Tracing the Past: a digital analysis of the Lady Chapel vaults at Ely cathedral

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***Abstract*— This paper describes how contemporary digital surveying and modelling tools are used to augment our understanding of medieval vault design. The Lady Chapel at Ely cathedral in the east of England forms a case study to demonstrate this process, which is contributing to a larger investigation of medieval vaults across England and beyond. The use of laser scanning to document church and cathedral ceilings is described and how subsequent outputs from this, notably orthographic point cloud images and 3D mesh models, enable us to interrogate key geometry relating to vault ribs. With the acquired digital data, a process of reverse engineering is performed, starting in plan followed by full 3D projections, to hypothesise how medieval vaults were designed.**

Keywords*— *laser scanning, reverse engineering, medieval design, vaulting, 3D modelling.

I. Introduction

Ribbed vaulted ceilings, found high up in church and cathedral interiors primarily in Europe, represent a high point in medieval design and construction. These work on the principle of first creating a series of ribbed arches, with the in-between spaces filled in afterwards using the rib geometry as a guide. In fourteenth-century England, ribbed vaulting progressed from relatively simple quadripartite forms expressing the basic structural principles of the bounding bay and diagonal ribs only, towards increasingly complex designs including intermediate or tierceron ribs and short lierne ribs creating a highly decorative effect. From surviving examples, it is thought that in order to create these forms, masons used a 2D tracing floor to experiment with ideas in plan, as well as projecting arcs from this plan to conceptualise the full 3D vault design.

Being built over 700 years ago, we do not know for sure exactly how the design process for a fourteenth century vault progressed, particularly when investigating different designs at individual sites. It is rare for original documentation to survive, and this almost never includes drawings or detailed specifications, therefore we must look to the existing structures for answers. Attempts have previously been made to understand their design and construction, most notably by Professor Robert Willis in the mid-nineteenth-century [1], however, evidence of this was difficult to obtain owing to the inaccessibility of vaults, often many metres above floor level.

Today, advanced digital surveying tools such as laser scanning and photogrammetry, are widely accessible, allowing us to record historical artefacts quickly and accurately, particularly when compared to analogue methods. Our project does not intend to demonstrate specific advances in digital surveying techniques, and instead shows how such tools are used to enhance understanding of medieval vault design. Here, we discuss one of our case study sites, the Lady Chapel at Ely cathedral in East Anglia (Fig. 1), the digital methodology we used, as well as our findings to date.

Fig.1. Lierne vaults in the Lady Chapel at Ely cathedral.

We are grateful for the Society of Antiquaries of London's Lambarde Memorial Travel Award for funding data collection at Ely cathedral.

Fig. 2. Orthophotos created using the point cloud model of the Lady Chapel in plan (left), long section (centre) and short section (right).

II. History

Ely cathedral, famous for the octagonal lantern at its crossing, features a series of complex vaults in its east end. The Lady Chapel itself is located north of the cathedral choir, as an almost independent building. The cathedral underwent a turbulent period immediately after the laying of the Lady Chapel foundation stone in 1321, as the crossing tower collapsed in February the following year. As such, it is highly likely that construction was halted in the Lady Chapel to concentrate on rebuilding the crossing tower to an octagonal design, as well as the choir bays to the east that were damaged [2]. The Lady Chapel altar was dedicated in 1352-53, giving a likely completion date. Pevsner and Metcalf [3] state it may have been possible that work on the Lady Chapel was not suspended and instead two building crews worked in parallel, however they argue it is more reasonable to assume that work resumed in earnest after the completion of the damaged choir bays around 1337. Unlike other scholars, Woodman [4] proposes that the vaults may be late fifteenth-century rather than mid fourteenth-century, based on the iconography of the bosses, the complex design and comparisons with Norwich cathedral, which we will investigate once we have enough data.

The Lady Chapel is made up of five bays arranged on an east-west axis. The vaults demonstrate sophistication and complexity of design, featuring three sets of tiercerons transversely and one tierceron set longitudinally, as well as numerous liernes, around the longitudinal ridge rib. We postulate that such a complex design was planned first on the tracing floor in 2D and then projected into 3D for construction.

