Development of Gothic vaulted space and perception of technology

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ABSTRACT

The provision of stone vaulting in the Gothic period as a response to a new spatial order and as an efficient fire-proof roofing system led to architectural expressions characterised by the concordance between shafts and ribs and the gradual disintegration of the lateral envelope. Moreover, the prominence of high quality tectonics in ecclesiastical architecture of increasing urban significance played an important role in consolidating technology at the heart of political and social development. The resulting possibilities in the scale and space unification of the buildings associated stone vaults with wealth and modernity, and they would become vehicles in the social progression of patrons and technical advancement of stone masons.

Essential insight into how such associations have happened can be found where experimentation or dissemination of new forms occurred. This paper seeks to discuss the architectural and technological culture of vaulted roofs in terms of their geometry, construction and performance, and a speculative area to explore is the experimental designs in Lincoln Cathedral (1192-1280) and its possible effects in Lincolnshire and Nottinghamshire.

INTRODUCTION

The spatial qualities, structural efficiency, fire-proofing qualities and tectonic integration of stone vaulting has served the design of early Gothic churches in England in a very variable manner. In modern terms, it is logical to expect that the (often impressive) spatial qualities of vaulted interiors in rich cathedrals and priories would have inspired other patrons and informed contemporary construction practice through the stone mason crews involved.

Lincoln Cathedral is characterised by experimental design of its stone vaulting and integrative spatial treatment with lateral walls that kept their Norman robustness[1]. English Gothic is often marked by single buildings (like Canterbury, Westminster) that produced abrupt changes in direction, followed by multidirectional exploration of their achievements in other buildings[2], and this speculative study explores such possible effects of Lincoln in vaults in the surrounding area of Lincolnshire and Nottinghamshire.

This work would also like to explore the kind of cultural act stone vaulting could have been in this region in the Early English period. The new treatment of natural daylight reflecting through the large windows to the vaults, the scale and rhythm of the new roof, the influence on the liturgical rituals and the use of music must have left a strong impression of progress and prosperity to the ecclesiastical patrons, the faithful and the masons. It is interesting therefore to understand any expression of these achievements in other opportunities to build in a similar scale.

The technical achievements in Lincoln can be summarised in the developments around the creation and appreciation of the skewed vaults in St. Hugh's choir (1192 to 1280): the slow deviation from the regular crossing of barrel vaults, the transformation of the ribs into increasingly decorative and three-dimensional tiercerons, the breaking of the vault into framed bays, the confident concordance expressed in a consciously unified structural scheme which accommodates efficiently the thrusts.

Most of these churches belong to monastic buildings and cover a NW-SE strip through Lincoln towards Yorkshire (Fig. 1): they are few and diverse, lacking the scale and vigour of Yorkshire abbeys for example, and often key parts are missing or were heavily restored which hampers the full appreciation of the range of possible vaulting solutions. Nottinghamshire abbeys may have had direct influences from the richer and architecturally complex Yorkshire abbeys, especially with those of monastic affiliation (Benedictine or Cistercian foundations).

Figure 1: Location of the case studies

The first impression is that with the exception of Southwell none of the vaults presents the dimensions or even structural challenges of the choirs in Lincoln. Technical progress however is a complex process in the construction industry of the period and area, clearly conditioned by patronage. Choices by some personalities or monastic orders could be tied to certain historical traditions or the values attached to specific architectural forms[3].

However, what appears as architectural form in these buildings should not be confused with advancements in construction techniques[4]. It is possible therefore that Lincoln influence was in those details that made such structures possible at all, even when patrons would only seek simplified quadripartite ribbed vaults. Project management of ambitious buildings like Lincoln Cathedral should have been a challenge as the presence of various crews working contemporarily in Durham has shown[5]. The scale of team endeavour[6] in Lincoln was not possible in smaller churches, reducing the possibilities of reproducing some of the features. Long spanning vaults, extensive stone carving (for ribs and shafts), large amounts of stonework and long leading times to allow lime mortar to set would not be affordable in smaller scales or at a purely local level.

