

Salisbury Cathedral and Its Diversity of Flying Buttresses

Johanna Mähner

Brandenburg University of Technology, Cottbus, Germany

ABSTRACT: The flying buttresses of Salisbury Cathedral are unique in their number of diverse types and in the irregular layout of these types in the Cathedral plan. Yet research on this topic has been neglected both from the fields of art history and construction history. Now the various types of flying buttresses were surveyed each as part of the complete section of the building and have been examined with the means of building archaeology within the research project presented here.

The section drawings form the basis for the ongoing research which aims at gaining a realistic understanding of the structural function of the flying buttress types. In this paper the analysis of the structural behaviour of a selected number of flyers is presented. The flying buttresses are examined as isolated structures under minimum thrust conditions in order to exemplify their strengths and weaknesses. The examination of the behaviour of the flying buttresses in the context of the overall system of the cathedral will follow.

INTRODUCTION

The structural function of flying buttresses aroused interest since the beginning of the gothic revival. Besides the ribbed vault they played a role in the discussions on the relation of form and construction in Gothic building. The essential structural role attributed to flying buttresses by Eugène Viollet-le-Duc is expressed in his comparison of a gothic cathedral without flying buttresses with a ship without keel (Viollet-le-Duc 1867, p. 60).

Georg Ungewitter and Karl Mohrmann dedicated a substantial part of the "Lehrbuch der Gotischen Konstruktionen" (Ungewitter; Mohrmann 1890) to the buttressing system and the flying buttress. Their analyses using graphic statics have been the basis for many later investigations. Jacques Heyman (1966) contributed a further step in methodology by applying plastic design principles on masonry and employing this limit state analysis to flying buttresses. The structural behaviour of flying buttresses was discussed in the overall system of cathedrals both by Helmut Weber (1957) and Jürgen Segger (1969), a new approach in this line of investigations was the photoelastic modelling by Robert Mark (1982) providing advanced insight. Recently Maria-Katerina Nikolinakou, Andrew Tallon and John Ochsendorf (2005, 2006) presented investigations on early Gothic flying buttresses that will be referred to in detail below.

This paper presents the intermediate results of a dissertation project on the structural behavior of flying buttresses at Gothic cathedrals. The detailed structural assessment is being executed at the example of Salisbury Cathedral with its variety of flying buttress types. The rare situation to examine a building as uniformly built as Salisbury Cathedral but still with several different solutions for flying buttresses is extraordinary. The findings of the project are meant to shed light among others on the following questions: To what extent do the buttressing systems contribute to the security level of the bearing capacity of the cathedral? Is a positive trend in the performance of the structural systems of the cathedral observable? How significant is the design of details?

METHODS AND AIMS

The focus of this research project lies on the analysis of the structural behaviour of flying buttresses at Salisbury Cathedral using the methods of "Historische Bauforschung" (building archaeology) and structural analysis. In a first step the cathedral was surveyed in five sections through the nave and the transepts by means of a tachymeter combined with CAD programs in its deformed state (fig. 1). Additionally selected details have

been surveyed and drawn by hand. Special emphasis was placed on any signs of failure and deformation that may give information regarding the functioning of the structure. The survey also focused on differences in the detail solutions of the flyers e.g. the head joint to the clerestory wall or the ashlar layout.

