The Dean's Eye window, a stunning example of the glazier's art © Buttress Fuller Alsop Williams

CONSERVING THE DEAN'S EYE

The stone tracery of the Dean's Eye window at Lincoln Cathedral had been failing for many years and the medieval stained glass required conservation, so by 2000 a complete reconstruction of the window was needed. Geoff Clifton was assigned to carry out the task of both preserving the original glass and ensuring that a stable, long-lasting structure was created around it. Here he writes about the history of the famous window and the process of careful and complicated restoration that was needed to save it.

In 1192 the construction began of the present Cathedral at Lincoln and the Dean's Eye window was built in the north gable of the great northwest transept in 1220. The design of the window must have been conceived by a glazier or a cleric because, whilst the glass is magnificent, the structural tracery is daring in the extreme and clearly a mason could not have been involved in the design.

It is apparent from both the records in the cathedral archives and from archaeological inspection, that the tracery was strengthened, partially replaced and repaired relatively soon after its erection. The window is nominally 7.5 m in diameter, but it is not round, being 120 mm shallower than it is wide. It is most likely that, during the first construction of the window, there was a slump at the top of the opening when the centring for the upper arch was withdrawn. This is evident from modifications to the stones and glazing in the upper part of the tracery, which were carried out at the time of the original construction.

It is of interest that the Dean's Eye companion window, the Bishop's Eye in the great southwest transept, failed catastrophically within 100 years and was rebuilt to a different design.

IDENTIFYING THE PROBLEMS

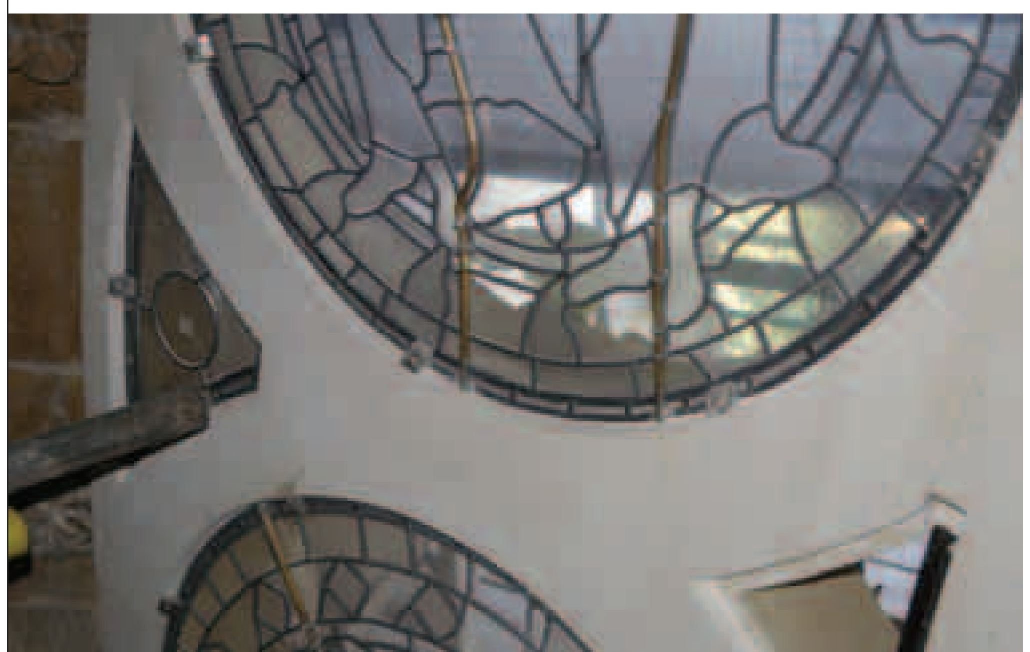
The Dean's Eye window is a stunning example of the glazier's art and still has its original medieval stained glass in place. The window is so-called because it overlooks the Dean's house outside the cathedral and throughout its life interventions