This paper therefore aims to explore the technical culture of stone-masons in approaching the design of vaulting and reciprocally the vaulting as a cultural act through its technical achievement. In the case of Lincoln, a key tool is the development of the technology of ribs as a vehicle for progress and cultural expression.

VAULTING TECHNOLOGY IN LINCOLN CATHEDRAL

The key achievements in technology and structural performance at Lincoln are found at the transition of the innovations from the skewed ("crazy")[7] vaults at St. Hugh's Choir vaults to the tierceron vaults at Angels' Choir and the nave (Fig. 2). The skewed vaults developed between 1192 and 1265, and were probably remodelled after the collapse of the tower in 1239. Two of their innovative aspects will be used in the discussion in this work: the potential of boldly detaching form and elements from their function[8] and the generation of unorthodox new surfaces that do not result from construction practice, enabled by the elegant use of ribs. The latter were treated as a 3D geometric and constructional device in order to define the complex intersections and cover the imperfections. Inevitably, hierarchies started appearing between the ribs (according to their function) and the true innovation was at the transition to the tierceron ribs at the nave and the Angels' Choir (1265 –1280), which would determine parts and their relationship with the overall scheme of the vault.

Figure 2: The skewed (left) and tierceron (right) vaults at the choirs of Lincoln Cathedral

Regarding the geometry, the span of the bay S (11.65 m) is double the rise of an equilateral triangle generated by the width W (6.4 m). This system created a more oblong vault that is probably more suitable to the wide transverse span. A lot has been said about how the twisted geometries break the regular bay rhythm and the reversal of the convergence of the ribs from the keystone(s) to the springings can be seen more as a mannerism[9]. The transverse vaults have however been attached to a hybrid clerestory window made of lancets, which appears as a conservative attempt to transparency, an evidence of the rather Norman traditions that still blended the design in Lincoln[10]. These windows have a large area and force the transverse vaults to stand on stilted spandrels (Fig. 2) in order to avoid narrow pointed arches and blocking of daylight. These areas however are relatively wide and create deep compartments. Later, the tierceron vaults controlled better the transverse barrel vault profile, which is probably the result of the better construction quality due to the presence of closer spaced ribs.

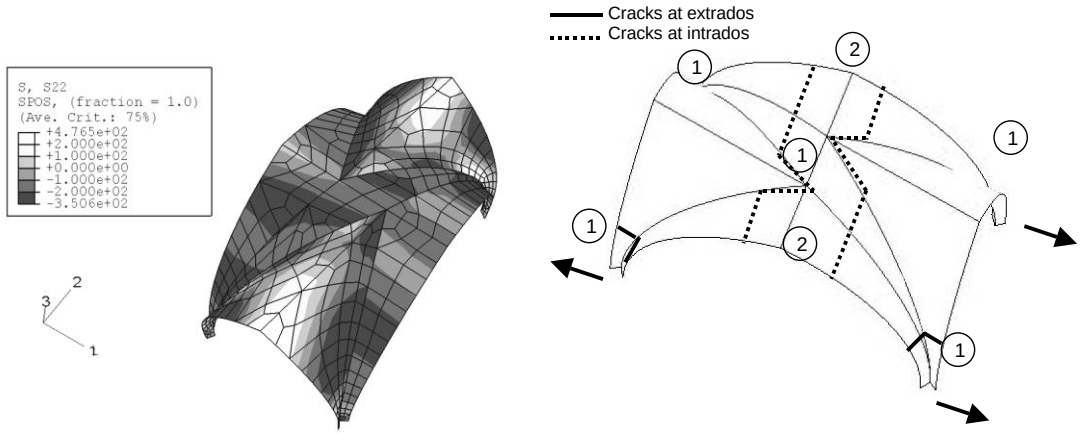

Figure 3: Skewed vaults (St. Hugh's Choir): transverse stress S22 at the extrados at self weight (kN/m^2) and possible failure pattern at a uniform spread of the supports at 500 mm

The structural behaviour was not perceived by the masons as loads or strength but deformations may have been apparent during the delicate construction process. A modern Finite Element spatial analysis[11] can reveal stresses and deflections and verify that the eccentrically placed transverse vaults cause a twist at the crown (Fig. 3). Analysis of the tierceron vaults shows that the alignment of the transverse vaults and the better construction quality due to the density of the ribs has a beneficial effect as a wider area of the keystone is under compression. The common failure cause due to supports outward movement starts at 91 mm with cracks in zones 1, followed by the area around the vertex (zone 2). Failure (creation of a mechanism due to these three cracks) will accordingly develop as a twist at the central section, at a 503 mm spread or 1/25 of the transverse span, indicating high stress reserves and highlighting what was probably perceived by the masons during the construction of the vaults.

