Building at a lonely height; erection and adjustment remains a human labour.

Swiss Re´s Building, London

This article describes the development of the structural design of the new 40 storey steel framed landmark office building in London known as 30 St Mary Axe. The development of building's unique form within its prime urban context, with its circular plan of varying size and spiralling lightwells, and the structural design solutions are explained from an engineering perspective.

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The site of the 30 St Mary Axe building lies at the heart of the City's insurance district. The former buildings on the site, including the home of the Baltic Exchange, had been severely damaged by a terrorist bomb in 1992. The location and history of the site demanded a design of the highest design quality that would make a real contribution to the urban environment of the City.

Swiss Re started developing proposals for the site in 1998. Swiss Re, being closely involved in sustainability issues in the realm of insurance risks resulting from global climate change, emphasised in their brief the need an environmentally progressive design, together with a high standard of internal working environment for staff.

Design, procurement and fabrication processes were integrated through the use by the design team of three-dimensional modelling of the steel frame and a parametric approach to the design, enabling complexity to be managed with reduced risk and greater economy. The project shows the ability of structural steel to enable radical architectural ideas to be realised.

The Architectural form

The development of the building form is the result of the synthesis of a number of criteria, many of which are a direct re-

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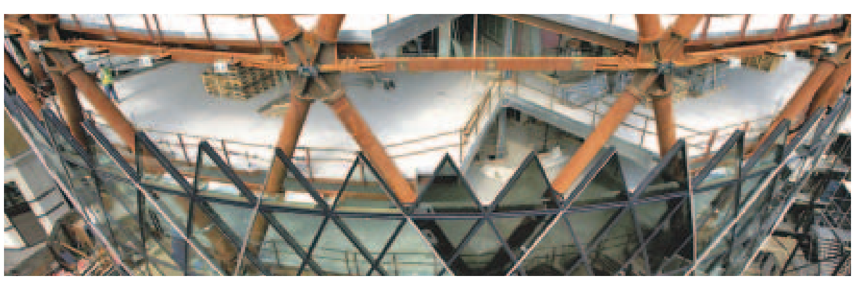
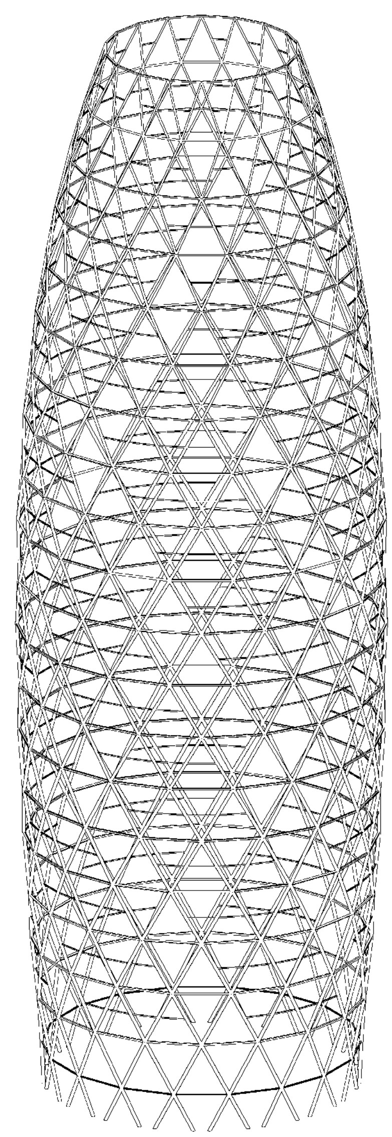
Swiss Re building as seen from the Thames.





sponse to the particular site and client requirements. In the case of the Swiss Re building the principal formative ideas can be summarised as:

- A net office floor area within the building of around 500,000 ft^2 (46,450 m^2)
- The enhancement of the public environment at street level, opening up new views across the site to the frontages of the adjacent buildings and allowing good access to and around the new development
- Minimum impact on the local wind environment
- Maximum use of public transport for the occupants of the building
- Flexibly serviced, high specification 'user-friendly' column free office spaces with maximum primary space adjacent to natural light
- Good physical and visual interconnectivity between floors
- Reduced energy consumption by use of natural ventilation whenever suitable, low façade heat gain and smart building control systems

Tall building designs offer the possibility of reducing the footprint at street level and help the office floors to be well proportioned for natural light. The maximum benefit to the urban environment is achieved by avoiding the creation of ➤

