On site: Great Court, British Museum

21st-century classic

Foster's design for a covered square in the heart of the British Museum meant the engineer had to sit 800 tonnes of steel and glass over the world-famous and grade I-listed Reading Room.

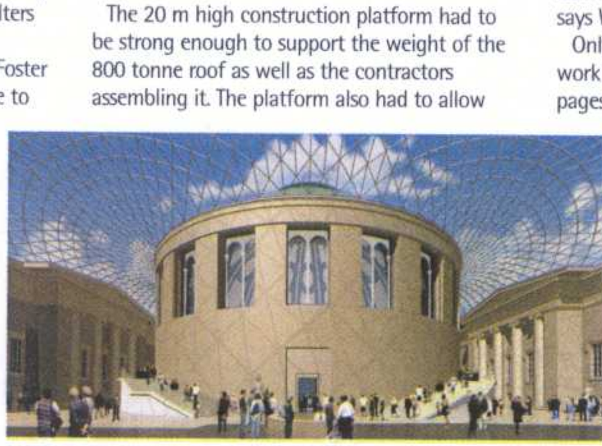
by Andy Pearson. Photographs by Andrew Southall

HIGH OVERHEAD, THE SPECTRE-LIKE SILHOUETTE of a solitary abseiler crosses the vast expanse of glazed roof. His shadow flits briefly across the gleaming Portland stone facades that enclose the largest and newest covered public square in Europe, the British Museum's Great Court. The abseiler is one of a team waterproofing the huge, bagel-shaped steel and glass roof that shelters the square.

The roof is the most spectacular part of Foster and Partners' competition-winning scheme to create a cavernous open space at the heart of the museum. A fine lattice of steel and glass spans the void between the classical facades of the buildings forming the courtyard's perimeter and the museum's famous circular Reading Room close to its centre. Its elegant sculptural form is a permanent memorial to the complex engineering design and precise construction work that have made it possible. Twenty-seven months into the project, its true magnificence is only now being revealed as the forest of scaffolding supporting the temporary deck from which the roof was constructed is slowly and carefully removed.

"The scaffold deck was key to the scheme's success," says Carl Wright, project director of construction manager Mace. "We had to get it right. And not just the scaffolding. We also had to take note of other work to be carried out and allow for the operation of a tower crane and hoists."

