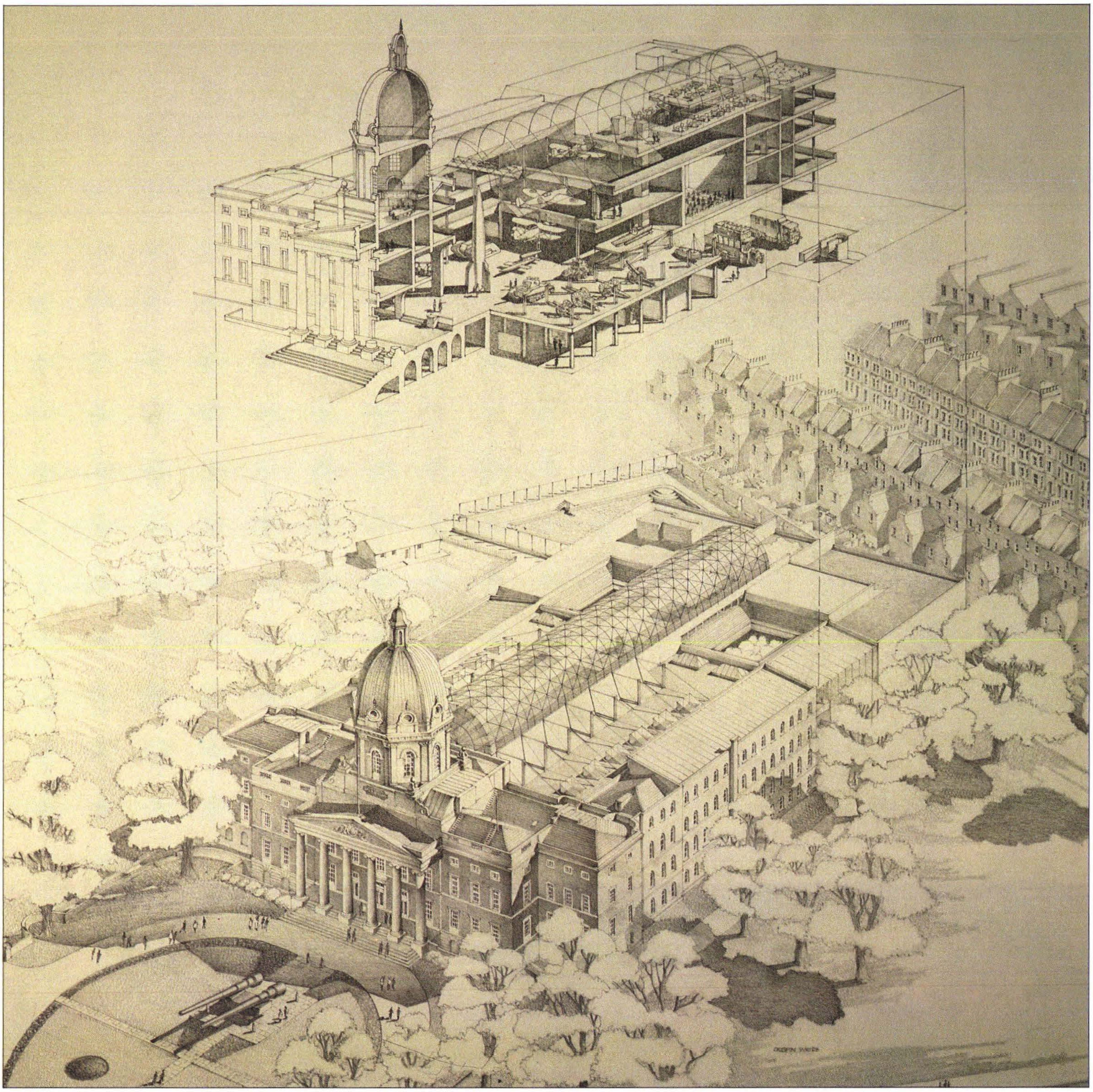
THE ARUP JOURNAL

WINTER 1988/89



THE ARUP JOURNAL

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Back cover: Spectrum 7, Milton Keynes: (Photo: Peter Mackinven)

The structure of the Imperial War Museum Extension

Anthony Ayiomamitis
Ian Blunn
Ken Butler
Gabriele Del Mese

Introduction

Arup Associates were appointed by the Property Services Agency in 1983 to prepare 'a detailed Feasibility Study for the redevelopment of the main building of the Imperial War Museum in Southwark, and to include recommendations for phasing to allow the existing building to continue in use throughout the work'. The purpose was to provide more exhibition space with room for study galleries and improved administration areas.

The building which currently houses the Museum was designed in 1815 by James Lewis as the Bethlem Royal Hospital or 'Bedlam'. The dome was added in 1846.

The Imperial War Museum took over the building in 1936. It is dedicated to exhibits of the First World War and all subsequent conflicts involving British forces.

The building is a Crown Property and is listed as grade 2.

Architectural concept

One of the main objectives for the new development was the creation of a memorable central space, strongly articulated by its enclosing structure. The project is phased into three stages, and the roof to the main space provides a strong visual link between them like a continuous spine through the length of the building. The supporting steel structure is exposed and detailed to emphasize this.

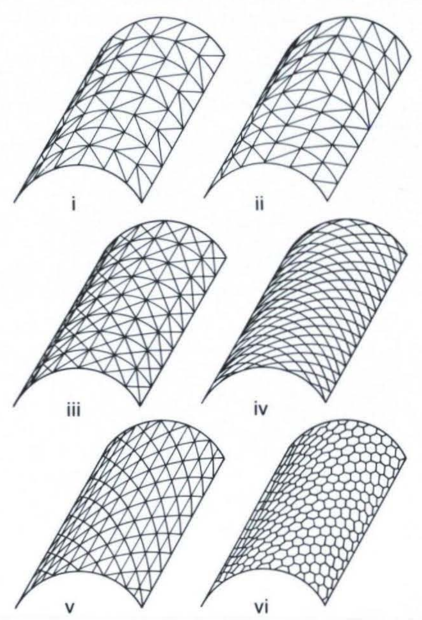
The heaviest exhibits will be housed on the lowest levels, A and B, which are in reinforced concrete. The steel structure above level B consists of two storeys of galleries (levels C and D), plus a level E over these, totally dedicated to services. The central area has a clear span of 22.7m, with a maximum height of 23.4m to the crown of the barrel vault. This will be used for large exhibits such as aeroplanes and rockets.

General planning solution

Various overall planning options for the courtyard area were investigated. They are diagrammatically shown in Fig. 3. Architectural, functional and economic considerations led the design team to develop option D into a full scheme design.

Foundations and superstructure

A site investigation was completed in August 1985. The lowest exhibition slab level was lowered 1m from the existing ground level, bearing directly onto compacted fill. Reinforced concrete pad footings bearing onto gravel were the natural choice for the foundation system. It was part of the brief that the main exhibition halls at levels A and B would be required to carry heavy armoured vehicles of up to 65 tonnes. Because of that, an early decision was taken to design them in concrete, using a two-way waffle slab on reinforced concrete columns.

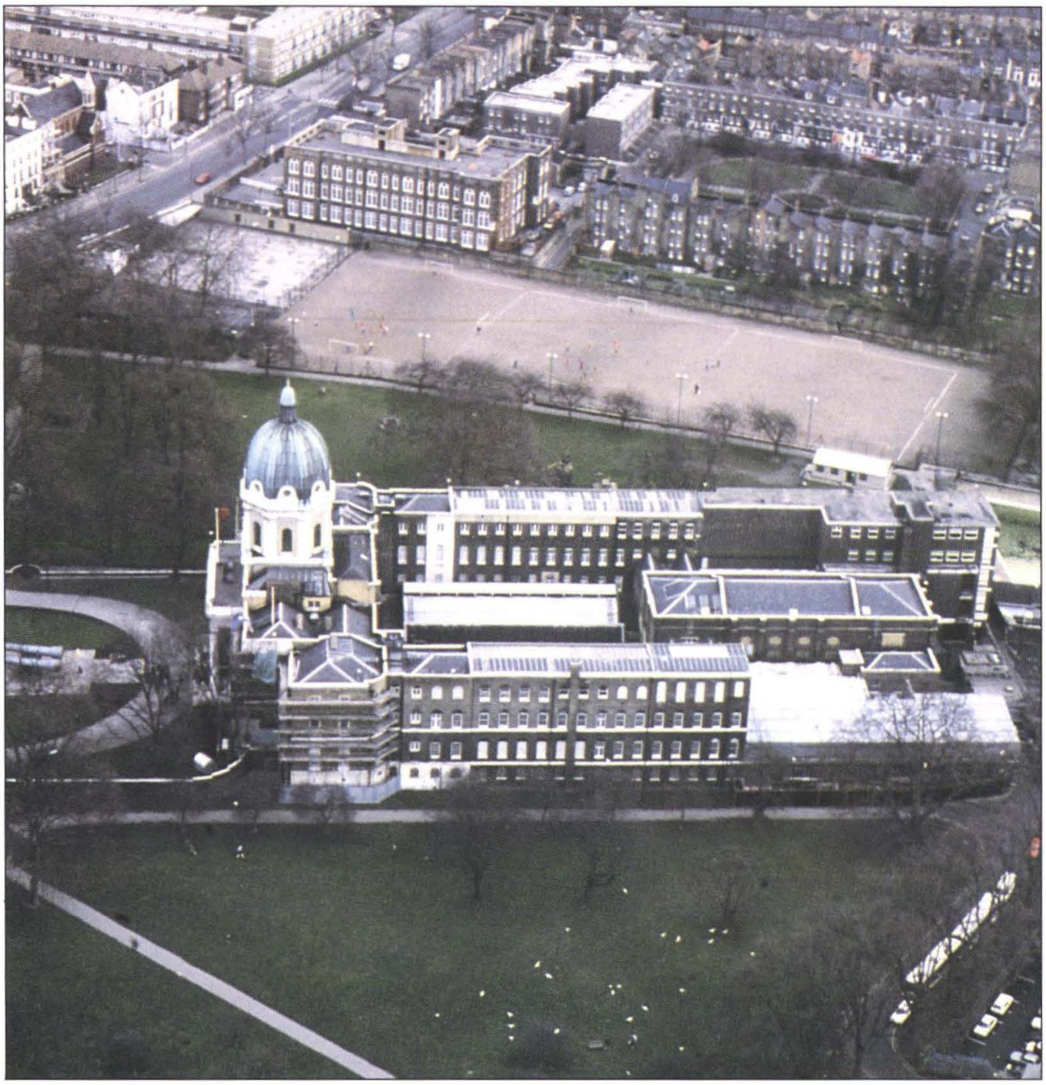


1. Alternative barrel roof forms

From Level B upwards there is a steel structure on three sides of the courtyard, which had to give a feeling of clarity while fulfilling its structural functions. To this effect many of the joints are clearly expressed and articulated, the columns are twin tubes, and the primary beams frame into them to form a pure skeletal frame.

The secondary beams are located on top of the primaries rather than into their web, as would be more conventional. This adds to the overall sense of clarity.

2. The aerial photograph shows the Imperial War Museum prior to the construction of the extension



The drawings in Fig. 1 show a series of alternative structural systems and the planning options which were considered during design are set out in Fig. 3.

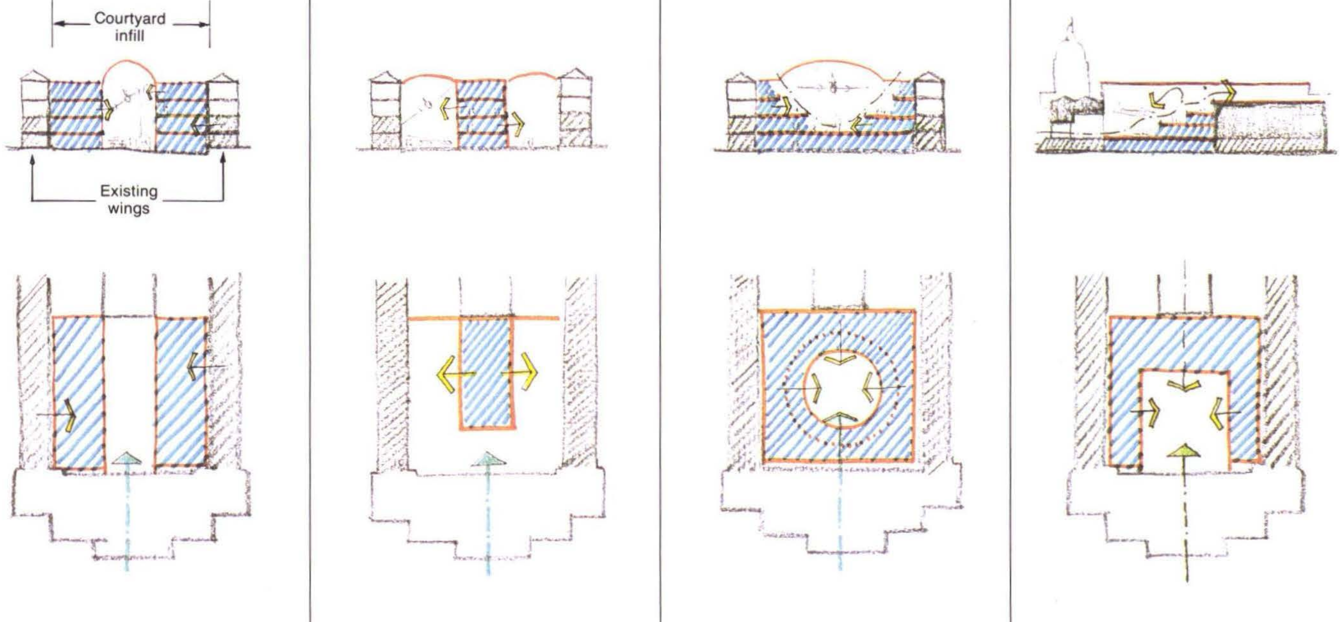
Option D formed the basis for the final proposal.

