Złote Tarasy, Warsaw, Poland

Darren Anderson Zbigniew Czajewski Stuart Clarke
Ian Feltham Paul Geeson Marcin Karczmarczyk
Richard Kent David Killion Zbigniew Kotynia
Maciej Lewonowski Robert Lindsay Philip Monypenny
Chris Murgatroyd Johnny Ojeil Raf Orlowski
Andrzej Sitko Darren Woolf

1. The main north-south canyon.

History and background

Złote Tarasy (Golden Terraces) takes its name from Złota (Golden) Street, one of the "metal streets" established in the 18th and 19th centuries in central Warsaw that also included Iron, Silver, Copper, Platinum, and Cast-Iron Streets. In 1854, Złota Street had 27 houses and five tenement buildings, mainly of timber. During the second half of the 19th century, these were gradually replaced by masonry buildings, some very stylish. Then, in the early 20th century, it became a place of urban innovations - gas lights, sewerage systems, and trams.

World War 2 put an end to the golden years. Nazi bombs fell on Złota Street in 1939, causing much damage. During the 1944 Warsaw Uprising, the street was barricaded; temporary hospitals and shelters were set up, but the buildings were devastated. A few survived the War, only to be demolished to make way for the Stalinist Palace of Culture, completed in 1956, that occupied the street's central section. The Złote Tarasy site, between the surviving section of Złota Street and Warsaw Central railway station, had remained undeveloped since the War except for some roads, car parks, and a bus terminus.

Client and designers

ING Real Estate began operating in Poland in 1995, where its first developments included some modern high-quality bank and office premises, and apartment blocks in central Warsaw. ING recognized the Złote Tarasy site's unique development opportunity: a new city centre for Warsaw, linking into a multi-modal transport interchange. As the land was owned by the city, an agreement was negotiated by ING whereby the city provided the site in exchange for a share in development profits.

**"ING Real Estate aimed to create the hallmark of the city of Warsaw, and thus breathe new life into the capital's city centre...
The design team and contractors did a marvellous job in creating this hallmark."**

Marcel Kooij, Deputy Director, ING Real Estate

2. The atrium cascade and the sunken plaza.

The Los Angeles-based Jerde Partnership was appointed as concept architect early in 1997, at the same time as Arup's Warsaw office was being established. Arup was initially involved in traffic and transportation studies related to relocating the bus station onto the railway station "deck", so as to vacate the site. Later in 1997, the firm was commissioned for the concept engineering design of the whole development, a geotechnical desk study, and a full site investigation. As the project expanded, the scope grew to include the entire structural, civil, and geotechnical design, transportation planning, acoustics, façade engineering, pedestrian modelling, building physics, and fire strategy. This harnessed key Arup specialist advice from many different disciplines, offices, and groups.

Project overview

The vision for Złote Tarasy was for a vibrant destination, revitalizing the area around the station and including offices, retail, dining, and entertainment in the premier mixed-use centre in Warsaw. Jerde's design, inspired by the historic parks of Warsaw that were saved from wartime destruction, had as its main focus four retail levels grouped around a central atrium, with an undulating glass roof reminiscent of tree canopies. The atrium area is carved through with canyons to allow light to penetrate to the lowest levels, while on the south side the retail and dining areas step back in a series of curved terraces. Above the terraces, the atrium roof flows down to a sunken plaza, with pedestrian links to the station on two levels (Fig 2).

These terraced retail and entertainment levels are surrounded by two curved 11-storey office buildings ("Lumen"), a 22-storey office tower ("Skylight"), and a multi-screen cinema. Below ground are four basement levels, with 1600 parking spaces. The scale of the project speaks for itself. A total area of 200 000m^2 includes 54 000m^2 of retail, restaurants and department stores, 24 000m^2 of offices, an eight-screen cinema including a premier auditorium of 780 seats, 14 000m^2 of public areas and malls, 40 000m^2 of underground car parking, a 6000m^2 truck service yard, and 6000m^2 of terraces and gardens.

The engineering challenges were immense. The basement car park occupies the site's full extent, requiring deep retaining walls next to live carriageways, and a raft foundation below the water table. The concrete frame had to be designed to counteract the overturning of the outwardly leaning "Lumen" office blocks, and to support long cantilever walkways around the curved atrium perimeter. And the atrium roof was of such convoluted geometry that it required some of the most complex analysis ever undertaken by Arup. Added to this, every specialist discipline faced complex, taxing challenges.

The concept and scheme design were done in Arup's Birmingham office before relocation to the Arup Campus in Solihull in January 2001. As the project progressed, and the Warsaw office grew, responsibility for the detailed design was passed there. In recognition of the project's size, the structural design was split between offices, with the substructure, superstructure, and atrium roof design each being handled separately by complementary teams in the UK and Warsaw. Arup's full-time project-manager, resident in Warsaw, was responsible for co-ordinating these teams and all the other Arup specialists.

The site

The 32 000m^2 site is bounded by roads on three sides and the railway station to the south. Roughly rectangular, it is 215m long and 165m wide. Across Złota Street, on the north side, are the "City Center" shopping centre and the Holiday Inn Hotel. To the east and west are the busy six-lane Emilii Plater Street and Jana Pawła II Avenue (Figs 3, 4).

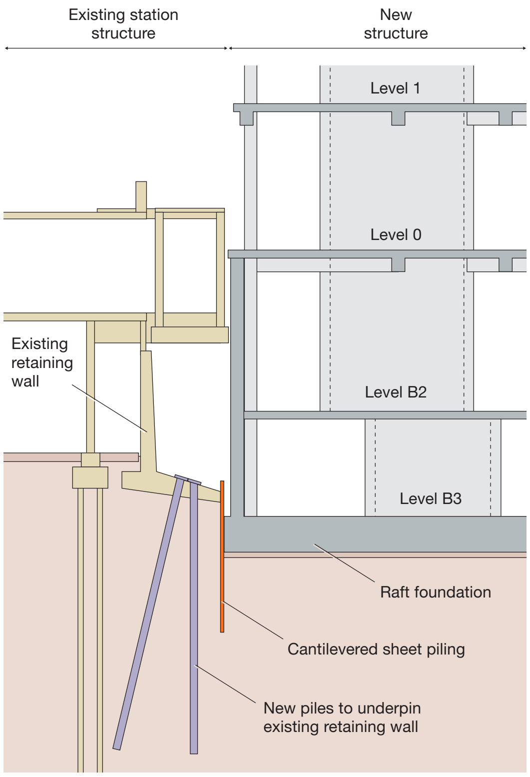
A grassy embankment up to 4m high divided the site in two, with the bus station occupying the half nearest the railway station, and access roads and a large surface-level car park elsewhere. Most of it was covered by tarmac, concrete or compacted stone. The southern half was considerably lower than the surrounding streets, the step being typically formed by retaining walls, up to 6m high.

The underlying ground is of good load-bearing capacity, but quite complex due to the numerous and uneven strata. Several metres' thickness of made ground and thin layers of sand and clay overlie a stiff glacial till, up to 24m thick, below which is a thick layer of dense fluvio-glacial sands and gravels, overlying Pliocene clays at depths greater than 40m.

Of the two groundwater tables, the upper forms a series of relatively flat levels and non-continuous surfaces, about 4m below ground level, whilst the main pressurized water table is 10m below ground level, in the sand layer under the till. Perched water was also found in numerous sand lenses within the till. This unusual combination of water tables proved a major challenge in designing the basement and retaining walls. The top of the pressurized water table is up to 3.5m above the lowest foundation level, resulting in considerable flotation forces.

3. Location plan.

4. The site during basement excavation in April 2003: (a) Jana Pawła II Avenue, (b) Złota Street, (c) The Palace of Culture, (d) Emilii Plater Street, (e) Warsaw Central Railway Station, (f) Złote Tarasy.



5. Cross-section through the basement abutting the existing station retaining walls.

Basement and foundations

Excavation

The Złote Tarasy basement, up to 13.5m deep, is one of Poland's largest. The site perimeter had all the usual problems of a congested inner city, with adjacent roads and buildings, and buried services close to the boundary. The railway station was tight against the southern boundary with a two-storey gravity retaining wall, and all the station's complex exhaust ventilation shafts crossing onto the site. Stone-clad concrete retaining walls, 6m high, supported the perimeter of the adjacent roads on the east and west sides, and an elevated ramp and access tunnel had to be incorporated into the scheme or reinstated, to serve the relocated bus station. Next to the railway station, the existing gravity retaining wall was underpinned with piles, and the new foundations at a lower level were built against a permanent cantilever sheet piling system (Fig 5).

Diaphragm walling was selected as the best solution for the perimeter retaining walls, both temporarily and permanently. In the temporary case, an 800mm thick diaphragm wall was designed to accommodate excavations up to 16m below the adjacent pavement level. In the permanent case, the basement floor slabs provide sufficient lateral restraint to resist not only the earth and surcharge pressures but also water pressures from the main water table and the large areas of perched water at higher levels.

Ground anchors were selected as ideal for supporting the diaphragm walls in the temporary state, providing the maximum working space whilst minimizing potential movement of the gravity walls next to the main carriageways. The contractor's final design incorporated multi-strand anchors into the glacial till, which proved to be very successful (Fig 6).

On the northern side, the proximity of existing retail buildings with basements ruled out ground anchors, so a raking prop scheme was planned and incorporated in the contractor's temporary works.

The need for over 1600 parking spaces meant that a fourth basement level was required over 60% of the footprint. This B4 level, 13m below ground, resulted in construction below the water table, so Arup specified a dewatering programme.

6. Diaphragm retaining wall with ground anchors, along the east edge of the site.

Raft foundation

To minimize the costs of retaining walls, Arup kept the deepest excavation to the site centre, for the B4 level. Slabs were kept at the higher B3 level on the critical north and south ends and along the western perimeter. This resulted in several folds in the lowest slab, further complicated by the need for lift pits and lowered plant areas (Fig 7).