III. Methodology

Since the inception of this project, we have experimented with several digital methods of surveying medieval vaults. We aimed to ensure accuracy whilst having to rely on surveys taken from church and cathedral floors, with vaults usually at least ten metres above. Accuracy is essential in establishing vault geometries as slight changes can have consequences to tracing floor designs, as we will show in this paper. Bork [5] states that the study of Gothic geometry is problematic due to imprecision, ambiguity and wishful thinking. This was particularly true in a pre-digital era, where survey data was likely to be less reliable than its digital equivalent, for example, the thickness of a line drawn in plan at a small scale could confuse a fraction of three thirteenths with a fraction of one quarter. In addition, an analogue survey was more likely to be unreliable due to the inaccessibility of vaulted ceilings, as well as human error in drawing. It is important to restate here that our primary intention was not to produce representations for the digital preservation of cultural heritage, such as early investigations at Beauvais cathedral [6], although these are beneficial. Instead digital tools are primarily used to interrogate vault design, such as parallel investigations by Wendland and Ventas Sierra in Germany using total station surveying [7] and Rabasa-Díaz in France and Spain using photogrammetry [8].

We have tested total station and photogrammetry as survey methods, however, we now rely on laser scanning as our main data source. We chose this due to its accuracy levels compared with photogrammetry, which has more potential for human error such as incorrect scaling as well as creating ‘fuzzy’ 3D models if enough photographs are not taken [9]. Total station scanning was also viable, however, as this only captures specific points within a space, it is less beneficial to us for the wider project. For example, on visiting Ely to collect the survey data we focused our total station scans on vault ribs only, whereas in future we will be investigating the webbing in between ribs, which were not captured using total station. On the other hand, the laser scans contain all the geometry of the medieval interiors therefore are much more useful to the project in the long term. We recorded scanning and post-production times and concluded that laser scanning was the most economical of the three methods, as well as establishing suitable tolerances, usually within 100mm [10].

We used a Faro Focus x330 to laser scan the vaults, typically capturing one scan per bay, therefore producing five scans in the Lady Chapel. As the height of the space is over 17 metres, we chose a scan resolution of 1/2, giving a point spacing of one every 3.1 millimetres at 10 metres, ensuring enough detail to analyse the data. The scans were then combined using Scene, Faro’s proprietary software, into a single homogenised point cloud model. To undertake initial 2D visual analysis we create orthophotos, where perspective is removed, which we can then use to determine basic patterns in plan and section (Fig. 2), however, to interrogate the vaulting further requires an investigation of each rib’s underlying geometry in 3D. In this process, scan-produced point cloud models are converted into mesh models, then exported to Rhinoceros. Next, intrados lines (the edges of each rib) are traced, which is crucial in understanding vault design as we can extract the rib’s key geometry: its radius, apex, as well as its centre point and relationship to vault rib springing points (Fig. 3). When tracing the intrados lines, we work with mesh models

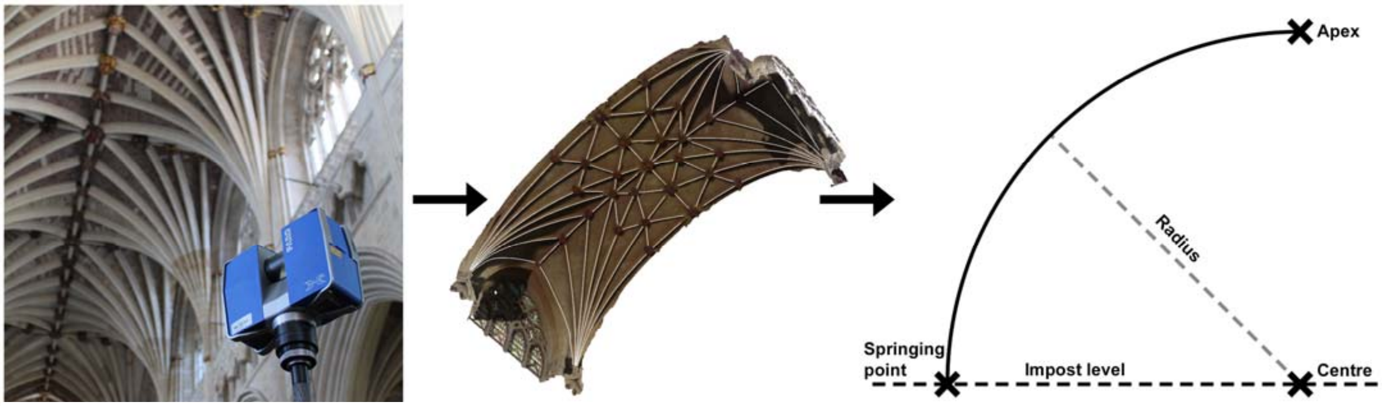

Fig. 3. A laser scanner captures the vaults (left) which is digitally traced along intrados lines as a mesh model (centre) and key geometry extracted (right).

rather than the point clouds themselves, as individual vault ribs are much easier to locate as the mesh is surface based. Once the intrados lines of the central three bays in the Lady Chapel were traced, we recorded averages for all the geometry into a data table, such as the eight diagonal ribs captured, and could use these to inform our hypothesis of the design process along with the orthophotos already created.