Option A
Central space flanked by four levels of gallery accommodation. The central open space is restrictive for large exhibits.

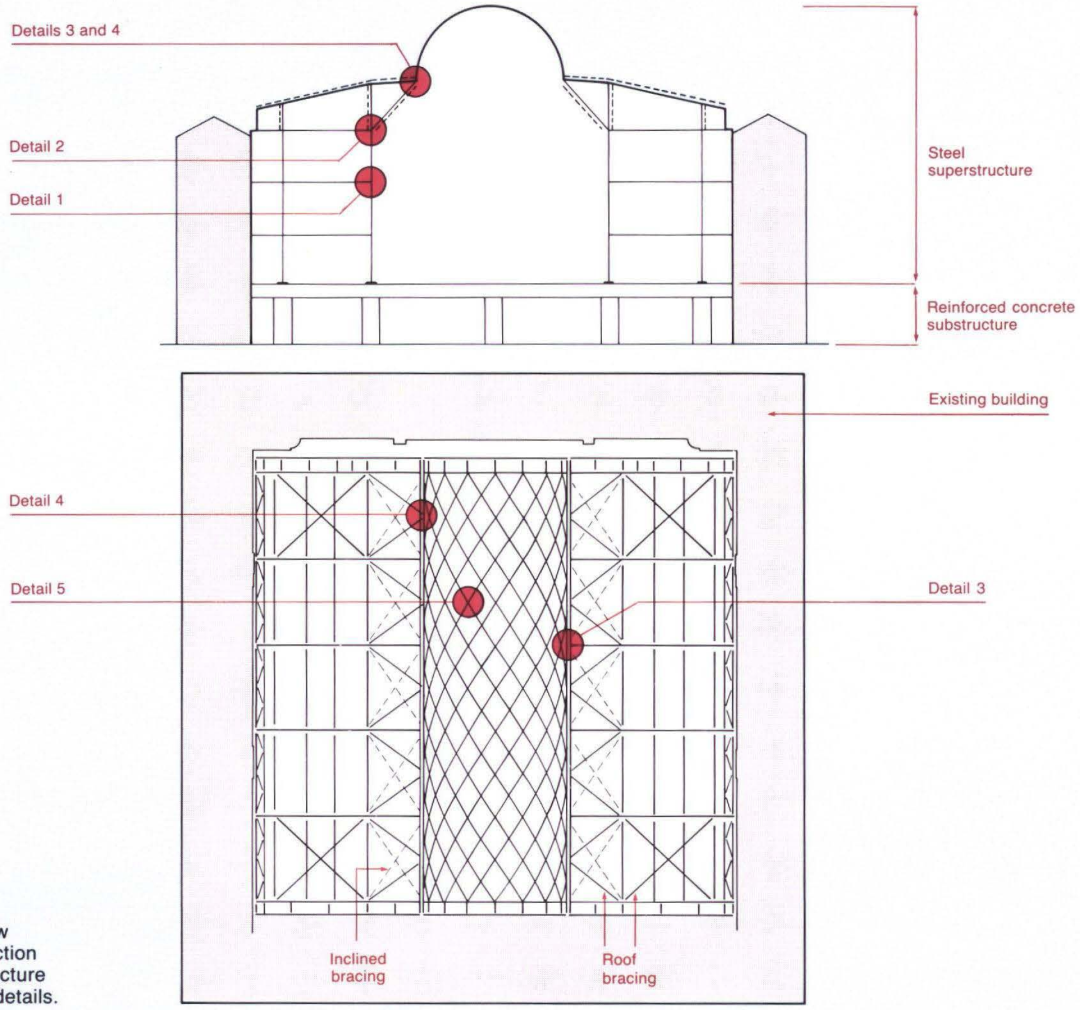
Option B
Accommodation in the central area with open galleries on both sides. The central plan does not maximize the area of gallery space within the courtyard.

Option C
Whilst providing maximum gross area the plan imposes a strong, finite, 'circular' form.

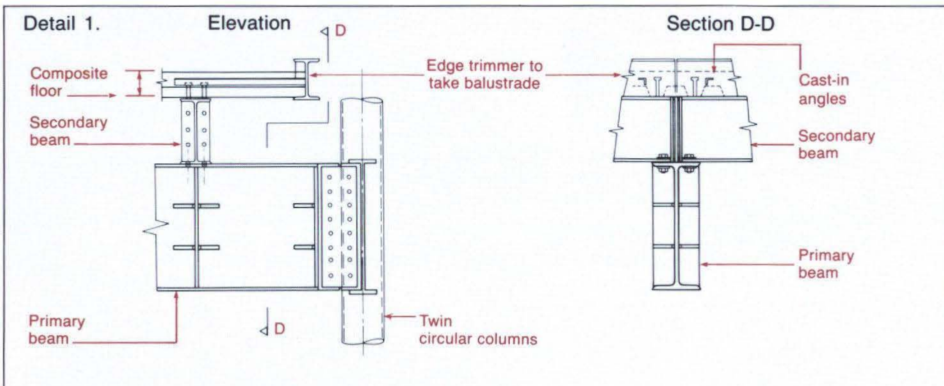
Option D
A large open space with surrounding tiered galleries was a favoured plan form on which further studies were based.

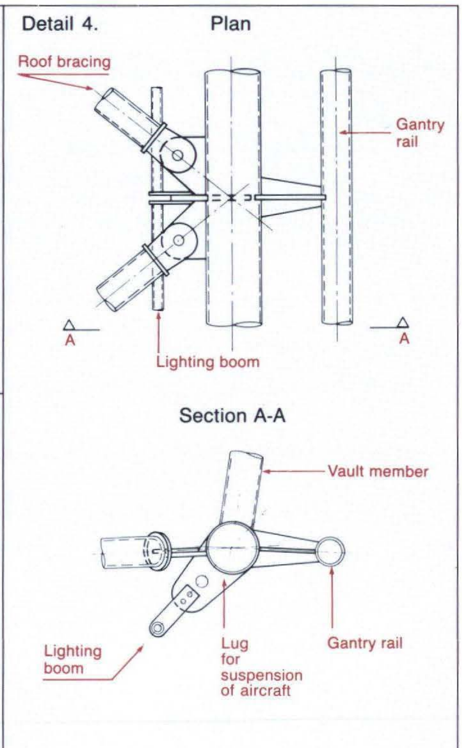


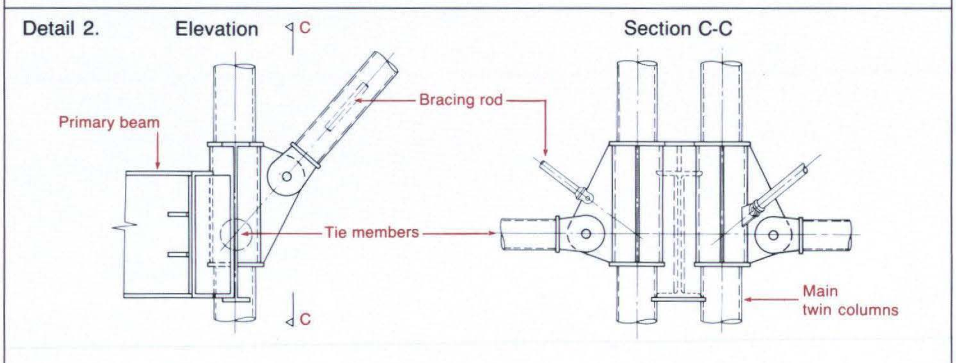
3. Planning options

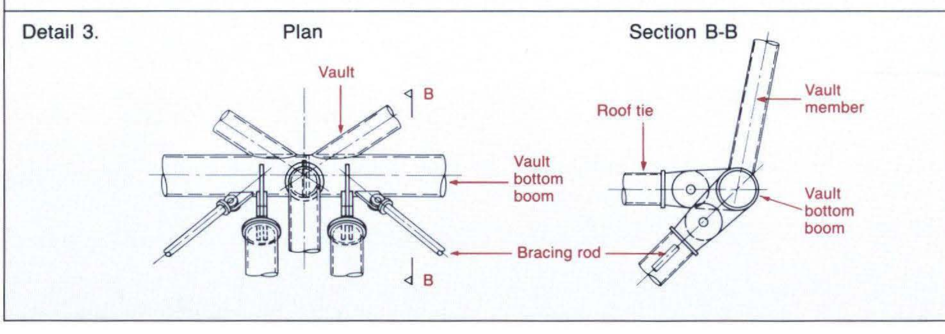


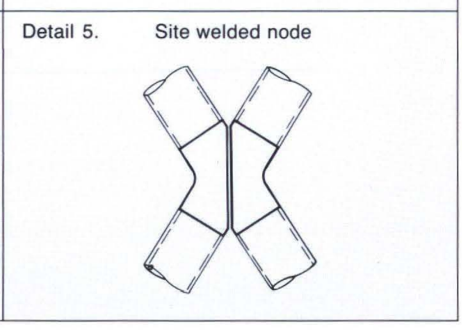
4. (right and below).
These drawings show the key plan and section of the new vault structure and a series of key details.











Above and right, the new vault structure which was put in place in September 1987. Below: Details of structural connections.

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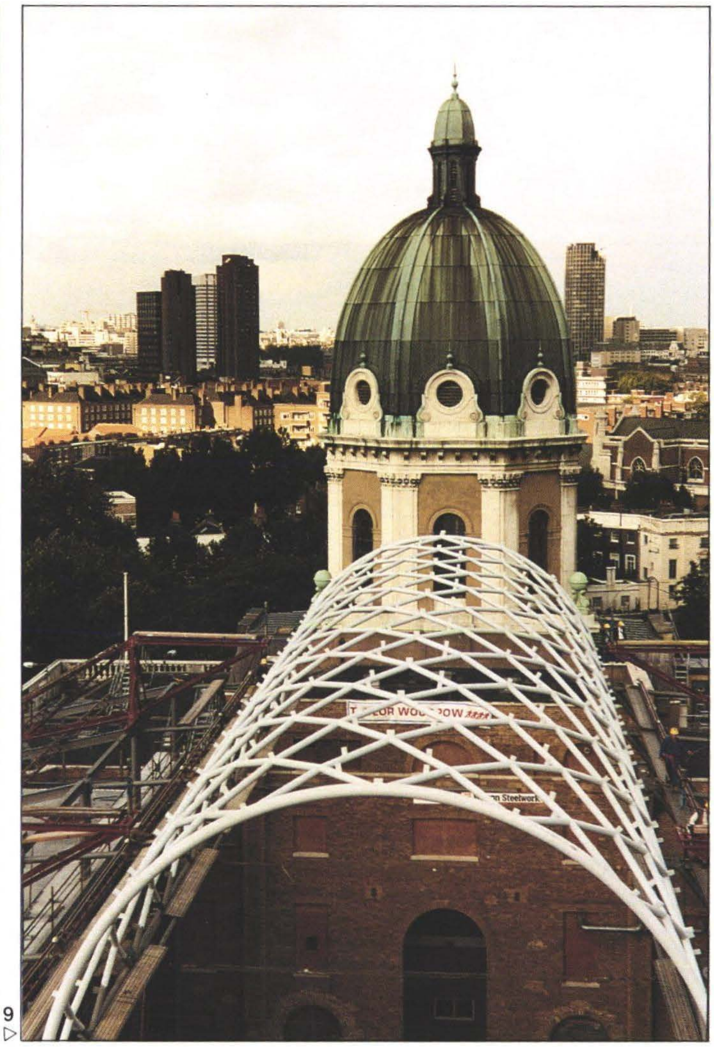

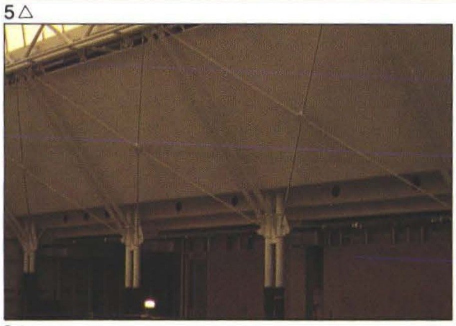

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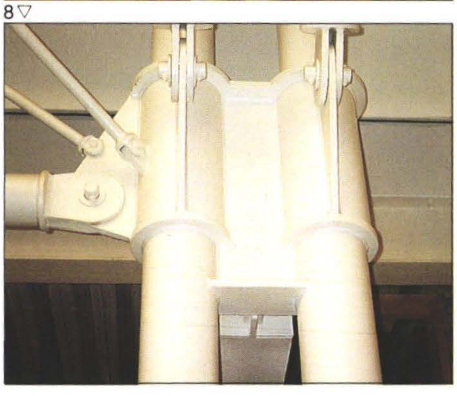

These secondary beams are designed as composite with the in situ reinforced concrete slab, the latter being laid on a galvanized metal decking.

