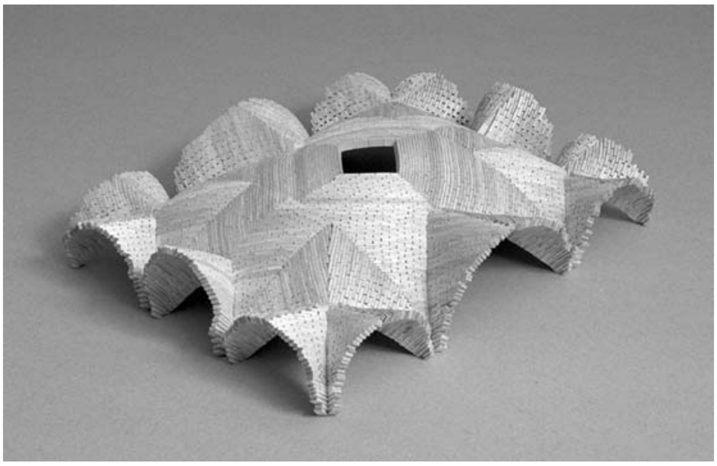


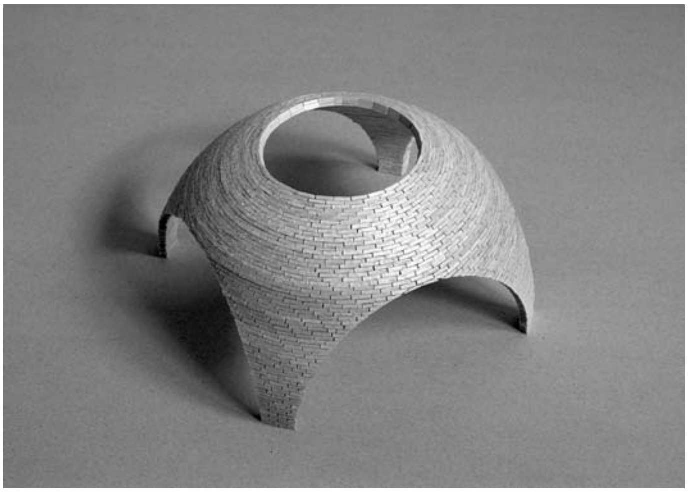
Figure 13, 14, Barrel vault closed by coves with lunettes, executed in the dovetail bond, using centering frames but no formwork; note the single portions of apparatus seamed together, and the arch-wise curvature of the courses.

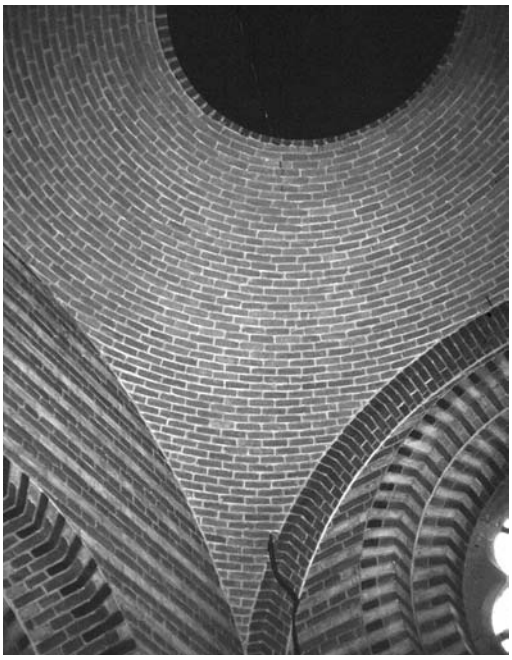
The cupola of Santa Maria del Fiore in Florence is a rare, although not the only, example of a cloister vault built with conical courses. The resulting uniform masonry fabric, especially its continuity over the corners, is a great advantage. However, difficulties might arise from the constraints that are created by such a uniform pattern and the resulting interdependence of all parts of the vault masonry, as any local correction of accumulating errors, genuine to the additional procedure of laying one masonry course on top of another, is very problematic.

2.4 Spherical vaults

Normally, spherical vaults, sail vaults and domes described by a rotation surface with vertical axis are built with horizontal courses that are stable as horizontal rings. As the courses have a radial inclination (except for corbel vaults), the resulting surfaces of the bed joints are conical.

A tool for the geometric control of the rising masonry of spherical vaults often described in the technical literature since the mid-17th Century, is a pole rotating from the center of the generating sphere that has the length of its radius, thus indicating the position of the intrados of the vault wherever needed and additionally indicating the radial direction of the courses. Problems may arise from the fact that the mortar bed is not plane, but, due to its conical surface, presents a double curvature. In fact, in the spandrels of sail vaults the courses tend to remain lower at the sides respect to the center: this problem can be encountered either on the model as in reality.





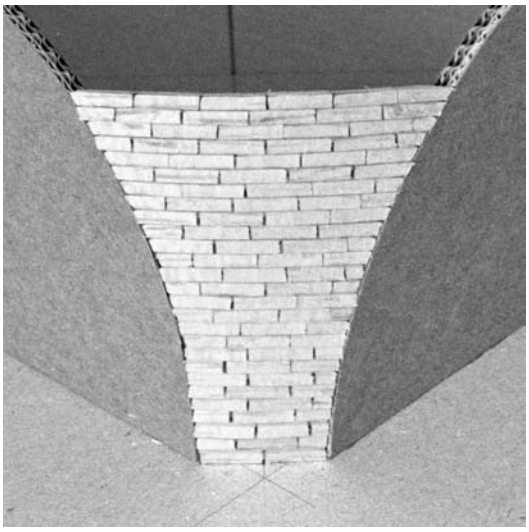


Figure 15-17, Spherical vault with conical courses. The difficulty of maintaining the courses horizontal and the tendency of bending down at the borders of the spandrels, as encountered in the model (right) is visible also in cases of constructed vaults (left).