The FE model showed little improvement of the structural behaviour with the addition of tierceron ribs. The complex folding however of the vaults results in very irregular intersections of the stonework that can be guided and even regularised by the use of ribs. The exposed stone courses in the later tierceron vaults show high quality that was probably the result of the dense rib network and this is also reflected at the shape and precision of the clerestory edge.

There is a single tier of flying buttresses whose pinnacles over the pier element becomes slightly more elaborate and better integrated in the tierceron vaults. It serves its function to contain the thrusts due to self weight (as demonstrated by the structural model) but the presence of an upper tier as bracing against wind forces was not perceived by the masons.

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It is interesting to explore how far the use of ribs in these vaults to highlight and strengthen complex junctions as well as the rest of technical innovations have established patterns for similar vaults in the immediate region. Starting with Nottinghamshire, there is no common geometric or even stylistic characteristic to link the buildings. Major, high vaults are found at the choir of Southwell Minster and the nave of Blyth Priory, while minor almost square vaults exist at the aisles of Worksop Priory and the undercroft of Rufford Abbey.

Priory of St Mary and St Martin, Blyth (1100-1230)

This Benedictine alien priory was dependent on Holy Trinity, Rouen, and the church was largely modelled to Jumieges Abbey in Normandy at its foundation ca. 1100. Following that model was important for political affiliations with Rouen and William the Conqueror's plan for Norman abbeys. Consequently stone vaulting was part of the original aisles, as it can be seen today, but no vaults were designed at the nave. Rather rough groin vaults were built at the aisles (Fig. 4), which are heavily deformed today.

Early English quadripartite ribbed vault were added on the Norman elevation at about 1230 and the use of such a relatively expensive roof is probably related to the high revenues of the Priory and its important location on a busy commercial route, where the Priory was offering hospitality. No further remodelling of the aisles or extension of the choir to the East occurred until the Dissolution[12] in 1536, which can be considered as an architectural transformation that respected the Jumieges/ Benedictine prototype. The vaults show an attempt for concordance with the existing Norman shafts (Fig. 4) and they are efficiently attached to the clerestory windows letting sufficient daylight in.

Figure 4: The aisle and high vaults in Blyth Priory church (2007).

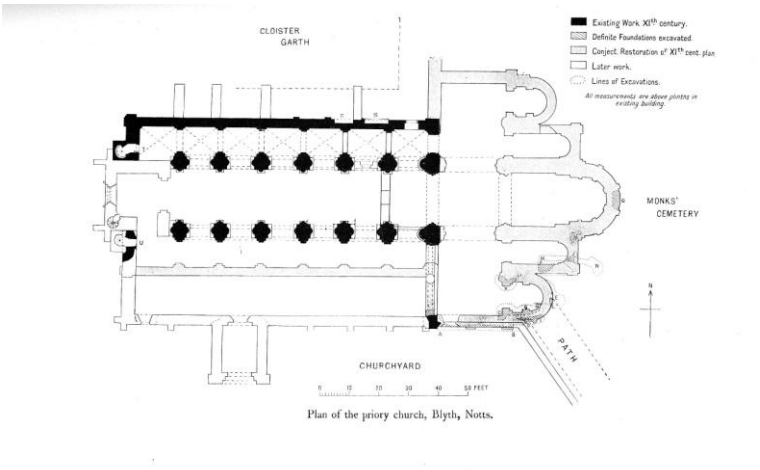

Figure 5: Plan of Blyth Priory church (1926) with a hypothesis for the apse[13]

The average dimensions of each bay are S = 5.6 m, W = 4.2 m (Fig. 5), resulting in a diagonal ranging between 7 and 7.5 m. The vaults spring efficiently from the cylindrical shafts and the rise F = 4.6 m. If a semicircular diagonal rib is assumed as construction practice, then the rise would have been 3.6m average, which means that the vaults are stilted in order to fit above the Romanesque clerestory windows. The vault masonry is rubble and plastered, and the nave ribs are well executed and mark carefully the intersections. No tierceron or ridge ribs have been used to frame the bays and no hierarchy of members was attempted.