The central element of a rose window has to transmit the loads from each spoke around itself and then balance the load from the opposing spoke. In the case of the Dean's Eye there are only four spokes, far fewer than in most rose windows, so that the loads in each spoke are large and the spread between their interaction with the central element is farther apart.

have been made to ensure the stability of the Dean's Eye tracery. The actions taken over the years have included the replacement of individual stones, often with stronger Clipsham stone; additional wrought iron ties at joints; mortar joints replaced with poured lead; short dowels from the edge stones into the transept wall; and, more fundamentally, cross-bracing both within the central quatrefoil and behind the window spanning across its full width – the latter being connected to both the tracery and the parent wall on either side.

A comprehensive understanding of the history of the window and the adjacent parts of the cathedral was essential in order to be able to work out the reasons for the failure of the tracery and then to be able to design its replacement, to ensure that it did not suffer a similar fate.

There were three main engineering challenges for the reconstruction of the tracery. The first problem was how to take out the existing tracery whilst ensuring the stability of the north gable and indeed the whole northwest transept. Second was the need to develop an acceptable design for the tracery without changing a form that had proved to be structurally unstable. Lastly, the new tracery had to be constructed in such a way that the key requirements of conservation were met as far as was practically and economically possible.



Isothermal glazing after it was attached to the tracery and before the glazing frame and stained glass were fitted. The lead came lines of the isothermal glazing were made to match the lines in the stained glass, so that from the exterior the window looks as if the stained glass is on the outside. It also shows the glazing bars (the bronze coloured vertical bars) that support the isothermal glazing © Geoff Clifton

CONSERVATION CRITERIA

The International Council on Monuments and Sites (ICOMOS) has set strict criteria for conservation. The five key principles that had to be addressed, together with comments on the extent to which they could be met, are listed as follows:

- *Intervention to be avoided wherever possible.* The tracery had failed so intervention was unavoidable.
- *Any intervention to be reversible.* The release of load on dismantling the failed tracery meant that the cracked stones would disintegrate. Dismantling was therefore irreversible but the valuable stained glass was fully conserved.
- *Conservation to be by addition rather than replacement.* The glazing was to be protected by isothermal glazing, but replacement of the tracery was the only viable option.
- *Ensure new materials are durable and sympathetic to the existing fabric.* The reconstruction of the tracery required the introduction of new types of material. A key challenge was to ensure that the essential character and aesthetics of the tracery were not changed.
- *Retain the historical fabric wherever possible.* The glazing is fully retained. Although the tracery had to be replaced, the original was archaeologically recorded in its entirety and has now been stored for posterity.

The conservation of the glazing followed accepted practice for the protection of fragile historic glass by the use of isothermal glazing. New clear isothermal glass has been installed in the original location of the medieval glass, which, after conservation, has been fixed in new frames on the internal face of the tracery (see opposite).

FORWARD PLANNING

The design of the replacement tracery was complex and was carried out according to four key criteria. First among these was the requirement for the new tracery to match the appearance and the existing deformed geometry of the original. Next was the vital requirement for the isothermal glazing and medieval glass to be safely supported without the existing cross bracings which, to meet the demands of the third criteria, had to be removed. Finally, it was asserted that the window had to have a design life of 500 years, with a period of 100 years to its first major maintenance.

By far the most significant load upon the tracery was the wind pressure and suction from a 1-in-500 year storm gust, this being roughly equivalent to the loading experienced by a typical office floor, acting horizontally on the tracery and glass.