A continuous raft, free of movement joints, was the ideal choice to control the risk of differential settlements and future cracking of the finishes. As the loading intensity varied significantly, Arup's in-house *GSA* (general structural analysis) software was used to predict the raft settlements, which were initially significantly higher under the "Skylight" office tower. Using iterative analysis, Arup optimized the design, equalizing predicted settlements under the critical sections with settlements of the surrounding areas. This was achieved by a piled-raft solution under the tower footprint, with 900mm diameter bored piles up to 20m deep beneath the raft on a closely spaced 3.6m x 4.0m grid. The piles were empty bored from the existing ground level, using support fluid, and founded in the fluvio-glacial sand and gravel layers overlying the deep Pliocene clay. The raft is typically 1.6m thick, varying between 2.65m under the tower to 1.0m under the lightly-loaded northern end.

Basement structure

Basement levels B1-B3 have reinforced concrete flat slabs, typically on a 10.8 x 8.0m grid supported by 800mm diameter circular columns with drop heads. In the more heavily-loaded areas, grid and column size could not always be maintained, so vary locally. Major core structures and ventilation shafts further complicate the layout. The principal car parking is on levels B3 and B4, with smaller zones above.

Conforming with local special fire requirements, the basement levels are divided by two perpendicular movement joints to form four independent quadrants. Due to the required four-hour fire resistance for the quadrant beneath the "Skylight" tower, it was separated at each level from the rest of the slab by a special movement joint. Although designed for 25mm movement under normal conditions, it has special crush zones capable of 200mm expansion in a fire.

7. Raft foundation under construction at B4 level. On the left is the soil berm left in place to support the diaphragm wall along Złota Street, on the other side of which are the "City Center" shopping centre and the Holiday Inn Hotel.

Due to architectural and functional constraints, the "Skylight" tower's structural core is limited in the basement levels to only 40% of its area on the upper floors. The loads are transferred to a set of push-pull columns by very large shear walls, 3.7m deep and 1.6m thick. The complex geometry of this transfer structure required a special finite element analysis, using *ROBOT Millennium* and Oasys *GSA* software, for its behaviour to be understood and the reinforcement designed accordingly. Apart from this unique structure, there are many transfer structures in the basement, and discontinuities of some columns from the upper levels resulted in some complex beam arrangements. Arup's design, however, ensured that the car park's functionality was never compromised.

Other features of the basement include the service yard, sunken plaza, and access ramps. The 6000m^2 service yard is formed by a double storey-height space at B2 level, providing sufficient space for deliveries to all the shops and restaurants, as well as emergency vehicle access down a central road. The sunken plaza in the south-east corner of the same level forms an open-air space with water features, and direct access to the lower levels of the railway station.

The main car park access ramp is from the centre of Złota Street, while on the site's north-west corner an existing tunnel under Jana Pawła II Avenue was used to provide the principal delivery and lower basement access. This tunnel is also used by municipal buses to access the bus station.

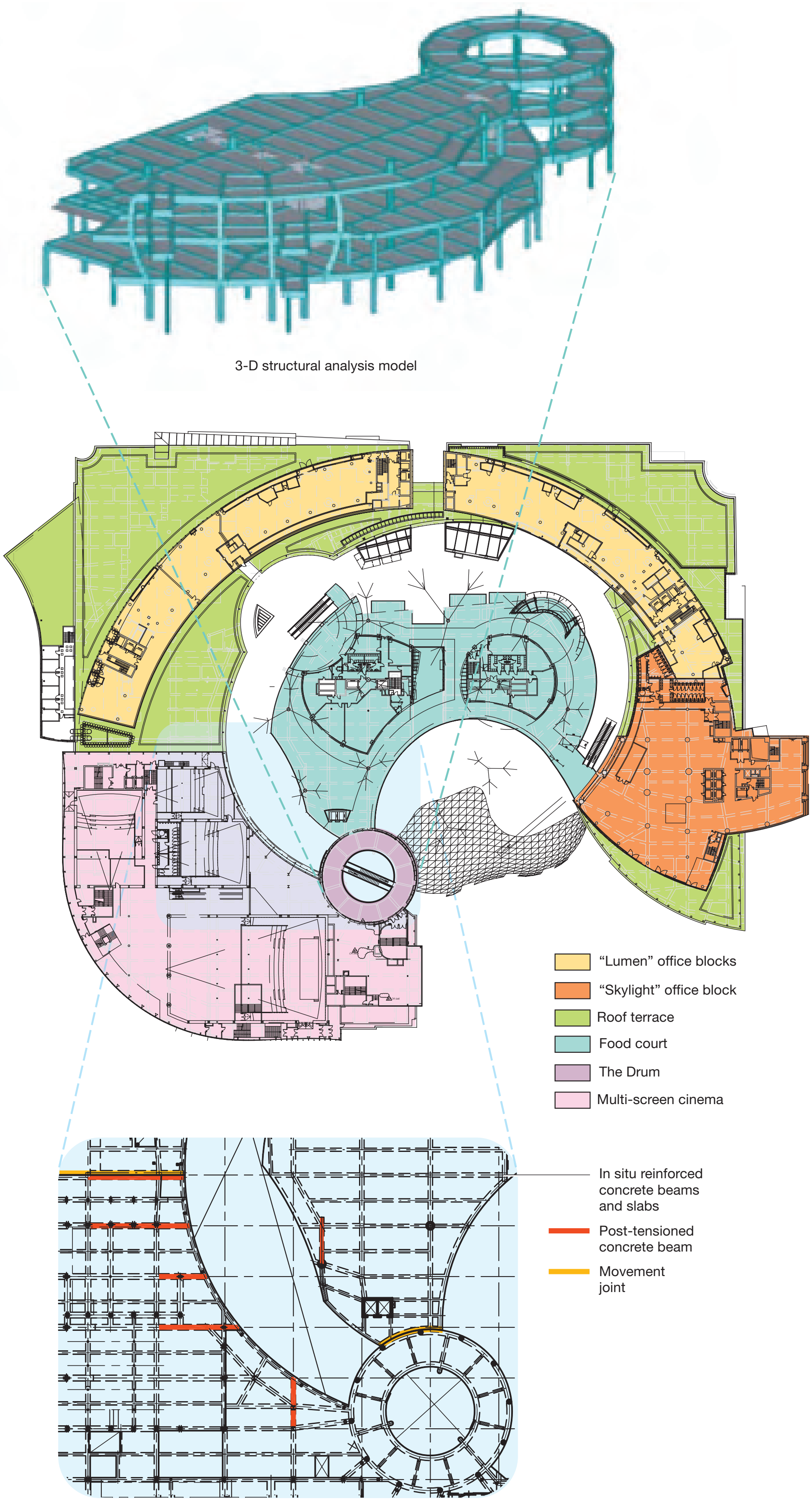
A new in situ concrete perimeter wall next to the railway station boundary, built off the raft foundation, incorporates the station link structure and the two newly-routed exhaust ducts for the railway station.

Superstructure

Basic structural concepts

To minimize basement excavation it was essential to avoid transfer structures wherever possible, and use the same column grid for the retail areas as for the basement car parking. Maximizing the latter's efficiency was the key to developing the basement and retail area grid.

The starting point was the use of 5.0m x 2.5m parking spaces with 0.8m-wide column zones, intended to give the high turnover of shoppers easy parking and a general high-quality feel. Column spacing parallel to the driveways was set at half a "bin width" of 8.0m. In parking terminology, one "bin" is the width of an aisle plus the parking bays either side. In this case the bin width was 16m (6m aisle plus two 5m parking bays).



8. Plan of level 3, showing movement joints and prestressed beams, together with part of the 3-D structural analysis model.

Perpendicular to the aisles, the grid was set at four parking spaces plus the 0.8m column zone, totalling 10.8m. Although columns every three spaces was less costly, the four-space solution was adopted because it gave greater flexibility in the retail floors above.

Arup accepted from the beginning that major transfer structures would be needed at level 3 between the retail floors and the offices and cinemas above to provide column spacing appropriate to each of these uses. Although the basic grid was intended to suit retail and parking, the complex geometry of the main retail circulation areas was expected to generate serious structural challenges at the interface between these uses. However, costly transfer structures were minimized through imaginative and well-integrated architectural and structural design.

An early requirement of the developing brief was that the structural design must accept post-construction changes by retail and office tenants, and be tolerant of on-going design development due to the scheme's geometrical complexity. Arup provided flexibility in both these aspects by using traditional in situ concrete beam and slab construction rather than the increasingly popular flat slabs. This had two benefits: individual slab panels could be removed after construction with minimal effect on overall structural integrity, and small column offsets could be introduced along beam lines, as was required in later design stages.

The use of in situ reinforced concrete for most of the structure acknowledged the track record of high-quality Polish concrete production, and the relatively low use of steel in Warsaw buildings in 2001-03. It was also eminently suited to the architects' complex curved shapes.

Sets of in situ concrete cores and shear walls provide overall stability. Local fire regulations necessitated structural separation joints which split the otherwise uninterrupted 215m x 165m building's lower-level footprint into four quadrants, each stabilized by at least two cores or sets of shear walls, and two smaller central islands, each with its own core. The complex arrangement of the cores in plan is matched by their vertical complexity: the cores are used for structural stability, stairs, lifts, and service risers, all with wide variations of space requirements at different heights.

A structure suitable for high specification retail

Jerde envisaged a characterful retail area with imposing circulation spaces and clear uninterrupted views of shopfronts across internal streets and open spaces, all within a large open atrium. From early in the concept design, the primary circulation routes were two “canyons”, one oval in plan, the other a straight north-south axis crossing the oval at two points. Central to the concept were canyon-side walkways with edges stepping back at each floor level, and inclined columns and balustrades. These followed the lines of the inclined “Lumen” office blocks above the atrium roof, so from the walkways there are impressive views of the towers above, as well as wide uninterrupted views around the canyons.

This ambitious combination of wide walkways, uninterrupted views, and complete departure from the regular basement parking column grid, set two major structural challenges: the design of numerous long cantilever beams, and the provision of transfer structures without creating headroom problems below (Fig 8).

