Deans Eye Window – Lincoln Cathedral, Lincolnshire, UK

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Abstract

The Deans Eye Rose window at Lincoln Cathedral has spectacular medieval glass, though the stone tracery of the window was by the end of the last century in a dangerous condition. This paper explains the investigations made to determine the most appropriate action to be taken and the consequent dismantling and reconstruction of the window with new reinforced stonework with the medieval glass protected by isothermal glazing.
Keywords: Lincoln Cathedral, rose window, medieval glass, stone tracery.

1 History

Lincoln Cathedral had a chequered history before being rebuilt in Gothic style from 1192. The Dean's Eye rose window is located in the North gable wall of the Great North West Transept and was constructed as part of this reconstruction in 1220. The window has a daring structural concept and there is evidence that it required strengthening from an early period. Whilst many interventions had been made over the years, the original glass has survived throughout.

2 Approval process

This project is a major intervention to one of the most significant medieval rose windows in Europe. It was therefore scrutinised by, and required approval from, a number of organisations.

The proposals were first agreed by the Dean and Chapter of the Cathedral and were then passed to the Fabric Advisory Council of the Cathedral for their approval. The proposals were next submitted to English Heritage and the Cathedral Fabric Commission for England (CFCE) for approval and for

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comment to various other interested parties such as the Society for the Protection of Ancient Buildings. Each party took advice and passed their opinions to the CFCE who, after many deliberations, granted the approval. Not surprisingly as English Heritage was providing much of the funding for the project their views carried great weight.

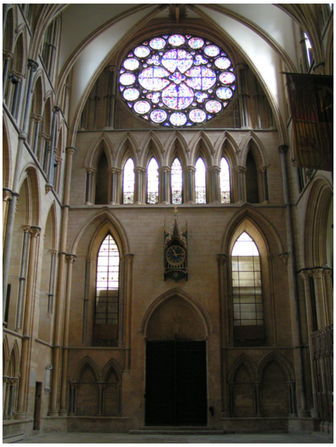

Figure 1: Internal view.

The process was lengthy with much debate and many reports. The approval process is however a vital part of the whole project, which challenges the design team continuously and rigorously, ensuring that all matters have been fully investigated and that the final solution is the most appropriate.

3 Condition of the window

Research into the history of the window showed that it had been failing for many centuries. In addition to many minor repairs two major strengthening measures had been undertaken. Firstly a pair of iron bars had been fixed diagonally across the inside of the window and connected into the tracery at intervals, this provided lateral support to the tracery and ties across the opening. Secondly a phosphor bronze cross bracing had been fixed on the outside of the glazing across the central quatrefoil (the diamond shaped stonework at the centre of the window) passing the compressive load between the radial spokes.

A three dimensional photo-grammetric survey of the tracery was commissioned to record the exact geometry of the window. This showed that the window was actually oval, being 120mm shallower than it was wide. It was also apparent that the window was out of plane with twists and distortions throughout.

Most of the stone tracery was of Lincoln limestone, but some of the radial spokes had been replaced with Clipsham stone. The joints between stones were mostly of lime mortar with some cement pointing, though a number of joints had been filled with poured lead, apparently as a repair. Wrought iron cramps and dowels were also present in a number of the joints. The glazing was fixed into the tracery with wrought iron glazing rings and saddle bars.

The state of the north gable wall was of key importance. The history of repairs to the wall were vague, but there was some evidence that that had been a local collapse in the 19^{th} century, which was rebuilt and that there may have been some grouting of the wall core during the major interventions in the 1920's. The stonework of the gable wall above the Dean's Eye forms a slender arch supporting the lancet windows and the roof above. Internal inspection confirmed the presence of a second arch supporting the edge of the vaulting to the north transept. The connection between the two arches is minimal and as the outer arch is lower and to one side, it will gain little support from the internal arch. As the external arch is slender, with limited restraint at its springing points, there was concern regarding its capability to carry the loads above. This is particularly relevant when the window tracery was removed as it may have been acting as an unintentional prop to the arch.