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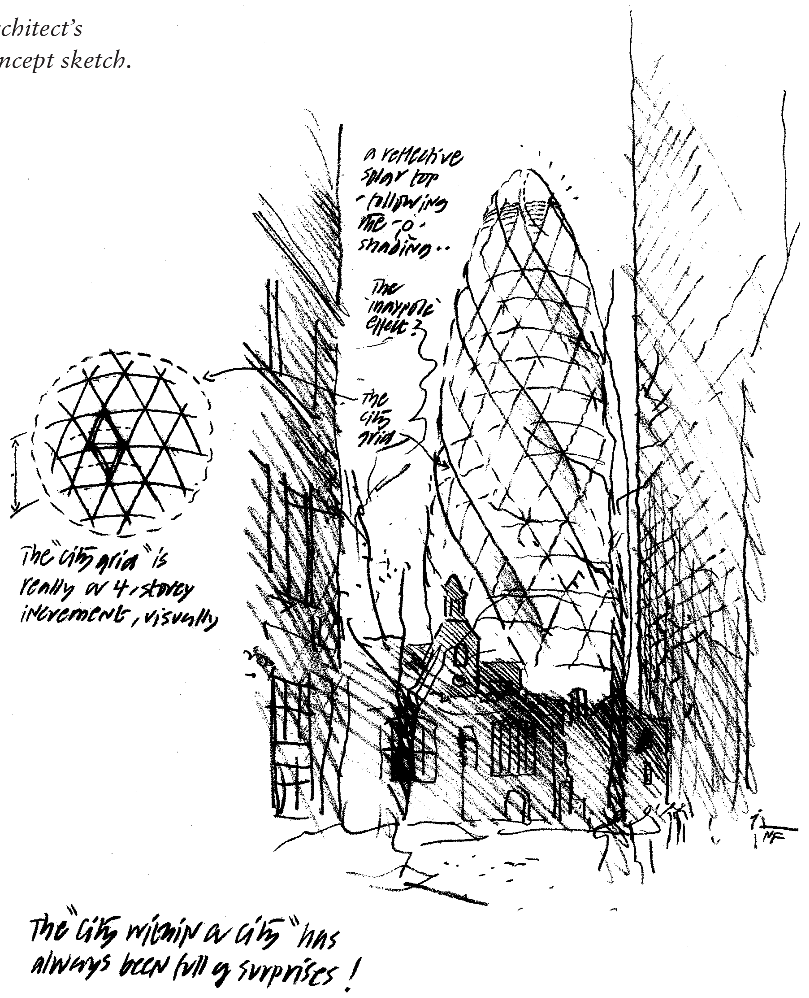
Architect's concept sketch.




Artist impression.

➤ windy conditions around the base of the building, and keeping the perception of the building's size in proportion with other buildings in the area. The curved form developed for the Swiss Re building achieves these two objectives simultaneously by virtue of its streamlined aerodynamics and in the nature of its convex surface, which recedes from the eye so that the building's size is not fully perceived from street level. The diameter of the tower is reduced at street level to maximise the external plaza circulation space and open up the areas in front of the adjacent buildings. The reduction in floor diameter towards the plant floors at the top of the building, culminating in the glazed domed roof, ensures that the building enhances but does not dominate the London skyline.

For flexible and adaptable office space a regular internal planning grid is required. The office floors are organised into six 'spokes' or fingers, arranged on a 1.5m grid around a circular service and lift core. Between the spokes are triangular zones that are used as perimeter light-wells. The result is a maximum14m 'core to glass' internal dimension, with all parts of the office fingers within 8.5m of a light-well. The light-wells are offset at each successive floor by 5 degrees. This twist creates balconies at each level and opens up dramatic views through and out of the building.

The perimeter 'diagrid' structure

The perimeter steel structural solution was developed specifically for this building in order to address the issues generated by the unusual geometry in a manner that was fully integrated with the architectural concept and generated the maximum benefit for the client. The final solution was one of a number of approaches that were assessed in detail for overall structural efficiency, internal planning benefits, buildability, cost and risk.

The design avoids large cantilevers and keeps the light-wells free of floor structure by inclining the perimeter columns to follow the helical path of the six-fingered floors up through the building. A balanced diagrid structure is formed by generating a pattern of intersecting columns spiralling in both directions.

The addition of horizontal hoops, which connect the columns at their intersection points and resist the forces arising from the curved shape, means that the perimeter structure is largely independent of the floors. The hoops also turn the diagrid into a very stiff triangulated shell, which provides excellent stability for the tower. This benefit of the diagrid means that the core does not need to resist wind forces and can be designed as an open-planned steel structure providing adaptable internal space. Foundation loads are also reduced compared with a building stabilised by the core.

Diagrid analysis

The unusual geometry of the Swiss Re building and its perimeter structure gives rise to significant horizontal forces at each node level, acting predominantly in a radial direction. These forces are best understood in terms of three independent geometric effects. The resolution of a vertical floor load into a raking column requires a horizontal restraint force. Adding a horizontal curveature to a diagrid structure in which the columns are wrapped around the plan form means that the column loads change direction at each node. Thus a cylindrical form of diagrid generates an outward spreading force at node points. Furthermore, if a vertical convex curveature is