Twin tubular columns at 7m centres rise up from the deck of the large exhibit hall to form the springing point for the crane jib frame at plant room level which supports the roof barrel. The projection of the jibs is 5.5m and the clear span of the barrel is 12m. This gives a central space 23m wide × 40m long by about 23m high at the top of the barrel.

The overall stability of the new building is achieved using reinforced concrete service cores extending from foundation to level E, above which steel bracing is used.

The steel frames were analyzed in a conventional manner. The columns were fabricated to the full length and were designed for combined axial and bending effects.

Roof structure

The central space of the courtyard between the cantilever jibs is 12m wide × 40m long. It was felt from an early stage that a single layer membrane would be the right structural and visual form to span it. Having briefly considered some of the latticed barrel vault configurations shown in Fig. 1, pattern iv was chosen as the most acceptable visually.

The barrel vault was analyzed as a complete spaceframe supported on the cantilever jib frames which were modelled as springs. Aluminium glazing bars are attached to prewelded lugs from the barrel tubes, the detail making allowances for thermal and load-generated movements. A cellular polycarbonate sheet covering was used as a roofing material.

One size of tube was adopted for all internal members with a larger diameter for the perimeter. The analysis was carried out using a proprietary finite element computer program accessed through a desktop microcomputer.

The general imposed loading was taken as 0.75 kN/m^2 with aircraft weighing up to 75kN (the heaviest being the World War II twin-engined Mosquito) to be suspended from the lower boom of the barrel. The effect of their components in space, combined with symmetrical and asymmetrical live load and wind, produced a total of seven loadcases.

A temperature change of 25°C was also considered.

Wind load was calculated using the current British Standard *CP3: chapter V: Part 2,* while pressure coefficients for transverse and longitudinal wind were derived from recommendations in the 'Wind loading handbook' by Newberry and Eaton.

The member sizes selected were 139.7 × 10 CHS internally and 219.1 × 12.5 CHS for the perimeter members, Grade 50 steel being used throughout. The average level of stress within the internal members was approximately 60% of the maximum permissible and the maximum deflection horizontally approximately 40mm.

It was important to have these low stress levels as many of the welds would be carried out on site and as tubular members were being used, only partial penetration butt welds could be achieved.

Fabrication and erection

It was of considerable importance that the components should be fabricated to very close tolerances and that assemblies be constantly checked for accuracy. In parallel with this requirement was that of appearance: it was essential that the workmanship be of the highest order. To this effect trial assemblies were made and checked for both quality and accuracy.

This was particularly difficult with the barrel vault, which was made in 12 pieces for ease of transportation. In order to ensure that

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problems of lack of fit did not occur on site, the vault was fully trial-assembled at the works prior to shipment to site.

Several purpose-made jigs were used by the fabricator and his subcontractor, and full-time inspectors were employed at both their factories during the fabrication and assembly processes. There was an extensive programme of non-destructive testing for the welds both on and off site.

The fabricator had decided at an early stage that he would use castings for the nodes of the barrel. There were some initial difficulties with surface quality but these were soon overcome, and the use of the castings proved very successful, particularly from the visual aspect.

The erection of the frame was carried out in traditional fashion with the twin columns being erected in one piece. The method chosen for the erection of the vault was, however, somewhat unusual. It was assembled in its entirety at the main exhibition hall level with individual sections being lifted over the existing building and assembled on the original jigs as used at the works. The 12 pieces were then welded at specially prepared joints.

Four hydraulic jacks were located one bay in from each end of the vault and supported on temporary masts positioned over the cantilever jib sections. Cables were attached to welded lugs on the lower boom of the vault, and the whole thing with overall dimensions of 40m × 12m and weighing approximately 34 tonnes was then jacked into position at the rate of approximately 3m/hour.

The vault remained suspended whilst connections were made to the supporting cantilever jibs and the cross-bracing rods were positioned, a process which took about four days. An analysis had been carried out simulating the condition whilst the frame was suspended from the four positions and the results of the deflected form plus horizontal thrust given to the steelwork contractor to ensure proper fit was achieved.

Fire protection

In keeping with the high standard required from the fabricated steelwork it was important that the finishes did not detract from the structural forms defined. It was essential, therefore, that the fire protection necessary for the gallery and plantroom floors supporting the structure were of the thin film intumescent paint type.

A duration of one hour was required for all structural elements and the system chosen was one produced by Nullifire, which at the time was the only product able to achieve one hour protection for circular tubes using a dry film thickness of 2.5mm on a two-part epoxy basecoat.

The intumescent paint was subsequently hand-finished on the circular columns in order to achieve a high level of uniformity of surface finish, and then sealed to provide a level of protection from damage and to give a cleanable surface. Fire protection to the roof steelwork was not required.

Suspension of aircraft

Five aircraft will be suspended in various positions and configurations from the edge beams of the barrel vault, while two light planes will be supported from the mezzanine structure. Modifications were needed to the aircraft, their baricentres located, and their position in space established helped by a 1:20 model of the museum courtyard.

Steel cables will be used for suspension and criteria for maximum and minimum angles have been established. The effects of these loads have been taken into account in the analysis and design of the structural frame and the vault.

Conclusion

The new steel structure which has been built at the centre of the Imperial War Museum is in contrast to the existing masonry building which surrounds it. It is a contrast which appropriately emphasizes the differences between this new large display hall and the brick fabric of the museum alongside.

The project, phased into three stages, received Treasury approval in the spring of 1986, and start on site was made in September of that year. The main structure for Stage 1 was completed by October 1987 and by Christmas 1988 will have been handed over. Stages 2 and 3 will follow when funds are made available.

Credits:

Arup Associates:
Architects + Engineers + Quantity Surveyors
Taylor Woodrow:
Management contractor
R. Watson:
Steel fabricator
M.J. Gleeson:
Concrete contractor
Photos:
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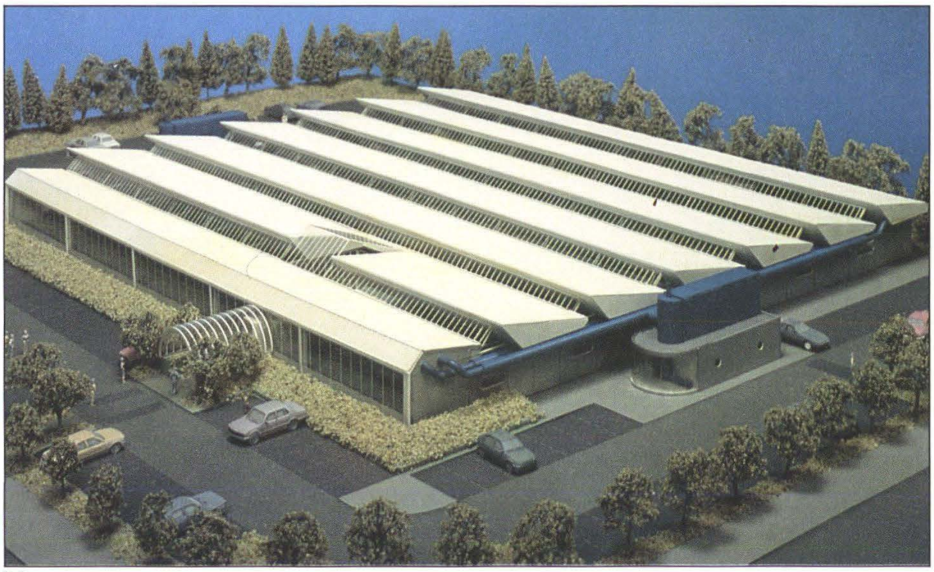
Spectrum 7, Milton Keynes

**Architect:
The ECD Partnership**

John Berry
Robert Pugh



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Introduction

The Rt. Hon. Cecil Parkinson MP, Secretary of State for Energy, joined Lord Chilver, Chairman of Milton Keynes Development Corporation, at a press conference in London in September 1987 to launch Spectrum 7 as one of the first commercial developments on the newly-created Milton Keynes Energy Park, a 120 ha site close to the centre of Milton Keynes designated for the development of shops, housing, a school and commercial schemes. As the name implies, the buildings have been planned to promote the efficient use of energy and create a high quality business environment.

Spectrum 7, completed in June 1988, is the first commercial building available for letting on the Energy Park and in itself represents a formidable achievement. A total of 3600m^2 of single-storey accommodation is provided, and a number of novel, energy-saving features have been designed into the building, such that energy running costs are projected to be 41% lower than would be the case for a normal building complying with the Chartered Institution of Building Services Engineers (CIBSE) *Energy Code Part 2A*. This highly flexible and energy-efficient building allows the end user maximum freedom of planning for office, research or production facilities.

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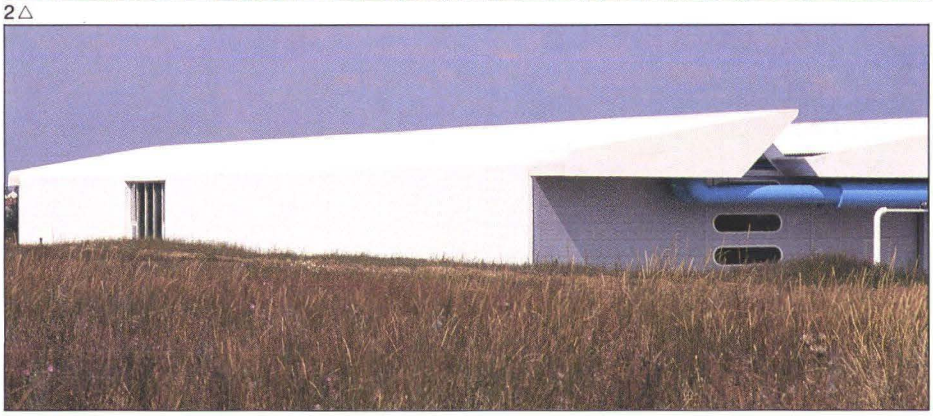
The building

Spectrum 7 has a clear floor to ceiling height of 4.0m throughout its area, the intention being to provide a large space which will give potential tenants the maximum degree of flexibility in arranging facilities. In order to maximize this flexibility of use, the principle service cores are located outside the main building envelope.

The building is organized on 1.2m planning/partition grid, with fabric, structure and services designed to allow varying degrees of internal provision. It may be used for open plan production, laboratory and development-type space, cellular office areas or a combination of the three. Allowance has been made in the design for the incorporation of a raised floor and flat false ceiling; at this stage only 50% of the floor area has been fitted out with a raised floor and false ceiling to office standard.



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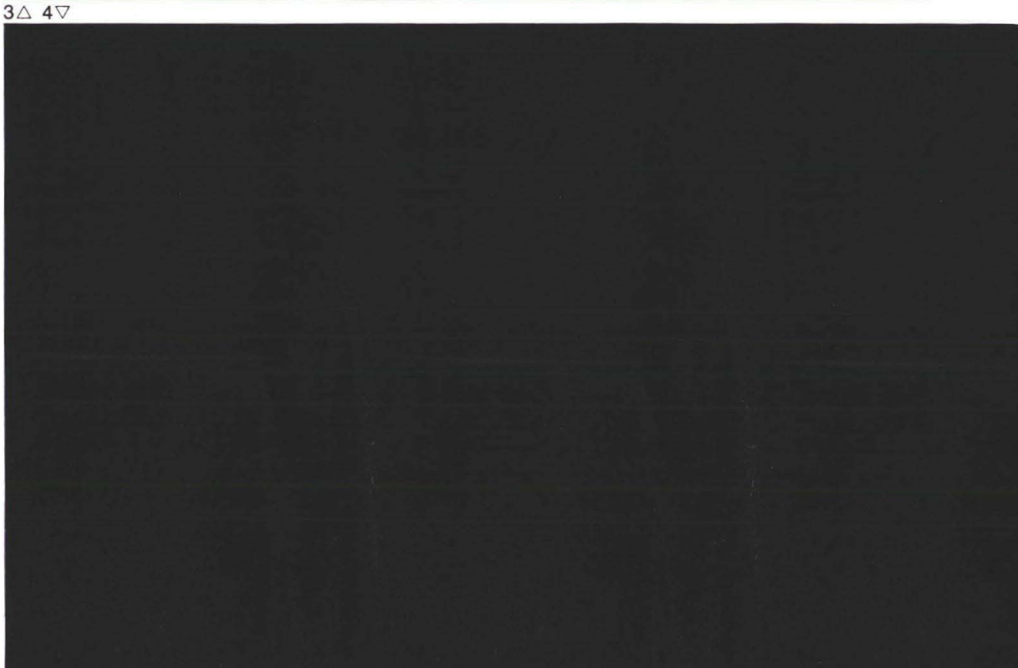


The elevations of the building and its roof are designed and orientated to respond specifically to various different environmental, climatic and functional requirements.