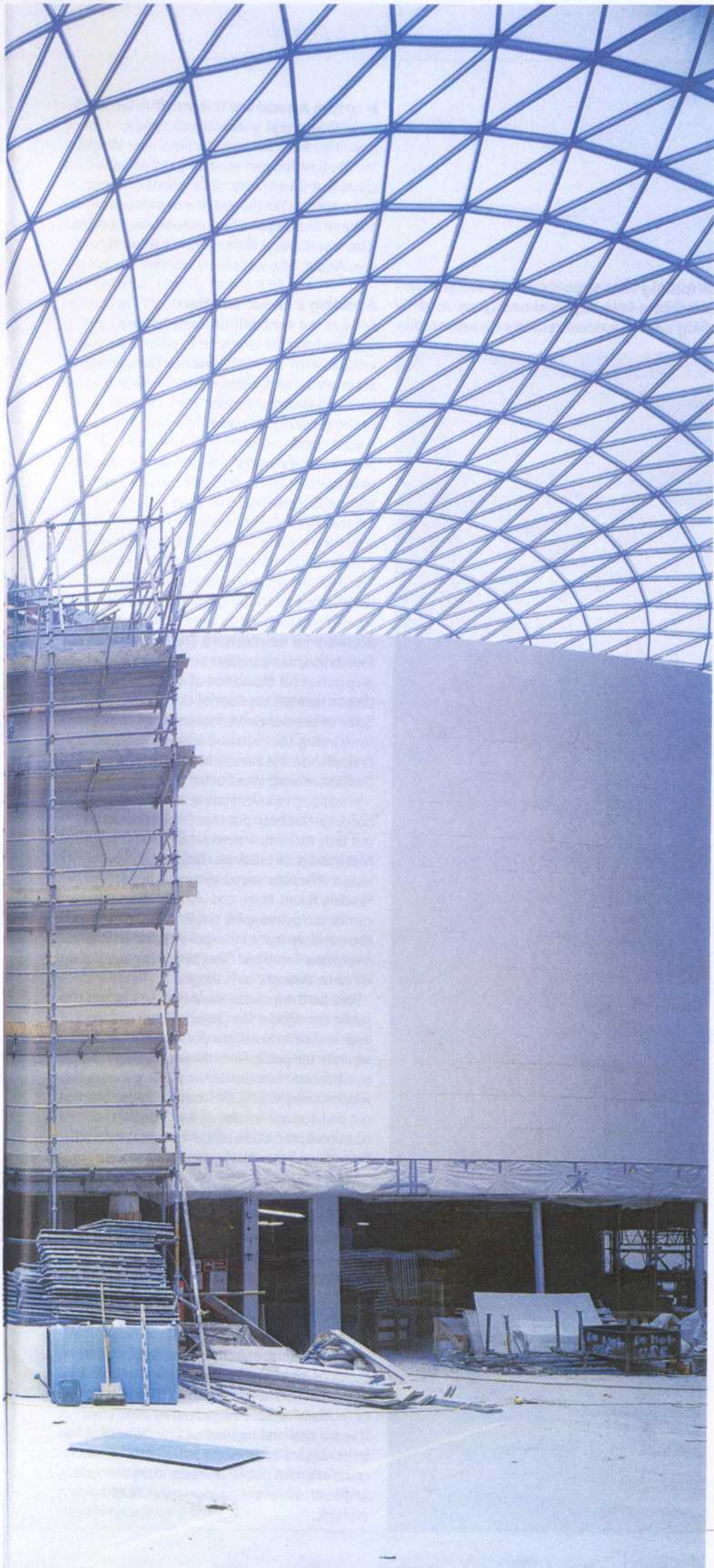
The 20 m high construction platform had to be strong enough to support the weight of the 800 tonne roof as well as the contractors assembling it. The platform also had to allow stonemasons access to the listed facades of the buildings fronting the square, which they were painstakingly restoring, and allow the contractor to erect new exterior walls to clad the Reading Room. It had to be fashioned in such a way as to maintain circulation routes amid the maze of scaffolding. "It also had to keep the weather out," says Wright.



Above: CAD image showing the project as completed. Opposite: The outer edge of the steel and glass roof sweeps down to rest on reinforced concrete beams behind the parapets of the restored facades that line Sir Robert Smirke's 1852 courtyard.

Only after the scaffold deck was in place could work begin on installing the high-tech roof (see pages 52-53). The roof is formed by radial elements spanning between the central Reading Room and the courtyard buildings, interconnected by two opposing spirals to form a steel shell into which more than 3300 glazing panels fit. Six thousand steel sections, each one different and manufactured to precise tolerances, have been used to construct the shell.

The steelwork sections were fabricated at steelwork contractor Waagner-Biró's base in Austria using a computer-controlled cutting machine commissioned specifically for the project. "To minimise the risk of weld failure, grade D steel, more often used for marine or petrochemical ▶



▶ applications, was used for the roof," says Stephen Brown, a partner in structural engineer Buro Happold. The sections of steel were then shipped to B&K Fabrications in Derby where they were assembled on jigs into a series of ladder trusses up to 10 m in length, before being delivered to site.

Critical support

With the public still visiting the museum, the trusses had to be craned into the square by lifting them high over the roof of the main entrance. Each section of truss was then carefully supported on temporary props positioned on the deck high above the courtyard. A total of 593 props were used to support the roof during construction. Their positioning was critical for the roof to be assembled accurately, so their locations were precisely defined in three dimensions from the designer's CAD drawings and carefully set out on site.