4 Conservation principles

The principles for the conservation of historic buildings are well defined from a number of sources such as the Icomos Venice and Burro charters and advice from English Heritage. In essence they stress the importance of all historic fabric and the need therefore to:

- avoid intervention wherever possible;
- any intervention to be reversible;
- if possible conservation to be by addition rather than replacement;
- new materials to be sympathetic to the existing fabric;
- historical fabric to be retained wherever possible.

Avoid intervention wherever possible. The tracery has had interventions from an early period in its existence by repairs and additions and is now in a state of failure so some form of further intervention was essential.

Interventions should be reversible. The tracery was being replaced and the glazing being conserved and returned into the window, though now to be protected by isothermal glazing. The work was reversible in that at any time an identical replacement to the original could be reinserted, with no alterations being made to the gable wall or the glazing.

Conservation should be by addition not replacement. The tracery has had a number of its sections replaced with new stone over the years, as well as having additions in the form of external metal bracing. The position had been reached where much of the tracery was so badly cracked that it could no longer be held in place by a reasonable amount of external support and the stone needed to be replaced. Further additions were not a viable solution.

New materials are to be sympathetic to the existing fabric. The tracery was to be replaced with a similar stone to the original. The metalwork used was stainless steel as opposed to wrought iron, but this is an acceptable change to ensure longevity.

Historical fabric is to be retained wherever possible. The existing tracery was in a very poor condition being heavily cracked and decayed and it should be noted was not completely the original as much of it had been replaced, . It could not fulfil its original function and had to be replaced, much in the manner of the ongoing stone replacement that occurs on all Cathedrals. The existing tracery was however archaeologically dismantled, recorded and stored for posterity so that it is available for inspection in the future.

An extra structural requirement is that the structure should act, where possible, in a similar manner to that in which it was intended. In this case I am very uncertain that there was an intended structural action. As Professor Huerta's recent paper on the "Gothic Theory of structural design" shows, there were a series of rules for the design of many elements in Cathedrals, but I doubt if there were for rose windows. Even if there were, this window most certainly did not follow them. The window as constructed was structurally vulnerable and the solution used for its replacement maintain the window in as near its original form as is possible and more nearly so than the interventions that had been carried out over the centuries.

5 Glazing

A decision had been taken early on that the stained glass would be protected by isothermal glazing. That is, replica plain glazing would be inserted in the original location on the rear of the tracery and the original stained glass would be fixed offset back from the tracery. In this way the medieval glazing is protected from the weather and the stress of having different environmental conditions on either side of it. It is located only 75mm or so behind its original position with light shields around it, so that from the ground it is not apparent that the stained glass is inside the line of the tracery.

The new glazing fixings had to be designed to carry the load of the glass and internal and external wind pressures, in case of failure of the external glass. The fixings and glazing supports both new and old involved four different metals, stainless steel, phosphor bronze, wrought iron and lead; great care had to taken to ensure separation of the metals to prevent bimetallic corrosion.

6 Structural design

The existing tracery was so damaged that it was clear that it required replacement and not just repair. The design of the replacement tracery had to meet four criteria:

- The appearance of the new tracery had to be similar to the existing maintaining the distorted shape.
- To contain the medieval glass on fixings to the rear of the glazing rebates which would contain the new isothermal glass.

- To remove the existing iron ties across the window and the central stiffening bars across the quatrefoil
- To have a design life of 500 years with a life to first major maintenance of 100 years.

The predominant loading on the window is the wind loading with a load of around 2.5 KN/M2; though estimating the maximum wind force for a 500-year period, particularly with the advent of global warming, is not an exact science.

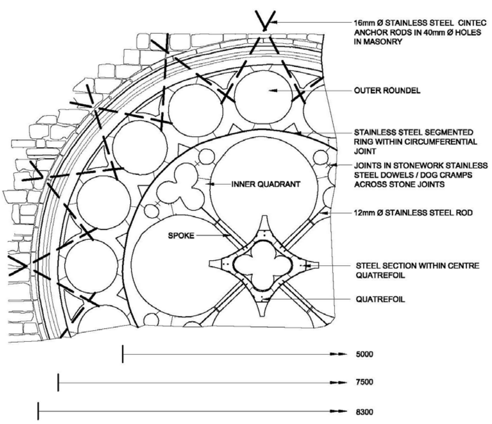

Figure 2: Structural solution.

