Geometry and Construction Techniques of Gothic Vaults in Brabant (Belgium)

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ABSTRACT: The present paper is concerned with the masonry webs of Gothic rib vaults built in the former Duchy of Brabant between the thirteenth and the sixteenth century. Contemporary documents providing information on vault geometry and construction are exceptional in Europe; they are non-existent or at best very fragmentary in Brabant. The buildings themselves are the principal source of information. Rib vaults are complex three-dimensional structures. In order to facilitate their understanding, four exemplary vaults were surveyed using a hybrid technique combining reflectorless total station measurements and digital photogrammetry. Four textured 3D computer models were built. After a short description of the surveying and modelling technique, the vaults are analysed and hypotheses are formulated on their construction technique. Emphasis is given to the close relationships existing between materials, geometry and construction techniques.

INTRODUCTION

Most of the numerous Gothic churches of the ancient Duchy of Brabant (henceforth simply referred as Brabant) in nowadays Belgium are covered by masonry vaults. In this paper, one particular component of the vaults will be discussed in detail: the webs. Other aspects and elements of gothic vaults are discussed elsewhere (Smars 2000; De Jonge et al. 2002).

Between the thirteenth and the sixteenth century, the construction mode of the webs changed significantly. The authors suspected that this change was related to a change of materials used for their construction but wanted to gather concrete evidence.

During the summer of 2007, four vaults chosen as significant examples of this evolution were measured and modelled by the first author using a total station, photographs and in-house software tools.

In this paper, the development of geometry and construction techniques will be analysed on the basis of those four new 3D models. The methodology used for surveying and modelling the vaults shall also be presented.

SOURCES

Original documents describing vault construction techniques are rare. Erlande-Brandenburg (1993), for instance, published the text of a fourteenth-century contract for the construction of two sections of vaults in Rouen with details on the construction process. The sixteenth-century Spanish architect Rodrigo Gil de Hontañón also left a description of vault construction, but he concentrated mainly on the construction of the ribs (García 1681). Philibert de l'Orme (1648), another Renaissance architect with strong medieval roots, describes a technique for the construction of webs in ashlar. These texts are certainly important for the understanding of vaults with complex rib patterns or stereotomy, typical of Spain or Germany in the late Middle Ages, but they are not very useful for the understanding of the construction of the webs of the simple rib vaults built in Brabant. More recently, Viollet-le-Duc (1854-1868) and Fitchen (1981) described possible techniques for the construction of webs but these are hypothetical, based on French examples; after careful observation of vaults in our region we strongly doubt that the systems that they described were used in Brabant. Hence it is necessary to rely on the material evidence.

SURVEYING

Position of the problem

To study webs; i.e. to understand their geometry and possibly their mode of construction, good representations are necessary. Rib vaults are complex three-dimensional structures but, seen from visitors' eye level, they all look very similar (a majority of the Brabant ones are quadripartite).

Photographs are easy to take but not very effective. An essential characteristic of vaults is their 3D nature and photographs convey this poorly. This is certainly the case for plastered webs which are very common in Brabant and appear flat on photographs.

Existing surveys are usually 2D; they represent vaults in plans or sections and were not prepared with the analysis of web geometry in mind. 3D or accurate photogrammetric surveys of vaults are still uncommon (references in Smars 2000).

An easy and expressive way to document the 3D nature of the webs is to prepare stereoscopic views of the vaults. In the framework of the PhD of the first author, numerous anaglyphs of vaults were taken (http://smars.yuntech.edu.tw/phd/inventaire/). They give a good insight into the vaults' geometry but no direct quantitative data. The vaults presented below were identified on the base of such anaglyphs as good candidates for further analysis.

Obviously, 3D computer models are sounder bases of geometry analysis. From them, it is possible to interactively study the vaults from different points of view, to prepare accurate 2D documents (plans with contour lines, sections...) or directly analyse the 3D data.