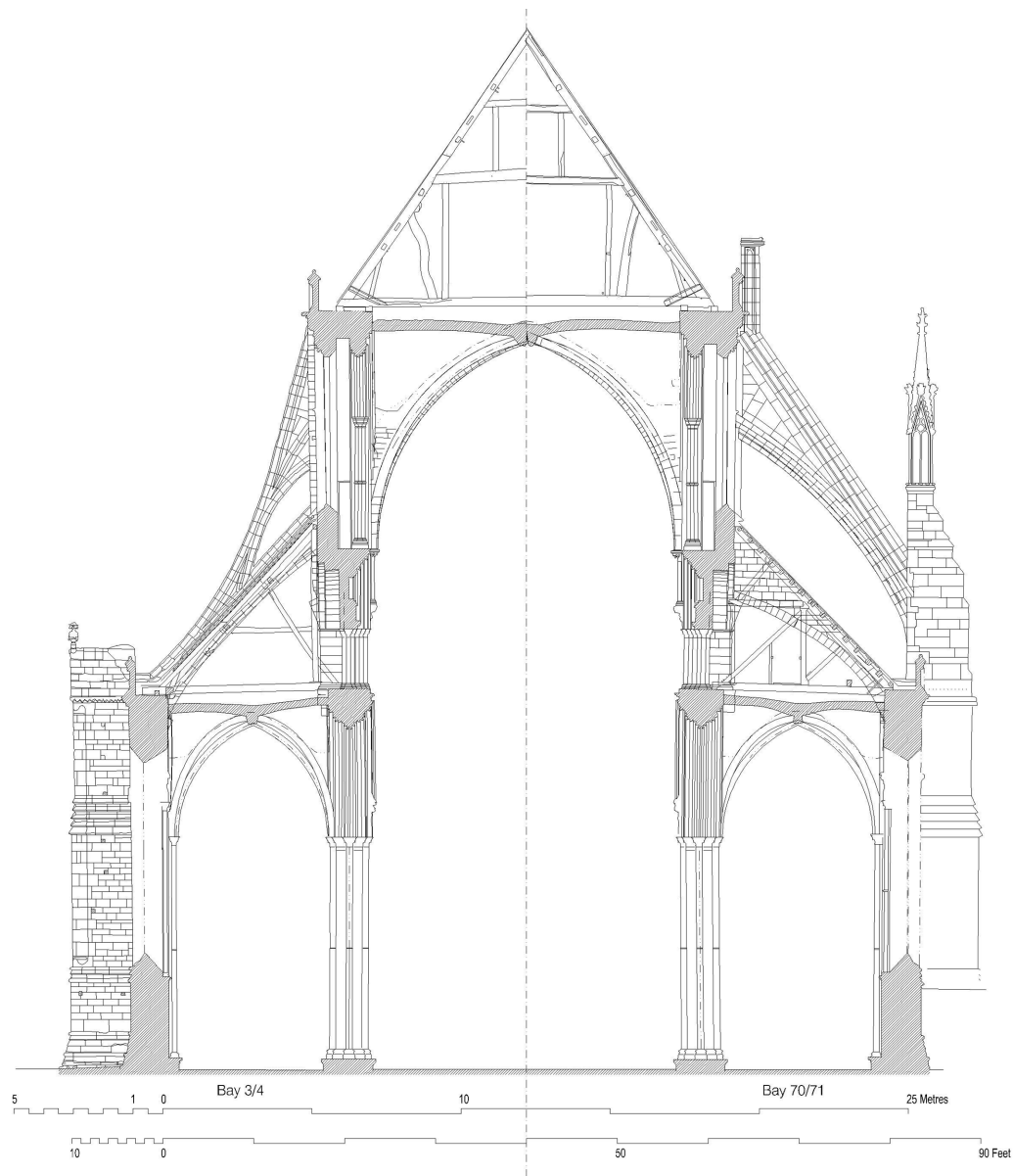


Figure 1: Salisbury Cathedral, nave section through bays 3/4 and 70/71; (Mähner A)

The second step has been the transfer of this information into the development of a structural model for the different sections of the cathedral. It is important for historic structures to take into account not only the current state of the structure but also its former states. In the case of Salisbury Cathedral and the specific questions concerning the structural behaviour of its flying buttresses this will include the change in the roof structures for the nave and the transepts as well as the side aisles.

The surveyed sections will be analysed as a whole mainly with the methods of graphic statics to discern the function of the flying buttresses in the specific system and the differences for the various types of flying buttresses found at Salisbury. But for a first estimation the flying buttresses are analysed as isolated structures – as presented below – in their passive thrust state (Heyman, 1966). This way of analysing flying buttresses was carried out for early Gothic flying buttresses in France by Maria-Katerina Nikolinakou, Andrew Tallon and John Ochsendorf (2005, 2006) and allows comparison with their findings. The essential second step to analyse the functioning of the flying buttresses in their specific system is being carried out presently.

The considerations of the dissertation project do not focus on the special situation, that was caused by the addition of the tower and spire, but on the general behaviour of the flying buttresses at Salisbury Cathedral. Therefore the flyers directly around the crossing are not taken into consideration as far as their load bearing behaviour is concerned but will in the following only be presented in the chronology of the building phases of the flying buttresses. Moreover in this paper the structural behaviour of three types of flying buttresses in the nave will be examined further.

SALISBURY CATHEDRAL: SHORT BUILDING HISTORY

Salisbury Cathedral is known as one of England's finest Cathedrals. It was built in the Early English Style during a relatively short time from 1220 to 1266 and shows a great uniformity in style. The Cathedral was built on a virgin site and the new town developed around the new Cathedral. The former Cathedral at the foot of Sarum Castle was abandoned thereafter. The building site lies on fluvial deposits of the river Avon.