Such vaults, however, can also be constructed with parallel plane bed joints which are tilted. In this case, the beds are not normal to the vault, thus the surfaces of the units not perfectly fitting to the vault's intrados. Such a pattern is shown in a Spanish manual (Ger y Lóbez 1869); its advantage is that the courses are much shorter and the beds are not curved but plane, facilitating the geometric control; still, the courses are self-supporting and no centering is needed at all.

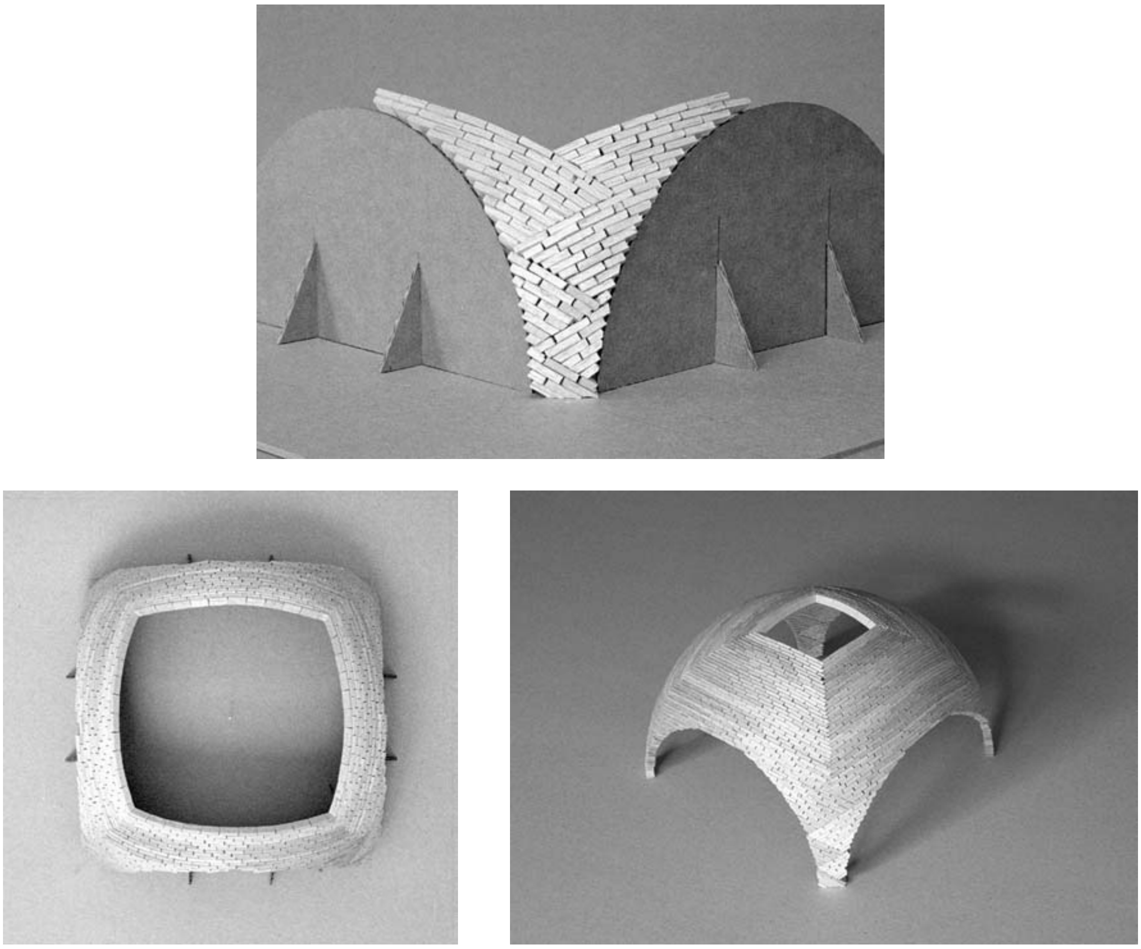


Figure 18-20, Sail vault with plane inclined courses (after Ger); the alternate direction of the vaulting pattern in the spandrel serves to avoid the seam in this narrow portion.

3 Conclusion

In the preceding considerations, only the most common vault typologies have been discussed, as they are presented in the current building manuals. Obviously, an infinite number of different shapes of vaults can be conceived in the variation or combination of those which have been mentioned. Beyond that, the vaulting patterns shown here and the concept of self-supporting courses in general can be principally applied to many forms of shells and vaults, not at all vinculated to the use of Euclidean geometry or regular surfaces or architectural canons. Even an adoption of this technology in modern shell structures built in masonry, constructed without formwork, can be imagined.

The understanding of the interrelation of the shape of the vault surface and the layout of the courses that ensures their stability during construction and a feasible masonry fabric, for which a brief outline has been traced here, is one essential aspect of a

technical description of the construction process of half-stone vaults built without formwork.

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Photo credits: Landesamt für Denkmalpflege Sachsen: Fig. 3; M.J. Ventas Sierra, D. Wendland: Fig. 4-7, 9-20.

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