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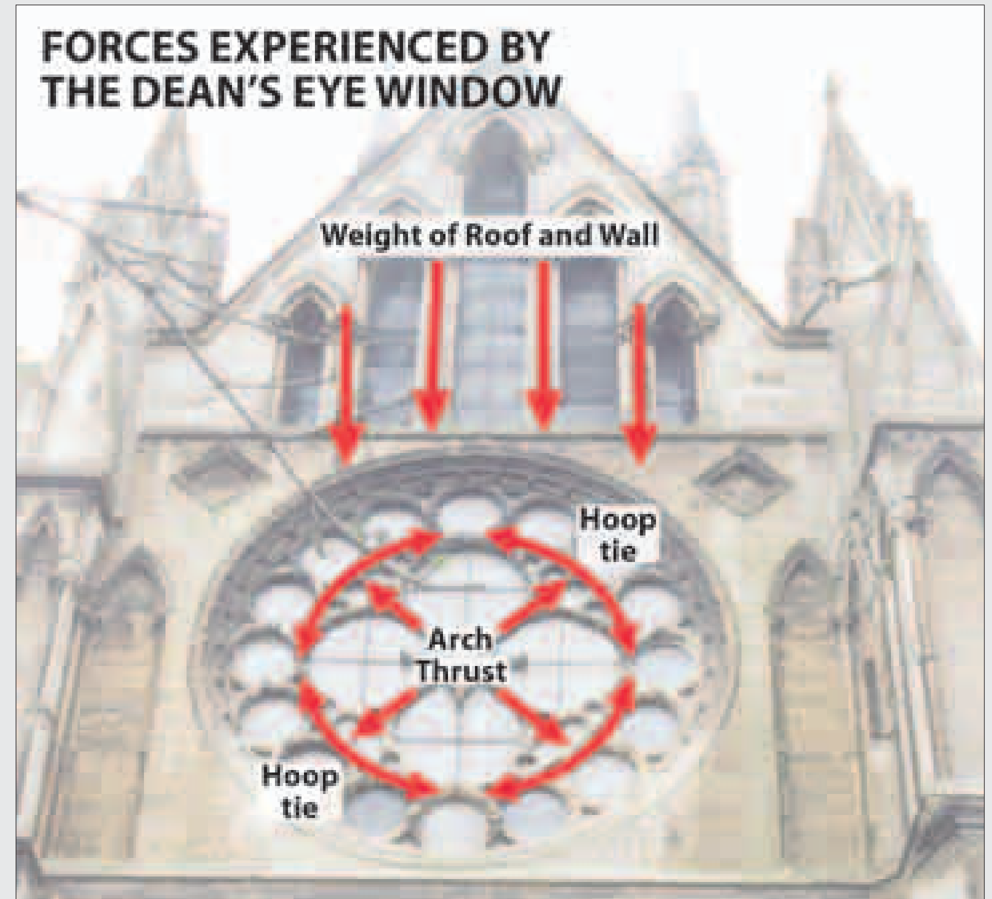
CREATING SUPPORTS

The key to making the tracery self sufficient, whilst retaining its original form, was to allow it to work differently as a structure. The concept was to make the perimeter section, consisting of the outer roundels, function as a



A view of the northwest gable and the Dean's Eye window prior to the restoration work. The image shows the structural lines of force that put stress on the window and the tracery. In addition to this but not marked up, are the pressure and suction forces experienced by the window from wind © Geoff Clifton