Landscaped car parking and service access areas surround the building on three sides with the fourth side left clear as a landscaped area. The main entrance to the building is located in an external projection to the plan leading directly to an internal glazed foyer.

1. Architect's model
2. North-west elevation
3. South-west facade
4. The main entrance

Approach to energy efficiency

A modern high technology building differs from a traditional office in three significant ways:

(1) There is a space planning requirement to provide wider spans and deeper buildings in order to increase their flexibility of use. This makes natural ventilation from the perimeter difficult.

(2) The allowance for heat loads produced by business machines has increased dramatically.

(3) Lighting is the most significant user of energy.

The first two factors are normally solved by the provision of air-conditioning, which uses significant amounts of energy, while the third factor is normally accepted as a fact of life.

The approach to energy efficiency at Spectrum 7 concentrates on removing the need for air-conditioning for all but the most intensively serviced requirements by using mechanical ventilation, supplemented by a passively cooled ground slab, and reducing the energy demand for lighting through the use of natural daylight where possible. Other energy-conserving elements have also been included.

Ventilation, heating and cooling

The conventional narrow plan office provides ventilation horizontally from one side of openings on the windward side to another set on the leeward side. Whilst crossing the building, the air is heated by lights, occupants and business machines, as well as the heating system, and this causes its temperature to rise.

There is a limit to the temperature rise which is acceptable to occupants. In practice it has been found that building depth is normally limited to 12-15m, and modern business machine loads tend to reduce this maximum depth still further before air-conditioning has to be introduced.

At Spectrum 7 ventilation has been considered in a different way.

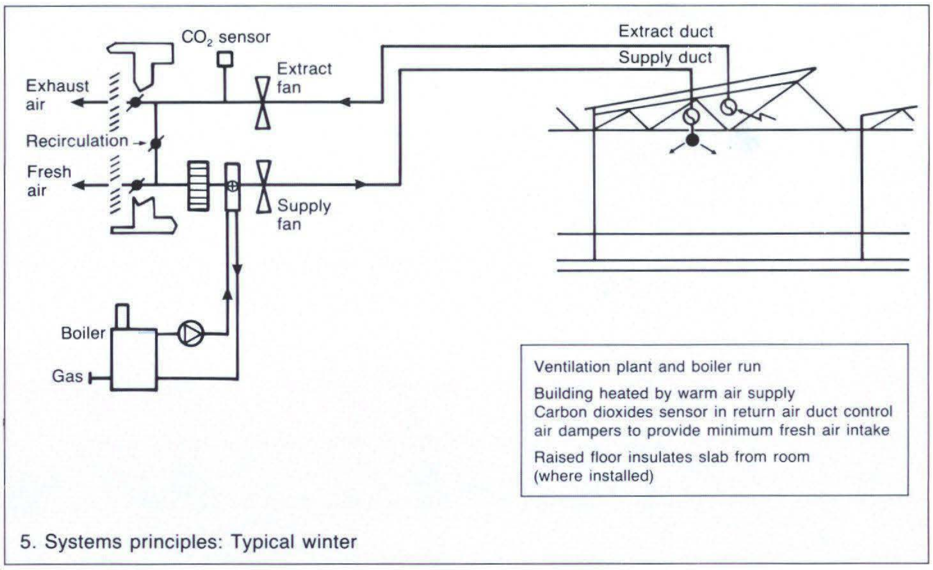
The principle is to provide a basic input and extract ventilation system at high level supplemented by a passively-cooled floor slab. In winter the input air is warmed to provide heating to the building.

In a production/warehouse arrangement the heat gains to the space are absorbed directly into the large area of floor slab, whilst in an office-type situation, where a raised floor is likely to be installed, small local fans are used. These small fans effectively re-circulate air from the office through the raised floor void; the heat from the air is absorbed into the floor slab, which therefore acts as a [redacted]

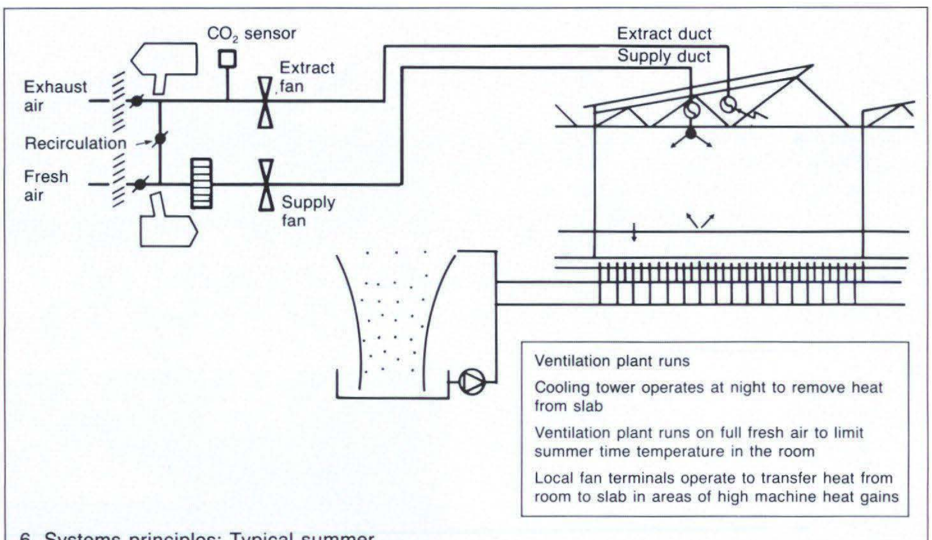
A network of 16km of 20mm diameter polythene pipes is installed within the thickness of the floor slab and connected to a conventional water cooling tower. This process of cooling relies on the temperature differences between the night time and day time ambient air. Cooled water at approximately 18°C is circulated through the slab at night in order to precool the structure and remove heat which has been stored during the previous day. The slab cooling only operates at night, when cheap tariff electricity is available. In winter the water is circulated around the slab to even out hot spots.

In general, the energy conserving measures of admitting maximum daylight while minimizing solar radiation, coupled with high levels of thermal insulation and basic mechanical ventilation, result in comfortable conditions even when the presence of the cooled floor slab is discounted. The cooled slab does, however, offer a significant improvement to the internal environment when enhanced occupancy rates or internal gains from office equipment are taken into account.

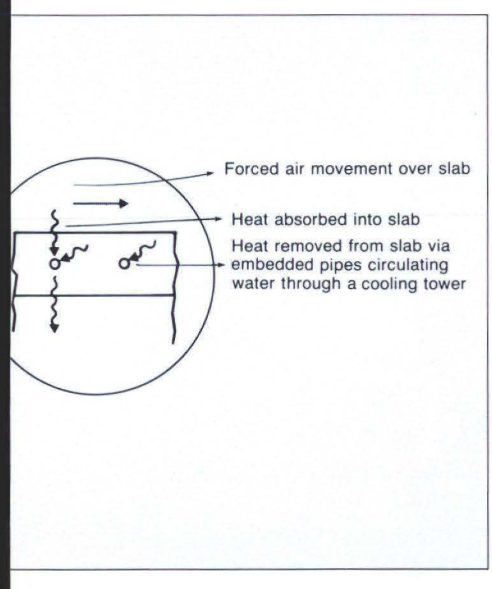
Should for whatever reason air-conditioning or mechanical cooling prove necessary, the cooling tower condenser water can be circulated to local heat pump units during the day, without affecting its capability to cool the slab at night.



5. Systems principles: Typical winter



6. Systems principles: Typical summer



Lighting

The lighting concept of the building is to use natural daylighting when possible and its single storey allows rooflights to give natural illumination to all spaces.

The choice of orientation of the rooflights has been affected by the need for daylight without sunlight, site orientation and internal space planning requirements. The orientation for daylight is therefore north-east which allows maximum flexibility of partitioning within the building. The spacing centres of the rooflights have been chosen to allow maximum flexibility of internal layout and partitioning, and good daylighting levels.

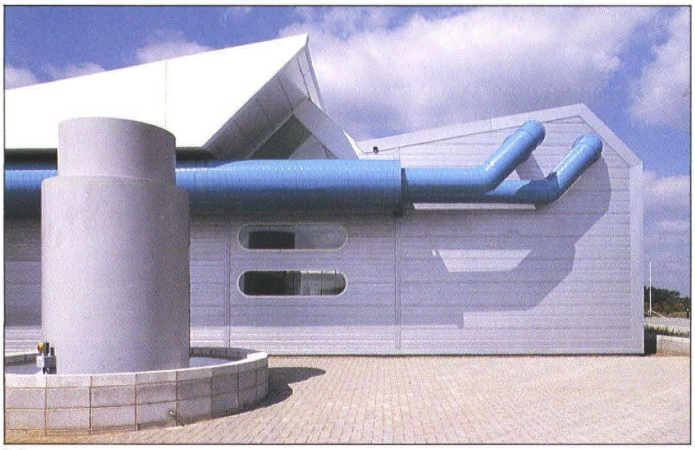
The form of the rooflights has been affected by considerations of shading, energy efficiency and servicing. Calculations show that a 60% shading cut-off angle is required, and that a sloping rooflight reduces total building energy demand by 17% compared with a vertical sawtooth. Overall, this solution uses 24% less energy than a totally artificially-lit building.

The vertical perimeter glazing has been affected primarily by considerations of view, daylighting and solar gain. The north-east wall where solar radiation is not a problem is therefore highly glazed to allow views into and out of the building.

Artificial lighting will still be required on winter days, in the early morning and evening. This is provided by high efficiency fluorescent fittings built into the ceiling grid in the closed office areas, and suspended in the open areas. The design of the fittings allows them subsequently to be built into the ceiling grid if required.

The lighting is controlled automatically by photo-electric cells which interrupt the light circuit at intervals when daylight levels are acceptable to discourage the use of unnecessary artificial lighting.

This general pattern of light switching can be bypassed in critical task areas and the system is designed on a modular basis so that changes in lighting control requirements can be accommodated easily and quickly.



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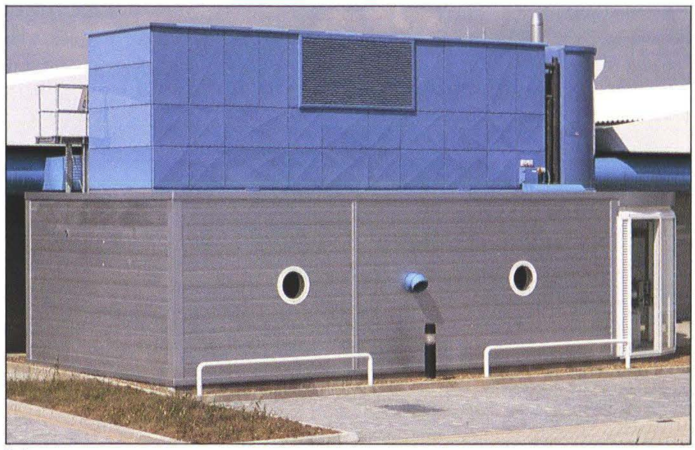

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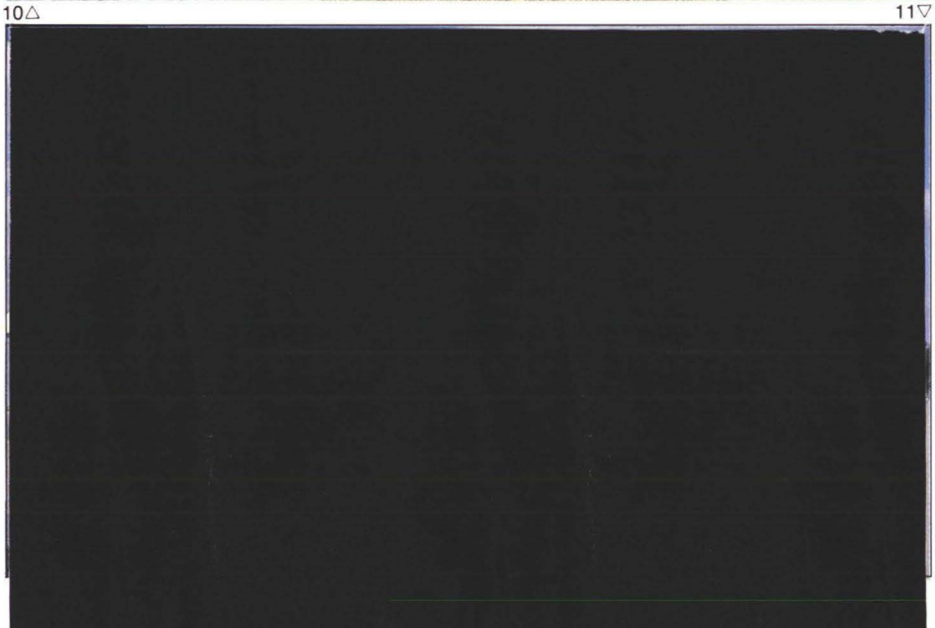
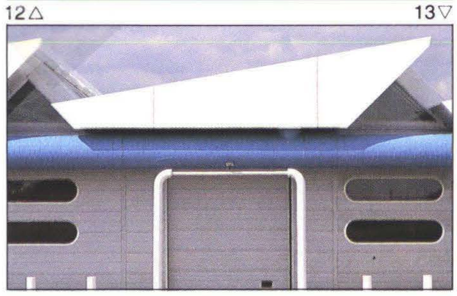




8. Close-up of cooling tower and external ducts

9. Ventilating plant above the toilets

10. The boiler room

11. Cooling tower, external ducts, and plant on north-west elevation

12. Atrium inside main entrance

13. Detail of elevation showing clerestory roof

A model of the proposed building was tested in the artificial sky at University College, London to confirm the daylight factors and the evenness of light distribution.