Until recently, this operation was complex and it was only conceivable to use models produced for other purposes than "construction history". Nowadays, with the advent of reflectorless total stations and laser scanners, it becomes possible to quickly produce reasonably accurate 3D models of vaults. This is good news for "construction history" as it provides a new and rich source of data.

A key to understanding web construction is also provided by the analysis of the block (or brick) courses. Image processing and digital photogrammetric techniques now allow relatively easily to project photographs on a 3D model, therefore providing measured information.

Process

The models were produced in several steps:

A dense array of points (between 3000 and 5000 for each vault) was measured in 3D on the surface of the webs using a total station (a Leica TCR 307 total station owned by the department of architecture, urbanism and planning of the Catholic University of Leuven). For each vault, one or two stations were necessary to cover the whole surface of the webs.

The resulting "point clouds" were meshed to produce triangulated representations of the webs: (a) the points are centrally projected from the position of the total station on a plane normal to the average pointing direction, (b) the topology of the mesh is produced by Delaunay triangulation (in 2D), (c) the defined topology is combined with the 3D coordinates of the points to produce a 3D triangle model, (d) large triangles are automatically eliminated (as they correspond to surfaces nearly tangent to the direction of measurement), (e) the model is checked and a few dubious triangles are eliminated, (f) the webs are assembled, (g) the model is slightly smoothed (to reduce noise in the data) and is re-sampled (more triangles are produced).

Photographs of the web were taken (with a Nikon Coolpix 5400). To reduce the noise in the often dark church interiors, a set of photographs was taken from a given position and averaged images were produced.

Reference points were measured on the vaults (usually 8) using the total station and marked on the photographs for later photogrammetric processing.

- The camera was calibrated (internal and radial distortion parameters) independently, measuring a large number of points on a reference building.
- The photographs were corrected for radial distortion (Fig. 3 is an example of a corrected image; the black areas in the middle of the sides of the images are the result of the correction of the pin-cushion distortion).
- The camera position and orientation was computed from the correspondence between the measurements of the reference points on the webs and on the image.
- The images were projected on the 3D model.
- Various figures were produced (orthophoto plans, sections, perspective views) and the models were studied interactively
- The data was processed using in-house software tools developed in the framework of various research projects (Smars 2001; Smars 2002 and an on-going project: *Surveying tools for parametric modelling of Architectural Heritage*).
- The four vaults were measured in July 2007. Each of the vaults required a full day of *neck torturing* work. The data was later processed in the office. In the meantime, the software tools were improved. Operations are now more automatic and therefore quicker, allowing a processing of the data entirely on the site.

MATERIALS

In Brabant, the ribs of the masonry vaults are always executed in stone.
Webs are either made of stone or of brick: in the thirteenth and fourteenth century they are always stone; in the fifteenth century bricks are progressively replacing stones and in the sixteenth century webs are always in bricks.
By far the most common stone used for construction in Brabant in the Middle Ages is an Eocene sand-lime stone. Three main types exist (from the *ledian*, *bruxellian* and *ypresian* stages) with quite similar characteristics (density: 2300-2500 kg/m³). Other types of stone were also used locally: ferruginous sand-stone is extensively used in the Demer valley, chalk occasionally in the South-East of the Duchy and schistose quartzite in the South. All these materials can be found in vaults.
It is not easy to measure the thickness of stone webs. The voussoirs do not have a standard shape (like the bricks) and, very often, they are not carefully dressed on the extrados. The thickness can only be measured in a few points (where there are holes). Actually, it would also be very interesting to measure the extrados surface. Unfortunately, this is a complex operation (access, possibility to see or aim at the points to measure).
After their disappearance at the end of the Roman period, bricks were reintroduced in Southern Brabant in the fourteenth century. In the fifteenth century, as stones became rarer, bricks were frequently used as a substitute and this became the norm in the sixteenth century. Possibly because of its association with modest constructions, this new material was not accepted straight away in church buildings. Initially bricks were kept hidden: they were used for the infill of walls, in attics and, in vaults, for the construction of the webs which were meant to be plastered.
The bricks used for web construction were the same as the ones used for the construction of walls. Their length is comprised between 20 and 25cm and their density is about 1500kg/m³.
The thickness of a brick web is easier to define. Small vaults may have a stretcher bond (half a brick thick) but the great majority of webs have a header bond (one brick thick). A few webs are thicker in their bottom part.

