CINTEC

Windsor Castle

Report by Richard Swift

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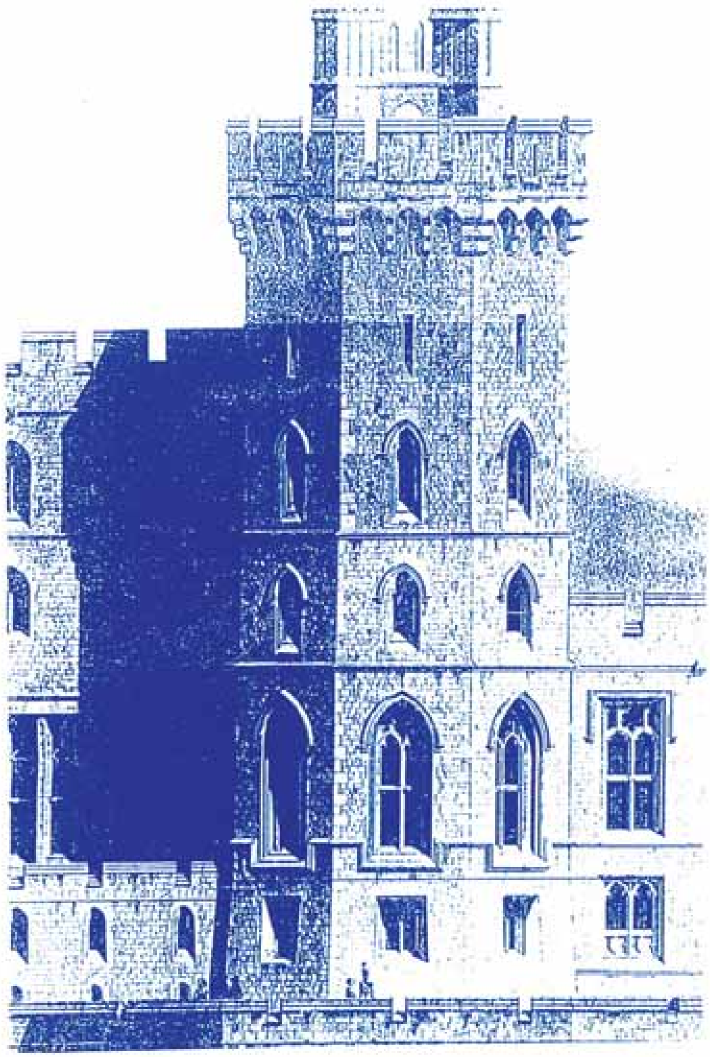

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WINDSOR CASTLE

After the *Annus Horribilis*:

Structural Conservation and Monumental Disasters

Abstract

The first reaction after a disaster is one of despair. This hopelessness can lead to an irrational response and the unnecessary destruction of buildings or structures that have probably survived other similar catastrophes.

As conservation professionals it is our responsibility and privilege to bring to bear some creative thinking, and to bring some optimism where there is none.

This paper will seek to describe the steps that were taken after the great fire at Windsor Castle of November 20 1992 and after the earthquake in Cairo of October 12 1992.

It is generally accepted that good conservation means minimum intervention to ensure structural stability, and a retention of the maximum amount of historic fabric. As engineers we need to understand how a building has historically transferred applied loads to the foundations. It is desirable that existing load paths should be maintained and that the surviving structure should be made to work. As the manifesto for the Society for the Protection of Ancient Buildings - England's famous SPAB - says, "we are only trustees or guardians for those who come after us".

As conservation experts we are more like detectives in our quest to understand fully the problems confronting a distressed structure. It is important to understand what happened, what damage has been done and how the structure has been altered.

This study may involve many modern non-destructive techniques to assess surviving structure. At Windsor this included the latest methods of materials testing, radar, ultra-sonics and dendrochronology. In Egypt there are several examples of buildings or structures wrongly assessed and where over-reaction or non-appreciation of hazards has led to an inappropriate response.

Television transported around the world the images of the flames shooting high into the night sky as the north east corner of Windsor Castle burnt fiercely. 20 November 1992 was the Queen's 45th wedding anniversary and was the final straw upon the back of a bad year. She described it as her 'annus horribilis'.