Energy performance

Calculations have been made using the CIBSE *Energy Code Part 2*. Based on 50% office use and 50% production use, they show that the building energy demand is 19.2W/m^2, the target for this type of building being 33.5W/m^2. Thus the proposal for Spectrum 7 is 41% better than the target.

The running costs of the building have also been calculated. The planned power consumption of 86.5kWh/m^2 would cost £2.28/m^2 annually, at the current prices of 39p per therm for gas and 5.2p/kWh for electricity (including maximum demand capacity and other charges).

Summary of energy conservation measures

(1) Mechanical warm air ventilation
(2) CO_2 fresh air sensor
(3) Deep plan without air-conditioning (except in highest gain areas)
(4) Passive cooled slab
(5) Natural daylight from rooflights
(6) Low energy artificial lighting and good controls
(7) Well-insulated fabric
(8) Modular gas boilers and good controls

Structure

Substructure

The 'greenfield' site strata comprise a thin layer of topsoil overlying clay with a slope of 1:40 over the depth of the building. The groundwater level is 4m. Consequently the single-storey building was founded on reinforced concrete bases at the column positions, 1m below finished ground level to minimize frost and seasonal heave effects.

Allowing for the stripping of all topsoil, the ground slab level was selected to give the most economic ratio of cut into the slope to imported fill. The 60m square slab was designed to be ground-bearing, and following road pavement construction practice incorporates a grid of longitudinal construction joints and transverse contraction joints to control shrinkage. The slab contains embedded 'cooling' pipework which was orientated parallel to the longitudinal joints to facilitate the alternative 'long' strip sequence of construction. The coolant operating temperatures were considered to be sufficiently high not to need to insulate the slab from potential frost heave. The top surface of the slab has a powerfloat finish.

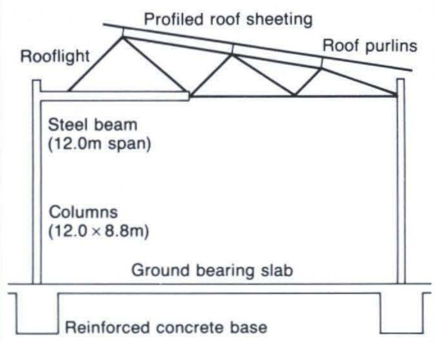
Superstructure

The natural form of construction for this type of building is a steel frame. Its profile resulted from the northlight geometry, the grid requirements and the need to minimize overall height.

Open plan grids appropriate to the building planning and intended use, while maintaining economy, were studied and a primary grid of 12.0m was adopted. Given the northlight principle, the roof shape and secondary grid dimension were fixed by the aperture size and frequency. A secondary grid of 3.3m was adopted. With the resulting three-dimensional nature of the roof, various types of lattice elements were studied, but the most economic solution was for a simple I-beam on the primary span and a light frame of angle sections to suit the profile of the secondary span. To lower the height of the roof the northlight gutters were arranged within the depth of the primary beam. This required the ends of the secondary frame to be modified to a reduced-depth, bending element over the width of the gutter as can be seen on Fig. 14.

However, this introduction of the bending element has resulted in a saving of 0.5m of cladding height all round the perimeter, which is significant for a single-storey building.

The roof is clad with profiled, insulated, steel sheeting supported on continuous, cold formed purlins, together with a patent glazing system forming the northlights.



14. Section through typical 8.8 m bay

Programme and construction

Approval to proceed with the design of the project was received in March 1987 with a required site start of September 1987. To achieve this a two-stage tender approach was adopted for the main building contract as well as the steelwork sub-contract.

The first stage tender documentation provided sufficient information for tender evaluation on the basis of rates. Meanwhile, the design was able to proceed in sufficient detail to enable a second-stage agreement on the contract sum and the award of contracts to meet the steelwork order and site start dates.

As soon as foundations were installed, the steel superstructure and roof were erected. Edge strips enabled the perimeter wall cladding to proceed, and with the building envelope well advanced, the ground slab was constructed in the protected environment. Completed sections of the ground slab offered immediate working platforms for the installation of high level services.

Spectrum 7 was completed at the end of May 1988 in a construction period of 38 weeks. Although the building has not yet been occupied we are confident that the concepts behind its approach to energy efficiency constitute a major step forward in our work on combining a pleasant working environment with the ever more economical usage of energy resources.

Credits

Client:
Bridehall Developments Ltd.
Architect:
The ECD Partnership
Structural and services engineers:
Ove Arup & Partners
Quantity surveyors:
Bucknell Austin plc
Photos:
Peter Mackinven

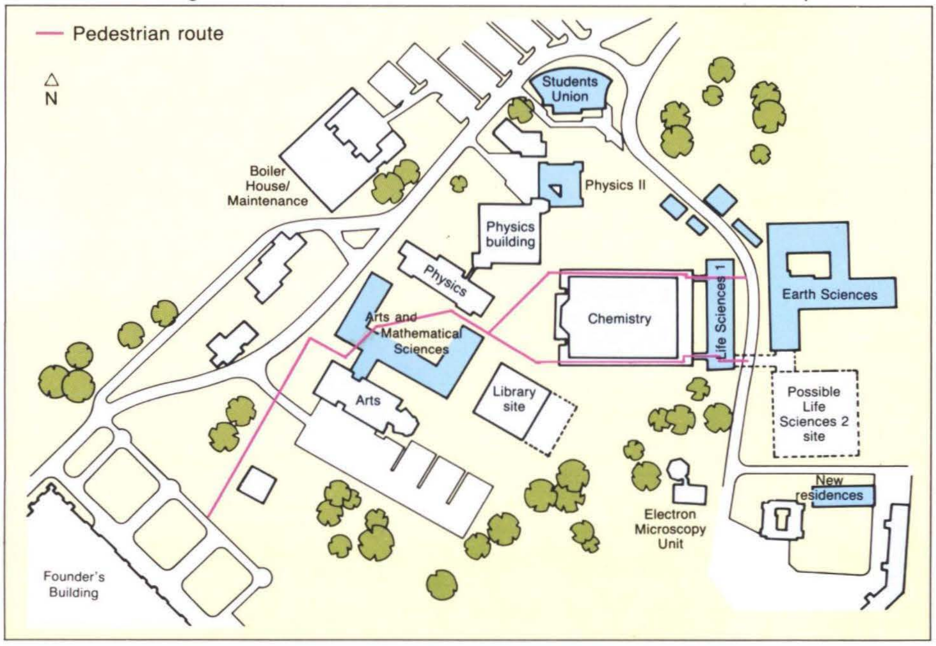
Royal Holloway and Bedford New College

Architects:
Powell Moya and Partners
Michael Brawne and Associates
Edgington Spink and Hyne

Derek Pike

△ Founder's Building

Development Plan ▽



Introduction

Bedford College and Royal Holloway College were among the smaller colleges of the University of London. They were both established in the 19th century as foundations for the higher education of women and they both had magnificent locations, Bedford in the heart of Regents Park and Royal Holloway overlooking the Thames Valley at Egham.

The education cuts of the 1970s hit hardest at the smaller colleges and, prompted by views expressed in the reports of the Murray Committee (1972) and the Swinnerton-Dyer Committee (1981), the two decided to merge and to move to the Royal Holloway College Campus. The Regents Park site is on Crown Land and had to remain an educational establishment, but it was sold to an American university and the proceeds used to finance the merger.

The new school, named Royal Holloway and Bedford New College, will eventually have a total of approximately 3000 students and 260 academic staff in Faculties of Arts and Music and of Science. As a result of the expansion a total of five new academic buildings were planned, together with a Students Union and two developments of student residences.

The site

The main site overlooking the Thames Valley at the top of Egham Hill is approximately 44.5 ha in area and is a mixture of heavily wooded areas and fields. It even has its own resident deer. Prior to construction of the original college in 1886 the area was mainly farmland with a brickwork industry located lower down the hill.

Royal Holloway College was founded by the Victorian philanthropist, Thomas Holloway, and the site is dominated by his Founder's Building, a startlingly ornate grade 1 listed building designed by W.H. Crossland who took as his model the Loire Chateau of Chambord. It was the original College building and housed lecture theatres, an art gallery, seminar and staff rooms, student accommodation and even rooms in the attic for the servants and companions of the young lady students. The infrastructure to support this establishment was equally impressive. The main boiler house, which is still used, is connected to the Founder's Building via an underground service tunnel and there were workshops, kitchen gardens and a piggery. It was entirely self-contained and surrounded by landscaped gardens and a continuous high brick wall, which is also grade 1 listed.

The Development Plan

In the 1960s the site was further developed to a low density. However, although much of the remainder was either wooded or steeply sloping, there was still enough land suitable for the planned new buildings of the 1980s.

As shown above, the Development Plan for the site, prepared by Powell Moya and Partners, attempted to provide a strong link between the Founder's Building, with its formal lawns and terraces, the existing Colquhoun and Miller Bourne chemistry building and the new teaching buildings. This was achieved by the planning of a series of courtyards surrounded by the new and existing buildings.

The design and construction of the new buildings was phased over five years, with the highest priority given to the Earth Sciences, the Maths/Arts and the Life Sciences I Buildings. In addition to the teaching and administration buildings, the plan also included the provision of residences for approximately 400 students.

On completion of the planning, Powell Moya and Partners were commissioned to design most of the new buildings. Physics II and the Students Union were, however, designed by Michael Brawne and Associates as an extension to their previous Tolansky Physics building, and Edgington Sprink and Hyne were commissioned to design the Electron Microscopy Unit together with the Student Residences on the site to the north of the A30.

Despite the fact that the proceeds from the sale of the Regents Park Bedford College premises were available, all of the new buildings were designed to the very restrictive University Grants Committee cost yardsticks. Consequently, the design development of each building involved a close collaboration between all members of the team, and this has resulted in the construction of a set of buildings which are well-planned and detailed and which make their own architectural statements.

The total Development Plan budget was approximately £16.5m and, after many false starts and redesigns, the buildings were constructed over a four-year period under eight separate contracts, using seven different main contractors.

Geotechnical engineering

The College grounds are situated on the south-east sloping side of the Thames Valley. The general stratigraphy of the area is Bagshot and Claygate Beds overlying London Clay. This was confirmed by boreholes which were sunk as part of earlier developments and by a series of trial pits excavated close to the sites of the new buildings.

The horizon between these two strata outcrops on a line which follows the site road, with the Earth Sciences building and Student Residences at a lower level than the road founded in the London Clay and the remaining buildings founded in the Bagshot Beds. The philosophy adopted for the foundation design of the two and three-storey buildings was to use strip footings designed for modest bearing pressures, with soft spots removed and replaced with compacted granular material where necessary.

Analysis of the lower London Clay slopes indicated that they were on the point of failure, and evidence of relict slip planes was found at approximately 2.5m below the surface in trial pits excavated at the base of the slope. As a consequence, the slopes adjacent to the Earth Sciences building and the student residences have been regraded and drained, and the footings for these buildings are founded below the level of the relict slips.

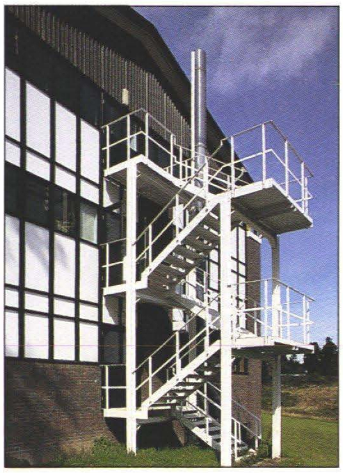
The buildings

Electron Microscopy Unit

Although included in the Development Plan, this Unit does not, strictly speaking, form part of the building works brought about by the merger. The Unit consists of two small, single-storey buildings, a heptagonal structure which houses five electron microscopes, linked to a more conventional office and laboratory building. Vibration analysis of the site was carried out by Arup Acoustics and their recommendations led to the provision of a substantial raft foundation. The superstructure is loadbearing brickwork and blockwork supporting a timber-framed roof.