On site, the first task for Waagner-Biró was to assemble the 10 m sections of ladder truss into lengths long enough to span the area between the four sides of the courtyard and the Reading Room. The contractor positioned the ladder sections alternately around the perimeter of the Reading Room and then carefully fitted and welded the cross members individually between nodes on the trusses to form the steel shell that would support the glass. "It was a precise operation," says Brown. The props stood on the scaffold deck, in turn supported on a new concrete floor slab which spanned the new theatre being built in the basement. Almost 500 tonnes of steel make up the roof structure, and as the weight of steelwork increased, the deck and the structure carrying it deflected. "The position of each node had to be monitored constantly during the frame's construction," Brown explains, "and every couple of days or so the props had to be adjusted to push the steel back into its exact location." It was a testing time for Waagner-Biró: the tolerance between each structural node was just 3 mm, and one mistake fitting a cross member could throw the whole roof out of alignment, causing it to fail. In all, 152 ladder trusses were installed. Once the structure was complete, the steel was painted and glass installation commenced.

The roof contains 3312 faceted double-glazed panels, each of them a unique triangle. Each unit is formed from a 12 mm toughened outer panel and 12 mm laminated inner panel, separated by a 16 mm cavity. The glass is screenprinted with small dots covering 56% of its surface area, to filter ultraviolet radiation and reduce solar gain – a technique called "fritting". The units were fitted from the outside.

With the glazing installed, the roof weighed about 800 tonnes, all of which was carried by the temporary props, in turn supported by the scaffold platform. Before the platform could be dismantled, the props had to be carefully lowered until the roof sank gently onto its final resting place on the facades surrounding the square. "The de-propping sequence was agreed ▶

The magnificent lattice crowns the space between the Reading Room and the perimeter of the Great Court.

Scaffolding that supported the weight of the delicate-looking steel and glass roof during construction is slowly dismantled.

▶ by Buro Happold and Waagner-Biró. We had to make four sweeps around the 593 props, lowering each a fraction at a time," says Wright. "All the time the roof was being monitored to check that it was performing as the engineers had predicted." In the end, the roof dropped 150 mm and spread 90 mm laterally as it settled. "This was less than the engineers had predicted," says Wright, who was clearly relieved.

Avoiding a knock-on effect

Some of the most difficult work on the project was emptying the courtyard to prepare for the installation of the scaffold so that work could begin on the roof. Mace was fortunate in having been appointed in October 1996, 15 months before construction was due to start. "There was a good amount of time to analyse, plan and programme the works," says Wright. "It allowed us to consider where problems might occur and to formulate solutions," he adds.

A major concern was with the works that affect the existing buildings. Long before construction began, Mace instigated a series of investigations into areas such as the snow gallery circling the roof of the Reading Room that was soon to be punctured by smoke ventilation ductwork for the courtyard. The Reading Room's foundations were another area probed in preparation for excavation of a new lecture theatre beneath the floor of the Great Court. Some of the stonework forming the facades surrounding the courtyard was also removed to find out how the stone was keyed in and how the facades were constructed.

In addition to investigating how the existing buildings had been put together, Mace carried out tests to see how demolishing the hodgepodge of buildings filling the courtyard would affect the surrounding galleries and Reading Room. Noise and vibration tests were carried out by dropping weights on the floors of the corridors next to the galleries. The walls are more than 1 m thick: "They are so massive not a lot came through," says Wright.

Because the museum would still be open to the public throughout the project, Mace used the lead-in time to install temporary partitions to separate the public from the site. To keep construction noise out of the public galleries, the windows overlooking the courtyard were boarded out and acoustic insulation was fitted. As an additional precaution, all exhibits were removed from the gallery walls fronting the square.

Mace also used the lull before the project started to appoint the specialist contractors for the scheme, including the roofing contractor, the stonemason, the demolition contractor and the mechanical and electrical contractors.