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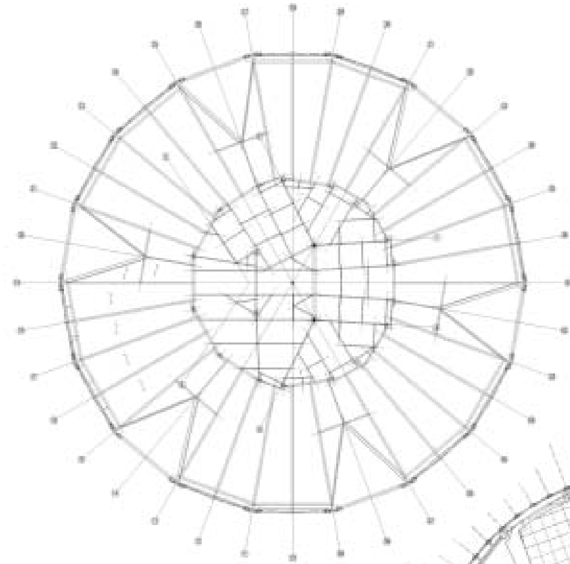
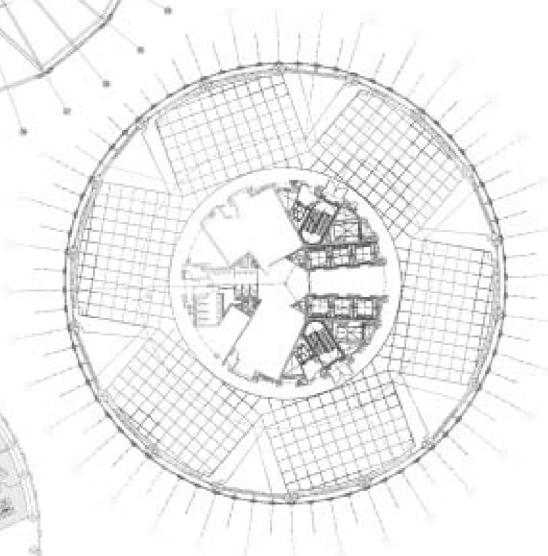
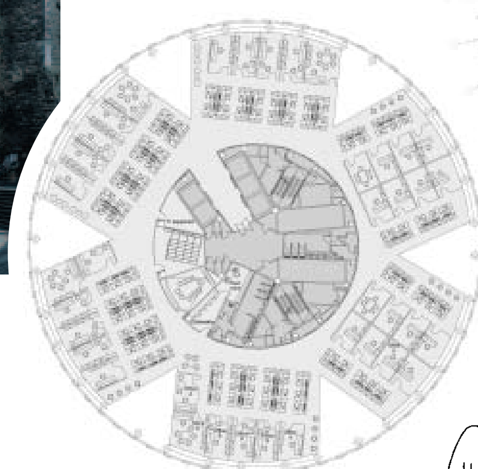
The real thing!



Structural plan near mid-height of building (showing arrangement of clear-span radial floor beams aligning with perimeter column positions and lightwell edges).



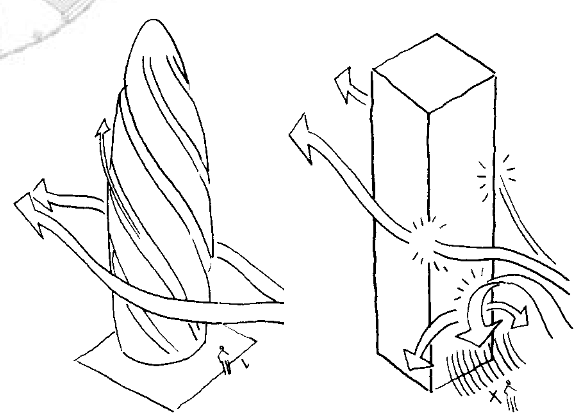
Plan of the 18th storey, with denotation of the grid of the raised floor.



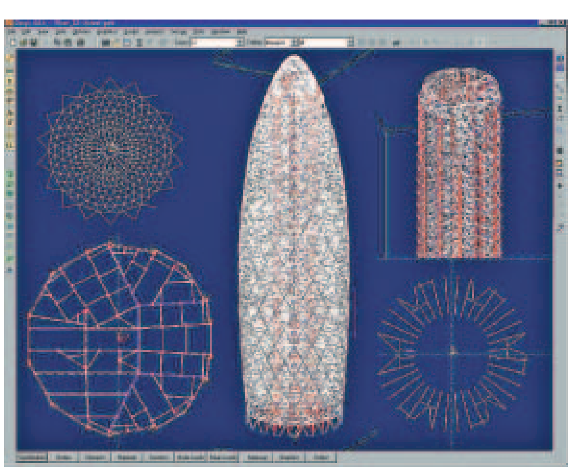
Office division (note: showing possible variations of office planning layout).

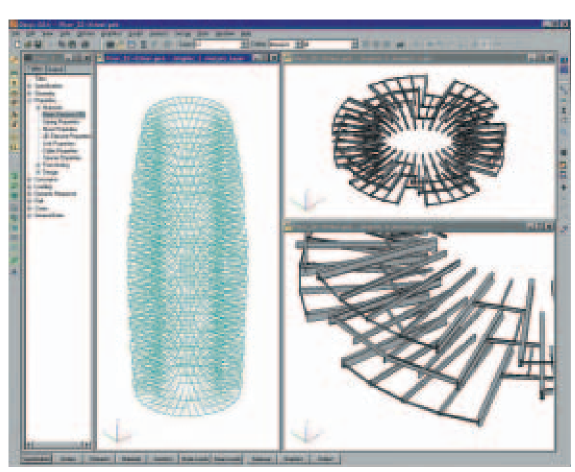
introduced, this increases the change in column angle and with it the spreading effect of vertical column loads.