The fire at Windsor started in the chapel when a tungsten lamp came into contact with the back of one of the high curtains screening the altar in the chapel. The flames penetrated into the roof void above St George's Hall and also explored the many hidden voids which were present in such a much-altered historic castle. Over the next 15 hours the fire had a devastating effect upon the medieval building, destroying over 105 rooms, 9 of them principal state rooms. The fire was left to burn itself out but not without the firemen having poured 1½ million gallons of water upon the flames at a rate of up to 4000 gallons per minute.

The effects upon the fabric of the building of the heat (over 1000°C) and the water, appeared to have caused irreparable damage.

The first part of the recovery had to be an assessment of what had survived. This was an operation fraught with danger. Whole floors were on the point of collapse. The four floors above the Green Drawing Room ceilings in the Chester Tower had all collapsed on to the ceiling, making it a very dangerous space to enter. In the Brunswick Tower, the debris at principal floor level was 12 feet deep. This was all that remained of the upper four floors. Paradoxically, it was this pile of debris that protected some of the finishes in the Octagon dining room, at the base of Brunswick Tower, from the very high temperatures achieved by the flames licking out of the top of Brunswick Tower.

The limestone bay window to the Crimson Drawing Room overlooking the East Terrace had been pushed out by the thermal expansion of the steel roof trusses. Firemen said that they could feel the bay move as they were fighting the fire.

In the Prince of Wales Tower, partly rebuilt by Salvin after the fire of 1853, the situation was equally dangerous. Salvin's fireproof floor consisting of brick jack arches resting on flanged wrought iron beams had in part been successful in resisting the fire. They had not collapsed but the wrought iron beams had expanded and increased in length pushing into their bearing pockets in the thick masonry walls. The beams had buckled and given rise to instability of the brick jack arches. Many were very loose. As the fireman had played their hoses on to the beams, the beams had shrunk back and pulled large panels of facing brick from the walls of the Prince of Wales Tower. These panels, separated by the four diagonal cracks emanating from each extremity of the top and bottom flanges of the beams, were now suspended and ready to fall.

The immense volume of water poured on to the medieval fabric by the firemen was to have a very serious consequence for the building. The one and a half million gallons, equivalent to Niagara Falls descending on to the building for a full two seconds, would give rise to major concerns over the condition of timbers buried within the structure, over the results of salt damage to the carved masonry and over the likely time that would be required for the building to dry out.

The initial estimate for the repair of the damage was put at £60m and an estimate for drying out of the fabric of 10 years before the finishes could be applied.

The first priority at the end of that November was to get a temporary roof over the whole site. With the likelihood of wet weather and strong winds it was important to protect the vulnerable damaged surviving medieval fabric.

Up to 46 scaffolders on site at any one time erected a temporary roof over an area 3,700 square metres (37,000 square feet) and a huge raking shore to give temporary support to the bay window to the Crimson Drawing Room. During the next 5 years over 75 miles of lengths of scaffold tube was to be used at Windsor.

Careful dismantling rather than demolition was undertaken by a specialist team. They were suspended from harnesses above the damaged structure and areas of the building which were considered dangerous were lifted and removed from above. This was dangerous work. Another reason for the dismantling being done from above was that it avoided the demolition contractors tramping all over the surviving mat of debris. Had they done so they would have crushed valuable fragments of plaster and ornament which could be salvaged, cleaned and re-used.

It was important that only those elements of structure which were dangerous should be taken down. Remember that this structure had been the home of English Kings and Queens since the twelfth century. It was imperative that as much as possible should be retained.

I had been fortunate in October 1992 to be appointed by UNESCO to advise the Egyptian Antiquities Organisation on the conservation of the monuments in Cairo after the earthquake of 12 October. I had seen the panic response to the crisis by an organisation eager to show that it was doing something. I had seen minarets dating from the thirteenth century taken down because someone said that they were leaning. No-one had made any measurements. I had seen scaffold towers erected 20 metres high in the middle of a busy street in a vain attempt to provide some bracing to a minaret 50 metres high, which someone had said was moving. Near vertical timber props had been put alongside leaning walls. All of these convinced me that a considered, rational approach was the appropriate course of action and that panic measures should be resisted at all costs.