This scheme allows a simple superposition of well-executed vault on an existing and archaic elevation, almost a simplified operation to what occurred at the choirs in Lincoln. These vaults appeared at the same time as Lincoln was being remodelled (and later Southwell) while no vaults in the major Benedictine priories of the Diocese of York (Selby, Whitby) were planned. There is an almost French simplicity and efficiency, which can be considered as a statement to the continuous row between the Diocese of York and Rouen for the control of the Priory.

Church of SS Cuthbert and Mary, Worksop Priory (1103-1240)

The building was the church of an Augustinian priory (Radford Priory) but only the original nave remains (Fig. 6, 7) after restoration in 1845-9 and 1922[14]. The nave (built between 1140 and 1170) has a Norman elevation similar to Southwell Minster (and to some extent to Selby Abbey), with alternating cylindrical and octagonal piers. The elevation and the straight support of the timber roof (Fig. 7), even in the restored configuration, show no signs that high vaults were ever planned. Stone ribbed cross vaults were built at the aisles, but were probably reconstructed or heavily restored in 1845. Any additions in Gothic style are visible in St. Mary's chapel at the East end (today's Lady Chapel), a gift by Lady Maude de Lovetot between 1240-50[15].

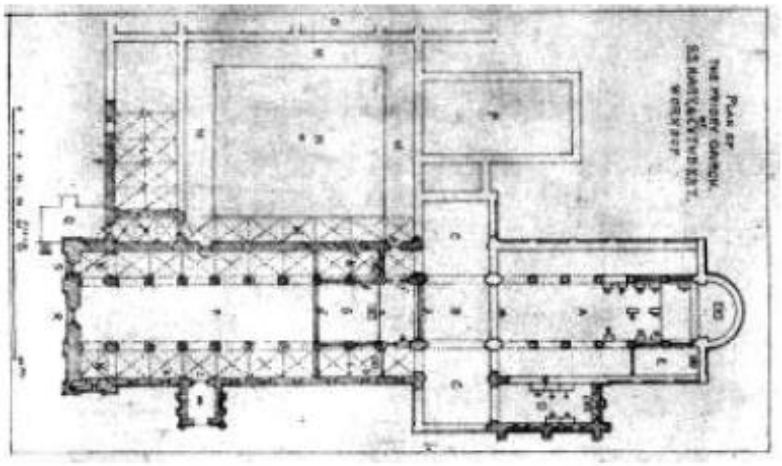

Figure 6: Original plan of Worksop Priory[16]

Figure 7: Interior of nave and aisle at the Worksop Priory (2010)

The design of the aisle vaults therefore seems to date from the original phase (1140-70). It appears they have collapsed in 1567[17] and they were probably reconstructed in 1845 using some original material from the ribs (Fig. 7) above the same footprint as the original vaults. Today they are defined by thin, elegant ribs that spring from corbels on the piers and wall without responds or shafts. The use of the ribs provides a clear and regular framing of each bay but without an attempt to identify primary and secondary members. The bay dimensions are S x W = 3.05 x 3.95 m.

Major addition of stone vaulting in the nave apparently never became necessary. A reason may have been the respect and fondness of the community and later the parish for this part of the fabric, as it became apparent later in the Dissolution of 1538 when the town asked for the nave to be kept and transformed into their parish church. Gothic vaulting may have been attempted in the Lady Chapel as some thin ribs springing from corbels at the corners suggest but they may have carried a timber roof (as in the choir of Selby). The restoration works may have been extensive leaving only limited evidence.