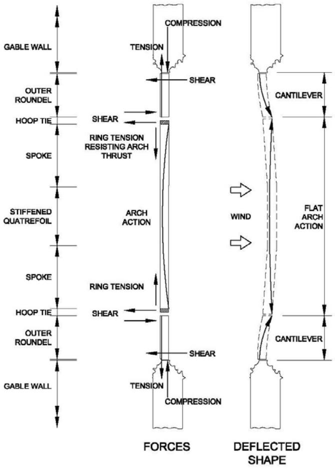

Figure 3: The structural analogy.

The masonry tracery clearly cannot act as beams or a grillage spanning across the space, nor as a flat arch, as the span to depth ratio is of the order of 35. A simple structural analogy was developed for the structural system that would form the basis of a design, with the intention of restricting the stress in the masonry to 5 MPa compression with zero tension. (See figures 2 and 3.)

The outer roundels are assumed to act as cantilevers out from the gable wall carrying the shear loads from the inner area of the window. In order for this to be feasible tension needs to be carried through the joint to the gable wall requiring the inclusion of anchors within the depth of the tracery. A pair of Cintec stainless steel anchors were drilled through each of the edge stones into the gable wall and fully grouted.

The inner area of the window is presumed to act as a flat arch to the edge of the cantilevering roundels. In order for this to be feasible the central quatrefoil needs to be stiff and the edge of the inner window area needs to be restrained so that the arch cannot spread. The edge restraint from the gable and outer roundels is insufficient so a tension ring of stainless steel was incorporated into the joint between the inner section of the window and the outer roundels to provide that restraint. (See figure 4.)

Figure 4: The Tension Ring.

The central quatrefoil needs to be stiff and able to transmit the compression loads across it if the flat arch analogy is to be valid. A purely stone shape is unable to do this even if it has no joints. The introduction of a steel armature within the stone work, directly connected to the stone spokes, can transmit the loads adequately and be sufficiently stiff, in the three dimensions, to allow flat arch action. (See figure 5.)

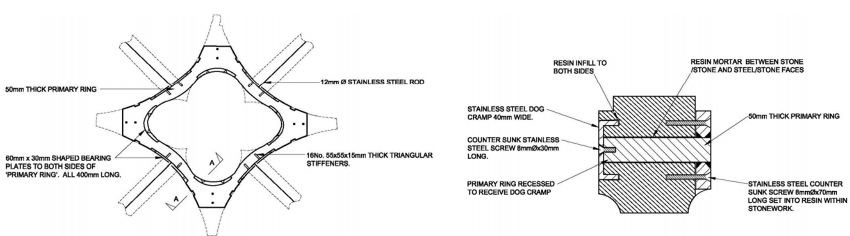

Figure 5: The central quatrefoil armature.

The structural design of the tracery was based upon these assumptions with deflections as the key criterion for the steel design to ensure that the arch action would be maintained.

A further key design element was that for the joints, they had to transmit the compressions and not allow joint rotation. The joints to either end of the spokes being the most critical and for these the ends of the stones were most carefully prepared to match. They were then joined with a 1mm lead slip between the faces and a low viscosity epoxy glue injected into the joint to ensure that there were no voids and that it was a fully mated joint. All joints had stainless steel dowels or cramps to allow the transmission of some tension across them.

7 Stone selection

The initial assumption was that Lincoln stone would be used for the reconstruction of the tracery, as the Cathedral owns a quarry close to the Cathedral. The Lincoln stone from the Silver Bed has a crushing strength varying between 45 to 75 MPa and has proved durable over the years.

The stones within the window need to be over 600mm long so the Lincoln stone could only be used if it was laid face bedded or if the number of joints was increased. The use of the stone face bedded, with the stone placed so that its natural sedimentation planes are vertically aligned, is not good masonry practice. This is particularly so in this usage as the stones would be in a tracery with three faces of the stones exposed and with the joints subjected to high edge loadings. It is highly likely that with face bedded stones there would be early spalling of the faces and a fast deterioration of the tracery. The option to increase the number of joints was considered but rejected. The joints are the weakest points in the tracery and by increasing the number significantly, there was a large increase in the risk of failure. It was decided after much consideration that it was not realistic to consider using Lincoln stone for the tracery.