The conservation philosophy was unclear in the beginning. The Property Section of the Royal Household wanted speed and efficiency, a dynamic thrust to the programme as well as ferociously tight cost controls. English Heritage, the government body responsible for preserving the National Heritage wanted authentic restoration and a full archeological sift of the site estimated at a cost of £1.1 million. Eventually an acceptable approach was agreed. Three options were considered: (i) Authentic Restoration - the use of historic techniques and materials to produce an authentic repair; (ii) Equivalent Restoration - the use of modern materials and techniques supporting traditional finishes; (iii) Contemporary Redesign - starting with a blank piece of paper and redesigning the spaces.

The Duke of Edinburgh, who chaired the Restoration Committee, and the Prince of Wales, who chaired the Design Committee, consulted with many advisers and eventually it was decided that the Grand Reception Room, the Green Drawing Room, the Crimson Drawing Room, the Octagon and State Dining Rooms were all to be reinstated according to the principles of Equivalent Restoration. The Private Chapel and St George's Hall were to be redesigned.

The problem of the huge volume of water trapped inside the structure was a major headache for the project managers, who needed rapid progress on site to achieve the required completion date, initially agreed as Spring 1998. Timber can be considered dry if it is below 12 per cent moisture and brick below 5 per cent. At Windsor most of the walls in the burnt area were well over 10 per cent. The shallow masonry vaulted ceilings in the basement were saturated at about 30 per cent. Some of the timber panelling on the ground floor was also at 30 per cent moisture content. Obviously the big problem with the saturation of the medieval fabric is the very high risk of development of moulds and the fungi, including Serpula Lachrymans, or dry rot. English Heritage obviously wanted the mediaeval wall linings and finishes to be disturbed as little as possible in order to ensure their conservation. The project managers, on the other hand, could see no way of drying out the huge volumes of water contained within the thick masonry walls unless the slate linings and timber panel finishes were temporarily removed. The figure of 10 years put forward for drying out was totally unacceptable. After some protracted discussion between the Project managers, the Property Section of the Royal Household and English Heritage, it was finally agreed that the finishes could be removed and taken away to a temporary store.

Seeping water can destroy stone. As the water comes to the surface, the salts in it crystallise in the surface layers of the stone, expanding as they do so. Effectively they push off the outer layers of the stone. As more salt-laden water seeps out more salts crystallise and more stone is destroyed. The masonry vaults in the Stewards Room and Servants Hall were slowly being destroyed.

English Heritage agreed that the gloss paint and any tiles, hard rendering or stone lining from the basement surfaces could be stripped. The bare stone that was then revealed was then coated in a sacrificial poultice or render, an outer layer of soft plaster and limewash into which the salts could safely migrate and crystallise, leaving the stone behind intact.

Once the finishes had been removed, ex•actor fans, open windows and dehumidifiers were all introduced to accelerate the drying out process. A system of electronic wetness monitors was pushed into the walls all over the fire damaged site and then linked by telephone to Hutton and Rostron, the Environmental Consultant's offices near Guildford. With this information the progress of the drying out could be monitored.

The assessment of the materials damaged by the fire was considered an important part of the remedial works. To discover how the brick, chalk, limestone and Bagshot Heath igneous stone had survived the fire was crucial in determining what could remain.

The assessment work was divided into five main parts, namely:

(i) Initial visual survey
(ii) In situ testing
(iii) Materials sampling
(iv) Laboratory testing of samples
(v) Reporting

A total of 102 cores were taken from various rooms: the Brunswick Tower, Prince of Wales Tower, Crimson Drawing Room, Kitchen Court, Steward Hall, Picture Store, Chester Tower, Private Chapel, Holbein Room, St George's Hall and the Great Kitchen. The number of core samples taken was greater than that originally envisaged, for three reasons:

(i) The results of the initial visual survey revealed a much greater range of material types within the walls of each room than was originally thought. This increased the number of material types to be assessed in each room.

(ii) There was considerable variation in the type and extent of fire damage within each room, couples with an uneven distribution of water. This increased the number of test areas required within each location.