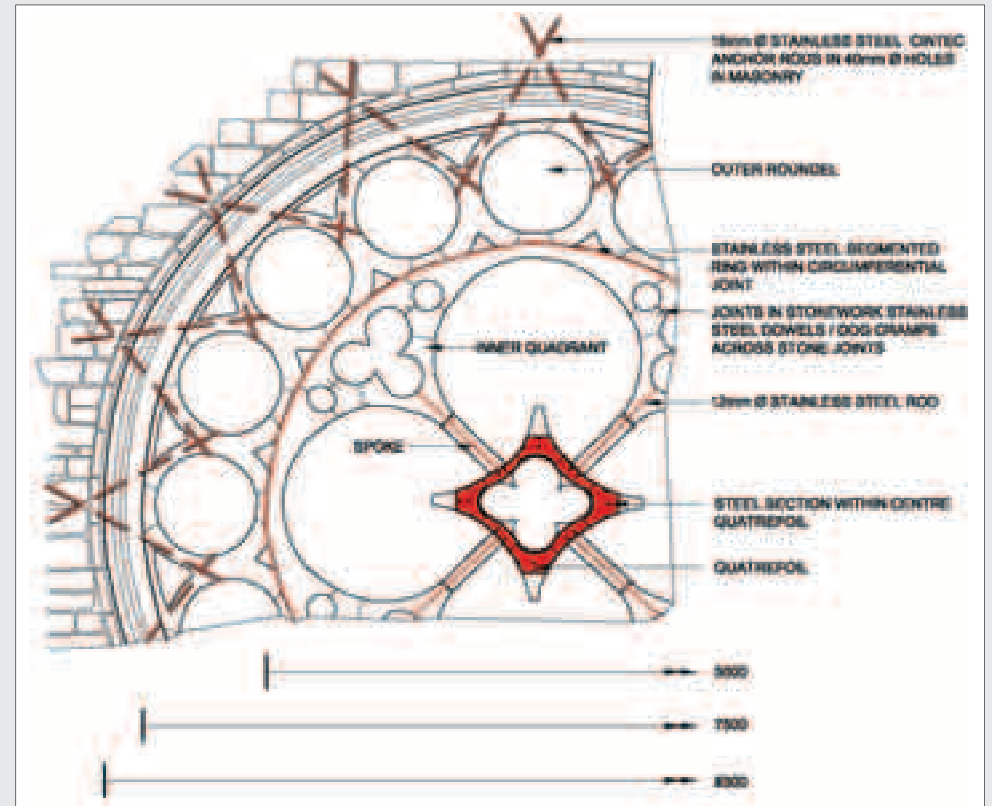


Figure 1. Showing the basic form of the Dean's Eye tracery. It consists of a number of outer roundels which are connected to a centre quatrefoil by four spokes. © Geoff Clifton

The only realistic solution for developing the structural adequacy of the central quatrefoil was to fabricate it out of a single piece of stainless steel, which was then clad in stone, internally and externally, to maintain the appearance of the tracery. The design of the armature was complex as it had to be rigid in three dimensions, as secondary effects from the out-of-plane geometry caused significant torsions.

cantilever with fixity into the transept wall (see Figure 3). The inner quadrant, spokes and quatrefoil were then to act as a shallow arch spanning across to the vertical plane of the outer roundels.

Securing the connection between the outer roundel section and the transept gable wall was achieved by drilling holes through the 'X' shaped stones, between the roundels (see Figure 1), into the core of the transept wall and grouting stainless steel rods into these holes.

The task of making the inner section act as a shallow arch was more complicated. The thrusts from the arch at its springing points had to be fully restrained so that the arch could not relax and the joints between the stones forming the spokes had to be sufficiently rigid so as not to allow any shortening of the arch and loss of its restraint. The central quatrefoil had to be able to transmit the loads in the spokes without overstress of the materials and with very limited deflections, both in and out of the plane of the window.

STABILISING AND TIGHTENING

The thrusts from the inner section, acting as a shallow arch, were not likely to be restrained by the main gable wall to the transept, indeed the arch above the window has moved, thus causing the wall to slump. The Cathedral archives hint at instability of the wall on occasions in the past, with loose wall core and even possible local collapse. The pinnacles above the wall are in need of reconstructing which will reduce the mass restraint at some point in the future. All these factors imply a lack of the stiffness required to restrain any arch movement. The solution was to install a tight stainless steel strap around the inner section of the window – in the continuous joint between it and the outer roundels – thereby restraining the whole inner section.

The joints at either end of the four spokes are critical to maintaining arch action. The correct 'action' of an arch depends on it being geometrically stable. This is achieved by restraining the arch laterally and ensuring that compression loads are absorbed around the shape of the arch and out at the supports.

To ensure the construction of rigid joints the ends of the spokes were accurately carved to match the mating surfaces and the joints were made with a 1 mm lead slip as the bearing material. A very low viscosity epoxy resin was then injected into the joint to ensure bearing across the whole mating surface. The remaining joints in the window were 5 mm wide, filled with hydraulic lime mortar and held in position with dog cramps (these are metal straps that tie joining stones together) or dowels as appropriate.