Earth Sciences building

The Earth Sciences building is situated on the break between the gently sloping upper site and the steeper slopes of the lower site. It was necessary to regrade and drain the slopes adjacent to the building and the strip footings were founded below the relict slip planes. The building varies from two to three storeys, thus relating the floor levels to the sloping site whilst maintaining a uniform roof line. The superstructure is a reinforced concrete frame of two-way spanning flat slabs supported by long and slender wall columns. The roof consists of a series of steel portal frames springing from the concrete columns which extend up to the cill level of the upper floor. The external wall columns are clad in brickwork with a timber curtain wall system between and continuous glazing at the upper level. Both the steel and internal concrete structure have been left exposed, with particular, complex structural junctions being highlighted. Natural ventilation is used throughout with the heating equipment housed in a separate adjacent boiler house.



Earth Sciences: Fire escape stair

Earth Sciences: Entrance on Site Road, below: Reception area

Earth Sciences: Courtyard, below: Roofscape

Earth Sciences: Below, elevation

Life Sciences:
Link block to Bourne chemistry building

Life Sciences building

Facing the Earth Sciences block across the main site access road is Life Sciences I. The appearance of the two buildings is similar, as is the structural solution. However, it has one to two more storeys, a more regular structural grid and is more heavily serviced, which necessitated a floor slab construction consisting of a one-way spanning ribbed slab supported on similar concrete wall columns. The planning restraint of Life Sciences I having to be connected to the existing Bourne chemistry building has been solved by using steel-framed linking blocks which bridge over the access to the service areas at the rear of the building.

Adjacent to Life Sciences I is a single-storey Reactive Gas Laboratory. The walls of this are blast-resistant reinforced concrete, clad in brickwork; they support a lightweight roof designed to vent any explosion upwards. Fortunately the design assumptions have yet to be tested!

Maths and Arts building

The Maths and Arts building, situated between the existing Arts block and the Old Physics building, thereby completes a trio of similar Powell Moya academic buildings. Its horseshoe shape defines a new landscaped and terraced courtyard on one of the main pedestrian circulation routes through the campus. The building varies from two to three storeys in response to the sloping site and the structure and architecture are similar to Earth Sciences.

Maths/Arts: Courtyard, below: Main entrance stair

Maths/Arts: Exposed roof structure

Physics II: East elevation

Physics II: Spiral stair to rooftop observatory

Physics II

The Physics II building, now named the Wilson laboratory, was designed by Michael Brawne and Associates to provide research facilities including specialist laboratories for work in low temperature physics. The strong diagonal theme of the earlier Tolansky Physics laboratory to which it is linked has been reinforced by the new laboratory block with the connection between the buildings occurring only at one corner. In complete contrast to the Powell Moya buildings, the three-storey structure is load-bearing brickwork supporting reinforced concrete ribbed slabs with some double-height laboratory and workshop spaces.

The requirement for a high percentage of penetrations through the external walls led to an interesting exposed steel wind mullion, which was incorporated into the design of the windows.

The Students Union

The Students Union follows the brickwork theme of Physics II, and ends the progression of buildings down the slope. The exposed steel window mullions are used again on the south face of the building and they are utilised to support an external balcony and pergola. The shape of the building is more freeform, with the north face of brickwork following the curve of the site road. A double-height hall and stage separates the two-storey administrative and leisure sections of the building. Internally the detailing is robust with paint being used as the only finish to exposed concrete and brickwork.

The Student Residences

The original Royal Holloway College was almost entirely residential, and during the merger discussions both colleges expressed the desire to maintain a high percentage of students housed on campus. This need was reinforced by the fact that the campus is relatively isolated with little opportunity for students to arrange their own accommodation, and the Development Plan therefore made allowance for residences to be built to house approximately 400 students. Two sites were identified, one close to the existing on-campus residences and the other on a separate site to the north of the A30. In both instances the housing units are arranged in two and three-storey blocks, with each unit accommodating up to eight students in individual bedsitting rooms with a shared common room and kitchen. The blocks are of traditional loadbearing blockwork clad externally in brickwork with reinforced concrete floor slabs and timber trussed rafter roof structures.

The Library

The last major academic building currently planned for the site is a three-storey Library which completes the southern side of another courtyard. The design and planning has been completed but tenders have not yet been called pending funding negotiations.

Due to the special planning and servicing needs and to the heavy design loading, the structure will consist of two-way spanning flat slabs supported by circular concrete columns. Concrete lift and stair towers provide the lateral stability and the roof structure will be exposed glulam timber frames and purlins supporting a traditional slated finish.

The foundations will be piled with the caps supporting a suspended ground floor slab.

Conclusion

The proposal to merge the two colleges was made to the University of London and the University Grants Committee in early 1983 following a period of intense negotiation and planning. The original timetable was to complete the transfer of all the academic departments by late 1985 in a complex phased operation with a minimum of disruption to the students.

Due to extended negotiations, this was not quite achieved, but the Earth Sciences building was in use by January 1986 and officially opened by Her Majesty the Queen on 16 May 1986. All of the other academic buildings and the student residences were successfully completed in rapid succession during 1986.

Credits

Client:
Royal Holloway and Bedford New College
Architects:
Development Plan, Earth Sciences, Life Sciences, Maths/Arts, Student Housing and Library:
Powell Moya and Partners
Physics II and Students Union:
Michael Brawne and Associates
EMU and Student Housing:
Edgington, Spink and Hyne
Project co-ordinator:
Baker Wilkins and Smith
Quantity surveyor:
Monk Dunstone Associates
Structural engineer:
Ove Arup and Partners
Services engineer:
Austen Associates
Photos:
Harry Sowden

Left: Students Union entrance (detail above)

York Minster: The new roof to the South Transept

Architect: Charles Brown
Surveyor of the Fabric

Peter Ross

The fire

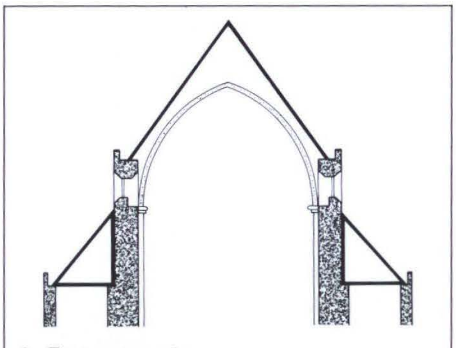
On the night of 9 July 1984 a storm passed over the city of York. There was heavy rain for a while, and some lightning was seen. In the small hours of the next morning, the alarm was raised at the Minster — fire had started in the roof of the South Transept. Worse than that, it had taken a good hold by the time it was discovered, and the Fire Brigade, although arriving promptly, were faced with a fire which was well alight and blazing. The height of the roof, and the difficulty of access, meant that fighting the fire at roof level was a losing battle, and there was a risk of it spreading to other parts of the Minster. The Brigade concentrated their efforts on demolishing the roof by deliberately knocking out the purlins which held the trusses in place, and soon the whole structure was on the Minster floor. Once this was achieved, the fire was quickly extinguished, but daylight found the smoking transept open to the sky, its roof removed with an almost surgical precision (Fig. 1).

Poul Beckmann went to York on the 10.30 a.m. train after having received a phone call from the Surveyor of the Fabric, Charles Brown, whom we had advised on structural matters since the restoration work of the 1960s. The Dean and Chapter quickly assembled a team and we were appointed as structural consultants. The work of reconstruction was carried out by the Minster workforce, under Robert Littlewood, Superintendent of the Works.

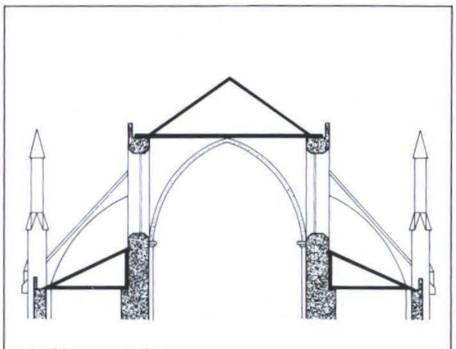
The existing structure

The original Cathedral dates from Norman times, and the long programme of rebuilding commenced with the Transepts in the 13th century (Fig. 2). The roof structure would at that time have been exposed to view inside the Transept, supported by the arcade walls with their small clerestory windows (Fig. 3).

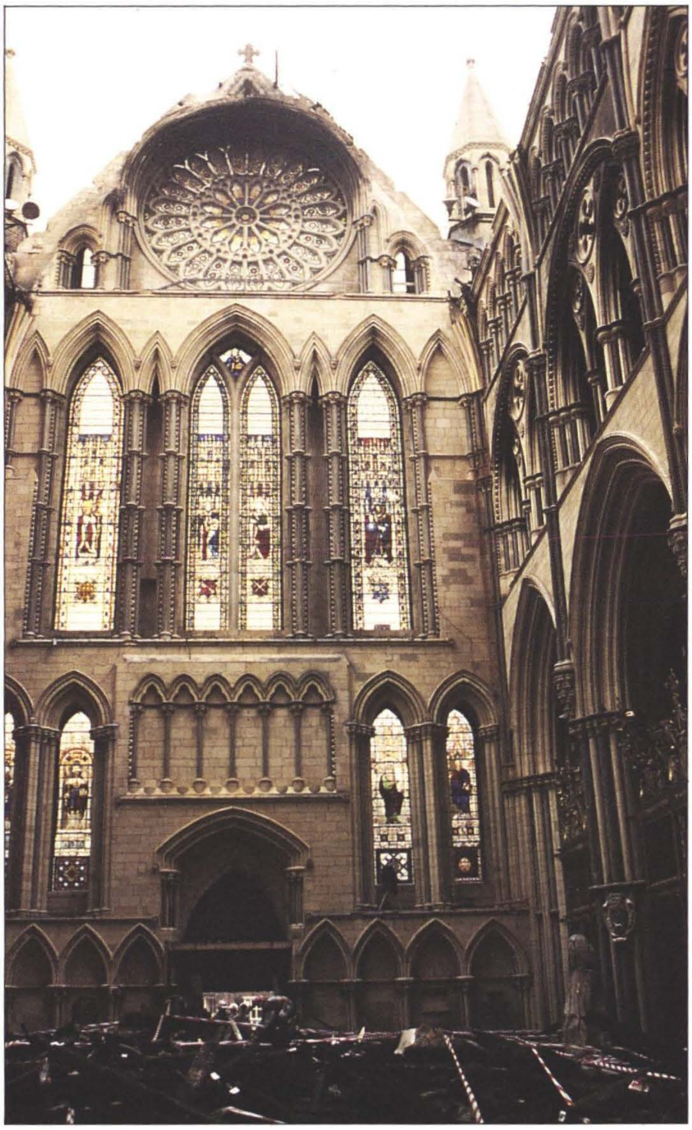
The flying buttresses, supporting the arcade walls, are concealed under the aisle roofs. The Nave and the Choir were demolished and rebuilt in the 14th and 15th centuries respectively. The Nave cross-section (Fig. 4) shows the development of the Gothic style, with the larger clerestory windows, and ribbed vaulting. At the end of the 15th century, with all this magnificent new work, the transepts were looking somewhat old-fashioned, and so the Dean and Chapter commissioned what we would regard as a refurbishment, instructing their Superintendent to vault the Transepts to match the rest of the Minster. Strictly speaking, this would not have been possible without a major rebuild, but a compromise was reached by building the vault up into the roof space. This in turn meant that the new roof trusses were not simple triangles, like the Nave, but A-frames, and that the vault would have to be built of timber, in imitation of stone, as the structure would have been incapable of restraining the out-thrust from masonry.