(iii) Extension of the original area of interest to include St George's Hall and underlying vaults (including the Stewards Room and Servants Hall), the Holbein Room and Stuart Tower. This increased the number of locations requiring investigation.

As a consequence of the visual inspection, a separate programme of core drilling was instigated to investigate the water content of the chalk fill beneath St George's Hall.

The laboratory testing of the materials was divided into 4 areas:

(i) Visual Appearance - Optical Microscopy

At least four different types of brick and four types of stonework were identified within the limits of the fire damaged area. The types of deterioration included: (a) vitrification of surfaces; (b) bulk cracking and disintegration of faces, typically to a depth of 10mm to 100mm; (c) discolouration; (d) dehydration and micro-cracking in the depth of the material. The consequences of these types of damage is surface spalling, which is accelerated by subsequent moisture and thermally induced movements and represents a potential long term durability problem. This was of particular concern in areas such as the bay window in the Crimson Drawing Room.

(ii) Chemical Properties - X-Ray Diffraction and Thermal Gravimetric Analysis

Direct wet chemical analysis of masonry materials is rarely helpful and so X-ray diffraction (XRD) and Thermal Gravimetric Analysis (TGA) were used to assess the crystalline phases present, the degree of hydration/desiccation and to check for signs of any fire induced phase changes.

(iii) Physical properties - Moisture Content, Moisture Absorption and Relative Density.

Moisture content and absorption measurements were used to obtain an indication of the total porosity and its relation to moisture movement and relative density.

iv) Mechanical Properties - Compressive Strength, Modulus of Elasticity (stiffness) and Ultrasonic Pulse Velocity

Compressive strength and stiffness measurements were made by direct compression testing of suitably prepared core samples to establish the load bearing and deflection characteristics of the various materials.

Measurements of the velocity of ultra-sound pulses through these materials were also made since it is sometimes possible to relate this property to the strength and/or stiffness characteristics. This is both cheaper and quicker than the mechanical testing of core samples and has the added advantage that in situ measurements can be made.

A number of metal samples were removed from beams in the Prince of Wales Tower, Brunswick Tower and adjoining corridor.

The results of the testing indicated that although the different types of brickwork showed signs of vitrification, lead contamination, spalling and micro-cracking the damage did not extend to depths greater than 100mm or the first layer of brick, despite temperatures around the 1000°C mark. The Bath stone, an oolitic limestone, suffered considerable crack opening at mortar joints as well as considerable dehydration and associated micro-cracking into the depth of the stone. A typical section through the stone revealed three main regions: (i) a 2-4mm thick surface layer of blue/grey appearance which had suffered severe dehydration, micro-cracking and deterioration; (ii) a 20-50mm thick layer of pink appearance which had suffered dehydration and micro-cracking; and (iii) original and apparently unaffected light cream material.

A detailed inspection of the bay window of the Crimson Drawing Room indicated the extent of the fire damage within the Bath stone. It was concluded that the type and extent of the damage would have implications for the future durability of the material. Subsequent demolition of the bay prior to its rebuilding confirmed the degree of deterioration with many of the blocks shattering during efforts to remove them on a block by block basis.

The deterioration of the York stone included cracking and spalling of entire stone blocks to depths in excess of 150mm and significant discolouration to a brown/red and dark purple.

Much of the exterior elevation of Windsor Castle is of Bagshot Heath stone. The fire resulted in extensive cracking and spalling of surface layers to a depth of 5-20mm. The material in the surface layers was badly weakened and could be broken down under light finger pressure.

The cast iron and wrought iron were largely unaffected by the fire. Although slight variations were found in the microstructure of the various samples, these were more likely to have resulted from variations in the manufacturing process than structural transformations due to the effects of the fire.