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The intention had been to use Lincoln stone from the Cathedral's own quarry. However the maximum bed depth of available stone here is only 180 mm whereas stones with depths of up to 900 mm were required for the window. A wide search was made for a compatible stone to meet the many needs of the tracery and eventually a compromise was found in Anstrude Roche Claire stone from Auxerre in France.

GETTING THE GO-AHEAD

Any permanent work to the Cathedral fabric is instigated by the Dean and Chapter and then has to be approved by the Fabric Advisory Committee (FAC) of the Cathedral, on which sit a number of external experts. The FAC then submit the scheme to the Cathedral Fabric Commission for England (CFCE), who seek the views of English Heritage, the Society for the Protection of Ancient Buildings and other such bodies, before themselves coming to a decision upon the acceptability of the scheme.

The reconstruction of the Dean's Eye was a major intervention to one of the most important rose windows in Europe and therefore received a great deal of attention. Numerous reports and meetings were required, with some decisions such as the selection of the stone being particularly contentious. Eventually all were satisfied and the scheme was approved.

Stainless steel straps restrain the inner section of the window © Geoff Clifton

The stone handling device: the vertical grey bars are the rails on which the machine moves up and down, these are themselves attached to two horizontal bars which are attached to the structural scaffold, allowing the machine to traverse the whole window. Through this, individual stones can be aligned exactly in the right position, despite the distorted geometry of the tracery © Geoff Clifton

A view of the upper section of the arch with the tracery removed. The timber blocks were wedged up to the arch to keep it in place while lateral wedges were installed to stop the main wedges slipping. At any one time up to two of the steel support beams (needles) could be taken out to allow removal or installation of individual stones © Geoff Clifton

RESTORING THE WINDOW

The geometry of the tracery had been captured using photogrammetry and the tracery was then drawn out at full size on a temporary setting-out floor established in the transept. Following the carving of all the stones and the manufacture of the metal elements for the tracery, a trial assembly was carried out on the floor to assist in decisions on the sequencing of the work and checking for fit.

Whilst this was in progress a structural scaffold was erected, both to give access to the window and to support the gable wall above the Dean's Eye while the tracery was removed. A system of monitoring the wall was also introduced to check for any movements whilst the dismantling and erection of the new window was carried out.

The exact positioning of the stones in the tracery was vital if it was to work as intended and the manoeuvring of stones weighing up to 500 kg was a significant health and safety risk. To overcome these difficulties a stone handling device was specifically designed and manufactured. The device, shown above, was fixed on horizontal and vertical rails attached to the load bearing scaffold to allow movement in both directions. The attachment plate for holding stones could be moved in from the line of the scaffold, into the plane of the window, and tilted for exact placement. All the movements were controlled by screw jacks. The attachment plate had a range of bolt holes to hold every differently sized stone.

TEAM EFFORT

The Dean's Eye reconstruction succeeded because of the continued involvement of all members of the team. The evolution of the engineering solutions and their implementation was a fascinating journey, during which it was vital to keep a clear focus on basic physics and material properties and was greatly helped by excellent communications and total commitment at all stages of the project. The exacting task required the early involvement of all members of the team. The masons and glaziers were part of all the early design meetings and the team was involved on site until the last piece of glass was fixed.

For the first time in many centuries the window can now be viewed as its original creator intended and it is a common sight in the cathedral to see groups of visitors staring up at the window in admiration. What more satisfaction could an engineer wish for!

BIOGRAPHY: Geoff Clifton

Geoff Clifton is the Director of Historic Buildings for Gifford Ltd, an international firm of Consulting Engineers. He is a member of the Cathedral Fabric Commission for England, the English Heritage Advisory Group, and is on the UK Scientific Committee of ICOMOS.

The architects on this project were Buttress Fuller Alsop Williams and the contractors were the Cathedral Works Department.