After the laying of the foundation stone on 28 April 1220 the Cathedral was built from east to west with several building phases being identifiable, but without significant discontinuity. The consecration of the largely finished Cathedral was held on the feast of Michaelmas 1258 and for 1266 the completion of the Cathedral is reported (Cocke; Kidson 1993, p. 4, 43). The famous tower and stone spire over the crossing, with 123 m today still the highest in Britain, were added at a later stage in the Decorated Style. No documentary evidence exists for the precise period of the building of the tower and spire. The proposed dating for the beginning of the construction of the tower and spire ranges from 1285 (Spring 1987, p. 52) and around 1300 (Morris 1996, p. 47; Tatton-Brown 1991, p.96) to the popular but today rejected date 1334 (see Tatton-Brown 1991, p. 94). At the time of the first completion of the Cathedral the tower had a low lantern and was possibly topped with a pyramidal roof (Tatton-Brown 1991, p. 77). The change in style between Early English and Decorated can be well distinguished in the elevation of the tower. The addition of the weight of the tower and stone spire caused many structural problems which resulted in manifold strategies over the centuries. This is visible at the Cathedral both on the outside and on the inside. Additional flying buttresses were one of the first measures to be taken against movements induced by the spire weight.

THE BUTTRESSING SYSTEM

Building phases

In its initial stage Salisbury Cathedral had a buttressing system that was well concealed beneath the side aisle roofs. The walls of the clerestory showed only small pilaster strips as they can still be seen in the bays without external flying buttresses. These initial flying buttresses will be referred to as internal flyers or type 0 in the following. They are shown in figs. 1, 5. Figs. 2 – 4 give an overview of the localisation of the different external flying buttresses of the monument.

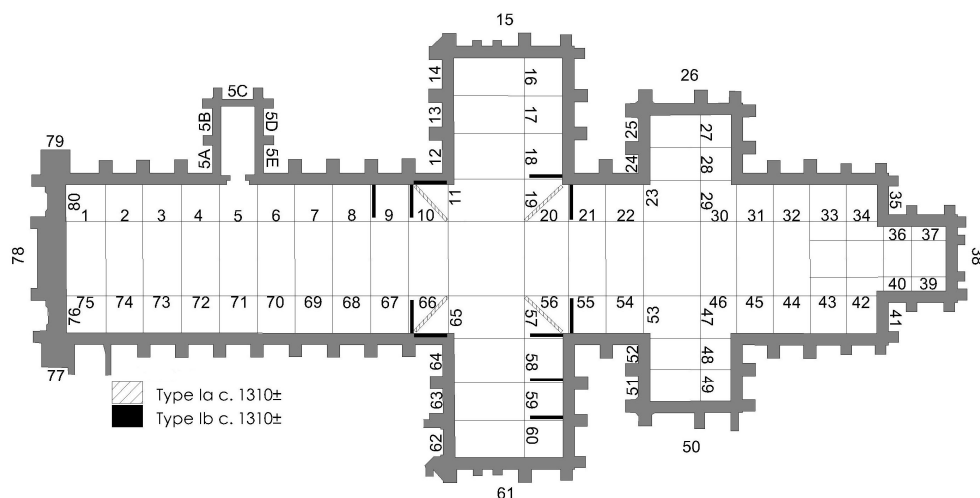


Figure 2: Salisbury Cathedral, Location of exterior flying buttresses type I; (Mähner B)

The first change in the buttressing system occurred shortly after respectively parallel with the addition of the tower and spire. The external flying buttresses of the first phase are located around the crossing. They are divided into two types (type Ia and Ib) because of their differing mouldings. Type Ia runs diagonally in the corners of nave and main transept and the flyers of type Ib are arranged perpendicular to the nave respectively the transept at the bays around the crossing. These flying buttresses form a cage around the tower. Two flying buttresses of type Ib (bays 58/59 and 59/60) exist at the south main transept and also one at the north side of the nave (bay 8/9). Richard Morris suggests a dating around c. 1310 for type I (The dating for the flying buttresses in the following are based on Morris 1996 as well).

Some of these flying buttresses of the first phase have been replaced around c. 1320 (type II), probably due to further displacements of the tower, which leaned to the south-west. At the south side of the nave two additional flying buttresses were added at the same time and with the same mouldings. As the external flying buttresses of the types I and II were added, the internal flying buttresses remained as they were. The new members function in addition to the former system.