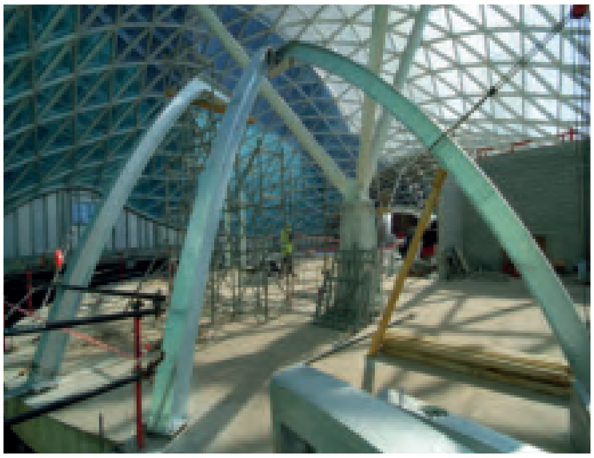
For the cantilever design, the challenge was to provide large spans without excessive structural depths. Arup’s solution emerged from a realization that the cantilever depths were controlled by deflection rather than strength. The team adopted an innovative system of partial prestressing, incorporating ducted post-tensioned tendons. These provide sufficient prestress to control deflection only, strength being supplemented by traditional unstressed reinforcement. This “hybrid” technology was untested in Poland. Initially it attracted some scepticism from potential contractors but, once accepted, there was universal recognition of its merits, simplicity, and relative ease of construction. Arup’s innovative approach gave the architect and client the uninterrupted views around the walkways that they wanted. Each shop front has maximum exposure to shoppers on both sides of the canyon, with no column obstruction.

In a building of such complexity it was difficult to ensure that prestress forces were transferred into the intended beams rather than absorbed by nearby stiff elements such as cores. The distribution of cores and shear walls was also a reason why wholesale prestressing could not be adopted. But its selective use in controlled situations like cantilevers and long-span beams provided the optimum solution.

Software used for the structural analysis included *GSA*, *ROBOT Millennium* (the 3-D finite element analysis model included 20 000 nodes and 30 000 elements), *Plato* and *ABC Plyta* for 2-D finite element analysis of slabs and beams, and *RM-Win* for steel elements. Complex structural analysis was required for the many curved structures, including the “banana columns” (Fig 9), the “Helmet” (Fig 10), and the “icon” on top of the “Skylight” tower (Fig 11).

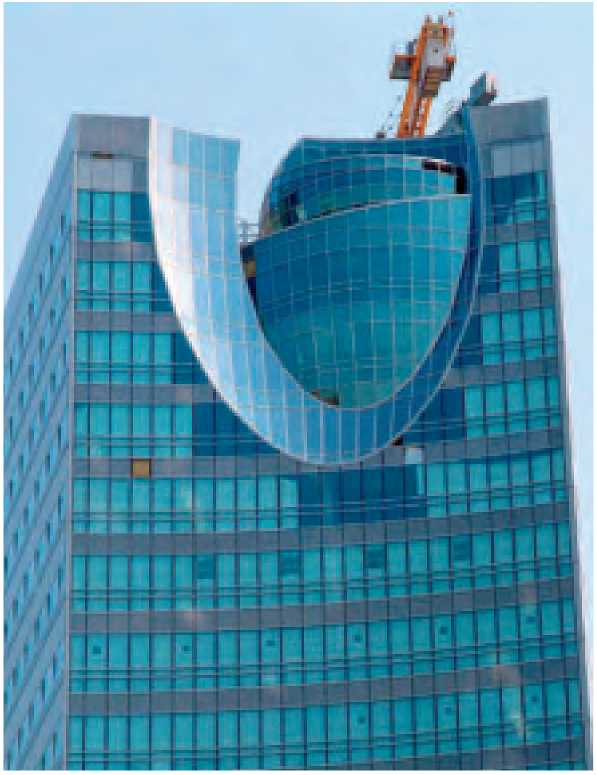
In the central retail area around the edges of the canyons many transfer structures were needed to marry the layout of the columns to the parking grid below. Minimizing structural depth was again a key to essential cost control. The floor-to-floor heights had to be kept to an absolute minimum to reduce the total cost of the high quality finishes and elevational treatments in the public retail areas as well as maximising the visibility of shopfronts between levels and shortening staircases and escalators. The solution was a two-part strategy involving detailed co-operation and co-ordination between Jerde and Arup. The first part, the wholehearted adoption of inclined columns, stemmed naturally from the architecture. The second part required extensive and detailed 3-D modelling and column-positioning workshops, aiming to transfer column positions in small steps over several floors to minimize transfer beam depths. This strategy successfully minimized floor-to-floor heights without compromising headroom requirements in the retail areas and walkways.

9. “Banana columns” for the “Bowl”, and cantilever support platform for escalators.



10. Steelwork under construction for the “Helmet”.

11. The “Icon” on top of the “Skylight” office tower.



Office blocks, level 3 transfer structures, and cinema

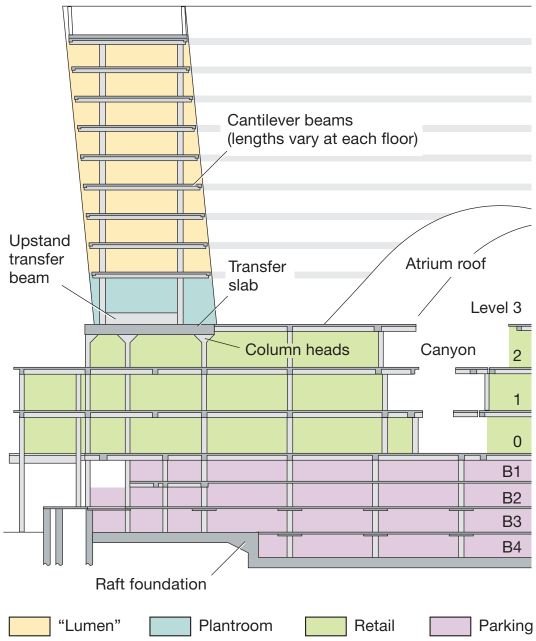
The two northern "Lumen" blocks are approximately semi-circular in plan, and slope outwards towards the surrounding streets. The inclinations vary from vertical at the axis of the main north-south "canyon" to about 1:10 at the extreme eastern and western ends. Early studies of these blocks aimed to assess cost-effective ways of achieving the inclined façades. Inclined columns would have created excessive overturning moments in the relatively small cores, so vertical columns were used throughout, with varied-length cantilever beams at each floor to suit the angles of inclination (Fig 14). In situ reinforced concrete is used for framing all the office blocks. Primary beams form the cantilever back-spans and contain various holes for main building services distribution, taking full advantage of the high quality of Polish concrete production and again minimizing floor-to-floor heights. This helped minimize overall costs, due to the expense of the inclined cladding.

There is a major mismatch between the heavily loaded columns for the curved eight-storey Lumen offices blocks above level 3, and the regular column grid of the retail floors below. Initially a complete storey height had been allocated between levels 3 and 4, to accommodate the transfer structures required. However, Arup's design refinements, including extensive finite element analysis, led to the transfer structures being fitted within a slightly thickened structure at level 3.

This was a major cost saving, as it permitted much of the plant to be relocated from the roof of the office blocks to the newly-created level 3 plantrooms. The final transfer structures include a 1.2m thick slab with upstand beams connecting pairs of office columns and dropped areas of slab with column heads below (Fig 14).

Structural steelwork was used for the cinema structural framing, due to the need for long spans, and precast concrete for the seating areas. Steelwork was also used for the complex three-dimensionally curved structures in the atrium, such as the "Helmet" (Figs 10, 15), the "copper houses", and the "Bowl" (Fig 9), as well as for the architectural "icon" on top of "Skylight" (Fig 11).

13. The "Skylight" office tower and one of the "Lumen" leaning office blocks.



14. Typical cross-section through one of the "Lumen" blocks.

12. The "Skylight" office tower, the "Lumen" blocks and cinema from above.

The atrium roof

Concept

The spectacular glazed atrium was conceived as the project's heart. As well as enclosing the central malls, terraces and food court, it was intended to be an instantly recognizable icon, establishing the development's brand values.

Three years' concept development between Arup and Jerde led to its unique shape; from 1998 to 2001, the roof evolved from a single overarching dome to a free-flowing, undulating form. Jerde's concept was a symbiosis of nature and technology, combining the natural forms of trees, forest canopies, falling water, soap bubbles, and soft textiles with mathematical concepts, scientific observations, and technological tools. By adopting this undulating form, Jerde created an intimacy with the structure that gives rise to constantly changing views as one moves around the atrium.

Due to limitations of engineering design and fabrication, roofs on this scale have historically followed geometrically defined shapes that can be readily analyzed, designed, and built with a large degree of repetition. Two recent developments have, however, combined to liberate architects from the straitjacket of regular geometrical forms: the increased power of computer-aided analysis, and advances in computer-controlled manufacture.

Roughly elliptical in plan, the 116m long x 100m wide roof rises in the centre to a series of domes, up to 35m above ground level, and on the south-west side flows into a spectacular cascade, dropping 25m in a column-free span to ground level (Fig 54). It thus forms the development's focal point, surrounded by the "Skylight" tower, the "Lumen" office blocks, and the multi-screen cinema, and links them with the main entrance from the railway and bus stations. It connects the heart of the development with the sunken plaza, allowing light to permeate the four retail levels, and opens up external views from the retail terraces, cafes, restaurants, and performance spaces.

Once the roof geometry was fixed, Arup's challenge was to develop a structurally efficient, buildable, economic, stable, and robust design. Due to the geometrical complexity, this required the highest levels of expertise, ingenuity, innovation, and teamworking.

Although the roof and its supporting structures (including the tree columns) act interdependently, they posed very different challenges, as discussed in the following pages.