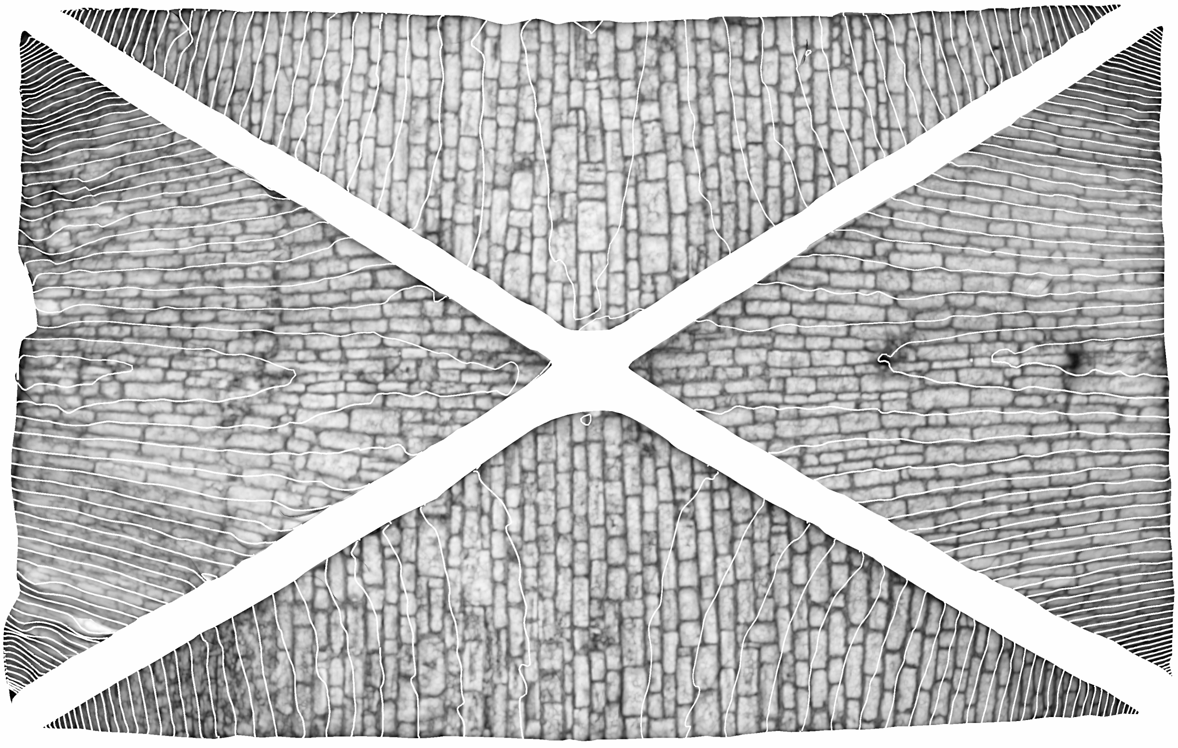

Figure 1: Church of Our Lady, Leuven. Vault of the sixth bay of the nave, starting from the West. The Northern web is on the right part of the figure (beware that the Eastern web is on the upper as the vault is observed from the bottom, looking up); the contour line interval is equal to 0.10m and the maximum span of the vault is 9.05m

WEBS

The webs can be defined as the curved masonry works spanning the space left between the ribs. A great majority of the vaults built in Brabant are simple *quadripartite vaults* with two *diagonal ribs*, two *transverse ribs* and (very often) two *wall ribs*. The space between the ribs is thus spanned by four webs: two *transverse webs* between the wall ribs and diagonal ribs and two *longitudinal webs* between the transverse ribs and the diagonal ribs.
In what follows four vaults will be presented.