In March 1998, demolition of the redundant buildings in the courtyard started. "It was a massive demolition inside a grade I-listed space," says Wright. Only the Reading Room was to be retained. With the courtyard packed so full of buildings, hand breakers had to be used to start the demolition before small mechanical breakers or "bobcats" could be squeezed in. Even then it was a slow and methodical task. "All rubble had to be skipped out over the roof using the tower crane or driven out by dumpers along the west and north basement passageways," Wright explains.

Once enough space had been cleared, larger demolition plant could be used. "We used little machines until we could get in some decent gear," says Wright. "After we had craned in a couple of 35 tonne machines and a 25-tonner, we were able to tear through the remaining buildings with peckers, jaws and grabs. With the works confined to such a small space, the noise was incredible."

Wright adds, smiling: "It was a bit of a gobsmacker for the museum too. They had never been that close to a construction site before."

Rising from the ruins

As the demolition progressed, the drum-shaped central Reading Room seemed to rise up from among the remains of the buildings that had previously crammed the courtyard around it. "The Reading Room is one of the most sensitive buildings in the country and we've been knocking seven barrels out of all of the buildings attached to it," says Wright. As soon as the Reading Room was exposed, work began on underpinning it in preparation for the installation of the new roof.

With the peckers and jaws making short work of the remaining buildings littering the courtyard, it was not long before the facades of the buildings surrounding the courtyard were also revealed. Work on their restoration began immediately, running parallel with the demolition. As soon as the courtyard was cleared, excavation began in preparation for work on the new theatre to be constructed beneath the courtyard floor. Meanwhile, inside the Reading Room, the delicate work of restoring the listed ceiling was under way.

"The key piece of structure to be built in the courtyard was the concrete ground-floor slab," Wright says. "Once this was done, we could put in the scaffold platform and begin work on the roof."

Even with the courtyard filled by a forest of scaffolding and installation of the roof under way from the elevated platform, work continued on other parts of the project. The stonemasons were reinstating the original portico to the front hall that had been demolished in the 1870s to make way for an extension. A wall was erected to clothe the naked facade of the Reading Room. A new concrete structure was erected that wraps around the north side of the Reading Room to create a café and retail space for the museum.

With less than six months left before the restored Great Court opens to the public, the final construction phase is now in progress. In the rooms below, the courtyard's new floor fit-out is under way; the ceiling of the Reading Room has been restored to its original glory, and the Great Court itself is about to be returned to the museum as the largest covered public square in Europe, 150 years after it was originally completed.

Although in many respects this is a restoration project, the original Great Court enjoyed only a brief life as a public square, since almost immediately after Sir Robert Smirke completed it in 1852, it was taken over by the museum's rapidly expanding library collection. With the roof now complete and the final sections of the access platform being dismantled, Smirke's Great Court is about to be rediscovered as the public space it was always intended to be.

Restoration of the stone facades lining the Great Court. Stonemasons also reinstated an entrance portico removed in the 1870s.

How the roof is supported by the existing structures

Spanning the British Museum's central Great Court and encircling the grade I-listed Reading Room with a delicate steel and glass roof was an immense challenge for the project's engineer, Buro Happold. Not only did the weight of the roof have to be carried by the surrounding listed buildings without damaging them or visually intruding on their classical facades, but the solution had to satisfy the planners' limit on the height of the roof.

The solution is described by Steve Brown, the Buro Happold partner who designed it, as "a bagel cut in half with the edges trimmed flat". A series of arcs span the courtyard's facades and the centra Reading Room, overlaid by two interconnecting spirals winding in opposite directions to create a steel lattice.

To explain the engineering, Brown enthusiastically delves into his briefcase and whips out a sheet of cardboard. "The roof is best thought of as a plate of steel with triangular holes cut into it," he says, bending the cardboard into a shallow arch. "With a lot of breadth you don't need depth to get the stiffness in the structure." If you were to cut his sheet of cardboard into thin strips, he points out, each strip on its own would have no stiffness at all.

Stiffness was important: the Georgian buildings lining the Great Court have big, heavy facades that are capable of transferring loads downwards but have no cross walls to give them lateral stability. "If the roof were to push laterally on these facades, they would just fall over," says Brown, "and I'd have to go and live in Brazil".