A specialist company expert in the use of ground probing radar and members of the Impulse Radar Users Association was commissioned under Gifford direction to assess the condition of the walls of the Brunswick Tower. This survey revealed the condition of the walls, the presence of voids and the areas of separation within the brickwork/masonry. The survey was valuable in assessing areas of potential defect and the need for intervention. In fact, the survey revealed the many concealed flues and the different stages of building of the Brunswick Tower. None of these details required major repair, only limited grouting and localised repairs. The use of radar was not used widely in the fire damaged area because although it is a useful tool, it is a relatively expensive operation to undertake, requiring 'hands on' access to the whole of the external elevation to produce the readout of the radar signal. It is also very dependent upon the expertise of the operative to interpret the readout and identify the possible hidden defects in the wall construction.

The fire damaged masonry gave cause for concern over several issues. Firstly, the delicate nature of the surfaces, particularly at window reveals, required consolidation. Secondly, the removal of the panelling revealed the many poorly bonded joints between periods of different construction. An example of this and where the above two features were evident together, is the north-east window in St George's Hall. The masonry structure around this window was in very poor condition. A specialist masonry stitching anchor known as the CINTEC anchor was particularly useful in stabilising this masonry. The anchor consists of a stainless steel anchor body contained within a woven polyester-based sock. The anchor body may be a solid bar, hollow section or threaded rod according to the designer's requirements. Anchors may be designed up to very significant lengths. Cavity Lock Systems Ltd, who manufacture the anchor, state that they have installed anchors up to 50m long. At Windsor, the longest anchor used was 12 metres in length. A hole was diamond cored into the masonry and the anchor introduced into the hole. A cementitious grout was pumped at very low pressure into the sock around the anchor body and filled the hole in the masonry. A very good bond is created between the parent masonry and the grout and between the grout and the anchor body. If movement of the masonry is likely to occur, it is resisted by low shear stresses between the parent masonry and the grout and hence into the anchor body. The system is very effective for weak masonry. The masonry around the window in the north east corner of St George's Hall was stabilised by a pattern of CINTEC anchors.

The CINTEC anchor was also used at the top of Brunswick Tower, where the fire had resulted in the movement of the crenellated parapet. The merlons had rotated outwards like opening up the segments of an orange. Initially it was considered that the only effective means of repair was the complete taking down and rebuilding of the parapet. This would involve loss of the patina of age and important architectural details of joint relationships and historic stone faces. An alternative solution was proposed, which involved the installation of CINTEC anchors like a corset around the faces of the Octagonal Tower. Holes of 40mm diameter were drilled, to accommodate the 20mm anchor body, at the centre of the thickness of the parapet. The anchor was installed and grouted and the entry hole pointed up so that there was little evidence of the remedial work. The movement cracks which had been created by the fire were monitored over a period of time to ensure that the anchors were effective in preventing any further movement.

The CINTEC anchor is capable of sustaining very high pull out loads on friable, delicate masonry. This was proved by the use of the anchor to resist the very high uplift loads exerted upon the temporary scaffold roof by wind forces. Windsor Castle sits high upon a chalk mound well above the general level of the surrounding countryside. Wind forces generated upon the nearly flat scaffold roof were anticipated to be very high. The only method of anchoring some of the scaffold legs down was to connect them by some means to the surviving walls of the fire damaged areas. A 2 metre (6 feet 6 inch) long anchor was drilled vertically into the thick masonry wall and tested to 170kN (17 tonnes). The anchor passed the pull out tests and was used to resist the uplift on the scaffold roof.

The Royal kitchen roof at Windsor presented a major dilemma. Before the fire it was thought that Wyatville in 1828 had swept away any remains of earlier roofs over the kitchen at Windsor. His softwood mouldings were much in evidence in decoration of the structure of the roof over the kitchen. After the fire, which came from above the roof, it became clear that in fact the medieval roof structure survived intact, concealed behind the softwood mouldings. It was a major benefit of the fire that such a discovery was made and revealed the oldest, substantially unchanged and still working kitchen in the country, and one of the oldest in the world. Before the fire there were thought to be no medieval royal kitchens in existence. It was now clear that the Great Kitchen at Windsor sited here, from documentary evidence, in 1259, had never moved. Dendrochronological analysis, by which the pattern of rings in timber can identify the moment at which the tree containing them was felled, suggested a date for the earliest timber of 1361. The Royal Household Property Section, conscious of costs, initially had considered removing the roof in its entirety and replacing it with either a new steel or green oak roof. However, because of its importance as one of the fore-runners of the hammer beam roof structure, it was decided to conserve all of the medieval timbers and provide additional steel supports which would be invisible in the finished repaired roof structure.

