The British Museum Great Court Project

One of England's most frequently visited places - the British Museum in London - is continuously undergoing important expansion and modernization to make space for an ever-increasing number of visitors. Installation of a new roof structure, spanning the Great Court and encircling the Grade One listed Reading Room, commenced at the Museum in the summer of 1999 and was completed in 2000. This newly-created space at the centre of the museum includes modern galleries, education and visitor facilities, as well as shops and a restaurant.

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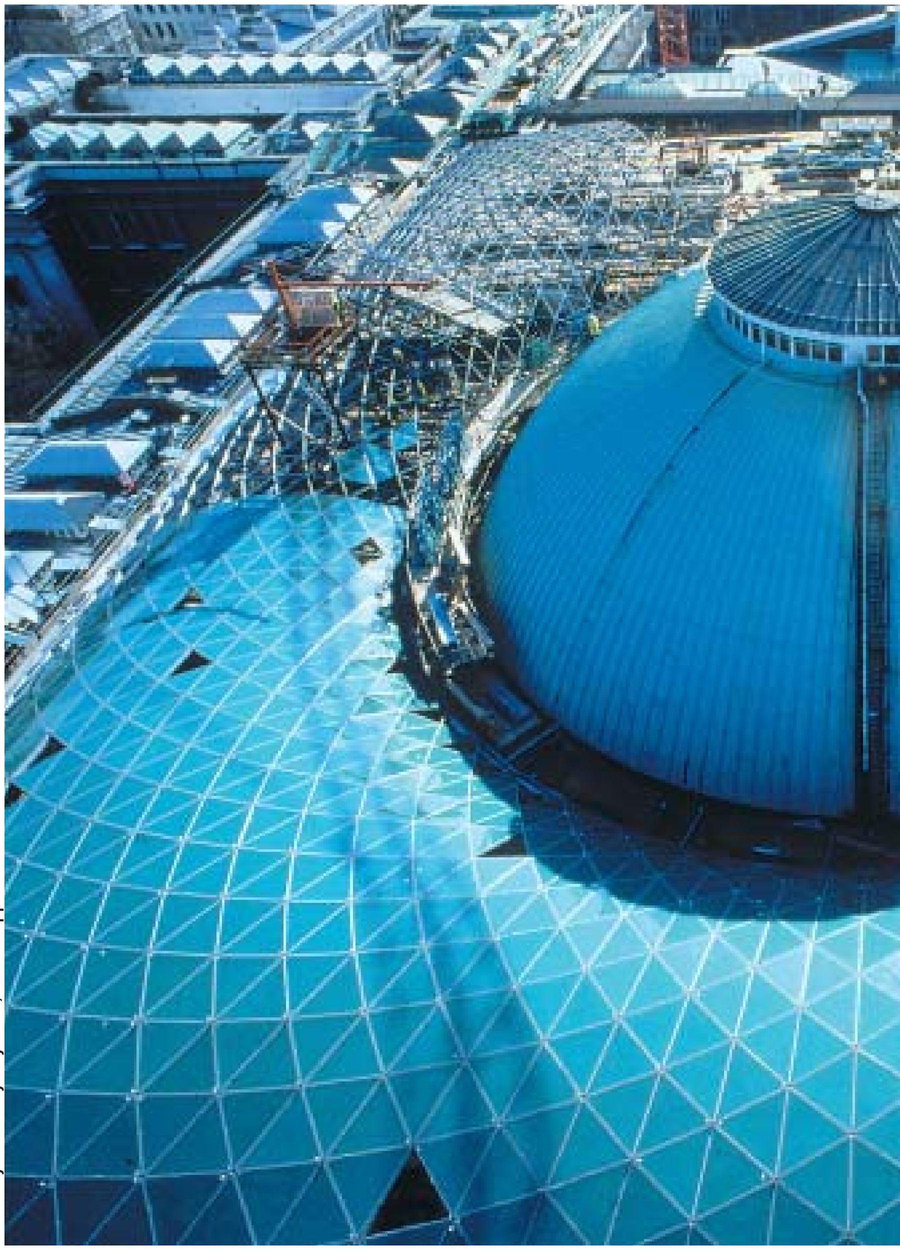
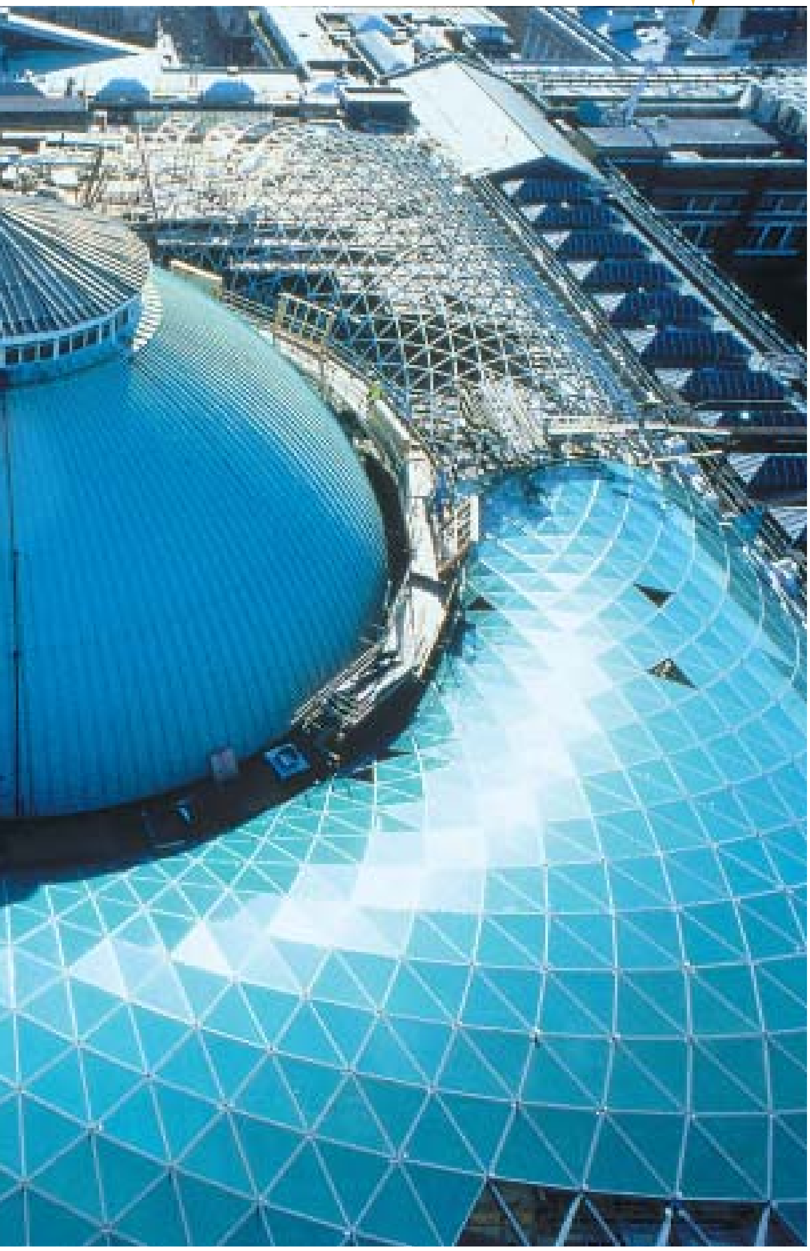