Abbey of Our Beloved Lady Saint Mary the Virgin, Rufford (1146 -1170)

The Cistercian abbey founded in 1146 by Rievaulx Abbey has not been reported to be exceptional, probably due to the austere living conditions promoted by the order. Construction of permanent stone buildings would continue by the 1160s using local craftsmen[18]. Vaults dating from 1170 survive today after the destruction by the Dissolution at the undercroft of the Lay Brothers' Block (lower part of W range of cloisters): groin vaults are supported on octagonal piers at the *cellarium* while ribbed vaults roof the refectory (Fig. 8), arrangements close to Fountains Abbey.

A typical bay at the *Frater* measures[19] ca 4.5 x 4.5m. The design and construction of the vaults are quite robust in both cases, probably due to the main purposes to support the building above and provide a fire-proof enclosure. The plain ribs, of trapezoid section, are well integrated with the vaults and truly serve as a skeleton to the masonry. In both cases, the fabric is made out of regularly laid and tightly packed together brick units and probably they were all plastered originally. No remains of the abbey church apart from the base of some piers exist to allow hypotheses of the original structural scheme.

Figure 8: Lay Brothers' Block at Rufford Abbey (2007):
Groin vaults at the cellars (left) and ribbed vaults at the adjacent frater or refectory (right)

Southwell Minster (1108- 1288)

The Minster developed as a quite ambitious building starting from a timber-roofed Norman aisled nave and the west towers (1120-1250) followed by the stone-vaulted Gothic choir, its aisles and the east transept chapels between 1233-60, probably as a renovation of the previous Norman *quire*.

At the nave aisles (Fig. 10), the vaults follow a rather archaic domical form and in combination with the robust ribs they create a deeply undulated rhythm, in contrast with the inert masses of the contemporary groined vaults at Blyth[20] (Fig. 4). Like in Worksop, no intention for stone vaulting (like shafts and concordance) is evident in the elements of the Norman elevation. The choir however shows a definite attempt to create a carefully framed stone roof (Fig. 11). The high vaults roof an 8.4 x 4.3 m compartment divided by the transverse rib and highlighted along their axis by the ridge rib. The transverse vault has a profile that is inscribed in an equilateral triangle and is attached on a clerestory with lancet windows that combines with a triforium gallery till the middle of its height. The real windows however open to the outer wall.

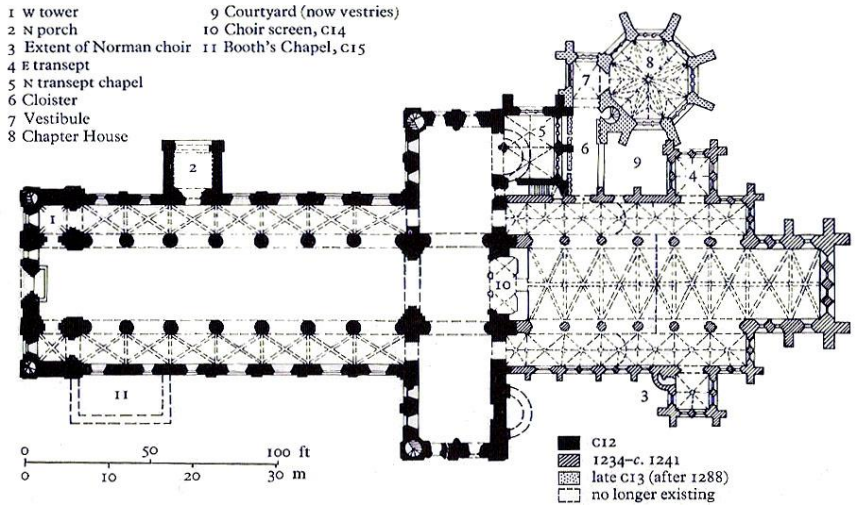

Figure 9: Plan of Southwell Minster[21]

Figure 10: The Norman nave of Southwell Minster and its aisle

Figure 11. Choir of Southwell Minster: aisle and high vaults (2006).

The solution is rather conservative and archaic and is similar to what was attempted at the contemporary St. Hugh's Choir in Lincoln. In addition, the ribs are used more consciously here to direct construction of the vaults and mask fabric inaccuracies but the treatment appears heavy-handed as in the case of the aisle vaults which appear as a hybrid between the spatial effects of the high vaults and the robustness of the nave aisles (an effect strengthened by the use of the same rib). Finally, the thrusts are contained by flying buttresses that abut the vaults higher and probably more effectively than in Lincoln.