Most of the seven lantern frames had been destroyed in the fire, however, the remaining charred structure was grit blasted at low pressure to remove the charring. The new steel supports were bolted to the existing frame and dry timber repair sections were introduced. The lantern was then formed in new green oak.

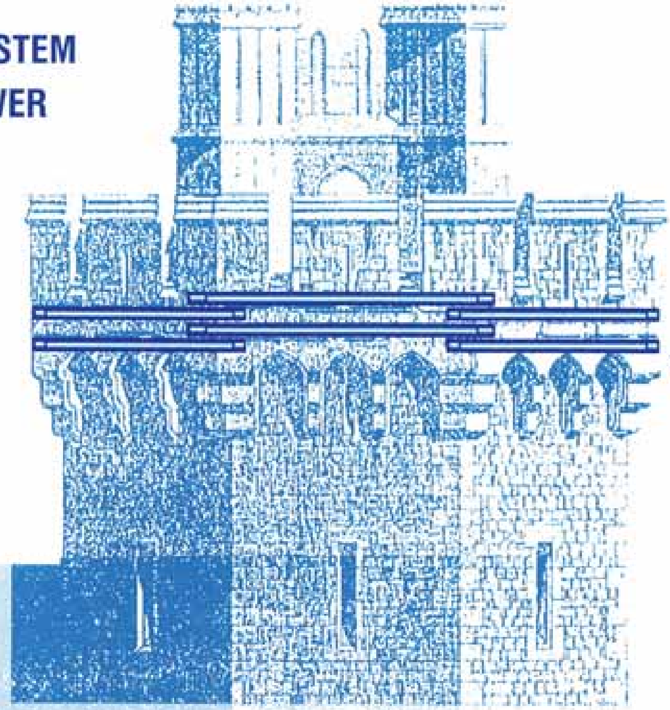
St George's Hall roof structure presented a different problem. The seventeenth century timber-trussed roof had been strengthened by Smirke in 1819 using cast iron and wrought iron trusses supporting the timber. Wyatville's scheme for St George's Hall had not been considered a success. The ceiling structure was considered too flat. It had been likened to a railway carriage.

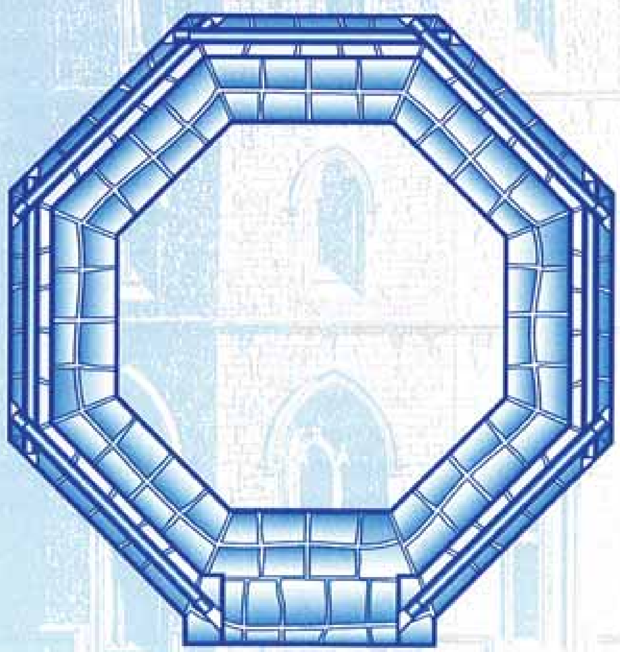
The fire destroyed the roof of St George's Hall. An early decision had been made to get a new steel roof over the whole of St George's Hall in 1993 to the same roof outline as the pre-fire structure. Giles Downes, architect, of Sidell Gibson Partnership, had won the commission for the re-design. The Prince of Wales committee pressed the architect to go for a new green oak ceiling structure. This would represent the largest, most elaborate and most complex green oak structure erected since the sixteenth century. The problem with green oak is that it shrinks and the movement is not always predictable. When delivered to site the timber may have a moisture content of about 50 per cent. After years in service the moisture content may have dropped to a figure of 10 per cent. Between those two extremes the transverse shrinkage across the width of a principal rafter may be 8-10%. The longitudinal shrinkage is likely to be much less, a figure of 0.3% may apply. These movements may be exacerbated if there is spiral grain in any of the selected timbers. This may cause the members to warp or rack. Joints in green oak have to be designed to be movement-tolerant.