Church of Our Lady, Leuven (50°52'44"N, 4°41'45"E)

The church of Our Lady in Leuven is one of the earliest and nicest examples of Gothic architecture in Brabant. The vault we surveyed (Fig. 1) covers the sixth bay of the nave, starting from the West. It was built in the middle of the thirteenth century (VIOE 2008). Sections seven and eight were built in the same century but are now plastered. The first four bays were covered by a wooden vault built in the fourteenth century and the fifth was rebuilt in the twentieth century.
The sixth vault is a good representative of thirteenth-century vaults in Brabant. It is built of stone with voussoirs of various dimensions arranged in a semi-regular fashion. The stone courses are sensibly rectilinear in plan and present no curvature in section. The webs have therefore a single curvature defined by the ribs. The slight curvature of the contour lines in the longitudinal webs results from the fact that, starting from the transverse ribs, the courses are slightly inclined upwards. In the transverse web, the courses are nearly horizontal. Only at the ridge, the courses are slightly inclined towards the wall ribs whose summits are slightly more than 0.20m higher than the summit of the diagonal ribs.
The contour lines are nearly straight but there is no continuity between the webs; each of them was therefore vaulted independently.
There is a hole in the vault and at this level it has a thickness of 0.22m.

Saint Martin's, Asse (50°54'39"N, 4°11'44"E)

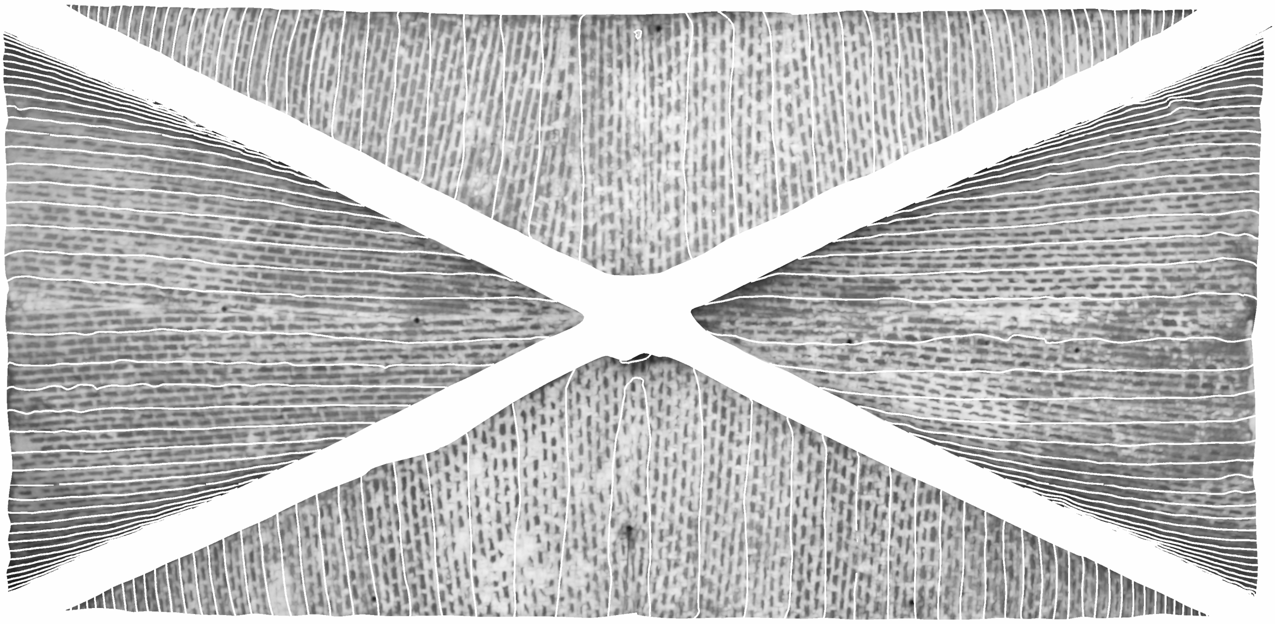

Figure 2: Saint Martin's, Asse. Vault of the easternmost bay of the choir (beginning of the fifteenth century). North on the right; contour interval: 0.10m; maximum span: 8.84m