15. Internal view of atrium roof and the "Helmet" at the level 3 food court.

16. Curved canyon around perimeter of atrium.

Generating the roof geometry

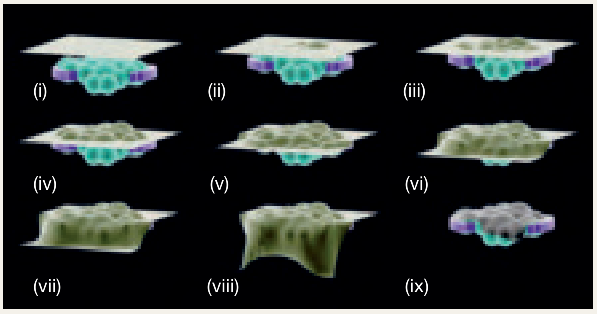
Jerde generated the undulating free-form geometry from an iterative computer simulation whereby a virtual cloth was "draped" over a series of spherical deflectors (Fig 17). Hundreds of alternative shapes were explored, varying the numbers of deflectors, their sizes and relative heights, the mesh size and "stretchiness", and the "gravity" force applied.
The drivers for the overall shape were to:

- ensure a positive rainwater flow across the whole roof, avoiding ponding
- maintain double curvature to the roof shape, as any "flat" areas would deflect too much
- create a variety of intimate spaces, hugging the profile of the stepped terraces and maintaining the minimum headroom at pinch points around the perimeter.

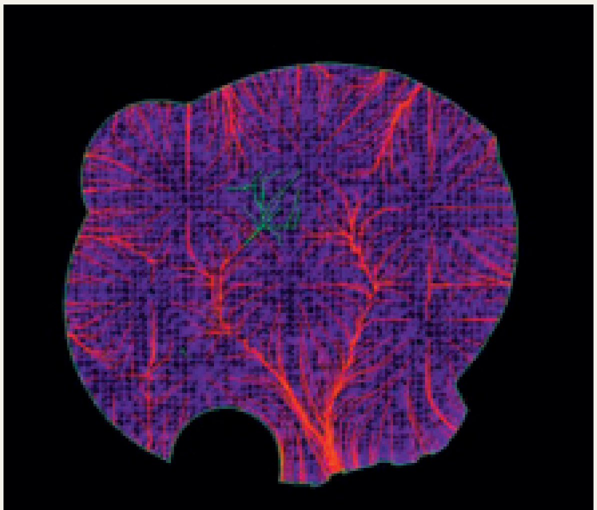
Detailed tracking of rainwater flows (Fig 18) showed unacceptable areas of ponding, which required adjustment of the roof geometry. The whole central area drains down to the front "cascade" above the main entrance at plaza level, and this feature resulted in some critical snow loading cases.

A function of the modelling was that although the glazing grid started as a regular mesh of isosceles right-angled triangles, the "draping" process introduced distortions as the mesh was moulded over the spherical deflectors. This stretched and twisted the grid, so that no two panels ended up the same size.

17. "Draped cloth" sequence.

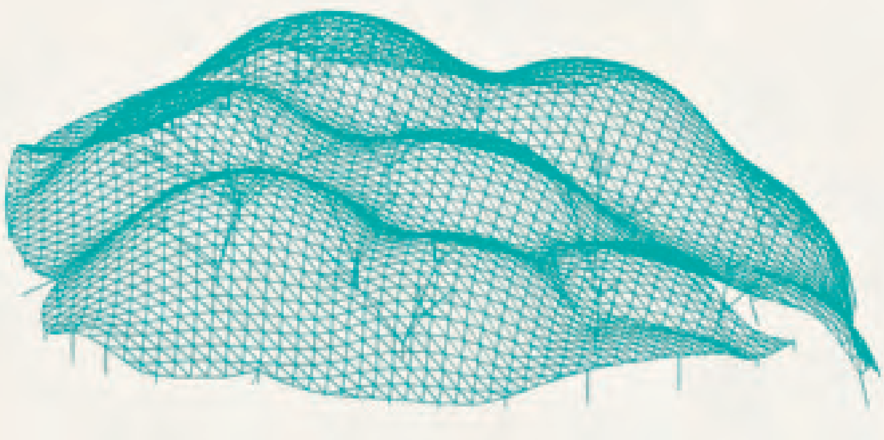


18. Rainwater flow modelling.



19. Perimeter smoke extract.

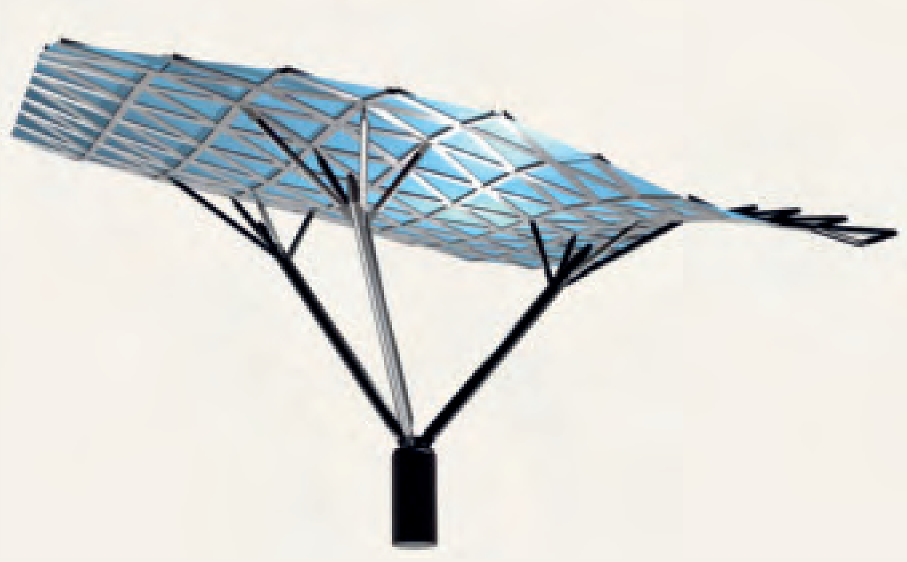
20. *GSA* image of final roof mesh geometry.



With the basic roof shape established, a long period ensued of developing and optimizing the mesh grid size. To fit the warped surfaces, the grid had to be triangular, as there was too much twist for square or rectangular panels to fit.

Arup explored numerous variations of size and angle, including grids based on isosceles and equilateral triangles. Structural and glazing costs, as well as aesthetic requirements, had to be balanced in the optimization process. Large panel sizes were the cheapest structural option, with the fewest members and connections, but the glazing would have been prohibitively expensive, and large panels would have created a faceted shape rather than a smooth change in gradient.
Small panels would have given the smooth shape, but with too many structural members and connections.

The optimum (Fig 20) proved to be a mesh of approximately right-angled triangles, with short sides around 2.1m long. This size and shape of glass units was the most cost-effective for glass manufacture. Although the basic shape was established early on, some significant changes followed during design development, most importantly a lifting of the "skirt" of the roof mesh in five locations around the perimeter, to allow space for smoke extracts (Figs 16, 19).



21. 3-D studio visualization of tree with branches and quads.

Structural design

Roof mesh and nodes

The over-riding architectural ambition was for the whole roof to appear as a uniform mesh, with constant-sized members. This proved extraordinarily difficult, and was achieved only through Arup fine-tuning the mesh design and its supports.

The end result is a continuous triangulated grid of steel rectangular hollow sections (RHS) of constant size, 200mm deep by 100mm wide, with wall thicknesses varying from 5mm-17.5mm depending on the forces in each member. Most are of grade S355 steel, but the 213 most heavily stressed members are in high-strength steel grade S460 - not normally used for building structures. By using the high-strength steel, every member was fabricated from standard hot-rolled RHS, avoiding the need for any fabricated box sections.

Six RHS members intersect at every node, a star shape with six arms, each arm bisecting the angle between two adjacent members. During design development, Arup tried to achieve some standardization of glass panel size, member length, and node geometry, but without unacceptable distortions of the roof geometry, the small level of standardization achievable had negligible cost advantage. In the end, each of the 2300 nodes, 7123 RHS members, and 4788 glass panels has a unique geometry.

Due to the internal supports (see below), the roof mesh spans are mostly less than 15m, except at the cascade and in the north-west corner, where spans of up to 25m are achieved by using the arching action of the mesh, making the roof exceptionally slender. The maximum deflection at any point is 43mm under maximum snow loads (Fig 22).

The most complex part of the roof mesh design was the node connections. Early analyses showed that they would need to transfer large bending moment forces. Most areas of the roof had insufficient curvature for a “pinned” node design to work. Each node therefore has to transfer a unique combination of axial forces, shear forces, and bending moments from one side of itself to the other. To help develop the most economic form, Arup involved specialist contractors at an early stage in the design.

Bolted and welded solutions were developed in tandem, with different contractors favouring different types of node. The welded option was preferred aesthetically, as it gave the most “invisible” connection, but the option of a bolted node was included in the tender documents to allow contractors maximum flexibility in their designs. It became clear that the node design would also influence the forces in each member, so the atrium roof specialist contract included the final design of the RHS members and nodes.

The chosen contractor, Waagner Biro, developed a fully welded node, as described later. The end result is a continuous, fully-welded, seamless structure, rigid enough to withstand wind and snow loading, yet flexible enough for thermal movements.

Supports

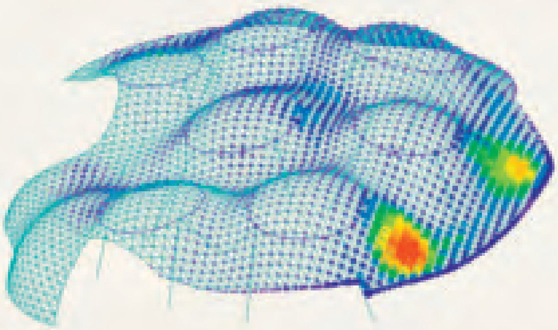
The roof is too convoluted to span 100m across the whole atrium, so it needed internal columns, as well as supports around the perimeter. Their number, nature, and location was a major challenge for Arup, and the subject of long design development through the examination and refinement of numerous options. The main drivers for the design of the supports were to:

- provide stability to the roof mesh
- avoid excessive deflections
- minimize local stress concentrations to achieve the required uniform mesh
- allow thermal expansion of the mesh without building up excessive stresses
- be structurally efficient
- be elegant and visually interesting
- bear on optimum locations in the reinforced concrete structure below
- minimize obstructions at floor level, allowing clear walkways and maximizing the lettable area
- allow ease of cleaning and maintenance of the glazing underside.