Courtesy of Mandy Reynolds, Buro Happold

The British Museum, the most visited museum of its kind in the world, is one of England's most popular venues, visited by millions of tourists, students and academic researchers every year. To create more space for the Museum's continuing expansion and modernization of its visitor facilities, it is witnessing change on a scale never before experienced on this tightly populated site.

The new roof of the Great Court during construction



THE ORIGINAL BUILDING

The Museum's Georgian buildings were designed by Robert Smirke who, in 1823, as Attached Architect to the Office of Works, presented the plans for the new British Museum to its trustees. These plans originally consisted of four wings containing galleries, set around a large rectangular courtyard. As work progressed, it became evident that additional storage was needed. This led to the construction of the circular Reading Room and adjoining Book-stacks (1854-57) in the courtyard, housing the library collections. Since then, almost all the open space within the courtyard has been filled with extensions added to the original buildings. Smirke's stone clad museum buildings forming the quadrangle and iron-framed dome of the Reading Room are now Grade One listed.

THE LARGEST COVERED COURTYARD IN EUROPE

With the moving of the British Library to new premises, the Museum has redeveloped the courtyard, demolished the Book-stack structures, while leaving the historic Reading Room as the centrepiece of the largest covered courtyard in Europe. The 6,700 square metre (92 x 73 metre) courtyard - a little larger than the size of a football pitch - has been enclosed by a spectacular glass and steel roof. This new space provides a hub at the centre of the museum complex together with modern galleries, education and visitor facilities including shops and a restaurant.

The famous circular Reading Room, designed by Robert Smirke's brother Sydney, is 42.7 metres in diameter. The iron frame of 20 ribs is clad externally with a brick drum pierced by large arched windows between the ribs. It rises 19 metres above the floor level to the Snow Gallery, a two-metre wide flat roof that encircles the copper clad dome. The dome is hemispherical, rising to a central lantern 12.2 metres in diameter, 32.3 metres above the floor. In overall structural terms, the Reading Room is a braced shell in which the iron framing and the brickwork provide mutual restraint and support.

THE ARCHITECTURAL SCHEME

Having worked with the architectural team from Sir Norman Foster and Partners, Buro Happold was appointed by the British Museum as the Structural and Building Services Engineers, Fire Engineers and Planning Supervisors for the Great Court Development project.

The architectural scheme proposed spanning the Great Court and encircling the Grade One listed Reading Room with a graceful streamlined glass roof enclosing the court below, providing a sunlit, comfortable space for visitors and museum staff. To meet the requirements of planning consent, the height of the new roof construction was restricted and the support of the outer perimeter on the quadrangle buildings does not visually intrude on, nor structurally disturb, the classical Georgian façades that lead into the Great Court.

STEEL STRUCTURE, FINE LATTICE SHELL AND COLUMNS

The roof is a fine lattice shell structure spanning in three directions from the four sides of the quadrangle onto a ring of 20 columns surrounding the Reading Room. The latter is actually not located at the centre of the courtyard, but some five metres towards the North façade. These columns carry the roof load down to the foundations ensuring that no additional load is applied to the Reading Room. They are of structural steel composite construction, to achieve the required fire rating and stiffness to span from floor level to the Snow Gallery, while remaining slender enough to be hidden

Great Court - roofwork completed

Courtesy of Mandy Reynolds, Buro Happold

behind the new stone cladding of the Reading Room. The columns, designed in accordance with Eurocode 4, were fabricated using tubular steel, an outer 457-millimetre diameter reinforced with an inner 250-millimetre square and filled with concrete.

Around the Reading Room, the roof is prevented from spreading laterally by the Snow Gallery, which acts as a stiff diaphragm, balancing the thrusts from opposite sides of the roof. To achieve this, the existing brick arched Snow Gallery was demolished and replaced with a new reinforced concrete construction, which also houses the main extract fans.

SLIDING BEARINGS AND TOROIDAL FRAMING

On the other hand, around the outer perimeter of the roof, to avoid applying any lateral load to the quadrangle buildings, the roof is supported on sliding bearings. These bearings allow the roof to spread laterally under load, normal to the relevant façade, and independent of the buildings. This freedom means that, for the roof to hold its form, the outer radial members near the perimeter quadrangle must work in bending and compression. These effects must pass through the joints in all directions. The size of the steel members, therefore, is smallest adjacent to the Reading Room and increase in size towards the perimeter, being largest at the corners. The forces generated by the abrupt change in direction at the corners are large and the structure is further stiffened in these areas with a tension cable across each corner.