In the Swiss Re building all these horizontal forces are carried by perimeter hoops at each node level, which also provide equilibrium for any asymmetric or horizontal loading conditions. The combination of these geometrical actions results in compression in the hoops at the top of the building, where the columns are more steeply angled and lighter loaded, to very significant tension ➤

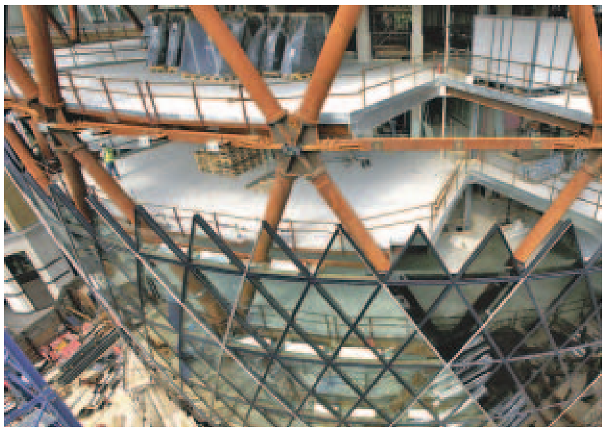


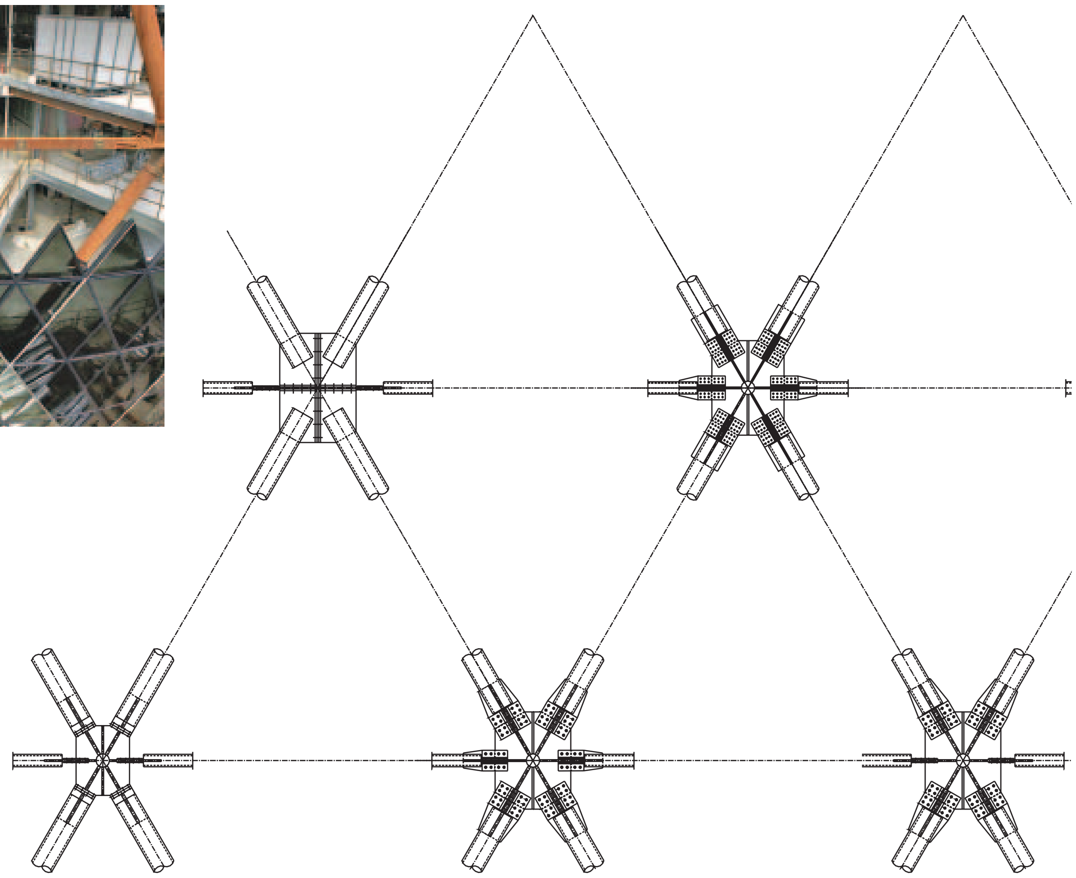
The shape of the tower is influenced by the physical environment of the city. The smooth flow of wind around the building was one of the main considerations.