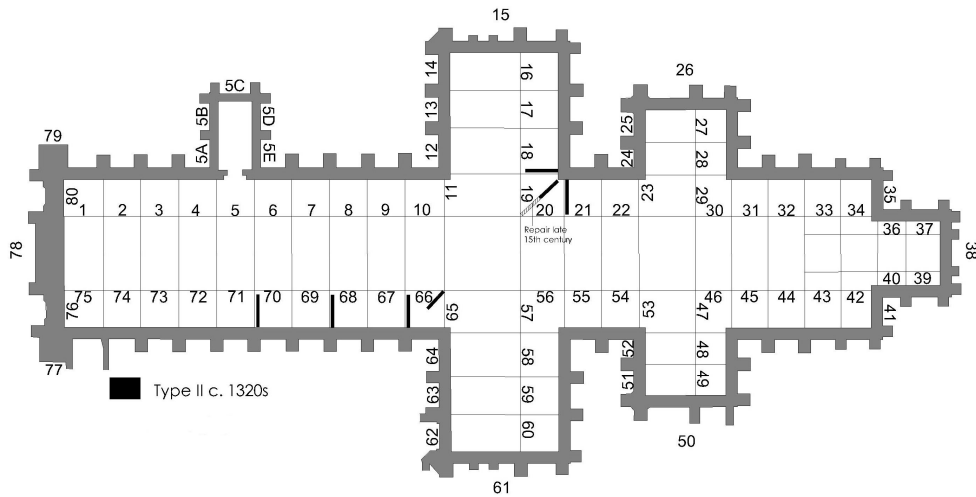


Figure 3: Salisbury Cathedral, Location of exterior flying buttresses type II; (Mähner B)

The next phase of flying buttresses was built in the 15th century. Three of these occur in the middle of the nave, one on either side of the North porch and one on the opposite side of the nave to the south in bay 72/73 (type IIIa). Another pair of flying buttresses can be found at the north transept in bays 16/17 and 17/18 (type IIIb). These flyers replace the original internal flying buttresses and form a new system that is external and internal in one member (see fig. 5). In the second half of the 15th century the last type of flying buttresses was built (type IV). Two flying buttresses of this type are located at the east end of the choir at the transition to the trinity chapel.

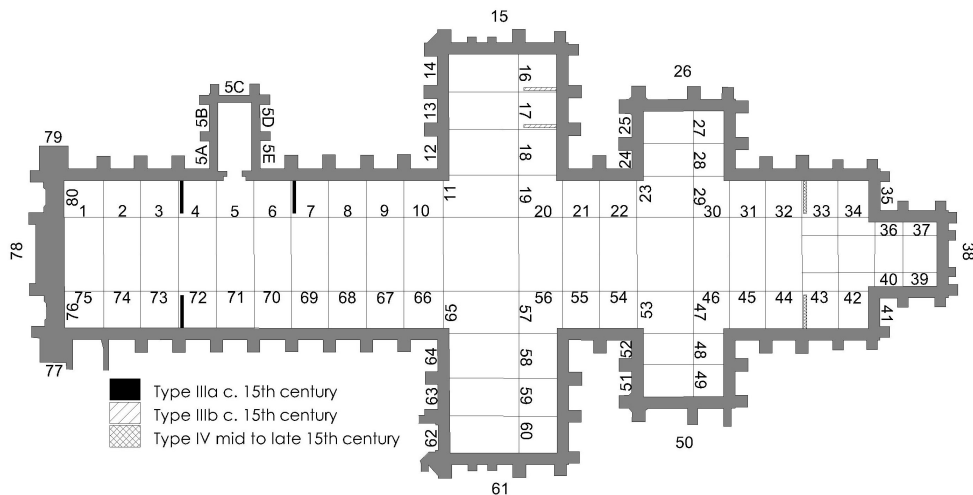


Figure 4: Salisbury Cathedral, Location of exterior flying buttresses type III and IV; (Mähner B)

Specifications

The specifications of all flying buttress types will be given here in respect to their shape and form. For the types that have been examined further within this project more detailed information will be provided. The geometrical specifications are listed in table 1.