IV. 2D PROCESS

Using a combination of the orthophotos and 3D tracings viewed in plan, we next hypothesised how the masons created the initial design of the vaults in 2D, which could then be projected into 3D. The 2D plan enabled the masons to create different patterns, which became increasingly elaborate during the fourteenth-century. The masons would have had several known factors to begin their design, for example the bay size in plan determined by the existing columns and walls, and window elevations informing 3D projections.

Starting with the rectangular bay plan on the tracing floor, straight edge and dividers are used to form lines and arcs, which can be divided proportionally to create different patterns, the results of which can then be copied in stone [11]. We replicated this process using the drafting software MicroStation. To ascertain the design of the Lady Chapel, we 'reverse engineered' it, working from the existing digitally traced plan (Fig. 4i). The first step was to create lines joining the two corners on each side of the rectangle to the midpoint of the opposite edge, for example chevrons AGC and AHB (Fig. 4ii). This process was repeated for all four sides, creating what Stewart [12] refers to as the Starcut diagram. The four chevrons have several crossing points, which create many opportunities for proportioning, for example in Fig. 4ii, the bay is divided into thirds transversely. Likewise, the crossing points enable the bay to be divided into quarters, fifths, sevenths, elevenths and further still. We have found variations of the starcut in use at several of our case study sites including St Mary's Nantwich, Wells cathedral and Exeter cathedral, as well as elsewhere at Ely. In the Lady Chapel, we have observed the use of thirteenths to create two sets of longitudinal tiercerons and one set of liernes. It is possible to find thirteenths using the starcut diagram by first finding thirds longitudinally and quarters transversely, which are then connected to create a grid of parallelograms (Fig. 4iii). The crossing of these are then joined longitudinally creating the thirteenths required (Fig. 4iv).

Once the starcut and thirteenths are drawn, we can use these and other simple moves to progress with the 2D bay geometry. Firstly, diagonal ribs are created by connecting corner points AD and BC, then ridge ribs drawn by connecting midpoints EH and FG, followed by transverse tiercerons by joining points AJB and CSD (Fig. 4v). Next, the longitudinal tiercerons are created using the quarters and thirteenths already marked transversely, for example, Fig. 4vi shows the longitudinal tiercerons drawn by connecting corners A and C to one quarter, six thirteenths and nine thirteenths of the bay transversely. For the liernes or shorter ribs, we make use of the starcut segmented into thirds and thirteenths, and then join the geometry already created to draw the final ribs (Fig. 4vii).

It should be noted that this hypothesis went through several revisions until we were satisfied with the proposed process, particularly as we had not previously encountered the use of thirteenths at other case study sites. The use of digital tools

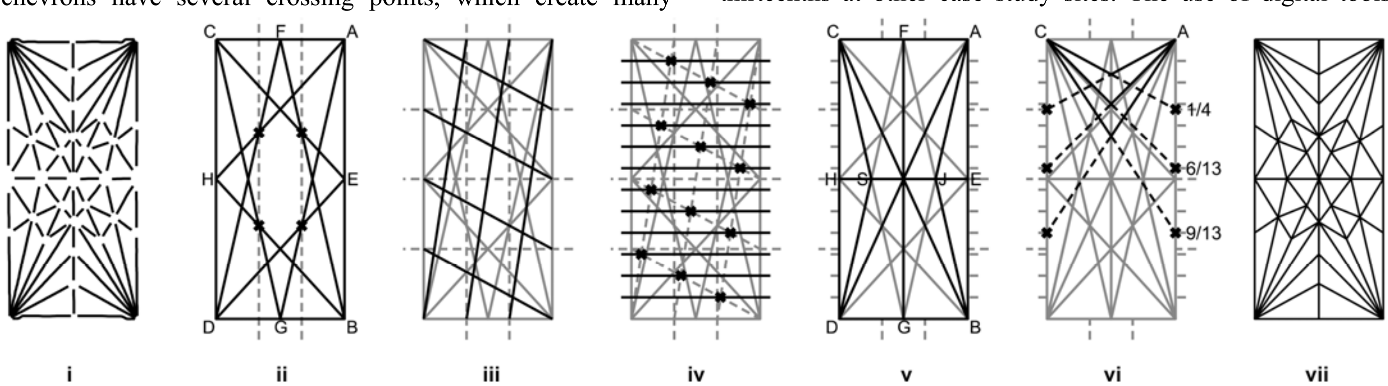

Fig. 4. Hypothetical two-dimensional design process.