These often conflicted, and extensive parametric studies and much ingenuity were needed to satisfy them all with minimum compromise. Initial concepts, with relatively few columns, resulted in local instability, large deflections, and excessive stress concentrations in the roof mesh.

Arup's final solution was to provide 11 internal trees (reduced from an initial 16), 26 perimeter posts at level 3, two sliding bearings at the drum, two rotational bearings near the “Lumen” office blocks, two “flying struts” near the “Skylight” tower, and 16 supports at the base of the cascade.

22. *GSA* model: atrium roof deflections under drifted snow loads.



23. Cow parsley - inspiration for the trees.

The internal trees were carefully located to minimize impact and obstruction in the prime rental space at level 3. Each tree has a 2m high tapered steel tubular trunk, filled with heavily reinforced concrete. They are located directly above the reinforced concrete columns below, into which they transfer some large out-of-balance bending moments. Splayed out from the top of each trunk at different angles are three tubular steel branches, each of which in turn splits into a "quad" of four tubular members that connect to the roof mesh (Fig 21).

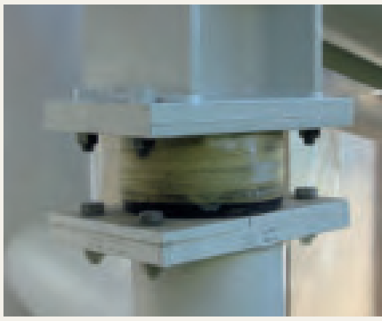
The trees are located outside the pedestrian walkways, with minimal loss of lettable area. The number and orientation of their branches was optimized primarily through the structural criteria of stability, stress, and deflection, but there was also a strong aesthetic element. The design was informed by natural tree and plant forms, particularly cow parsley (Fig 23).

Early designs included anything between one and seven branches per tree, refined as the design developed into a unified three-branch form whose angles and orientation have a pleasingly organic feel as well as being structurally efficient (Fig 24).

Around the whole atrium perimeter above ground level is a 355mm diameter steel tube, tying together the ends of the roof mesh and supported, above the level 3 roof, by perimeter posts and bearings.

Up to tender stage, the perimeter tube was connected to the adjacent structures at frequent intervals by “flying struts” to counteract the “spread” which occurs at the base of a simply supported arch. But as Arup refined the design it became clear that these flying struts gave too much restraint against thermal expansion. By allowing the atrium roof mesh to “float” above the level 3 roof, it could “breathe” in and out as temperatures changed, and the perimeter posts were given articulated joints to allow horizontal movement in all directions (Fig 25). Only two “flying struts” and two rotational bearings were retained to prevent excessive horizontal movement where the perimeter tube changes direction sharply. Similarly, the tender design included seven bracket supports from the drum columns around which the atrium roof wraps, but during detailed design these were reduced to two by using the arching action of the roof mesh, with elastomeric bearings provided to avoid imposing high forces onto the drum structure (Fig 26).

25. Perimeter post detail.



26. Elastomeric bearing at the drum bracket support.

Atrium roof numbers

Plan size: 116m x 100m

Glazed area: 10 240m^2

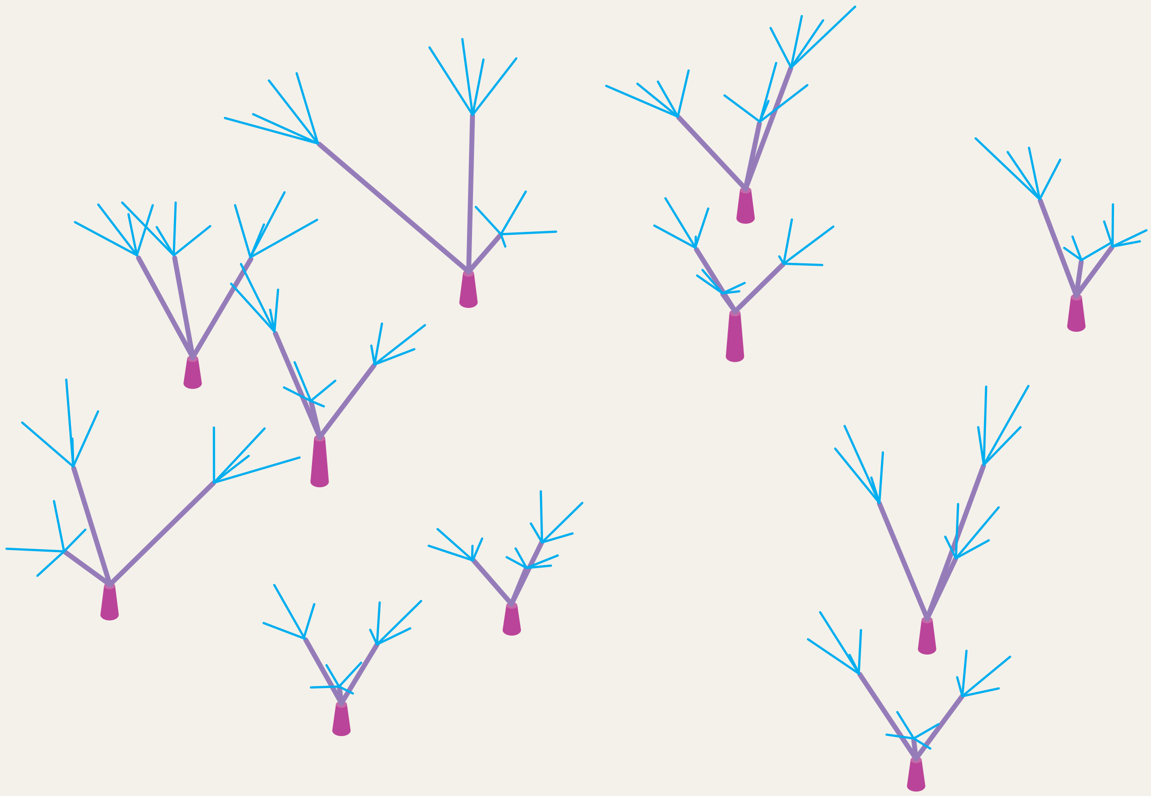
Steel weight: 630 tonnes

Number of steel RHS members: 7123

Number of steel nodes: 2300

Number of glass panels: 4788

24. Each of the 11 trees was unique in the length and orientation of its branches and quad members.



27. The main entrance at ground level, approaching from the station.

At the base of the cascade, the roof mesh lands on the reinforced concrete structure at 16 points, each of which provides vertical support to the roof, and resists horizontal thrusts and wind loads. The base of the cascade includes three large openings for the main entrance doors, but the triangulated form of the roof mesh makes it stiff enough to span across these (Fig 27).

Wind and snow loads

The roof geometry was far beyond anything envisaged by the Polish wind and snow codes, British Standards, and Eurocodes. Dr Jerzy Żurański, of Warsaw's Building Research Institute and one of the authors of the Polish wind and snow codes, undertook research into possible effects. In parallel, Arup commissioned a specialist testing company, RWDI from Canada, to carry out wind tunnel testing (Fig 28), and snow drift (Fig 29) and sliding snow modelling. This proved invaluable for the detailed design.

The wind load results from RWDI were substantially lower than predicted by Polish codes, resulting in significant cost savings, but by contrast some of the predicted snow loads were higher than code predictions.

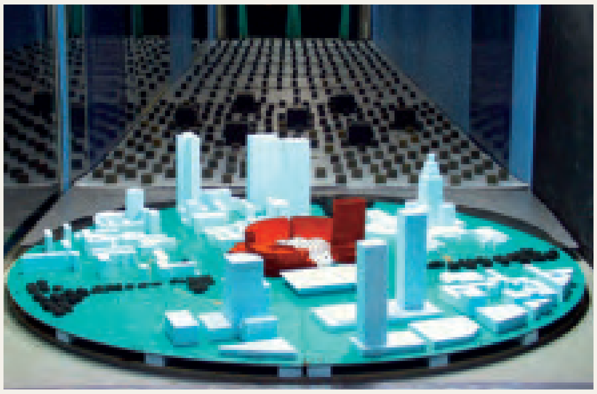
RWDI used three methods to predict snow loads: physical testing, computer modelling, and hand calculations. The physical testing was done with fine sand in a water flume, mimicking the effects of snow drifting under different wind speeds and directions. This qualitative method revealed areas of the structure where snow drifts could occur, and some were surprising, including a series of drifts along the tops of the domes, caused by downdrafts and eddies from the surrounding buildings (Fig 29).

The physical testing was backed up by FAE (finite area element) modelling, based on 50 years of recorded temperature, snowfall and wind speed data from Warsaw. The FAE modelling gave quantitative values for maximum snow loads, which could be combined with the basic uniform snow loads, and drifted snow load patterns.

Due to the uncertainty revealed by the water flume tests in predicting where snow would drift, Arup approached the problem from two directions: the likely locations, and where the most adverse effects on the structure would be. The former included predictable areas such as against adjacent buildings, and on the leeward side of the domes, together with areas highlighted by the water flume study. Locations with particularly adverse structural effects included loads on areas identified by the buckling analysis, and areas that would cause the maximum out-of-balance forces on the trees. In total, nine different drifted snow load patterns were included in the final analysis.

The combination of RWDI's testing and Dr. Żurański's research enabled Arup to establish a conservative set of uniform and drifted snow loadcases, typically with a peak value of 1.75kPa.