Type 0

Type 0 are interior flying buttresses (figs. 1, 5). They are located beneath the side aisle roofs in the triforium level. They consist of two arches which form an irregular pointed arch with its peak near the main aisle wall. The minor arch can be regarded as a special form of head support for the main arch. The main arch consists of one row of plain arch-stones with ashlar masonry with horizontal courses on top. The springing from the side-aisle wall is built in tas-de-charge on top of a projecting ashlar as a base. This projecting stone will have served as abutment for the centring. The minor arch has a tas-de-charge springing from the triforium pillar and develops to a single row of arch-stones as well. The detail of the point of the arch differs in the pattern of the joints. The flying buttress ends right underneath the roof, the upper termination is hidden by the roof structure. The masonry of the flying buttress is coursed in with the masonry of the main aisle wall. Except for the arch-stones the masonry is a two shell ashlar construction with a rubble core.

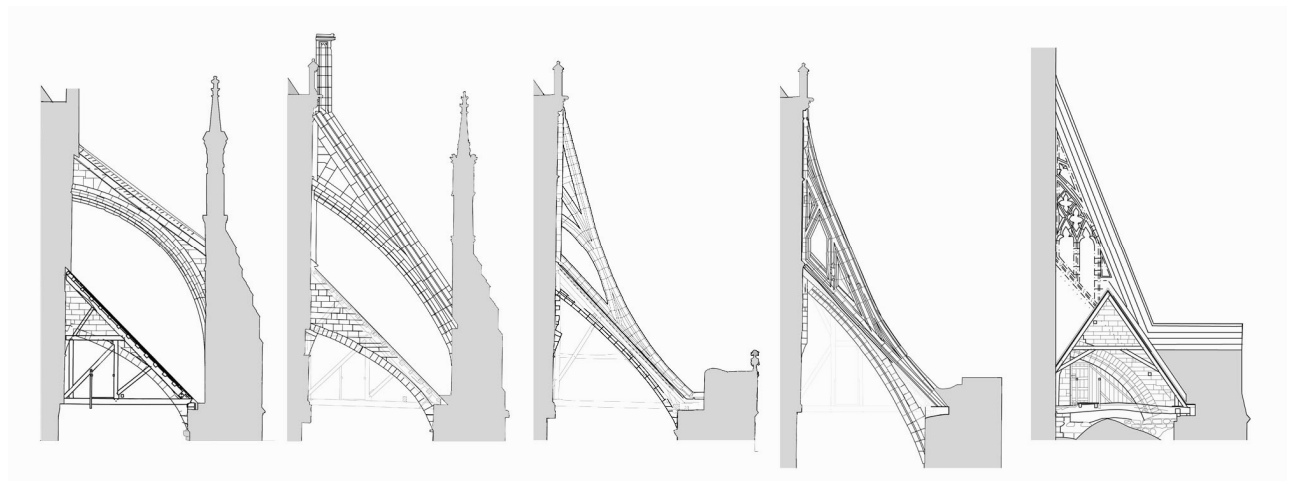


Figure 5: Schematic representation of the flying buttress types 0/Ib, 0/II, IIIa, IIIb, IV (left to right); (Mähner C)

Type I

The flying buttresses of type I are exterior flying buttresses (type Ib see fig. 5). They are divided into type Ia and Ib regarding their moulding, but they also differ in shape due to their different location at the building. Besides the difference in span the corner flyers abut the tower at a higher level.

The flying buttresses of type I show an inclined straight extrados line and a curved intrados line. The intrados curve of type Ia can be described by a circular arc. The flyer consists of one row of elaborately moulded arch-stones, plain ashlar masonry on top and a moulded coping. The masonry pattern follows in its courses the curve of the intrados. The coping has courses parallel to the extrados line.

The intrados curve of type Ib can be described by a circular arc. The flyer has three rows of moulded arch stones, a masonry infill with horizontal courses and a coping. The coping has courses parallel to the extrados line. The stones of the coping have a carved surface that gives the coping a shingle-type look.

Type II

Type II flyers (figs. 1, 5) are situated solely on the exterior of the Cathedral. Around the tower several of the type I flyers were replaced by type II (see figs. 2, 3). In their basic design with an inclined straight extrados line and a curved intrados line type I and II are the same. The intrados curve of type II can also be described by a circular arc. The whole flyer is elaborately moulded except for the spandrel part. The intrados line is formed by one row of arch-stones. The coursing in the lower part of the profile is aligned to the arch-stone and shifts for the upper part to courses parallel to the extrados line.