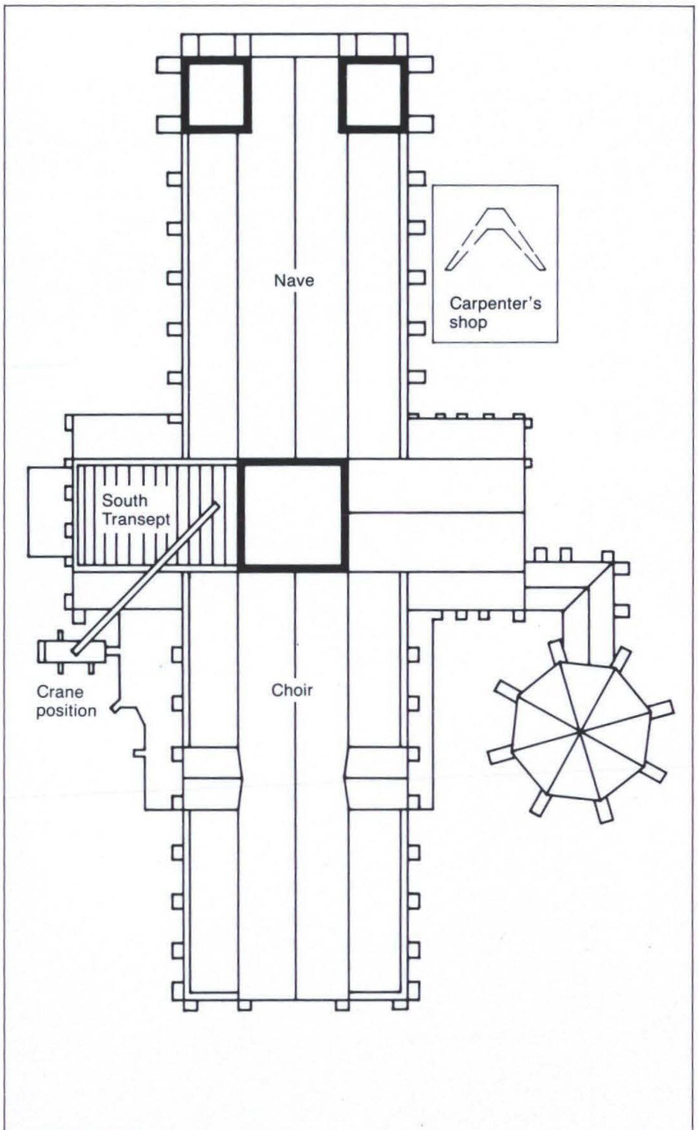
3. Transept section



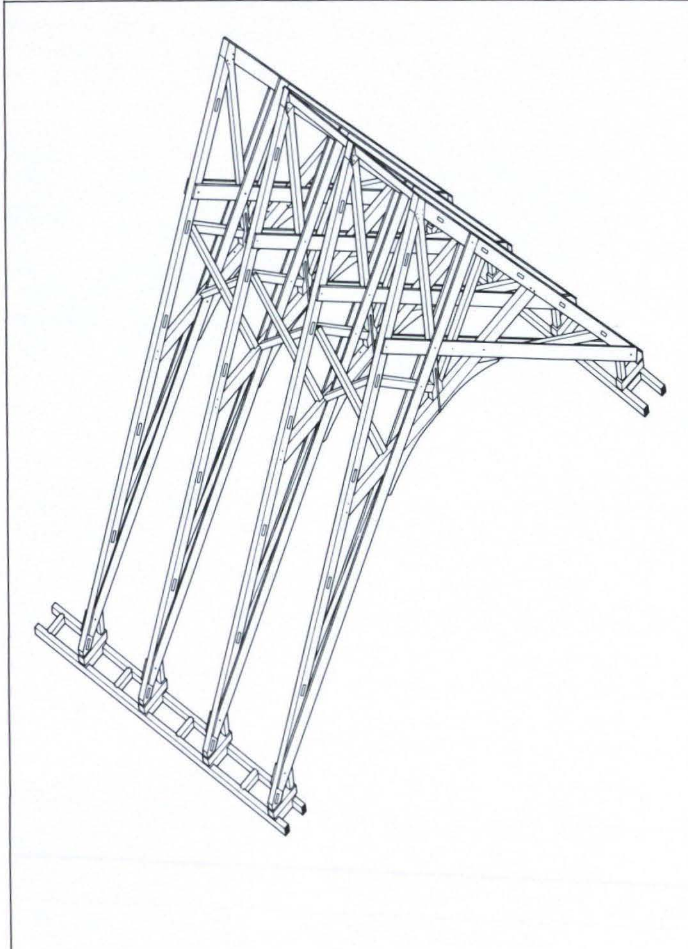
4. Nave section



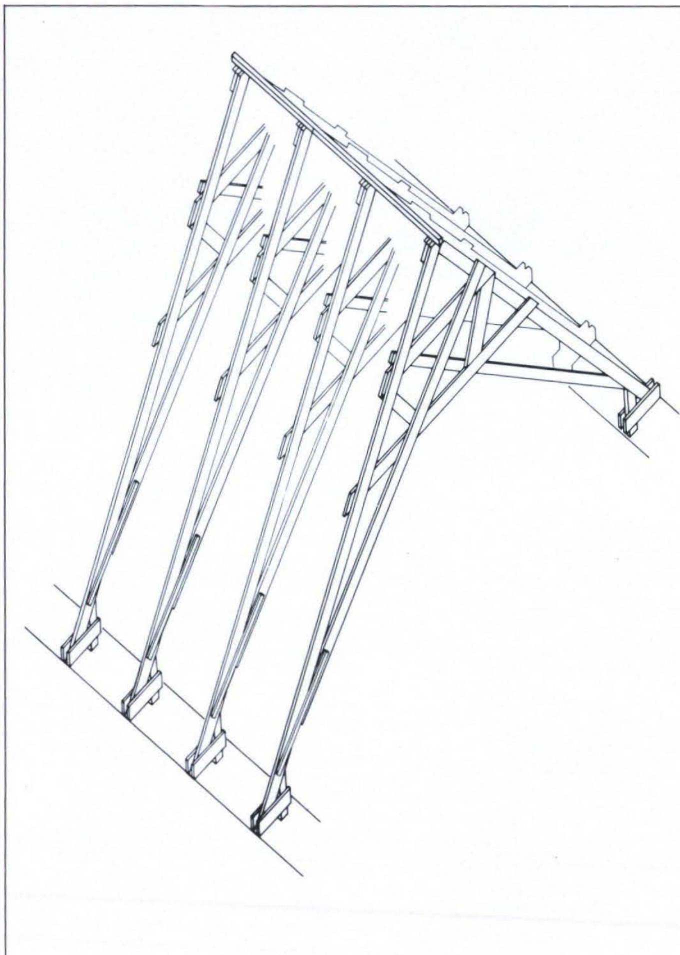
1. The morning after the fire



2. Minster plan



5. The pre-1984 roof structure showing the 18th century trusses overlain with 19th century scissor braces



6. The new roof structure

Some of the original vault timbers were still preserved in the 1970s, but much repair work had been done. Indeed, the original roof had suffered a previous fire, and the existing trusses dated from the middle 18th century. They in turn had been strengthened with scissor braces by the architect, George Street, during the restoration of the 1870s. (Fig. 5).

Thus, although the roof was of archeological interest in terms of the record which it gave of the work of various periods, it had in fact been much altered and strengthened with time as was found necessary.

The options for restoration

Ideas were offered in abundance for the rebuilding. Why not leave the Transept roofless, or provide a glazed roof? Or build new vaults in concrete or glass-fibre? Against the proposals of the modernists, the traditionalists demanded an exact replica of what was there before the fire — or even a 'day one' approach, rebuilding a vaultless 13th century roof, although the details were totally unknown.

On the practical front, it was clear that an exact replica would give the same performance in a future fire, and there were arguments for increasing the fire resistance of the vault, and the survival time of the structure.

In the event, sanity prevailed. The vault has been reinstated to the original lines, with modifications to the web construction to improve the fire resistance. The options for the new roof structure were, in practical terms, limited to 'lightweight' framing, that is timber or steel, by the height and cranage reach. These options were considered by us in detail, but the Dean and Chapter eventually chose timber as the most direct replacement for the original — the work was, after all, being funded by their insurers. Moreover, timber had a 'known' durability, and was a more familiar material to the Minster workforce in terms of maintenance.

The new structure

Thus the decision was taken that the trusses would be of timber — the traditional species being oak, based on its durability. In view of the size of the principal members which would be needed, enquiries were made with major suppliers, and it became clear that suitable timbers could be obtained, but not from existing stock. Thus in order to build to any practical timescale, the trusses would have to be fabricated from timber that was not just green, but freshly cut. This restriction to unseasoned timber became the most significant factor in the design of the structure.

The truss outline is determined by the profiles of the roof and vault (Fig. 7). A truss of this form, with no eaves tie, produces an outthrust at its feet. There was some evidence that the original roof had caused small outward movements of the clerestory walls, and so it would be necessary to limit the horizontal reaction of the new truss.

Performance of the new structure in a fire

The existing roof had been completely destroyed in the fire, and it was only possible to salvage for re-use six vault bosses from the debris. It was desirable that any future reconstruction should be designed to give a longer period of fire resistance even though the basic frame would still be made from timber.

Timber does in fact burn and char at a predictable rate. It is possible to size the frame members so that they still retain their integrity after a specific period, albeit with a reduced factor of safety. If, in addition, the vault were to be suspended from the trusses by protected hangers and the vault webs rebuilt in plasterwork rather than timber, to establish the fire-break which is normally provided by a masonry vault, then the damage caused by a future fire would be greatly reduced, provided that it could be put out within one hour.

Design of the trusses

In view of the repaired form of the original structure, and the fact that it had been completely destroyed in the fire, there was no requirement to reproduce or match it exactly.

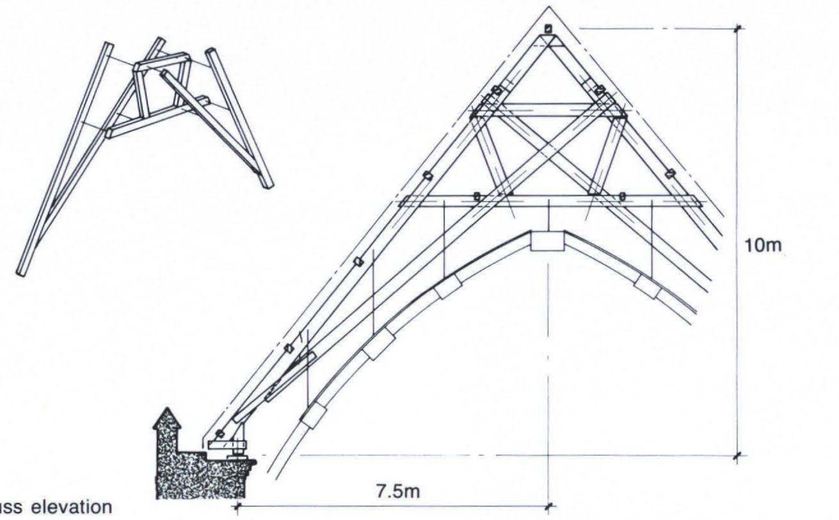
Instead it was felt more appropriate to create a 20th century design, which most directly fulfilled the brief. A typical truss (Fig. 7) consists of an upper and lower collar, with scissors legs applied to each side. This arrangement minimizes the length of the principal members, but 12.5m long pieces are still required. These needed to be 300mm × 150mm in cross-section for a 'fire-surviving' design. There are 13 trusses in all, which places each truss over a line of vault bosses.

A check of the clerestory masonry indicated that the outward component of reaction of a fixed-foot truss which supported both the roof and the vault would give an unacceptably low factor of safety against overturning.

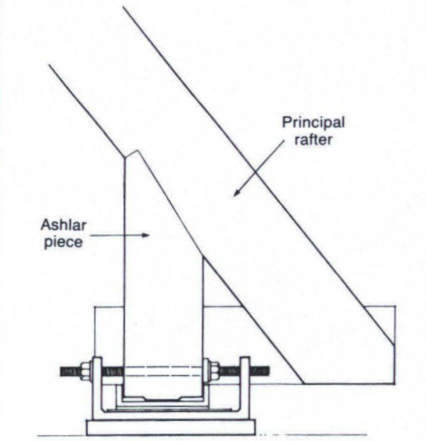
It was decided to reduce the outward reaction by allowing one foot of each truss to slide after completion of the roof, and then fixing it for the addition of the vault loading (Fig. 8).

The timber was supplied by Venables of Stafford, who obtained it from estates throughout Britain. The programme of construction meant that the timber had sometimes only been cut two months before fabrication, with moisture contents in the range 70%-90%. Significant shrinkage would obviously occur at a later date across the grain, and for this reason almost all the joints, with the exception of the small notch for the ashlar piece, are simple laps, with no halving or housing of one member into another.

Since most of the members are only in face contact with each other, the obvious method of connecting them is to use bolts. However, most of the joints are near the ends of the members, and so there would be an unacceptably high risk of splits developing



7. Truss elevation



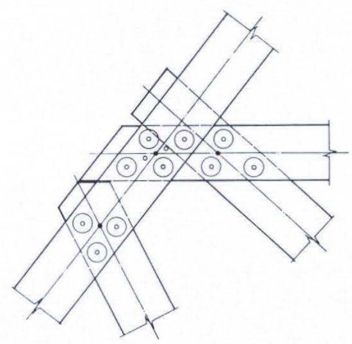
8. The east sliding bearing, showing the ashlar leg restrained by a threaded rod

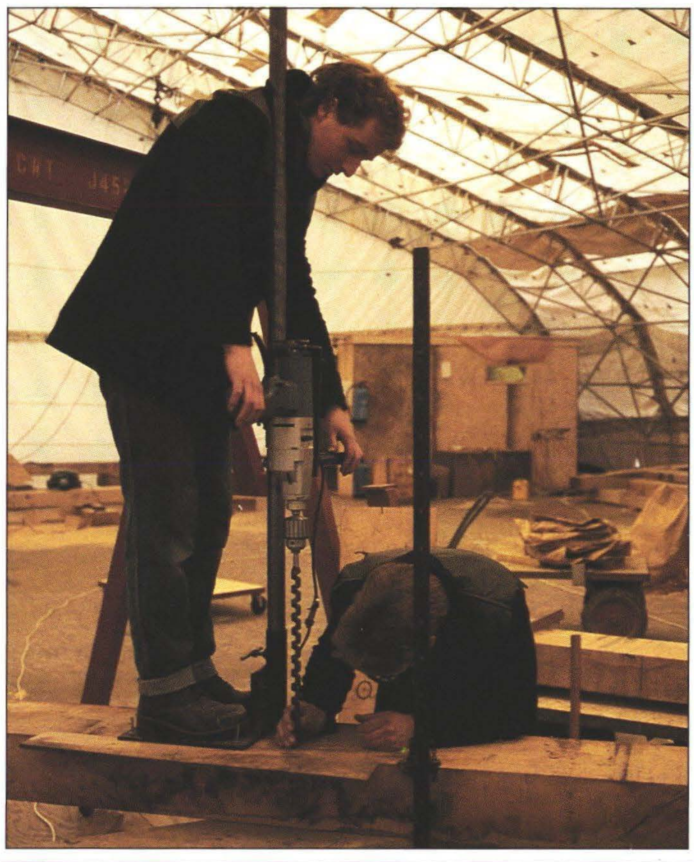
through the bolt holes. Therefore, in addition, connectors were used, as they are much more tolerant of splits in the timber, with the overlap of two timbers allowing the use of four 102mm connectors. The split ring connector is the more efficient, but if on drying twisting of the timber should occur which could not be restrained by the bolts, then the purchase of the ring in the timber would be reduced (Fig. 9). For this reason double shear plate connectors were used on each bolt. All metal components are made from Grade 316 S16 stainless steel, including the shear connector castings and bolts, which are in fact rods threaded at each end.