The vault we surveyed (Fig. 2) is the easternmost vault of the choir. It was built at the beginning of the fifteenth century (VIOE 2008). This is an interesting case because it is a rare example of an intermediary stage between the thirteenth-century stone vault type and the later brick vaults: its webs are built in bricks but its geometry is closer to the geometry of the stone vaults.
The vault has a very regular geometry. Brick courses are almost straight and nearly horizontal. In the transverse webs the courses are slightly converging towards the keystone and in the longitudinal webs they are slightly diverging. This is a natural consequence of the proportion of the vault. The span of the wall ribs is narrower than the span of the transverse ribs and wall ribs have a higher impost. The lower part of the transverse web is vertical and rests on the diagonal arch. It starts with the "tas-de-charge" (solid springer) in stone and continues as a simple vertical wall in brick. The first course leaving the vertical plane therefore joins a point at the springing of the wall rib with a point already at some distance of the springing of the diagonal rib resulting in the aforementioned convergence.
On an anaglyph photograph (not reproduced in this paper because it requires colours (see http://smars.yuntech.edu.tw/phd/inventaire/) and on the 3D model it is clearly visible that the surface of the webs is made of a succession of roughly planar masonry "panels". The junction between panels can be seen on the plan because, at their junctions, the direction of the courses often changes slightly. It may be conjectured that the reason behind this change of direction is the willingness to keep the courses close to the horizontal. As construction progresses the difference of level between starting and ending point of the course increases. When the difference becomes significant, a few incomplete courses are laid to prepare a new horizontal base for the upper courses.
The brick courses are long, straight and relatively thin. It is therefore clear that the vault is not auto-stable before its completion. Lime mortar hardens slowly and the last course of brick completed (the construction front)

does not form a sufficiently rigid base for the construction of the next brick course. In consequence, the webs were most likely built on a complete centring. For similar reasons this must also have been the case for the stone vaults. In the latter case another factor came into play; i.e. the weight of the individual blocks (denser, bigger and thicker), which complicated their handling and decreased the influence of the fresh mortar on the stability of the last block laid.

Church of Our Saviour, Hakendover (50°47'39"N, 4°58'53"E)

Figure 3: Church of Our Saviour, Hakendover. Vault of the northern bay of the transept (beginning of the sixteenth century)

The vault we surveyed covers the Northern bay of the transept of the church of Our Saviour in Hakendover. It was built at the beginning of the sixteenth century (VIOE 2008). It has an irregular shape, illustrating the flexibility of Gothic construction techniques. Unfortunately some of the reference points necessary to orient the photograph were badly measured and we could not project the photograph on the model. Here we present a photograph of the vault (Fig. 3) and the contour lines computed from the 3D model (Fig. 4) separately.
The main difference between this vault and the two vaults discussed above is that the brick courses are now curved both in plan and in section. The main advantage of this curvature (and of the resulting double curvature of the webs) is that it allows the webs to remain auto-stable at each stage of construction, consequently enabling the construction of the webs without a complete centring. Furthermore, the irregularity of the curvature of the courses and the differences between the webs rule out the use of tools or instruments to support and/or guide the construction of the courses. In this case, the webs were indeed constructed without any centring under the unassisted guidance of the mason.
The brickwork of the five webs presents significant differences. One can even see asymmetries between the two sides of a single web. The mason clearly had some freedom of execution. But it can be safely ruled out that those patterns, however interesting, were chosen for artistic or symbolic reasons. They are present in many other vaults (always visible on their extrados) and most of them are plastered over.
As at Asse several zones can be identified in each of the webs. At their interface the direction of the courses changes and becomes more horizontal. In the case of Hakendover there is another interesting advantage to the change of direction insofar as it may shorten the length of the courses and thus facilitate their freehand construction. This clearly applies to the ridge of the second and third web but also to the middle part of the first and fourth web.