THE CINTEC ANCHOR SYSTEM AT THE BRUNSWICK TOWER WINDSOR CASTLE –

The latest Diamond Drilling Techniques were used to create a network of holes within the stonework.

The Cintec Anchors were then installed creating a reinforcing ring, within the fabric of the stonework, maintaining the original appearance of the tower.





The illustration shows the arrangement of anchors used in the restoration of the Brunswick Tower.

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Capps and Capps, a specialist contractor based in Wales near Hay on Wye, felled the timber and constructed the heavy ceiling structure. They obtained the timber from a nearby managed estate and used 350 of the one hundred year old oaks to construct the ceiling. The form of the ceiling structure is Gothic in principle and meant to represent a hammer beam roof structure. The constraints of the new steel roof limited the pitch to something less than the 45-55° that one would expect for a hammer beam roof structure. The fourteen trusses of this roof are immensely complicated. The two halves of each truss are symmetrical about the ridge line and each half is itself divided into two parts: the main centre arch springing towards the ridge and the lower arch coming down to the corbel on the wall. At the junction between the two is a pendant post from the bottom of which a large boss hangs down into the hall and contains concealed lights. At the top of the pendant post, the point around which the whole structure works, four different timbers have to be accommodated: the top chord or principal rafter coming up from the wall plate and then going on up to the ridge; the pendant post purlins coming in from east and west, and of course the pendant post itself. Each of these members had deep mouldings run in them so that shrinkage cracks would form in the shadows of the moulding and each of these roll mouldings, some as fat as rainwater pipes, had to run into each other where the members met each other. All of the joints had to be housed. At the top of the pendant post the joint was described as 'central pegged stop end tenon with reduced pegged bridle-bearing and face-scribed housings to purlins with haunched top tenons'. Most hammer beam roofs fail by the horizontal thrust at the eaves pushing out the tops of the wall. The top ridge joint opens and the ridge itself drops. In order to give some continuity of structure at the ridge we introduced an elbow joint on the underside of the junction of the principal rafters. It is a large and very heavy, curved piece of timber - and the curve cannot be cut out of a straight section; the curve must be grown if the drying grain is not to split the piece open. The means of fixing the elbow was described as 'two folding wedges in a double ended stop played and tabled scarf with under squinted transverse key and four face pegs'. In order to test the strength of the joint, we requested that Southampton University set up a jig and using a purpose made joint supplied by Capps and Capps undertake pull out tests. Timber pegs and loose tenons were also checked for shear capacity.

Although the original programme for completing the roof anticipated a six month period, the complexity of jointing the structure actually took two weeks short of a year.

In the ante-room to St George's Hall, glulaminated oak has been used to create the eight columns and the curved ribs which rise from them to create a lily-like structure with a glazed roof lantern surmounting the whole. This represents a tremendously complex geometrical form and most of the cutting was done by computer controlled routers.

The architect produced a similarly complex geometry for the ceiling structure of the new chapel. The flat fan vaulted ceiling is again constructed of glulaminated oak ribs. Each of the six bays of the chapel, which is not a big room, has over a thousand different pieces of oak built into it. Taylor Made Joinery, who undertook the work, relied heavily on computer aided design to produce the finished form.

The Queen and Duke of Edinburgh's fiftieth wedding anniversary and the fifth anniversary of the fire was 20 November 1997. This was the completion date for the restoration project. On 17 November the Queen held a reception in St George's Hall for all of those contractors, craftsmen and consultants who had been involved in the project and expressed her deep gratitude for returning Windsor to her in all of its newly established glory. The project had taken five years, resurrected the skills of many craftsmen, and cost £36.5 million.

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