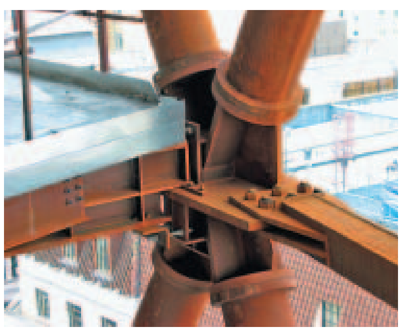




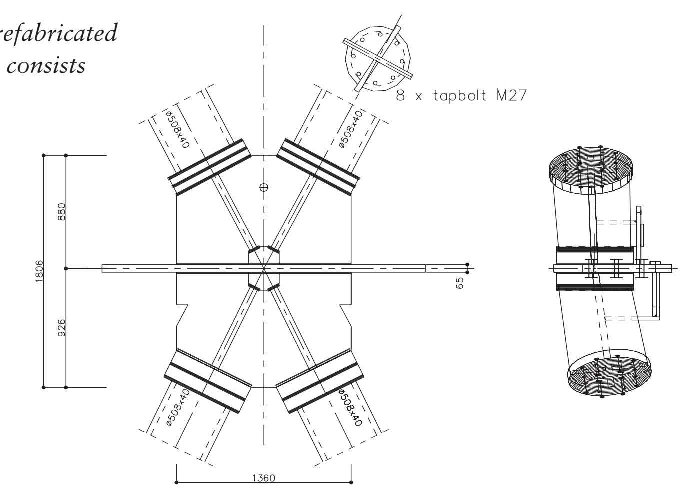
The 3D- model proved to be indispensable in the communication. The structural engineer made the initial coordination model with centrelines and sizing, the contractor and subcontractors used it for detailing and interfaces with cladding and MEP services.



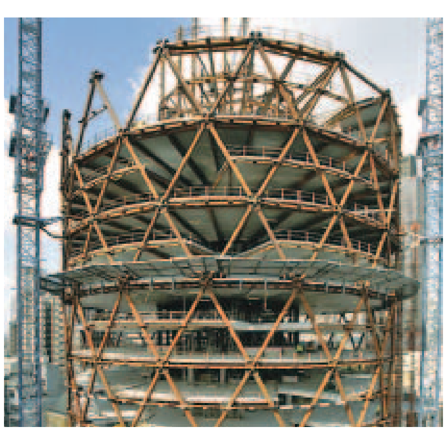




The produced node is prefabricated in the factory. The heart consists of a solid block of steel of 240 by 140 mm.



The tower was assembled in construction cycles of two storeys, with one cycle every two weeks.



➤ forces at the middle and lower levels. The sizing of the steel elements is governed by strength criteria – the total sway stiffness of the diagrid is sufficient to limit the wind sway to 50mm over the full 180m height and provides a very good level of overall dynamic performance.

The development of the diagrid nodes

It was recognised at the outset that the node connection detail would be fundamental to the success of any diagrid scheme. The local geometry of the connection varies at each floor level, due to the differing floor diameters. The triangulated nature of the diagrid demanded a detailed consideration of the control of fabrication and erection tolerances.

Two design approaches are possible: one can focus on the individual elements and fabricate end details to suit each situation, or use separate node pieces acccommodating all the geometric variation and allowing simple stick elements to be used. The latter approach allowed a simplification in the connection geome-

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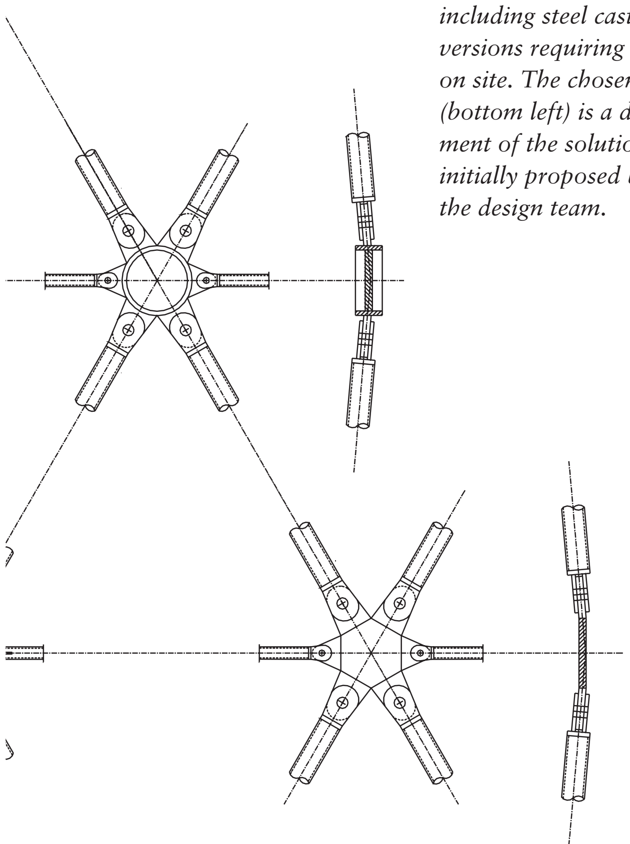
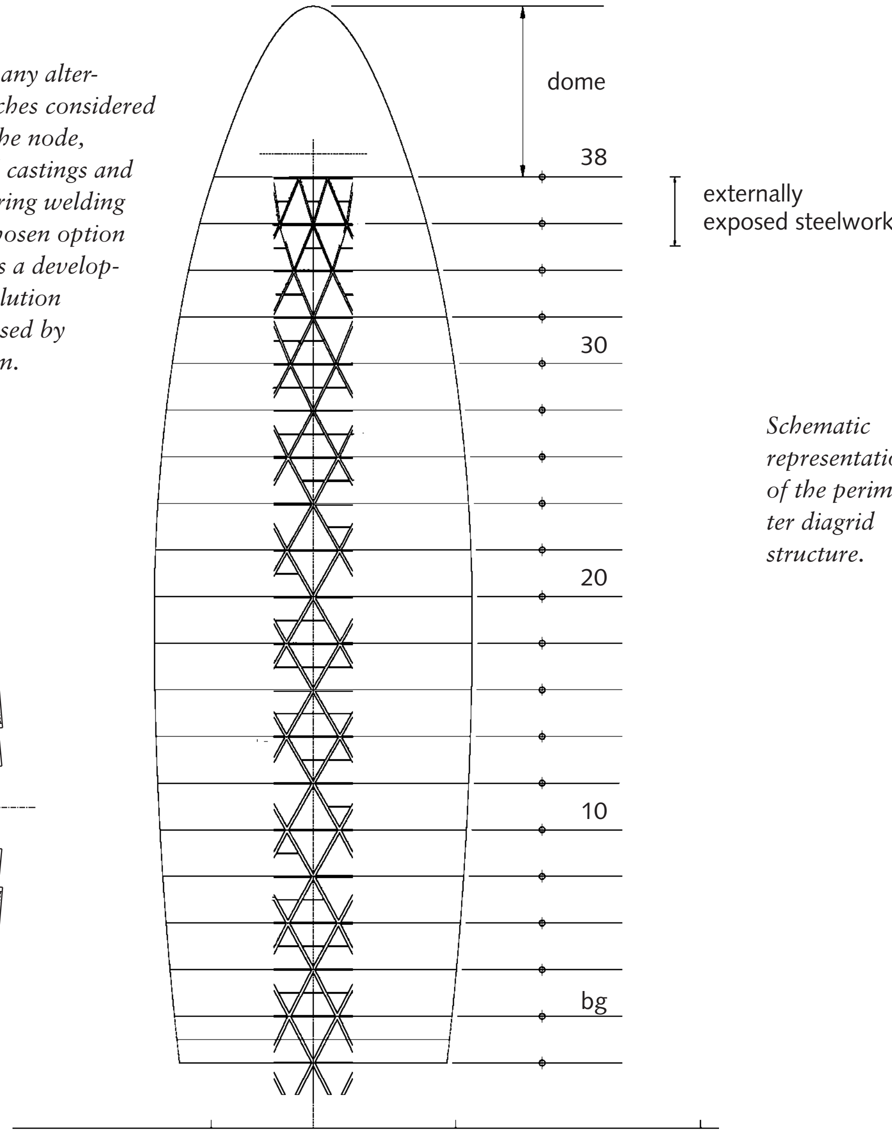
Some of the many alternative approaches considered by VB-H for the node, including steel castings and versions requiring welding on site. The chosen option (bottom left) is a development of the solution initially proposed by the design team.