Courtesy of Mandy Reynolds, Buro Happold

Internal view of the Great Court

The toroidal framing of the roof has been generated to provide an easy transition from the circular form of the Reading Room to the quadrangle of the surrounding Museum buildings. The geometry was defined using a customized form-generating computer program solving both the architectural and structural requirements. The result is a smooth flowing roof that adheres to height restrictions, while curving over the stone porticoes in the centre of each of the quadrangle façades. The high points in the roof are located such that the lateral forces exerted on the Snow Gallery from opposing sides of the roof are generally balanced, minimizing the risk of any net force being applied to the Reading Room's iron frame. As a further precaution, the new reinforced concrete Snow Gallery is supported on sliding bearings, so that the stiff ring floats above the historic frame.

STRUCTURAL GRID

The roof's structural grid follows that of the glazing supporting each panel along its edges, minimizing the complexity of the glass fixing. Therefore, the maximum size of glass available set the final structural grid size. The grid is formed by radial elements spanning between the Reading Room and the quadrangle buildings, inter-connected by two opposing spirals so that the roof works as a shell. While rectangular fabricated hollow sections are the preferred solution for the structural elements, an alternative, slightly finer option using solid sections was prepared. For both options the elements taper to smoothly accommodate their increasing depth towards the Quadrangle buildings. This reflects the architecture, maintaining the sharp flowing lines of the structural elements dividing the individual glass panels.

With the roof having only one line of symmetry, there are 1,826 individual structural nodes where six elements are connected. All connections are fixed to transfer the forces and bending moments between the structural elements.

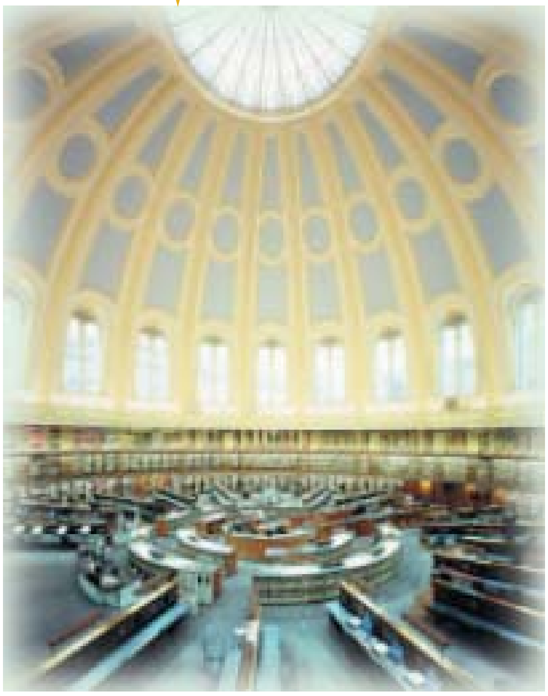
THREE-WAY LATTICE

Design of the roof evolved using a three-way lattice of steel members, which add in plane stiffness, creating a very efficient form. The roof shape itself is curved to a tight radius of approximately 50 metres, which means it can act much in the same way as a dome, while imposing minimal loads onto the existing surrounding structures. The curvature of the roof has allowed Buro Happold to develop a lightweight construction relying on arch compressions. The curvatures of a perfect torodial are usually steep so that it acts in an arching fashion, converting vertical loads into compression in radial members. In this project, the Great Court roof is restricted in height and the outer perimeter is unrestrained laterally.

Wind tunnel tests carried out by Bristol University provided information on the external and internal pressures, which will influence internal ventilation and air movement of the Great Court once it has been covered over. The results showed that wind flow separates at the outer perimeter of the museum, and does not re-attach over the new steel and glass roof in the Great Court. This means that the wind pressures on the roof are small and consistently negative (uplift). On this basis, the net once in 50-year uplift force does not exceed 0.3kN/m2. This is well below the total dead weight of the roof with double glazed cladding.

The roof's outer perimeter is supported at every other nodal point by a short steel column down to the new reinforced concrete parapet beam system around the top of the existing façades. The roof is laterally stabilized around the perimeter with cross bracing situated behind each of the porticoes working parallel to the relevant façade. At the centre of each side of the roof, behind the porticoes, the lateral spreading movement of the roof is one directional, normal to the line of the façade. At these locations the roof can be laterally restrained, parallel to the façades, sitting the stub columns on one directional sliding bearings without inducing awkward secondary effects.