enabled us to rigorously test many scenarios. For example, using six thirteenths to plan the second set of longitudinal tiercerons could have been mistaken for one half, however, the creation of thirteenths elsewhere in the plan, as well the accuracy of our survey data and digital analysis tools gave us confidence in the results. Also, as we had data from multiple bays, the possibility of settlement seemed less likely.

V. 3D PROCESS

Next, we could investigate the projection from 2D to 3D. Here, using Rhinoceros for digital analysis was crucial as it enabled us to quickly and accurately test different scenarios. To project a rib, we need to identify two fixed elements, which are used to infer the third unknown element using a simple process of geometry. The variables are the arc's radius, its centre point, and its apex height. We had already identified the springing points of all ribs in plan. The laser scan orthophotos and mesh models were very useful for identifying fixed elements. Firstly, the existing longitudinal window apexes to the north and south gave us a fixed point for the longitudinal wall rib apexes (Fig. 2 centre image) and likewise, the apex of the east window of the Lady Chapel gave us a fixed height for the longitudinal ridge rib (Fig. 2 right hand image), which runs horizontally along the entire chapel. The transverse ridge rib, spanning between the two apexes above the window to the north and its counterpoint to the south, has an upward curvature to meet the ridge rib running longitudinally. By analysing the radius and centre point of the traced lines, we observed that the centre point of the curved transverse ridge rib was located at the level of the ground floor (Fig. 2 right hand image). It is highly likely therefore that the medieval masons used this arc to determine the exact geometry of both ridge ribs above the window openings. Additionally, as the ridge ribs form the apex for all ribs except liernes (which are already determined in plan) we thus know one of the three fixed elements for all major ribs.

We believe the second fixed element is the radius, because distances derived from the plan are similar to the radii of the arcs projected above. For example, the radii of the transverse ribs, diagonal ribs, transverse tiercerons and the third set of longitudinal tiercerons are all akin to the length of the transverse rib in plan, which is 6.74 metres. Likewise, 7.41 metres is the distance in plan of the diagonal ribs, which is akin to the radius of the first two sets of longitudinal tiercerons. Using identical radii simplifies construction as rib voussoirs with the same mouldings can be used interchangeably.

This leaves the arc centre point in relation to the impost level as the unknown element. In the Lady Chapel this is much lower than we have found with ribs at other sites, where usually one principal arc's centre point aligns with the springing level, however, in the Lady Chapel, the closest any rib centre point gets is 0.73 metres below it. Nevertheless, using the known radii and drawing two circles with their centre points at the known apex and springing point, one of the crossings of these two circles provides the unknown centre point, which can then be used to create the final rib arc. With this process, we can define all the principal ribs and tiercerons, and finally we can add the liernes based on the 2D plan already created. The masons thus had the geometry needed to construct the formwork for the vaults, and subsequent stonework.

VI. REFLECTIONS AND CONCLUSIONS

In this paper, we have outlined our methods of digitally capturing 3D data at a specific case study site, and demonstrated how this is interrogated in order to hypothesise how medieval masons designed a vaulted ceiling. Repeating this process across several sites in England is allowing us to find trends, for example the use of the starcut diagram, which is divided as far as thirteenths at the Ely Lady Chapel, the largest division we have identified to date. We can also test previous scholarship, such as Woodman's suggestion that the vaults are most likely fifteenth century, akin to Norwich cathedral, once we have surveyed the vaults there. Another future step is to compare such findings with researchers working in continental Europe and beyond.

Besides our main aim of enhancing understanding of medieval vault design, the process has enabled us to create accurate digital records of design features of churches and cathedrals across England, which we have already begun to share with key stakeholders as heritage assets and to assist with modern interventions. In addition to traditional dissemination such as articles and images, we will investigate and include tools such as rapid prototyping and digital models to further explain our ideas, which have already started to test at our pilot site of St Mary's Nantwich.

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