Schematic representation of the perimeter diagrid structure.

try to the consideration of three intersecting planes relevant to a node, as opposed to six individual element orientations. One plane is defined by the axes of the horizontal hoops, one is common to the upper columns, and one to the lower columns. Principal compression loads are transmitted through milled end bearing surfaces, and tension through bolted splices.

The significance of the diagrid connection detail to the steelwork contractor's method of working in both shop and site made it important for all potential contractor's to be given the opportunity to develop their own ideas and approach. Steel sub-contractor Victor Buyck - Hollandia JV (VB-H) developed the detailed node design to meet a number of defined performance criteria, including:

- Loading combinations involving primary structural actions, local floor eccentricities and cladding loads
- Robustness tying requirements
- Movement and restraint requirements between the diagrid structure and floor slab
- Erection tolerances and fit within cladding geometry

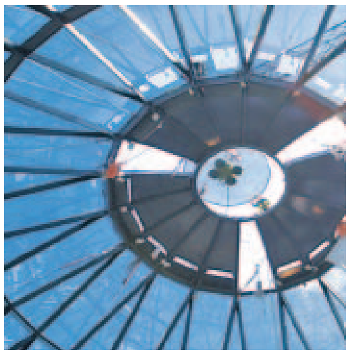
The chosen approach followed the same basic layout as had been defined in the initial design. Great emphasis was given to the accuracy of fabrication of the prepared bearing surfaces of the nodes and columns, which were milled to a tolerance of 0.1mm. This ensured a very good level of fit with minimal site adjustment needed. This was despite the fact that alternate bands of steelwork were fabricated in separate yards and had not come together until erected on site. VB-H developed and tested an innovative tied corbel connection detail between the floor steelwork and the node which allowed the required radial spread of the diagrid during construction whilst providing a reliable degree of restraint to the diagrid nodes. The detail also provided for fine adjustment of the node position during erection using radial tie bolts. This ensured that the ring of hoop tension elements could be closed without the use of oversized holes or pre-tensioned bolts.

Floor framing

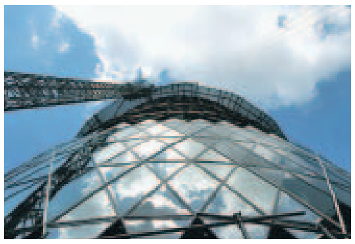
The circular floor plates are framed between the core and perimeter structure using radial beams on 10° centrelines. This leads to a range of spans for the composite floor slab of up to 4.75m between beams at the perimeter on the largest floors. Arup worked closely with Richard Lees Steel Decking to develop a design based around the Ribdeck 80 profile to achieve these spans without the need for temporary propping. The overall slab thickness is 160mm with a similar weight to the more conventional 130mm, and also provides improved overall floor plate vibration dynamics due to the increased rib stiffness.