Two types of pattern can be observed on the ridges of the webs: the ridge of the first web presents an "almond" pattern and the ridge of the other webs, a herringbone pattern. Both types can be seen in many other vaults. In nave vaults, because of the proportions commonly used in such bays, the almond pattern is more common in the longitudinal webs and the herringbone pattern in the transverse ones.
Given the span of the vaults, a thickness of 0.20m or more may appear exaggerated: double curvature vaults of that type can be very thin. However, because vaults have to be auto-stable during the construction, the course of brick on the construction front has to resist as an arch and must be thicker.
The vaults were built without "tas-de-charge", possibly indicating that the vault construction was not planned.

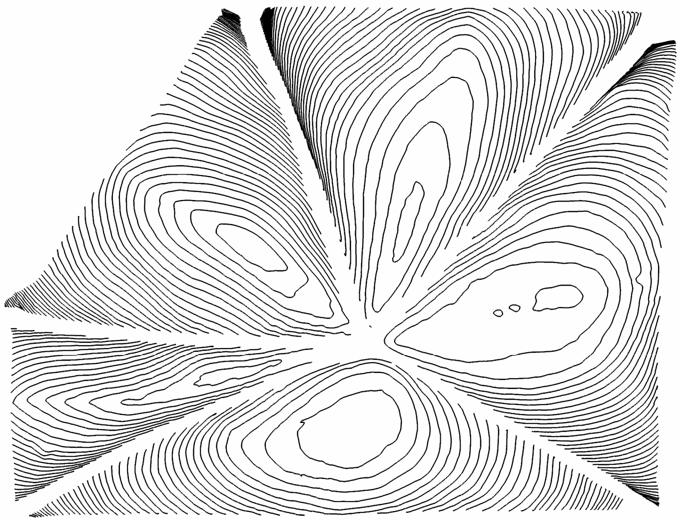

Figure 4: Church of Our Saviour, Hakendover. Vault of the Northern bay of the transept (beginning of the sixteenth century). North on top; contour interval: 0.10m; maximum span: 9.32m

Saint Catherine's, Humelghem (50°54'11"N, 4°31'02"E)

The vault we surveyed (Fig. 5) covers the easternmost sections of the Northern side aisle of Saint Catherine's in Humelghem. It was built in the sixteenth century (VIOE 2008). The vault is smaller than the examples presented above but its characteristics are also typical of many other sixteenth-century and later vaults (for instance in the nave of Saint Martin's in Asse). It was chosen because it is not plastered over and because the brick courses are clearly visible.
The domical character of the webs, already present in the vault of Hakendover where the summit of the web is also higher than the apex of the various ribs, is now even more evident. The difference of level between the summit of the diagonal ribs (higher) and the summits of the transverse and wall ribs (lower) has also increased. This new system has a strong influence on the spatial impression produced by a succession of vaults. It clearly marks the individuality of the vaults and upsets the spatial continuity.
As at Hakendover the four webs present some differences in the laying of the courses. Those differences have only a limited influence on the final geometry, however. The geometry was the objective and variations in the execution were possible to achieve it.
In a way, three stages of development of the web construction technique left traces on the webs of the vault of Humelghem. The Southern web presents a herringbone pattern, the Eastern web a small almond pattern, the Western web a bigger almond pattern and the Northern web a cupola pattern. In this last web the herringbone pattern has completely disappeared: there is almost no discontinuity in the direction of the courses which are now ovoid. In particular, the brick courses are parallel to the transverse and wall ribs at their summit. This has to be compared with the brick courses in Asse which were perpendicular to the transverse and wall ribs.
Domical rib vaults are certainly easier to build and lighter than stone vaults but they also have some inconveniences. Apart from the influence of the technique on the spatial continuity, from a structural point of view they are also much more sensible to displacements of the abutments; small movements can easily produce cracks or a separation of the ribs from the webs.