Of greater significance to the structure were the predicted loads from sliding snow. For most normal structures, vertical loads from sliding snow are less than those from drifted snow, so are commonly ignored. But due to the roof shape, large quantities of snow could partially melt and slide from the domes into the valleys and thence down to a relatively flat area above the cascade. Meltwater from the domes could collect in the lower areas and refreeze. The combination of these effects gave rise to predicted snow loads up to 10kPa, far in excess



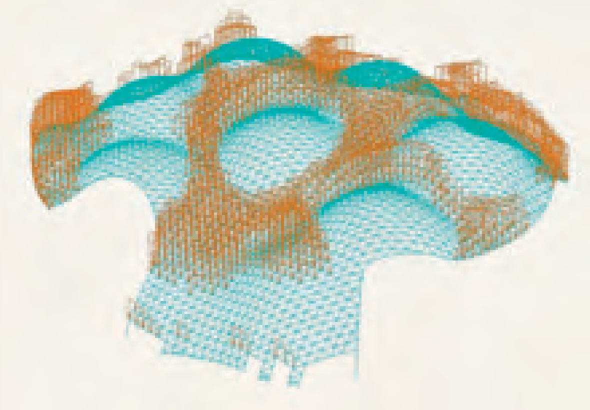
28. Wind tunnel test.

29. Snow drift modelling in water flume.

of what could be taken by the glazing without a very large cost increase. The valley areas of the roof mesh were also the most heavily stressed, and this additional load would overstress some members. Rather than design for these loads, Arup's solution was to avoid them by providing a series of snow fences around the domes and in the valleys to limit snow accumulation to 2.5kPa. A typical sliding snow loadcase included in the structural analysis model is shown in Fig 30.

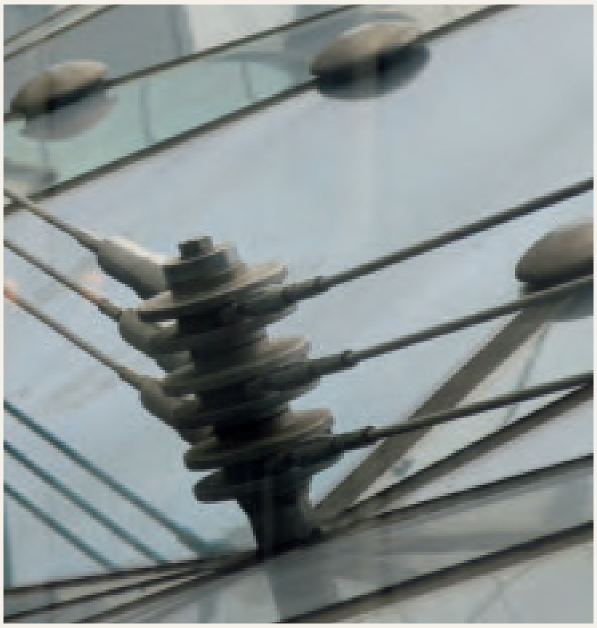
Arup, RWDI, Jerde, and Waagner Biro together designed what ultimately were minimalist fences made from stressed wires (Figs 31, 32) supported by stub posts projecting from the roof nodes. Similar solutions support the *Latchways* safety system for external maintenance, the lightning protection, and the external roof-mounted lighting. The lowest snow fence incorporates a heated tube to gradually melt snow and avoid icicles or slabs of snow falling down the cascade, which could otherwise injure pedestrians below.

32. Snow retained on the roof by the snow fences.



30. Sliding snow loadcase 2 modelled in *GSA*.

31. Snow fence detail.



To allow for hanging loads, every node was provided with a threaded socket designed for a single point load of 500kg, or a simultaneous load of 20kg at every node. This means that the atrium has built-in flexibility for uses such as displays, performances or product launches.

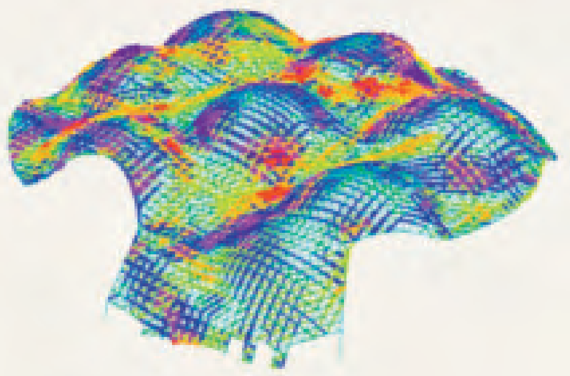
Thermal movements and differential settlements

Since the roof has no movement joints and is over 100m long, with steel members directly below the glazing, thermal movements were always likely to be significant. To establish a likely range of temperatures for the steel, Arup performed some finite element modelling of the RHS members with the aluminium glazing bars and glazing fixed above them. This determined maximum likely temperatures, but also revealed significant difference in temperature between members depending on their angle of incidence to the sun. With it directly overhead, the steel is sheltered by the glazing bars, and at shallow inclinations most sunlight is reflected off the glazing. At moderate angles, though, there could be significant heat gain, so among the thermal loadcases investigated were those with a higher temperature for members running east-west, compared to a more north-south direction.

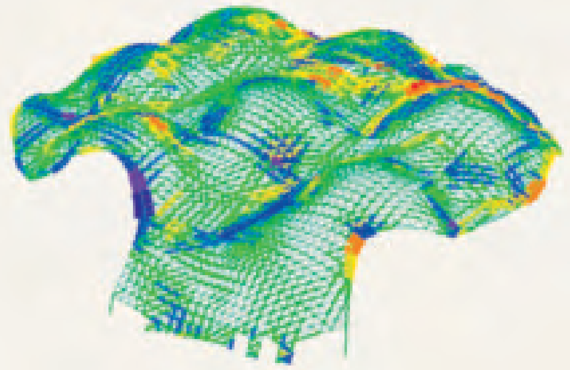
The design of the articulated perimeter posts and bearings that allow the roof perimeter to "breathe", as already described, meant that thermal expansion was not critical for most roof members.

Another major influence on the design was the fact that the atrium structure is supported on six different reinforced concrete structures below, all separated by movement joints. The atrium roof is seamless, so its design had to cater for differential movements of the supporting structures - horizontally due to shrinkage and wind loads, and vertically due to foundation settlements, and beam deflections, including some significant long-term creep deflections.

These vertical deflections were in some cases substantial, as many of the beams were long span or cantilevered, and some post-tensioned. Since the triangulated mesh is relatively stiff in plane, the relative deflections of adjacent supports makes a large difference to the forces in the mesh, even to the extent of causing load reversal. Close liaison between the roof designers and those of the concrete structure was needed to establish maximum and minimum boundaries for likely movements, as well as the relative stiffness of each support point.



33. *GSA* model: typical distribution of axial stresses.



34. *GSA* model: typical distribution of bending moments.

Structural modelling

The roof was modelled using *GSA*. Support conditions were modelled using output from the *ROBOT* model of the reinforced concrete superstructure, ensuring compatibility. Jerde's basic roof mesh geometry was imported from AutoCAD, and manipulated using additional software to orientate every RHS member perpendicular to the bisector of the angle of the two glass panels it supports. Some Visual Basic routines were also developed to map the wind loads from the wind tunnel test directly from each pressure tap location onto every structural member.

As the design developed and the wind tunnel, snow modelling, and thermal modelling results became available, the number of loadcases and load combinations grew to include 14 wind loadcases, 12 snow loadcases, five thermal loadcases, and 98 differential settlement loadcases, including individual loadcases with each support settling more or less than the adjacent ones. Altogether there were 1700 different load combinations for the ultimate limit state.

The numbers of members and of loadcases made this one of Arup's largest *GSA* model analyses, stretching computing power to the limit. Typical results of the static analysis are shown in Fig 33 (axial loads) Fig 34 (bending moments), and Fig 22 (deflections).

To provide greater confidence in the results, Arup insisted that the atrium roof contractor carry out a completely independent analysis, using different software. The results were compared, and by the end of the final design, agreed to within 5%. Increased safety factors were also used, in view of the complexity of fabrication and erection, and the possibility of eccentricities and stresses being introduced due to lack of fit.

Second-order and buckling effects

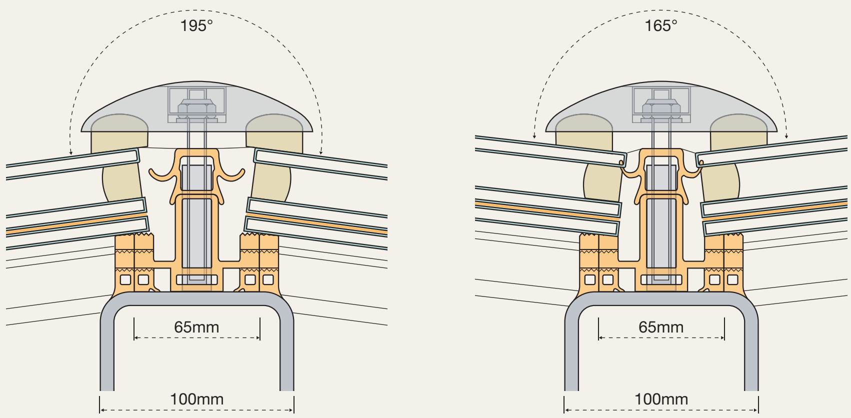
In addition to the static analysis, second order buckling effects were also investigated. Simple linear static analysis is based on the assumption that straight members are perfectly straight, but in practice any member may have fabrication imperfections. When compressive forces are applied, these imperfections cause additional bending moments, known as P-Delta effects, to arise (the bending moment is equal to the axial load "P" multiplied by the deflection "Delta"). Bending moments are also magnified as a result of buckling. These additional stresses in members are collectively known as "second-order effects".

The design rules in structural codes ensure that standard components like columns and the compression flanges of beams have sufficient stiffness to prevent buckling, and are strong enough to resist not only the applied forces but also any secondary forces that arise because of their flexibility. However, these rules do not cover structures as complex as the atrium roof, which have to be designed from first principles in a similar way to the development of the code methods. Fundamental to any procedure is determination of the buckling mode shapes, buckling loads, and their associated deformations. Simple estimates of these properties are very difficult and any approximation is necessarily very conservative, leading to a much heavier roof design.