A search was then instigated for an alternative source of stone to meet the following criteria:

> A Jurassic Oolitic limestone; appearance, texture and colour similar to Lincoln stone; capable of carving well and holding detail; a minimum bed depth of 900mm; compressive strength preferably 30 to 45 MPa; microporosity < 30%, saturation coefficient <0.6%; commercially available at reasonable prices.

Six sources in the UK were examined in detail, but none were found that were a sufficient match to all the criteria. The search was then widened to other areas in Northern Europe. Anstrude Roche Claire from a quarry near Auxerre in the Yonne department was finally selected. It was a compromise, the strength of the stone and its probable durability were rather less than that of Lincoln stone, although inspection of buildings where it has been used have shown it to last well. The stone was a reasonable match for appearance but was whiter than Lincoln stone when cut. The tracery was therefore given a limewash after erection to blend it into the colour of the gable wall.

8 Construction

Lincoln Cathedral has its own works department which acted as Principal Contractor with all glazing, masonry, conservation and joinery work carried out by the in-house team under the control of the works manager. External sub-contractors were used for the support and access scaffold, the laying of the setting out floor and the drilling and installation of the Cintec anchors.

The Cathedral masons, conservators and glaziers were fully involved in all the decisions. From the start of the design, their detailed knowledge of stone and glass, their knowledge of the reliability of different details and methods of construction were crucial to the whole process. A key factor was the selection of construction methods that would achieve a safe method of working.

The agreed sequence for the reconstruction was to install all the outer roundels, then to install the lower two quadrants with the hoop ring, followed by the lower two spokes. At this point the steel assembly for the quatrefoil was installed and held in place and the upper two spokes fixed. The upper two quadrants were then placed with the assistance of centring and the last section of the hoop ring tightened. The final task was to clad the quatrefoil steel assembly in stone.

Figure 6: Setting out – floor.

A complication was that the arch above the window was known to be barely capable of supporting the wall above and that the North East pinnacle, which provided some of the mass to restrain the arch, was to be dismantled and rebuilt in parallel with the work on the Deans Eye. It was therefore necessary to provide not only an internal and external access scaffold for the works, but to combine these with a structural scaffold to carry the load from the upper gable wall whilst the work was being carried out. A scaffold was designed with needles which passed through the window openings to carry the wall above. The needles were designed so that of the eight in place, any two could be removed at any one time to allow for dismantling and in due course reconstruction of the tracery. The design of the scaffold was based upon deflection criteria, as the key requirement was to prevent movement of the wall above the window, not just to support it.

The programme of work was to fully complete all the stone preparation and to test it for fit on the setting out floor, before the existing tracery was dismantled. The trial assembly was most useful as the sequencing of stone erection could be assessed easily on the ground and where need be the order of stone erection amended.

The dismantling of the tracery was a key moment, as there had inevitably been assumptions made that would be confirmed or found to be wanting. The dismantling showed just how fragile was the existing masonry and the author was surprised that it had survived so long.

The installation of the new tracery required the accurate placing of large stones and in the case of the edge roundels these had to be held in place whilst drilling through them into the wall core for the Cintec anchors. A stone handling device, supported from the structural scaffold, was specially designed and manufactured to hold and accurately locate the stones. It could manipulate the stone in three dimensions, including tilt, and hold them sufficiently rigidly to allow the drilling into the wall core through pre-drilled holes in the stones. This was a vital piece of equipment to ensure the safe handling of the stones and to reduce the risks of working at height.

The reconstruction of the tracery was an eight-month task. The masons performed well and the tracery was erected to close tolerances of within 3mm across the opening, a far tighter tolerance than one would normally expect on masonry.

The glazing was installed as expected within 4 months and the project completed to acclaim within programme and budget.

Figure 7: External view of completed window.

Acknowledgements

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