Beam depths are minimised by use of wide flanged (European profile) beams. The beam depth is most critical in the primary services distribution zone ➤

➤ around the core, whilst there is a less critical fit at mid-span. This enables the beams to be specified without precamber, whilst maintaining adequate clearances for services. Within the cores the beam spans are much reduced, allowing the horizontal separation of structural and services zones. The only area where beam web penetrations are required is around the perimeter where supply and exhaust air is ducted via plenum boxes connected to the back of slotted façade transoms.



Looking through the dome from the inside during installation of the top doubly-curved glass 'lens' that crown the building.



Arial view during installation of the glazing to the dome, showing external access hoist and platforms. View from street level during main façade installation. The specially designed safety fan allows steel erection to continue above.

Working in 3-D

A fundamental characteristic of the Swiss Re building is the use of a consistent unifying system combined with a constantly varying geometry vertically through the building. This type of geometry is particularly suited to a parametric design approach: many of the detailed design conditions can be investigated by setting up fixed mathematical relationships between a relatively limited number of geometric parameters defining the building shape.

This approach was used to drive optimisation studies, to build up data bases of various design conditions allowing rationalisation of structural components and details, and to generate 3D model geometry for analysis, co-ordination and structural design. An example of this approach is the analysis of the relationship between perimeter column setting out and the facetted cladding geometry which allowed the team to home in rapidly on the optimum geometry for the diagrid.

A full Xsteel model, incorporating centreline geometry and sizes for all structural elements was created by Arup during the detailed design phase. This ability to exchange data in 3D enhanced the level of confidence within the team that the detailed co-ordination was accurate and provided a firm basis to develop the rest of the design documentation. The model provided all steel subcontract tenderers with comprehensive material list reports, ensuring a common basis for logistical planning and pricing. This alone represents a significant saving in effort for a building in which there is very little repetition of beam lengths.

The 3D model was subsequently adopted and developed by the steel subcontractor to generate fabrication information. The continuity of model information from analysis through to fabrication greatly reduced the scope for errors in interpreting the design requirements. The steel 3D model provided the basis for detailed coordination of several trade interfaces including cladding and building services.

Dome

The upper three levels of the building from level 38 provide corporate facilities for Swiss Re and other tenants, including private dining rooms, restaurant and an upper viewing mezzanine offering 360° views over London. These levels are enclosed with a steel and glass dome structure of 30m diameter, rising 22m from its support on the top of the perimeter diagrid. The dome steelwork is a fully welded lattice of intersecting fabricated triangular profiles. The efficiency of this structural arrangement results in very minimal steel elements that are only 110mm x 150mm in section.

Steel erection

With planning permission granted, enabling works for the single level basement were able to start on site in December 2000. Steel fabrication started in Holland and Belgium in July 2001, with steel arriving on site in October of that year. The erection sequence progressed in two-storey bands in the following pattern:

❶ Erect core steel complete with access stairs and a small amount of temporary bracing
❷ Deck core and establish survey points
❸ Erect diagrid columns and nodes as A-frames (pre-assembled at ground level)
❹ Erect radial beams and plumb A-frames, install hoop members to complete diagrid
❺ Complete floor framing and decking, including crane tie bracing where required
❻ Concrete floor

The steel erection progressed at approximately one band per fortnight, with concrete poured 8 storeys below the core erection front. The last diagrid A-frame to level 38 was erected in October 2002, to an overall plumb tolerance of less than 10mm over the 160m height.

The erection of the fully welded freestanding dome lattice steelwork required a different erection approach from Waagner-Biro. Off-site welding of transportable sized sub-assemblies ensured that site welding was kept to a minimum. Jigs were set up on the plaza slab allowing two adjacent sub-assemblies to be joined together to form sections of the dome measuring approximately 12m by 8m, which were then erected onto temporary locating jigs at the top of the building. Si-