The engineer's solution was to rest the roof on a series of sliding bearings supported on a reinforced concrete beam mounted behind the parapets of the facades. The sliding bearings stop lateral forces transferring to the facades, so the weight is only transferred vertically.

At its inner edge, the roof meets the drum-shaped Reading Room, located not in the exact centre of the courtyard, but 5 m closer to the north side. The Reading Room is constructed around a series of cast-iron columns tied by wrought iron straps to give it stiffness, much like a barrel. These columns could only take about 10 mm of movement before cracking, and the building itself could take only limited differential movement should the foundations settle. As Brown points out: "There was no capacity for any extra loads either vertically or horizontally."

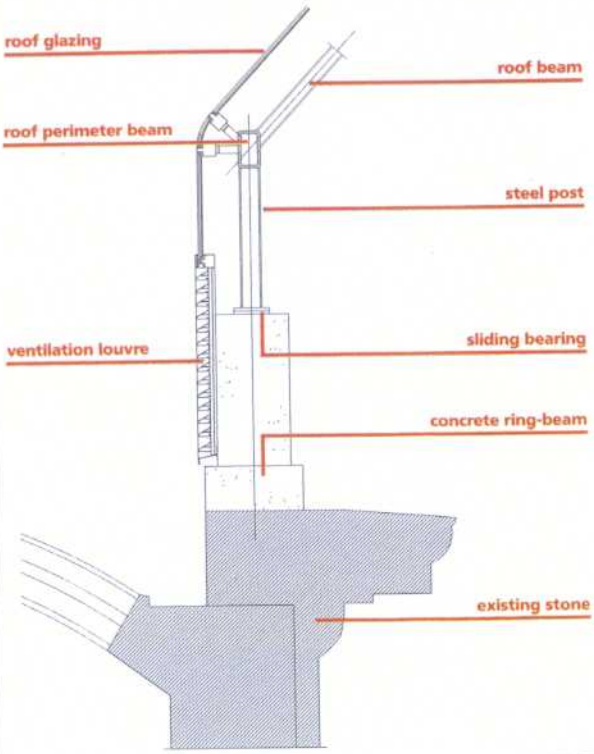
The engineer had to encircle the Reading Room with a ring of columns to carry the weight of the new roof and enhance the foundations by underpinning. This complex operation involved cutting a series of holes in the ground around the building's base using high-pressure water jets and filling the holes with grout – a process known as jet grouting.

The tops of the columns are linked to a compression ring formed from a structural steel beam cast in concrete and mounted on sliding bearings. This collar stops any lateral load transferring to the Reading Room and balances the thrusts from opposite sides of the roof. To install the beam, the arched brick snow gallery around the perimeter of the Reading Room's domed roof had to be demolished, and to stop differential settlement, the engineers had to ensure that the weight of the new structure matched exactly the weight that had been removed by demolishing the existing gallery.

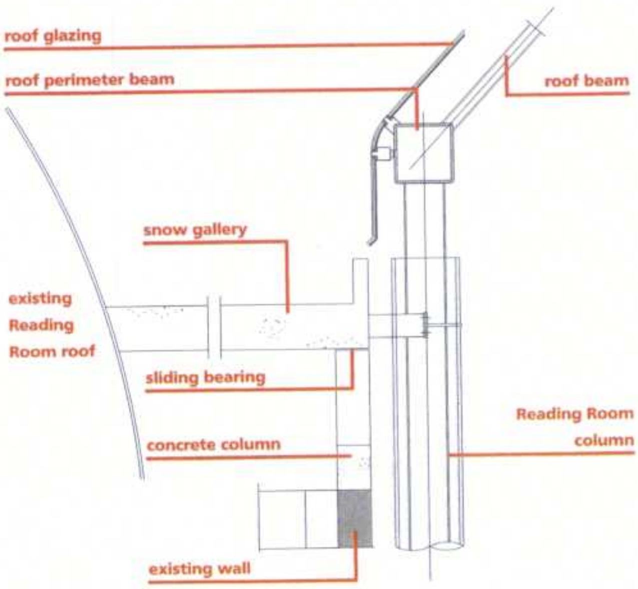
The huge expanse of roof is restrained at the centre by the compression ring but, with sliding bearings at the perimeter, the roof was unrestrained and could slide out flat. "The roof was so heavy it would collapse," says Brown. The easiest solution would have been to tie the roof into an arch with cables, but the architect described this as "too messy". The structure's stiffness became "a fundamental part of the solution", says Brown. "All I needed to work out was how big I could make the holes in my steel plate."