The frame is basically triangulated, but a strict application of the principle of intersecting centrelines would make it necessary to connect three members together at most joints. This would involve drilling through a total thickness of 450mm of timber, with each bolt taking four connectors. Small offsets of the members allow joints to be made between two pieces of timber only, which considerably reduces the problem of fabrication (Fig. 10). The eccentricity is limited so that the resultant moments and shears still lie within the capacity of the member.

In order to prevent the bolts from becoming the Achilles' Heel of a fire-surviving structure, all the heads are recessed and covered with 40mm timber plates. Periodic tightening of the bolts will, of course, be necessary for some years.


9. Sample timbers dried out, showing distortion of the cross-section


10. Bolt groups connect two timbers only


11. Drilling the boltholes. Note the use of the first temporary transept cover forming the workshop for fabrication of the trusses

The roof covering

The trusses are linked together by oak purlins, which support the decking. The fire-surviving properties of the trusses would be of little use unless they were held in position for the required period, and so the purlins are also sized for fire, and notched down between the trusses, strutting them from the masonry at each end of the Transept. The purlin restraint of the trusses serves a double purpose, for it also keeps them firmly in line during the drying-out period.

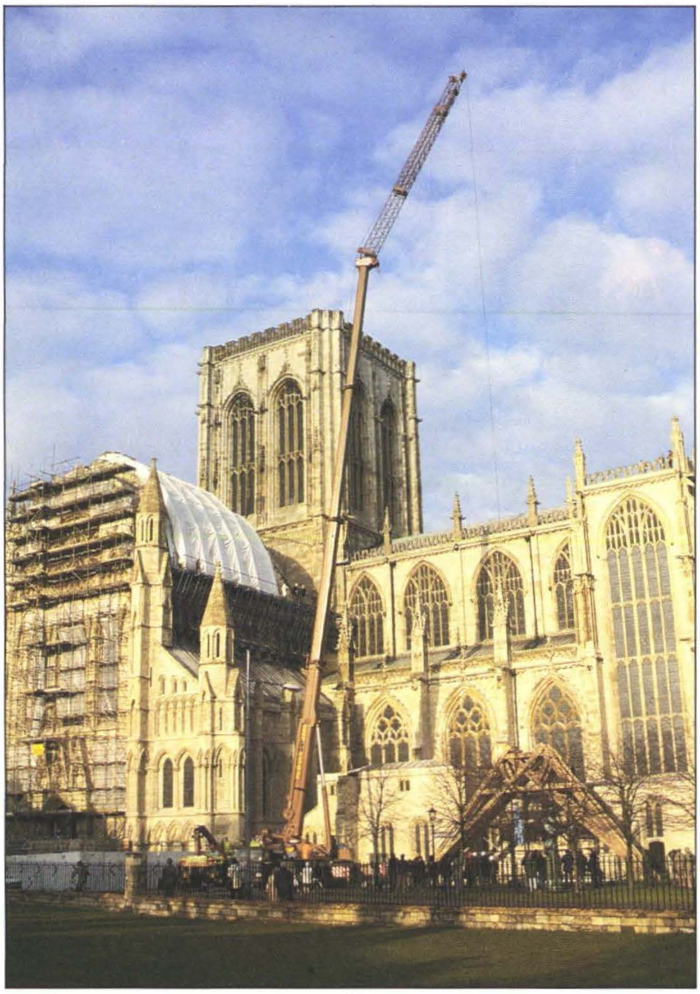
Temporary covers

A cover for the Transept was obviously required, to protect the remaining masonry structure from the weather, and to allow repair work to proceed without interruption. The first temporary cover, designed and built by Weatherbeater Ltd., consisted of aluminium framed arches covered with pvc sheeting. Successive frames were built at the gable end, and 'launched' out over the Transept on alloy rails set in each gutter line on the head of the wall, as the well was not yet scaffolded out. The Transept was covered within three weeks of the fire.

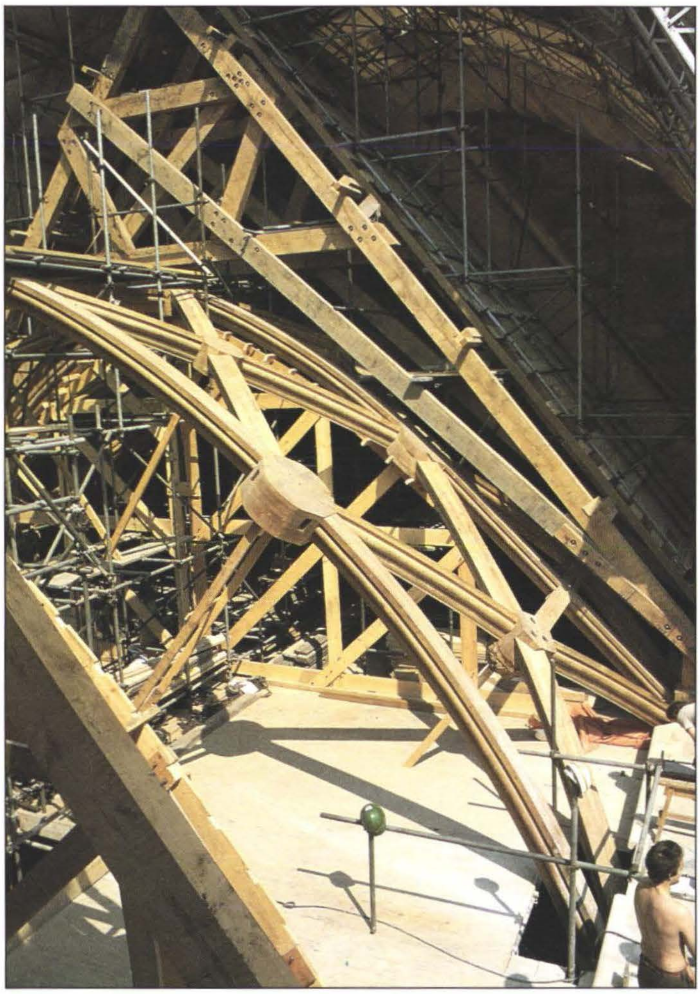
The first cover was high enough to accommodate the work on the vault, but would not contain the roof. A higher cover was needed — 'Weatherbeater Two' — set on rails cantilevered out from the clerestory walls, and in three separate, moveable sections. This would enable the trusses to be placed by crane and allow all the lead sheet to be fixed under cover. The second cover was erected over the first, which was then dismantled and re-erected in Dean's Park to become the workshop for the fabrication of the trusses.

Fabrication and erection

The trusses were fabricated in a temporary workshop erected on the north side of the Nave (Fig. 11). The profile of the truss was drawn on the floor, and the large timbers were manhandled over it using simple shear legs — assembly techniques which almost certainly had medieval antecedents.



12. The crane ready to commence lifting



13. The roof trusses erected over the vault ribs

The high moisture content of the timber meant that if, after fabrication, the truss was taken apart for any length of time, re-assembly might prove difficult. The problem was solved by avoiding it; the trusses, once made, were left assembled until a group of four were complete. With a Sunday road closure, the trusses were taken around the West End of the Minster by mobile crane and stacked against a side chapel, ready for lifting into position the following day by a larger mobile crane (Fig. 12).

The trusses weigh around 3.4 tonnes, and require a crane capable of lifting them to a maximum radius of 34m — not, of course, a medieval technique, but an economic alternative to piece-small lifting and re-assembly.

The first four trusses were lifted in December 1985, followed by the second group of four in February 1986. The work of fabrication followed closely on the delivery of the cut timber, and the last group of five trusses was lifted in June 1986. They are all similar in form except for truss 13 (nearest the South Gable), which has a higher collar level. This modification is necessary in order to clear the ridge of the vault, which rises steeply in the last bay to meet the top of the Rose Window.

As soon as the first trusses were in position, the work of fitting the purlins and rafters commenced. The profile of the roof is not constant for the length of the Transept, as the span reduces by 200mm, and the ridge line rises by 250mm, from the Central Tower to the South Gable. Rather than attempt to make 13 trusses with different dimensions, a mean size was used for each group. The resulting steps in profile were 'sweetened' by adjusting the depth to which the purlins were notched over the trusses.

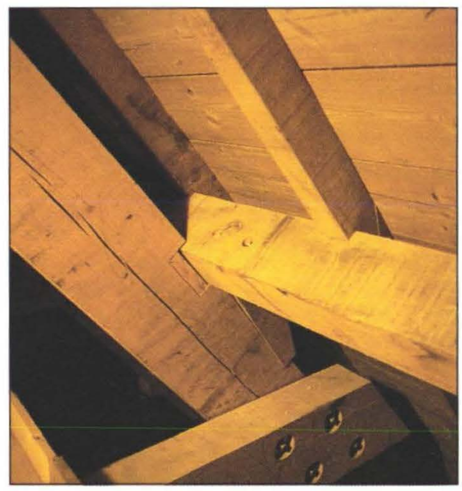
During the autumn the roof was completed by fixing the oak rafters and the preservative-treated softwood boarding, and then covering the whole structure with lead sheet, double-welted at the seam. Now the roof was watertight, the temporary cover could be dismantled.

With the full load of the roof in place, it was now possible to relax the truss feet, using the threaded rods built into each bearing on the east side. In order to monitor the outward thrusts, three of the rods were fitted with small flatjacks connected to pressure gauges, which acted as load cells. The centre trusses (6 and 7) were relaxed to give a residual 10% thrust, obtained with an outward movement of 30mm. The relaxation of the other trusses was tapered down to zero at trusses 1 and 13, as the purlins were fixed to the masonry at each end of the Transept.

The roof was now complete, but much work remained to be done on the vault. The curved ribs, of glued laminated oak, were painstakingly fitted together to recreate the vault, and each web was infilled with plaster on a base of expanded metal lath. When all was dry, the decoration and gilding could commence.

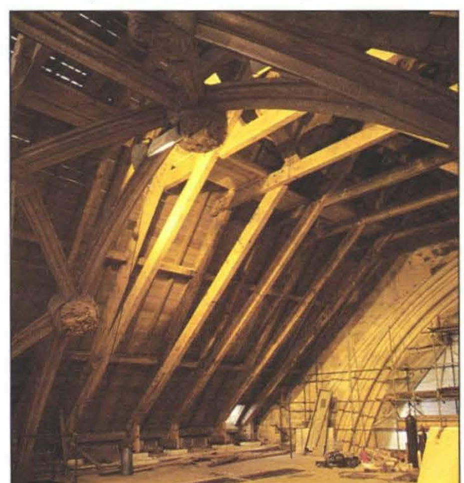
The roof trusses had been drying out all this while, and the resulting shrinkage across the grain had produced the inevitable longitudinal splits (Fig. 14). These are all well within acceptable limits, however, and the trusses have remained true to line. Checks in the summer of 1988, with the timber some three years cut, showed that the heart timber was down to a moisture content of about 28%.

The old carpenter's rule of an inch a year doesn't look far out. If we had not accepted green timber as a parameter of design, the work could scarcely have begun. As it is, it has been completed in less than four years, in time for the official ceremony of reconsecration in November 1988. Our luck has been to have two 'campaigns' on one of our major medieval cathedrals, for with the work done to the foundations in the 1960s, we can honestly say we have given the Minster a new hat — and a new pair of shoes.



14. Drying split down centre of rafter

15. Completed roof, with vault part erected



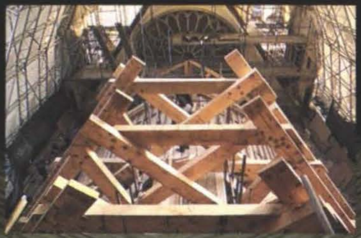


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Photo of vault: Jim Kershaw, Haxby, York

Credits

Client:
The Dean and Chapter of York Minster
Architect:
Charles Brown, Surveyor of the Fabric
The work on site was carried out by the Minster workforce directed by Robert Littlewood, Superintendent of the Works.
Structural engineers:
Ove Arup & Partners
Oak supply:
H. Venables and Son Ltd.
Covers:
Weatherbeater Ltd.
Photos: (Except as otherwise credited)
Poul Beckmann, Peter Ross

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