Table 1: Geometrical specifications of the design of the flying buttress types

type	inclination :		centre point	opening angle
	intrados	extrados		
0	40°	46°	inside nave pillar	50°
Ia	~50°	~44°	inside nave	~40°
	~72° (upper strut)			
Ib	47°	37°	inside nave	80°
II	50°	54° – 56°	~centre line of the nave	36°
IIIa	48°	66°	inside opposite nave pillar	20°
IIIb	46°	64°	inside transept	29°
IV	41°	68°	inside nave wall	58°

Type III

The flying buttresses type III (figs. 1, 5) vary distinctly in shape and form from types I and II. They are situated on the inside and on the outside and combine the two levels of flyers in one structure. This is accomplished by splitting the flyer at the middle in an upper and lower section. Intrados and extrados line are formed by curves with an opposing curvature thus enabling the splitting.

The intrados can be described by a circular arch and lies under the side aisle roof. The extrados curve differs slightly for types IIIa and IIIb. More significant are the differences in the design of the intermediate parts. Basically type IIIa is dominated by flowing curved lines and type IIIb by austere straight lines.

Type IIIa has a curved extrados line with varying curvature, whereas the extrados of type IIIb is described by two straight lines with rounded angles. This is emphasised by the linear design of moulded bars that run along these lines. The intermediate part is shaped by a framework of moulded bars as well as plain spandrels and one opening. The upper element of the flyer type IIIa has an intrados formed by a circular arch, leaving an

opening of segmental shape between the upper and lower part of the flying buttress. The curved lines are also emphasised by paralleling mouldings.

The former interior buttresses of type 0 were removed. Remnants of the original internal structure can still be found where the flying buttress were coursed in with the masonry of the walls. In the nave the interlinked ash-lars at the connection to the main aisle wall were left projecting as they were. In the transept the gaps between the interlinked ash-lars were filled with fitted ash-lars to form a pilaster strip. The springing of the original internal buttress was reused in bay 72/73, in bay 3/4 only the corbel stone of the springing remained and at the remaining bays the springing of the flying buttresses was built completely new.

Type IV

Type IV differs greatly from the other types (see fig. 5). The flying buttresses of type IV form a plane with the east wall of the retrochoir, the Trinity Chapel being only as high as the side aisles. The inner part of the flying buttress in the triforium level is rather a wall pierced by an arch. This arch abuts directly on the triforium wall and consists of two rows of arch-stones, the inner moulded, the second plain. The exterior part has a steep straight extrados, the area between the strut forming the extrados and the roofing is filled with bar tracery.

Analysis and evaluation of the structural behaviour of the flying buttresses

The structural behaviour of the three types of flying buttresses in the section shown in fig. 1 has been examined with the means of graphic statics and their minimum thrust lines were obtained. They are given in fig. 6; for the flyer of type 0 two states are represented, as a continuous line the minimum thrust line for that geometry and the dashed line showing the minimum thrust line restricted in its formation by open cracks in the flyer recorded at the survey.

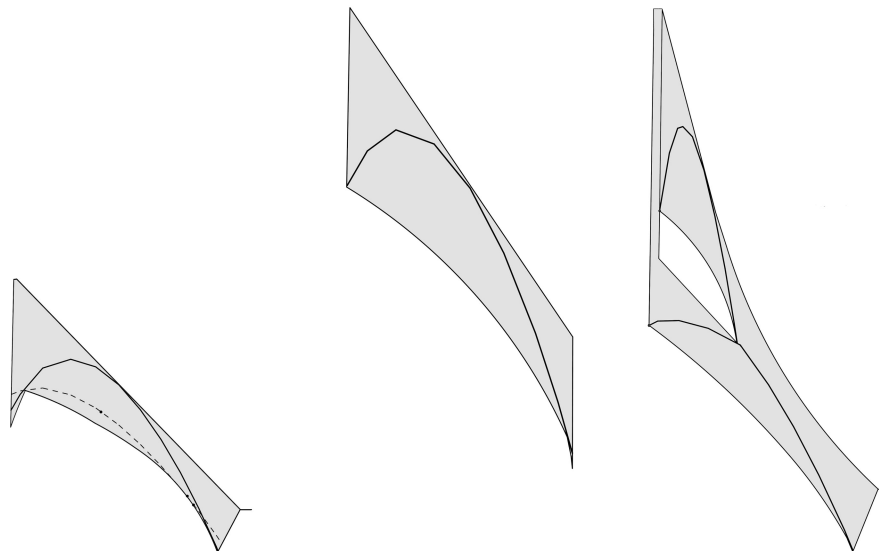


Figure 6: Minimum thrust lines for flying buttresses type 0, II, IIIa (left to right), drawn to scale.