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The examples in this county are surprisingly even less and no major vaults exist.

Kirkstead Abbey (1230-40)

The vaulted structure in Fig. 12 has an uncertain origin: chapel *ante portas* (gate chapel) of the Cistercian Abbey in Kirkstead, a church predating the abbey, or even the site of the original abbey church[22]. Most of the chapel has a quadripartite ribbed vault except for a sexpartite one at the chancel bay. Sexpartite vaults have been built at the transept of Lincoln or the E end of the choir in Southwell and the intention to link such patterns with the hypothetical original crown ending at St Hugh's choir in Lincoln may have given birth to the skewed vaults there. The chapel demonstrates the possibilities of such a form, even in a space where no complex architectural effects between clerestory windows and arcades were designed.

Figure 12. The interior of St. Leonard's chapel at Kirkstead Abbey[23]

Thornton Abbey (1282-c. 1308)

The Chapter House is the only significant structure that remains from the Augustinian priory dedicated to St Mary in 1139. The octagonal structure was begun in 1282 and the surviving walls are decorated with blind window tracery[24]. Most probably there was a stone vault roof with quite pronounced ribs, judging from the remaining edge moulding along the blind tracery. The quality of the decoration and its combination with stone vaults suggest the experiments from Lincoln have started finding a more integrative way of expression that involved the entire fabric, although the walls are still rather robust in their essence.

Figure 13: The ruins of the Chapter House in Thornton Abbey [25]

DISCUSSION

It is clear there is an absence of major vaulting examples directly resulting from Lincoln. Southwell still shows the very tentative steps towards detachment of form from construction process occurring at the same time as the skewed vaults while Blyth shows preference for simple French prototypes in an effort to integrate respectfully with the Norman elevation. Authors often find the effect of the experiments in Lincoln in the increased presence of linear decorative elements like the tracery[26].

The cultural act committed by the patrons of these few vaulted buildings was probably the will to supply a stone vaulted roof. The ribs became slowly a reliable device to trace the complex intersections in oblong bays and integrate imperfections but such benefits would be apparent for large scale vaults as in Lincoln (11.65 m span). Blyth (S = 5.6 m) showed plain vaults can be built (and left without buttresses), while Southwell (S= 8.4 m) becomes the limit. The Augustinian priory at Worksop was probably tied more to local than French traditions and stone vaulting was never contemplated.

Norman, rather conservative elevations and especially clerestory windows characterise all these churches. The high vaults examined here had to be stilted in order to maximise the daylight through the openings, with various degrees of success. The addition of increasingly refined vaults and ribbed systems did not go alongside a disintegration of the lateral envelope, showing that the masons did not have the confidence in the structural capacity of the linear elements as in France. In terms of fabric, this is a characteristic of Gothic in the wider region[27] and it would be interesting to explore whether there were different crews involved in the design of the more innovative vaults than in the vertical structure.

The activity went alongside the construction of important churches like Lincoln or the Yorkshire abbeys but by the second half of the 13th century focus on renovation using stone vaulting stopped from expanding further. Apparent reasons could be sought in possible satisfaction of the communities with buildings of hybrid forms, a respect for pre-existing fabrics, changes in the priorities of patrons, lack of skills among the masons or even employment of the most skilled ones in the huge and complex site of Lincoln Cathedral. Any technical transfer[28] afterwards would happen in the creation of tracery and the slow emergence of the Decorative style (as in the case of Newstead Abbey).

This study aimed to show the facets in the creation of a technical and architectural culture around the theme of vaults, focusing more on the abilities and progress of the stone masons, as a result from the presence of an important experimental centre like Lincoln Cathedral. The stone vaulting must have impressed many people in the region and there were (few) cases where a bold step was taken to remodel existing Norman choirs. The response shows a mixture of conservatism with a restrained innovation and the importance of concordance (especially in Blyth). Despite the lack of a local "school", the examples show a genuine preoccupation of local patrons and builders for wider developments and are a testimony to their progressive attitudes that eventually characterised the advancement of Gothic technology.

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