The procedure to check the second order and buckling effects of the atrium roof was developed in Arup several years ago, but its use was complicated by the size of the necessary *GSA* model compared with the computing power available. Buckling and second order analyses are more complex and take much longer than standard linear static analyses, and over an hour was needed on the highest specification PC then available (1GB RAM) to run an analysis that gave the lowest 25 buckling modes. Analysis time increases exponentially with the number of modes required, so when 50 modes were later determined on the same computer, the analysis took over 12 hours.

The buckling analyses for the atrium roof produced a series of buckling mode shapes, with a critical load factor for each mode. Because most of the roof is highly curved in two directions, no overall buckling modes affected the whole roof. The significant buckling modes only affected local areas of it – generally an out-of-plane "dimple" comprising an area which is relatively flat, or of long span, or highly loaded. For each mode shape, the dimple diameter was measured, together with

35. Glazing system with glazing buttons, showing the range of angles of inclination of glazing.




36. Glazing gasket installation.

the amplitude of deflection. From the analysis results and subsequent calculations, the additional bending moments due to the second order effects were estimated for each "dimple" with a critical load factor less than 10. For most areas of the roof, these were less than 5% but in the worst cases, the moments were increased by 25%. The lowest mode had a critical load factor of 4.9 for the combination of dead, live and full snow loads. The deformed shape comprised an out-of-plane dimple with a diameter of about 8.8m.

Another form of instability called snap-through buckling - as when an umbrella blows inside out - was also investigated by comparing the small changes in curvature of the roof from the P-Delta analyses with the initial curvature. It was found that snap-through buckling cannot occur under normal loads, because the roof is sufficiently curved to prevent it.

Procurement route and programme

Such an adventurous architectural concept was a high-risk item, requiring an extended design period with early input from specialist contractors. The roof fabrication and erection was on the critical path, so a two-stage tender procedure was developed by Arup and the project manager, Mace. This enabled the design team to harness specialist contractor expertise in advance of the main contractor appointment to Skanska, and allow sufficient time for detailed design, fabrication, and erection. Input from steelwork contractors and glazing suppliers to inform the design before tender gave greater confidence in the roof's feasibility and practicability, and ensured that the tender documentation allowed sufficient scope for the tenderers to incorporate their own designs.

Arup developed the atrium roof design up to tender, and submitted the design for building permit in November 2001. The design was then refined as wind and snow test results became available. The atrium roof first stage contract was awarded to Waagner Biro in July 2002, and six months' design development followed. During this stage, responsibility and "ownership" of the design remained with Arup, as did control of geometry. By the end of the first stage tender, Waagner Biro had completed an independent analysis. This was verified by Arup, who then handed over responsibility to Waagner Biro to complete the design and detailed calculations for the node connections.

Waagner Biro's specialist expertise proved invaluable, in particular its experience of the detailed design and construction of the glass roof for the British Museum Great Court in London, which has some parallels with the atrium roof, though with much simpler geometry. Arup and Waagner Biro's combined experience and expertise reassured the client that such an innovative and unusual design could be confidently designed and built on time and within budget.

Final structural design and glazing system

In parallel with the structural design, Waagner Biro developed a unique four-part silicone gasket system to support the glass panes and accommodate the wide variety of glass angles, while also providing a second line of drainage (Fig 35).

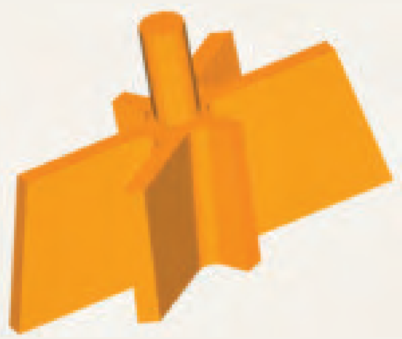
The glass design was informed by the structural loads, and by the tough performance requirements determined from Arup's CFD analysis together with the requirements of the specialist lighting designer. The sealed double-glazed panels have an outer layer of 8mm toughened glass with a "low E" coating, a gap of 16mm, and an inner layer of 16mm laminated glass (2 x 8mm). The total glazed area is 10 240m^2 with a combined weight of 555 tonnes, and 17.5km of silicone gaskets (Fig 36).

The original design was based on using structural silicone to retain the glazing, but this proved unacceptable to the Polish building authorities, so a "button" fixing was developed, with two stainless steel buttons on each side of each glazing panel to restrain the glazing (Figs 35, 37).

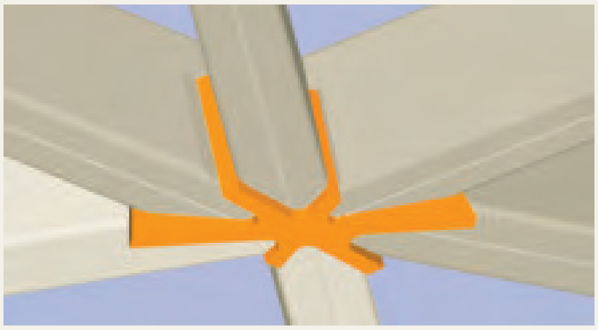
Following handover of final design responsibility, Waagner Biro made two small but crucial changes to the geometry. The first related to the glazing and gaskets. The original geometry had the centrelines of the six RHS members at each node intersecting at the same point, but due to differences of angle and twist between each member, this resulted in unacceptable steps in the level of the tops of the RHS members - and highly complex and expensive glazing gaskets. The geometry was subtly shifted so that at each node, the six planes of the underside of the glazing panels coincided at a single point.

This simplified the gasket details, but added another layer of complication to the steel nodes. With the centrelines of the top flanges almost intersecting, any twist in the axis of the member is magnified in the offset of the bottom flange. In addition, since the centrelines of the six members no longer intersect, extra bending moments are induced in the RHS members, the eccentricities increasing local stresses in the steel.

37. Glazing buttons.



38. Node visualization.



39. Visualization of node in position.

The other change in geometry was due to the construction process. The roof mesh was designed to be erected on scaffolding with frequent props to hold each node in the correct position. But after depropping, the roof would deflect under the steel and glazing self-weight. Waagner Biro therefore calculated a new “zero geometry”. The level of each node was raised by a value equal to the predicted deflection, so that after depropping, the roof would achieve the original geometry.

The shape and design of the steel node connections were unprecedentedly complex. Many areas of the roof are like a saddle, convex in one direction and concave in the other. Achieving a smooth flow in these areas required a high degree of twisting of one RHS member relative to its neighbours. This effect was magnified by the eccentric offsets described above, so that each node became a complex three-dimensional form. (Figs 38, 39). To verify this innovative node design, Arup specified the destructive test of a sample node in September 2003 (see opposite page).

Waagner Biro’s engineers developed an automated design process, whereby the geometry of every node and member could be automatically generated from the “zero geometry”. Each was designed and checked for stresses from the combination of self-weight, snow loads, wind loads, thermal loads, and differential settlements.

Construction

The 630 tonnes of steel for the atrium roof were fabricated in Katowice, Poland. Having completed the final design, the geometry of every member and node was automatically passed to the fabrication workshop. To hand-cut the ends of each RHS member and node would have been prohibitively expensive, time-consuming, and probably inaccurate. Fabrication was only possible by automating the cutting process, including developing new equipment to do so. The unique pattern of each end of every member, node, and glass panel was fed from the computer model to the cutting robots and to the glass production factory.

To maximize off-site fabrication, the roof was subdivided into 129 “ladder frames”, each the maximum size that could be transported to the city-centre site by low-loader. The tree columns were erected with temporary props and internal bracing between the branches, and surrounded by scaffolding. The ladder frames were then lifted onto adjustable props, connected to the trees, and set to the precise level and location of the “zero geometry”. Once several ladders had been erected, the gaps between them were filled with individual “loose” RHS members, site-welded in place (Fig 40). Erection of the roof steelwork took seven months, from May to December 2004.

Glazing installation started once a sufficient area of steelwork had been fully welded and painted (Figs 36, 41). On completion of a significant area of glazing, the steelwork was sequentially depropped in small increments, then the scaffolding removed to allow following trades to start below.

40. Erection of ladder frames.

41. Glazing sealant installation.

The team recognized this early on and to counter it, emphasized adherence to the use of approved welding procedures, the use of approved welders (important for all welding, but essential for site welders as the skill requirements are greater), and supervision. One problem was that the specification for welding procedures is based on standard test pieces that do not reflect the difficulty of many connection types.

Initial teething problems were due to the lack of fit-up in assembly, before welding. Mostly this was evident during prewelding visual inspection - essential if the connection prevented the use of ultrasonics for final inspection. Typical defects included porosity, lack of penetration, lack of fusion, or cracking. Other problems arose from the incorrect use of welding consumables, and failure to preheat prior to welding. Similar problems were encountered on site, exacerbated by the additional problems of overhead welding. Nonetheless, Waagner Biro and its subcontractor overcame the difficulties and achieved the required standards of structural integrity and aesthetic consistency.

Node mock-up and testing, and weld testing

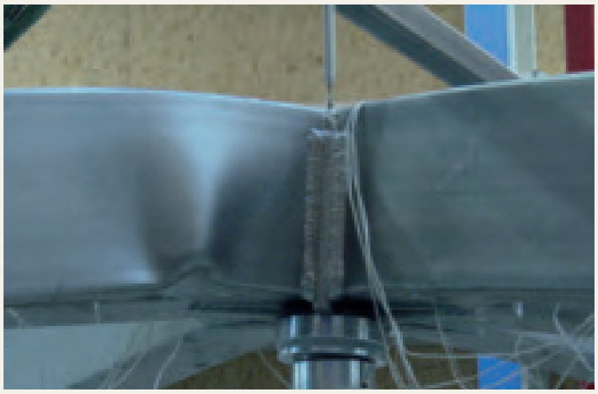
As part of the node design development, Waagner Biro made several mock-ups (Fig 43). The nodes are prominent in the finished building, so the mock-ups allowed their appearance to be approved by the architect, and any fabrication difficulties to be resolved before production started. In addition, Arup specified a destructive test to verify the design, which was far beyond the scope of normal codes and standards. This was done in September 2003 at the Technical University of Graz in Austria in the presence of Arup and Waagner Biro engineers. The mock-up comprised six RHS members welded to a node, with their far ends supported and restrained from moving while an upwards force was applied to the node by a hydraulic press. Strain gauge rosettes were attached to the top of the elements at 20 points, with strain gauges on the top and bottom side of sections close to the node and deformation readings at the joint and member ends (Fig 42).