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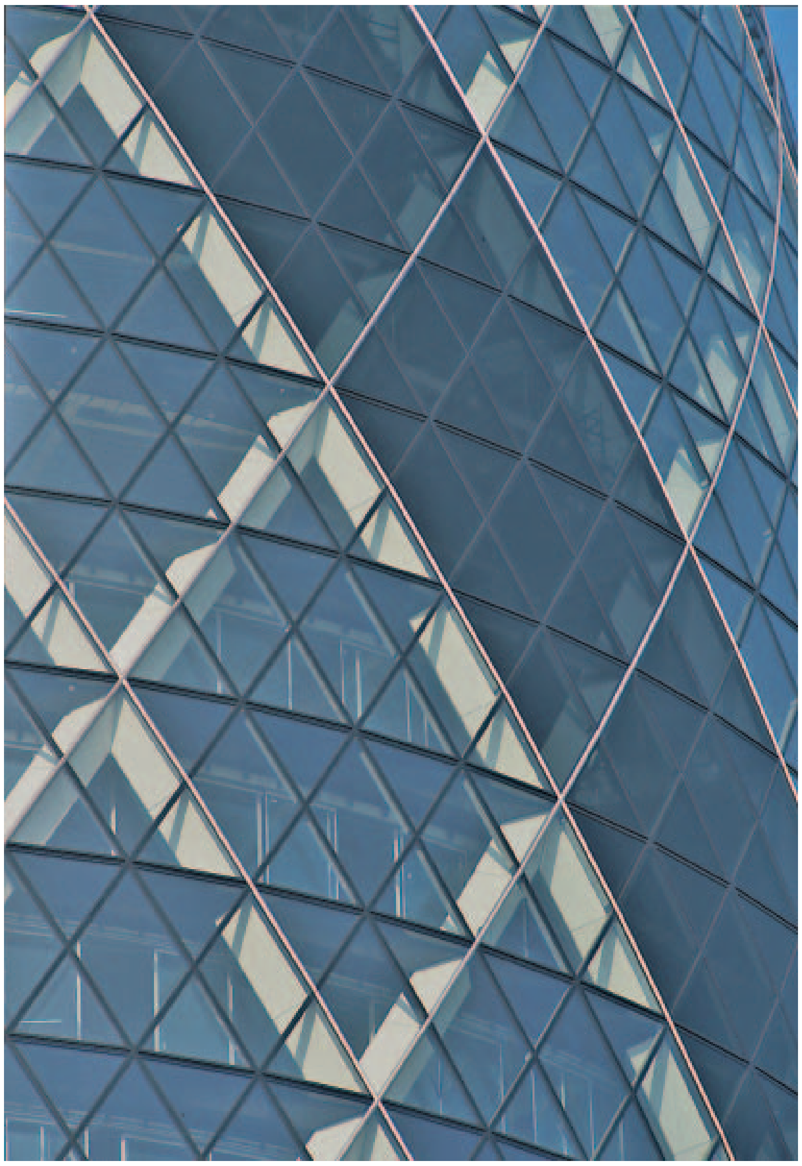
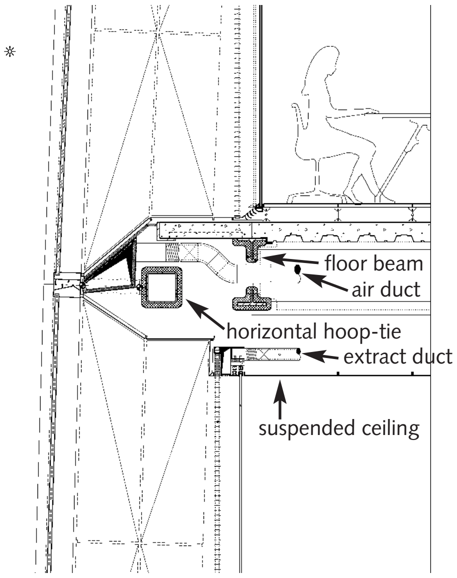
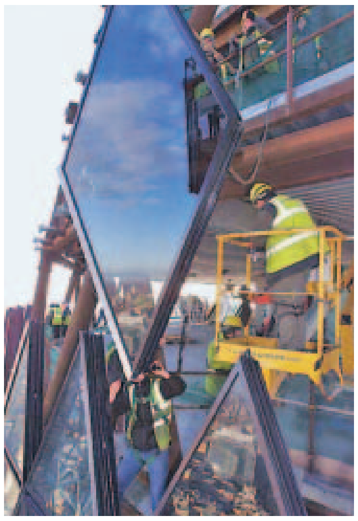




The elements of the facade.
- *Openable glass screen.*
- *Perforated aluminium louvers (internal sun-screen)*
- *A column casing of aluminium*
- *Façade frame of extruded aluminium*

te welding the members between erected sections completed the dome framing in two level stages, before the removal of the temporary supports. The top 'spider' section was erected in one piece in March 2003. ❑



Facts and figures

Dimensions

Height to top of dome:	179.8 m
Height to highest occupied floor level:	167.1 m
Number of floors above ground:	40
Number of basement levels:	single basement across whole site
Largest floor external diameter (lvl 17):	56.15 m
Site area:	0.57 hectares (1.4 acres)
Net accommodations areas:	
➤ Office	46,450 m²
➤ Retail	1,400 m²
Office floor-floor:	4.15 m
Gross superstructure floor area (incl. lightwells):	74,300 m²

Tower Structural Steelwork

Total weight of steel (from Arup Xsteel model):	8,358 tonnes
of which:	
➤ 29% is in the diagrid	
➤ 24% core columns	
➤ 47% beams.	
Total number of primary steel pieces:	8 348
Total length:	54.56 km
Diagrid column sizes:	
➤ Ground – level2:	508mm f, 40mm thick
➤ Level 36–38:	273mm f, 12.5mm thick
Hoop design tension at level 2:	7 116 kN
Perimeter column maximum design load:	15,460 kN
Core column maximum design load:	33,266 kN

Foundations

750mm diameter straight-shafted piles into London Clay	
Number of piles:	333
Total length of piles:	9 km
Total design capacity:	117,000 Tonnes

Credits

Client:	Swiss Re
Project Manager:	RWG Associates
Architect:	Foster and Partners
Structural Engineer:	Arup
Building Services Engineer:	Hilson Moran Partnership
Cost consultant:	Gardiner & Theobold
Fire Engineering:	Arup Fire
Main Contractor:	Skanska
Structural Steel sub-contractor:	Victor Buyck – Hollandia
Dome sub-contractor:	Waagner-Biro