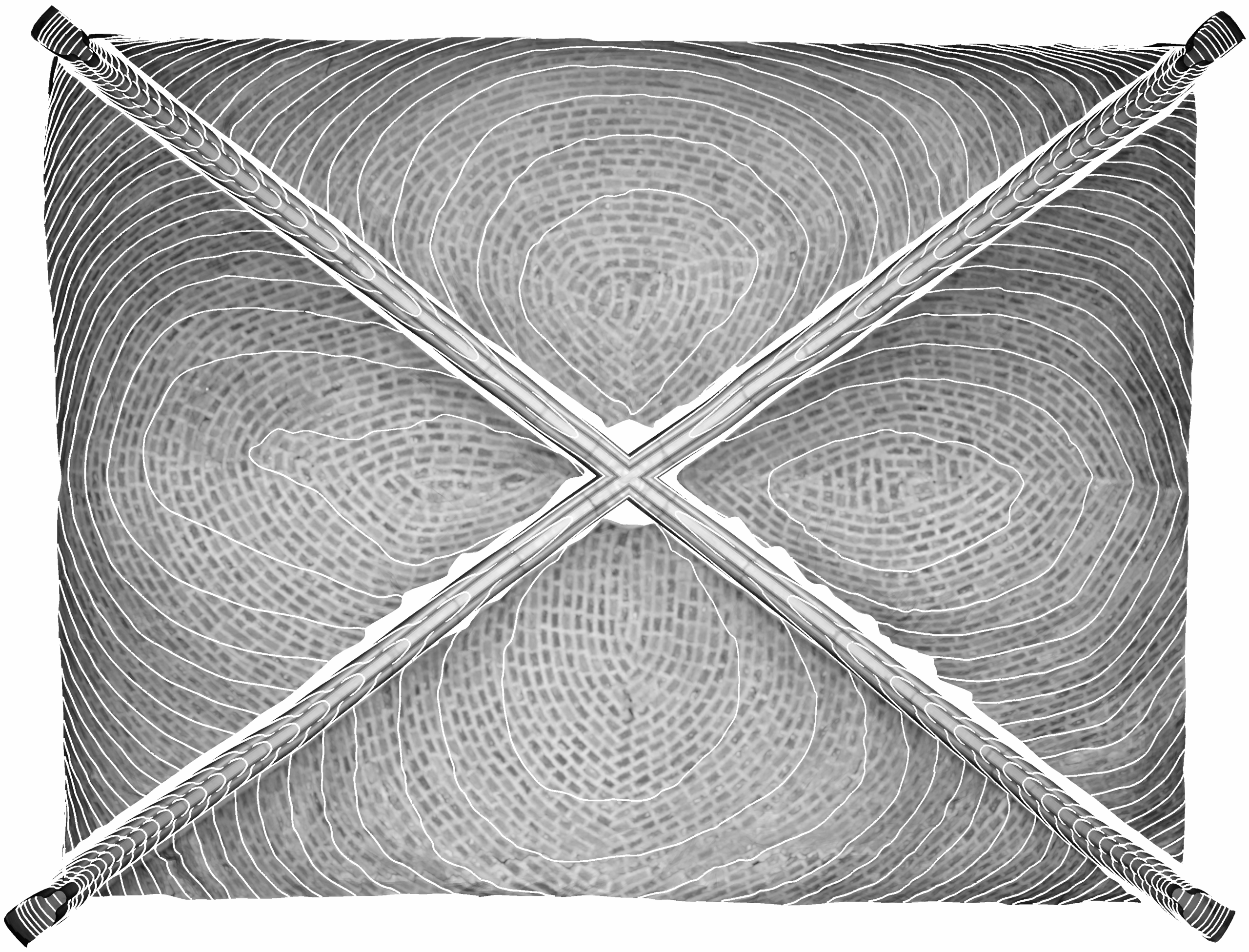

Figure 5: Humelghem, Saint Catherine's. Vault of the easternmost section of the Northern side aisle (sixteenth century). North on top; contour interval: 10cm; maximum span: 4.06m