The steel plate Brown describes as forming the roof is in fact a series of fabricated box sections with thickened top and bottom plates to improve their capacity to withstand bending. Brown describes the box section as "an I-beam with the central web cut in half". I-beams could have been used to construct the roof "but they'd

Perimeter detail



Reading Room detail



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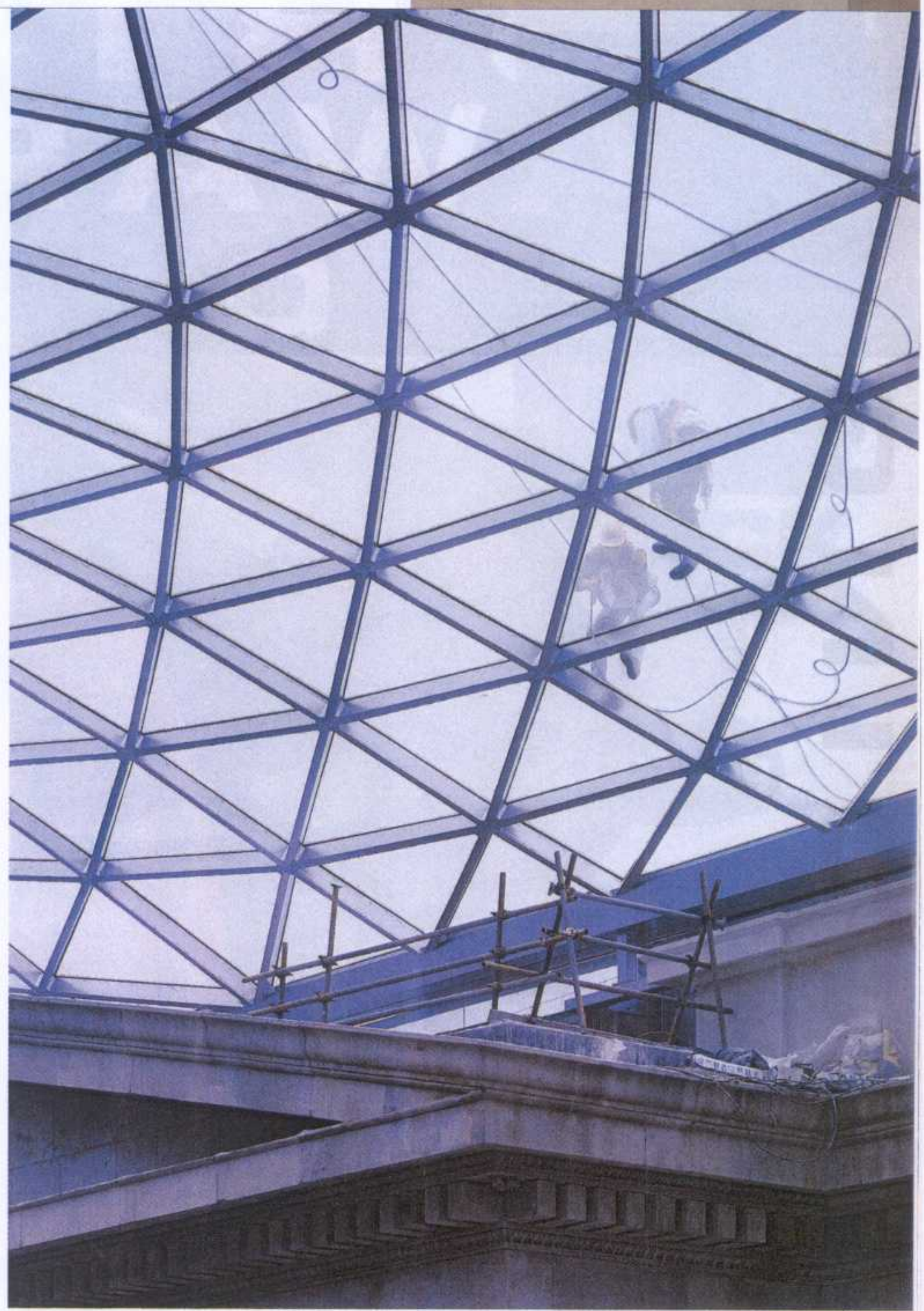