Maria-Katerina Nikolinakou and Andrew Tallon formulate the following three criteria of the minimum thrust state for the evaluation of the effectiveness of flying buttresses:

- a. The lower the minimum thrust, the lesser the load exerted by the flyer onto neighboring structures (clere-story wall, culée), and the larger the outward displacement of its supports able to be sustained before collapse.
- b. A more vertical line of thrust at the culée increases stability, because a horizontally directed force would tend both to overturn the supporting structure and to induce shear stresses in the upper culée masonry.
- c. Conversely, a more horizontal line of thrust at the head increases stability, because a predominantly vertical force component can cause sliding among the first few claveaux, whose joints at the flyer head are nearly vertical. (Nikolinakou; Tallon 2006, p. 2350)

These criteria form the basis for the following analyses. In addition the general structural behaviour and the corresponding values of the horizontal thrust will be compared.

The minimum thrust lines for flyer type 0 and II resemble each other in their form. Type II generates a minimum horizontal thrust that is about 25% higher than that of type 0. But a comparison between type 0 and II regarding their minimum thrust values is in the context of the structural system of the cathedral rather pointless, since the two are abutting on the nave wall at completely different levels and serve different tasks in the structural system. Therefore the thrust values of the upper and the lower flyers respectively flyer parts are compared in the following.

The minimum thrust for the restricted section of type 0 is about 125% higher than that for the complete section and about 25% higher than that of the lower part of type IIIa. Furthermore the minimum thrust value for the lower part of type IIIa is about 75% higher than the value for the complete section of type 0.

In the upper part the relation is far more striking: The minimum thrust value for type II is more than 700% higher than the value for the upper part of type IIIa. For flyers abutting on the upper part of the clerestory wall mainly above the springing of the vault, a low minimum thrust on the one hand has to be considered positive for the system, but correlating with a steep rise of the thrust line the risk of sliding increases. There is no need to counterbalance any permanent internal forces such as the horizontal thrust from vaults. But it is important for these flyers to be able to react to a broad spectrum of variable wind loads. Thus for upper flying buttresses criteria a. and c. rival in the efficiency of the flyer.

The flying buttress types II and IIIa can be viewed as examples for this conflict of aims. Type IIIa exerts a fraction of the horizontal thrust compared with type II but gains this advantage by a higher risk of sliding. The passive thrust line for type IIIa runs almost parallel to the head joint, but this risk is counteracted by the shape of the ashlar at this point – for both types.

Type 0 also shows a relatively steep rise at the head with a risk of sliding if the masonry joints are orientated in a similar angle as the thrust line. This potential problem was circumvented for the joint to the nave wall by the design with the little secondary arch with a tas-de-charge construction for the springing. But with this measure the problem was just shifted to the point of the arch. The risk of sliding depends in this case on the orientation or better still the lack of a masonry joint at the point of the arch. A variety of different treatments for this detail exists in Salisbury Cathedral without the definite evidence for a beneficial development regarding the problem of sliding. In a few single cases (e.g. bay 9/10, 21/22) sliding has actually occurred.

The comparison of the lower flying buttresses shows that the structural behaviour of type IIIa is very suitable to counterbalance the passive thrust of the vaults with no risk of sliding, whereas for type 0 this risk remains. The structural behaviour for the restricted section of type 0 shows that the structure formed a structural system (the arch stones themselves have formed a statically determinate system with three hinges) that suits criteria a. and c. under the prerequisite that the passive thrust of the vaults has to be met.

The inclination of the thrust lines at the springing is for all types relatively steep and the risks mentioned in criteria b. are therefore marginal.

CONCLUSION AND OUTLOOK

In a preliminary estimate the structural behaviour of type IIIa appears well adjusted to its structural role in the system. This is particularly interesting since the construction of these flying buttresses required far more effort than the addition of an external flyer as practiced before: The nave wall had to be supported while the initial flyer was taken down and the new one built. The side aisle wall was partially dismantled to build the new springing of the flyer. The side aisle roof had to be opened, if not partially reconstructed. Additionally there was no evidence found at the building that would hint to failures in the former construction in the area where the new flyers were built that would necessitate action. On the contrary the cracks recorded on the flying buttresses type 0 decrease from the crossing towards the west considerably and are present at the adjacent bays in a small extent only. From a modern point of view the decision to build these flying buttresses presumably goes along with great confidence in the enhanced performance of the new construction to justify this effort. The structural analysis so far points out that the designer estimated their performance quite well.

The structural behaviour of the flying buttresses type II with its high horizontal thrust corroborates that this structure was designed to withstand permanent loading as induced by the weight of tower and spire and not specifically active loads. But the builders kept to one design for all flying buttresses built in one phase.