CONCLUSION

In this paper we presented and illustrated the main phases of development in the construction of masonry webs between the thirteenth and the sixteenth century in the ancient Duchy of Brabant by a sample of four cases. These represent, however, a much larger population which has so far only been analysed through anaglyphs (Smars 2000). The most interesting aspect of this evolution is the influence that the adoption of a new material; i.e. brick had on the evolution of the technique. The programme remained sensibly the same; i.e. the construction of quadripartite vaults – vaults with more complex rib patterns are much less common before the later sixteenth and seventeenth century – but the execution and the details evolved. In the first stage, at the beginning of the fifteenth century, masons remained faithful to the traditional technique used for the construction of stone vaults. In the second stage, during the fifteenth century, they discovered the potential of the new material and started to take advantage of it. Bricks are smaller, lighter and thinner and, with the introduction of a double curvature in the webs, it became possible to build them without centring, with obvious advantages on cost and execution time. In the third stage, from the sixteenth century, masons moved away from the last references to groin vaults (an intersection of two barrel vaults) and started to build cupolas on the ribs.

In the European context, the closest parallel to this technique can be found in the German examples described by Ungewitter in his classic handbook on Gothic construction (Ungewitter 1890, pp. 14-15, 57, 93, 107, 110-112, 120, 131-133), but this comparison can probably be extended.

Our study also demonstrated the value of reflectorless total stations and digital photogrammetry to build 3D models in a relatively short time, providing new data for studies in "construction history".

REFERENCES

De Jonge, Krista (ed.); Geleyns, Piet; Hörsch, Markus; Smars, Pierre; Verpoest, Luc 2002: *Gotische architectuur in het voormalige hertogdom Brabant* (Gothic architecture in the former duchy of Brabant), unpublished research report, Province Vlaams-Brabant (shortened version now in press).

Erlande-Brandenburg, Alain, 1993: *Quand les cathédrales étaient peintes*, Paris, Gallimard.

De l'Orme, Philibert, 1648: *Architecture*, Rouen (facsimile, Liège, Mardaga, 1981).

García, Simon, 1681: *Compendio de arquitectura y simetria de los templos conforme a la medida del cuerpo*

humano con algunas demostraziones de geometria, manuscript (facsimile, Churubusco, 1979).
Fitchen, John, 1981: *The construction of gothic cathedrals, a study of medieval vault erection*, Chicago and London, University of Chicago Press.
Smars, Pierre, 2000: *Etudes sur la stabilité des arcs et voûtes, confrontation des méthodes de l'analyse limite aux voûtes gothiques du Brabant*, doctoral thesis, Leuven, Catholic University of Leuven.
Smars, Pierre; Van Balen, Koen; Nuyts, Kris, 2001: Layered Geometric Information System. In: *XVIII. International Symposium CIPA 2001 (Surveying and Documentation of Historic Buildings - Monuments - Sites Traditional and Modern Methods)*, Potsdam, pp. 462-468.
Smars, Pierre; D'Ayala, Dina, 2002: Parametric shape model for conservation oriented surveying. In: *World Heritage in the Digital Age, Heritage Management Mapping: GIS and Multimedia*, Alexandria.
Ungewitter, Georg, 1890: *Handbuch der Gothischen Konstruktionen*, Leipzig, T.O. Weigel Nachfolger (3rd ed.).
Viollet-le-Duc, Eugène-Emmanuel, 1854-1868, *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle*, Paris (facsimile, Paris, Bibliothèque de l'image, 1997).
Vlaams instituut voor het onroerend erfgoed (VIOE), *Inventaris bouwkundig erfgoed*, 26 October 2008 http://paola.erfgoed.net/sdx/inventaris/

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