Abseilers give the roof its final waterproofing. The structure required each of the 3300 triangular glazing panels to be a unique size and shape.

look awful and would have been a pain in the butt to keep clean".

The next problem was to design the roof to provide an easy transition from the circular Reading Room to the square courtyard. Buro Happold used a customised form-generating software program to resolve both architectural and structural requirements. The easiest way would have been a high arch, but planning restrictions put paid to that. The software generated a series of steels spiralling out from the edge of the Reading Room in two directions, criss-crossing to form thousands of different-sized triangular glazing holes on their way to the courtyard's perimeter. The transition from the relatively small perimeter of the Reading Room to the lengthy perimeter of the courtyard means the small triangles on the inside become progressively larger towards the outside.

Until then, the high point of the roof had been envisaged as being halfway between the supporting walls, but with the size of the holes progressively increasing towards the outside edge the strength of the structure also had to increase to accommodate the greater spans between the structural nodes – so roof members had to increase in depth as they neared the perimeter. The revised design saw the high point of the roof shifting further to the outside to accommodate the increased weight at the perimeter.

During construction, the weight of the roof was carried by a series of props strategically positioned beneath the entire canopy. However, once these supports were removed, the entire 800 tonnes would be carried at the inner and outer edges. Because this would cause the roof to deflect, the design had to allow for this deflection and the roof had to be deliberately constructed out of shape.

When it came to assembly, the designers were keen to find a system to ensure that the team on site could not force a piece of steel into the wrong place. Thus each of the 6000 steel sections forming the roof is unique: "The last thing we wanted on a Friday night when it was almost beer o'clock was a guy hitting a piece with a hammer to get it to fit – it could have thrown the whole structure out," says Brown. Steel fabricator Waagner-Biró came up with a way of manufacturing each section slightly differently so that each section could be connected only to one particular node.

Waagner-Biró also brought to the design a practical knowledge of assembling large steel structures. The strength of the welded joints between sections was critical because the roof will move constantly under the heat of the sun. Waagner-Biró simplified the weld design to make it easier to assemble the steel sections on site. The roof was expected to be the most difficult part of the scheme to construct. In the event, "the roof went in without a problem", says Carl Wright, project director of construction manager Mace.

Project team

client British Museum Development Trust
project manager British Museum
architect Foster and Partners
structural and services engineer Buro Happold
fire engineer Buro Happold (FEDRA)
planning supervisor Buro Happold
cost consultant Northcroft
construction manager Mace
access consultant All Clear Designs

Specialist contracts

Trade contract	company	£m
Demolition	H Smith Engineers	4.2
Jet grouting and piling	Keller	0.7
Concrete substructure	John Doyle Construction	4
Roof steelwork and glazing	Waagner-Biró	10
Mechanical installation	Sulza Infra	6
Electrical installation	NG Bailey	3
Facade restoration	St Blaise	2.75
Specialist restoration and decoration	Hare & Humphreys	1.6
Stone cladding	Grants of Shoreditch	3
Stone paving	Grants of Shoreditch	1.3