This study including the survey of the five different types of flying buttresses at Salisbury Cathedral and the examination of the structural behaviour of the first three types as isolated structures has already produced some interesting results. This restricted examination already proved the combination of the two aspects building archaeology and structural analysis to be very serviceable for the research. This will be even more so when examining the flying buttresses within the structural system of the entire building. This is the next step in this dissertation project. It will remain interesting to find out whether the first evaluation of the different flyer types is confirmed by the further examination within the overall system of the cathedral or if different aspects play a role in this context.

Furthermore the detailed analysis of the flying buttresses will be extended with the Discrete Element Method. The flying buttresses will be modelled as they have been surveyed in detail stone by stone in order to represent their structural behaviour and failure mechanism realistically.

Eventually the aesthetics of the flying buttresses should not be left out of consideration, since this aspect may very well have decided for or against certain design ideas of the builders.

REFERENCES

- Cocke, T.; Kidson, P., 1993: *Salisbury Cathedral. Perspectives on the Architectural History*. London: HMSO.
 Heyman, J., 1966: The stone skeleton. *International Journal of Solids and Structures* 82, pp. 249-279.
 Nikolinakou, M.A.; Tallon, A.J.; Ochsendorf, J.A., 2005: Structure and Form of Early Gothic Flying Buttresses. *Revue européenne de génie civil* Vol. 9 – n° 9-10, pp. 1191-1217.
 Nikolinakou, M.A.; Tallon, A.J., 2006 : New research in Early Gothic Flying Buttresses. In: Dunkeld, M. et al. (eds):

- Proc. Second Intern. Congress Construction History*, Cambridge, pp. 2347-2361.
- Mark, R., 1982: *Experiments in Gothic Structure*. Cambridge, MA: MIT Press.
- Morris, R.K., 1996: The Style and Buttressing of Salisbury Cathedral Tower. In: Keen, L.; Cocke, T. (eds.): *Medieval Art and Architecture at Salisbury Cathedral*. London: British Archaeological Association, pp. 46-58.
- Segger, J., 1969: *Zur Statik gotischer Kathedralen – Dargestellt am Kölner Dom und statisch verwandten Kathedralen*. Aachen.
- Spring, R., 1987: *Salisbury Cathedral*. London: Unwin Hyman.
- Tatton-Brown, T., 1991: Building the tower and spire of Salisbury Cathedral. *Antiquity* 65, pp. 74-96.
- Ungewitter, G.; Mohrmann, K., 1890: *Lehrbuch der gotischen Konstruktionen*. Leipzig: Weigel.
- Weber, H., 1957: *Das wechselseitige Verhältnis von Konstruktion und Formung an Kathedralen Nordfrankreichs*. Hannover.
- Viollet-le-Duc, E., 1867 : *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle*. Paris : A. Morel.
- Mähner A: Fig. 1: Surveyed and drawn by A. Wittek, J. Mähner, J. Fuhrmann, 2008. Incorporating existing surveys by courtesy of the Dean and Chapter: Exterior of bay 3/4 surveyed by PHOTARCH 1999, checked and corrected by H.A. Jones, 2007. Nave roof trusses surveyed by The Downland Partnership Ltd., 2002.
- Mähner B: Fig. 2-4: Drawn by J. Mähner; dating based on Morris (1996); standard bay numbering for the cathedral.
- Mähner C: Fig. 5: Surveyed and drawn by A. Wittek, J. Mähner, J. Fuhrmann, 2008. Incorporating existing surveys by courtesy of the Dean and Chapter: exterior parts of type IIIa + b surveyed by PHOTARCH 1999 checked and corrected by H.A. Jones 2007 + 2004, interior of type IV surveyed by H.A. Jones 1996.

ACKNOWLEDGEMENTS

Financial support for this research was provided by the Brandenburg University of Technology by means of a dissertation scholarship for the author. Prof. Werner Lorenz kindly offered to supervise and support this thesis within the International Graduate School Cottbus.

The survey could be carried out by kind permission of the Cathedral and Peter Edds, Head of Buildings and Estate, who kindly granted us access to all relevant sites at the cathedral. I am very grateful to Tim Tatton-Brown for his comprehensive information and suggestions regarding my research. Finally, I want to express my thanks to Prof. Stefan Breitling from the University of Bamberg for supporting my research by supervising a master's thesis on the building archaeology of the flying buttresses – executed by Ann-Christin Wittek – providing the drawings of the sections and very useful discussions on the topic.