The Reading Room



Courtesy of Mandy Reynolds, Buro Happold

MATERIALS

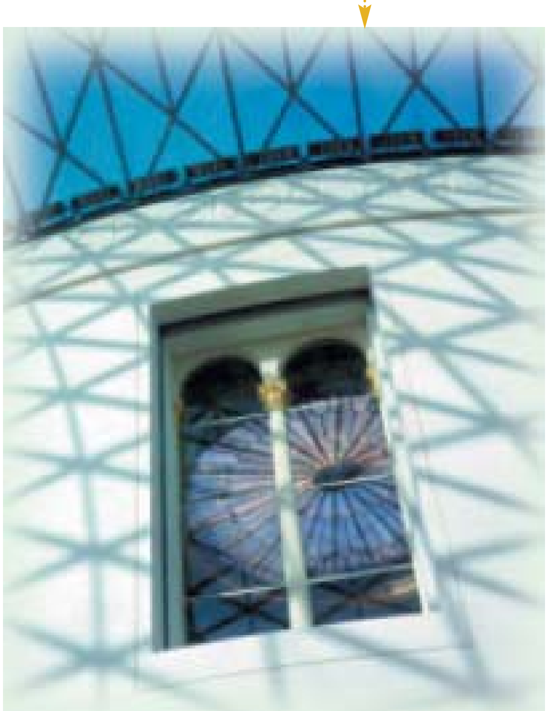
A wide range of materials was considered for the construction of the structural support for the roof grill before steel was selected as the most appropriate. Steel is commonly selected for long span structures for many reasons, particularly because it provides high strength and stiffness at low cost. It is easily connected by bolting or welding, and with a surface coating, has excellent weathering characteristics. By suitable selection of different components to form the whole cross section of the beam elements, the amount of fabrication can be kept to a minimum and the efficiency of the section can be maximized.

The successful connection of the some 6,000 individual members is critical to the integrity of the roof structure. The high stresses and slenderness of the steel elements lend themselves to welded connections. To minimize the risks of weld failure, Grade D steel - more often used for marine, or petro-chemical applications rather than construction - was used. With such a precise project, it was felt that the impurities present in lower grade steel could allow too much margin for welding error. Buro Happold sought the advice of The Welding Institute (TWI) when preparing the structural welding specifications to ensure that the welded joints would have sufficient ductility to prevent brittle failure. The specification included a stringent testing programme to ensure that the quality of the steel and welding would allow the structure to behave as predicted.

LIGHT AND CLEAR APPEARANCE

The architects were keen that from the ground, the double glazed roof has as light and clear an appearance as possible. This led to the use of fabricated steel box beams, with sufficient self-weight to resist any wind induced uplift, and with enough strength to carry the roof and its cladding. The steel weight for the entire roof is approximately 420 tons, or 75 kilos per square metre. The double glazed cladding system adds another 60 kilos per square metre. This light-weight form of roof minimizes additional loads imposed onto the existing façades.

Detail of the roof structure



Courtesy of Mandy Reynolds, Buro Happold

CONSTRUCTION AND INSTALLATION

The roof was constructed in a series of prefabricated ladder beams erected off a crash deck that covered the entire court. As there was only a very limited degree of repetition in the node types, the use of steel castings to form the nodes would be uneconomic. As a result, the star shaped nodes, some 200 millimetres deep, were cut from single thicknesses of plate, the points of each star shape set at the appropriate relative angles for each and every node. Members between nodes were made as a series of straight elements meeting at the nodes.

The prefabricated ladder beams were assembled using precise jigs in the steel fabricators' workshop. Because of the cramped, congested site there was no area for storage, so the ladder beams were trucked to site to meet immediate requirements. On site, the ladder sections were craned over the museum buildings - that remained open to the public throughout the construction process - onto a precise system of temporary props. Adjacent ladders were then stitched together using on-site welding techniques. The installation of the glazing followed the steel erection. Only when the structural lattice was complete and the vast majority of the glass installed were the temporary props systematically removed. During this process the roof was carefully monitored to ensure that it behaved as predicted to achieve the defined final shape. Installation of the steel roof structure commenced at the museum in the summer of 1999, and was completed in 2000. ■

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