As predicted, collapse was not through failure of the node or any of the welds, but by plastic deformation of the walls of the weakest RHS member (Fig 42). The force required was within 6% of calculation. The test not only helped verify the design, but also provided reassurance that the node connection was stronger than the members to which it was connected, ensuring considerable built-in robustness in the atrium roof. In the unlikely event of local damage to any roof member or tree, disproportionate collapse would be prevented by the stiffness of the geometry, and the strength of the nodes.

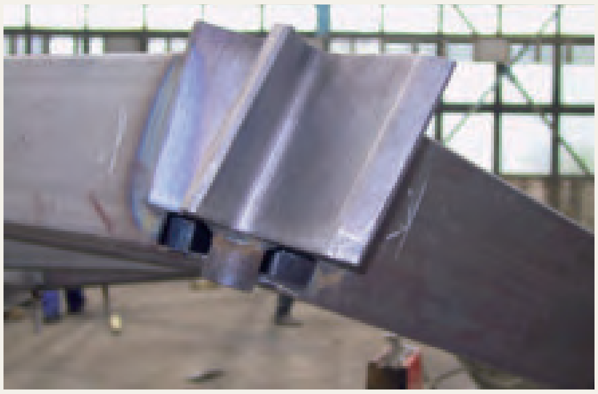
The mock-ups and testing also enabled Waagner Biro to understand the complexities and practicalities of the welding operations to come. The welding details at the nodes were of particular concern due to the differing geometries involved, making the use of precision jigs of great importance to ensure that dimensional stability and fit-up was achieved. The small number of higher strength grade S460 members required more onerous welding procedures than usual (including greater preheating) and more rigorous inspection - visual, dye penetrant, magnetic particle, and ultrasonic where possible.

The fabrication, complicated enough on the drawings, was yet more challenging in reality. Many of the connections had physical limitations, making access for welding difficult and inspection either limited or ineffective.

42. Destructive node test.



43. Partial node mock-up.



44. Looking up inside the drum from level B2.

The drum

The drum is a free-standing cylindrical tower enclosing a bank of escalators that rise from the car parking and sunken plaza at the B2 basement level right up to the food court and cinema entrance at level 3. The escalators pass up a four-storey high void in the centre of the drum (Fig 44), surrounded by a doughnut ring of floor slab at each level. This provides a major hub for pedestrian circulation right by the main entrance from the station.

The drum is framed in reinforced concrete below level 3, and tubular steelwork above. Due to the complex and sinuous interface between drum and atrium roof (Fig 45), the drum steelwork and glazing were included in the atrium roof sub-contract. The scheme design had connected the atrium roof to the drum, so that the latter could provide stability, but thermal expansion of the roof was found to induce unacceptable stresses in the drum steelwork, so the two structures were separated by a movement joint. The geometry of the atrium roof is such that at level 3, on one side of the drum people can walk through to the food court, below the atrium roof, while only a short distance away, they can see out through the drum to the roof exterior (Fig 46). This “inside-outside” feeling is repeated at other areas around level 3 where from inside the atrium, you can see through one part of the roof to view the outside of another part.

To avoid any diagonal bracing members, the drum steelwork was designed as a vierendeel frame, with fully welded connections between the columns and ring beams. The structure for the circular lid of the drum was inspired by a bicycle wheel, with radiating spokes all connecting to a central hub (Fig 44).

Building physics

The building services were designed by Tebodin in the Netherlands, but informed by building physics studies undertaken by Arup specialists in London. One major area of focus was comfort and condensation within the atrium. The atrium design studies had the following major objectives:

- environmentally, to control comfort temperatures within acceptable limits, minimize solar gain in summer, and minimize condensation risk in winter
- daylighting, to limit average light transmissions, with targets set for different regions
- architecturally, to maximize façade transparency with no fixed shading, and with low reflectance to the surrounding buildings.

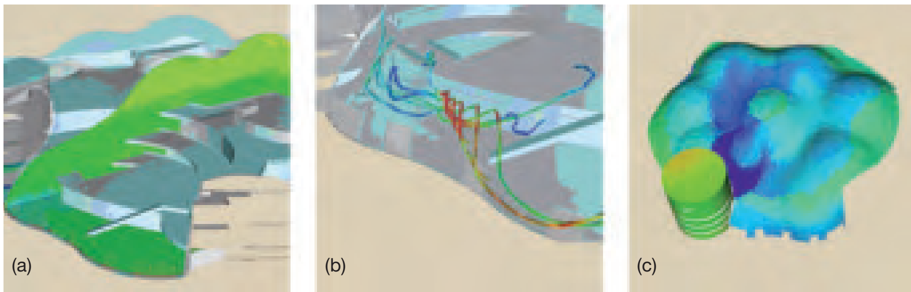
To some extent these conflicted, for example the requirement to maximize transparency while minimizing solar gains. The environmental analysis study carried out by Arup’s fluids team included dynamic thermal modelling and CFD (computational fluid dynamics) (Fig 47).

Comfort study

For summer conditions, the interaction between the space and external environment had to be understood, particularly the influence of solar gain, which proved to be the most important factor. The study was then used to optimize space conditions by guiding the choice of glass and the location of the radiant floors.
For winter conditions, understanding of likely comfort conditions together with the potential for downdraughts was the aim. Interactions between the perimeter heating, radiant floors, and mechanical air supply systems were investigated.
The comfort study became a primary driver for the design development of the atrium space, ultimately providing confidence that internal conditions within the occupied areas were likely to be acceptable with a high-performing façade and large areas of radiant floors. By controlling solar gains, the mechanical air system was then able to maintain air temperatures to within acceptable limits.

45. Interface between the drum and the atrium cascade.

46. View from inside the drum at level 3.



47. CFD models: (a) air temperature distribution; (b) air movement; (c) difference between the dew point and surface temperatures.

Condensation study

For condensation to form, the temperature of a surface must be lower than the dewpoint of the air in the space. This often occurs on clear, cold nights with maximum radiation losses from the surface. For the atrium roof, however, the highest condensation risk is when external air temperatures are quite moderate but there is high internal humidity - a combination of high internal moisture gains and very moist air entering. This is partly due to the glazing's high thermal performance and the fact that the space dewpoint temperature is mostly dominated by the moisture content of the supply air and air transferred from the retail units. The mass of moisture gains from people in the atrium is only a small proportion of the total in the space. Taking these factors into account, the "worst case" or design scenario combined a design time of 5pm on a September day, the atrium roof fully "wetted" on a very rainy day, and 50% of the people having wet raincoats.

An innovative three-part study was carried out, comprising:

- a dynamic thermal model for the whole year on an hourly basis, to determine the design time and provide the CFD model with surface temperatures
- a CFD analysis for the design time, to assess the air temperature and moisture distributions
- a thermal bridge model at the design time, taking boundary conditions from the CFD analysis to assess the risk of condensation at the fixing bolt connection detail of the roof glazing. The CFD analysis provided realistic design moisture content levels close to the glazing for this analysis.

Assessment of condensation risk was thus possible, based on actual moisture sources, its transport, spatial, and detailed structural considerations, and the conclusion was that condensation was very unlikely.

Acoustics, noise, and vibration

The initial acoustic concern was the railway station's proximity to the multi-screen cinema and the possibility of low frequency groundborne train noises being heard during screenings. Extensive vibration measurements on the cinema site and subsequent predictions of residual noise in the auditoria indicated no need for special vibration isolation measures, despite the cinema operators' stringent background noise requirements. Rigorous standards were also set for sound transfer from cinema to cinema, down to the lowest audible frequencies (31.5Hz octave). Sound insulating constructions were recommended, based on Arup's considerable experience of cinema design. Once construction was complete, the final commissioning tests, witnessed by Polish acousticians, showed performance to be satisfactory.

The atrium area also presented an acoustic challenge. As glass is highly acoustically reflective, such a large public space covered by a glass canopy could prove excessively noisy. Initially, Arup recommended incorporating acoustic absorption into the glazing framing, where it would have been highly effective, but this proved too difficult in practice. Instead, the absorption was located in the walkway soffits in the main circulation areas, where it controls noise locally as well as throughout the whole space.

Transport planning and pedestrian modelling

Arup's initial commission was for a transport assessment to support the principle of a mixed-use development here. A local sub-consultant, BPRW, was engaged to run a traffic model that it had developed for the central Warsaw area. This enabled Arup to formulate the access principles and advise on major improvements, including a completely new bus station integrated with the site and the railway station. The design for the new bus station was formulated, including altering the main access area and providing space for taxis and general traffic to circulate, drop off, or pick up.

Working closely with the architect, Arup advised on several additional aspects including car parking, service yard planning, signage, access issues, pedestrian planning, and detailed design and contract documents related to the car park.

Key output from the traffic assessments included advice on the quantity of car parking required. This was based on local and European experience of similar developments, most notably in Budapest, Hungary. Spreadsheet models were derived to produce daily parking demand profiles for 1600 car spaces, and potential conflict periods between the various land uses were identified.

48. Basement level B4 car park, showing the drop heads to the columns.

49. The new bus station.

Technical details determined by Arup included car park dynamics, layout efficiency, layout allocation, ramp locations, and internal flow search patterns. Arup also provided technical advice on car park equipment, eg barrier quantity and layout, payment machine quantity and location, and white line measures with pedestrian corridors. The scope of work expanded to designing a car park colour code that integrated into the architect's vertical design elements (Fig 48). The team then provided car park contract documents that included equipment schedules, white line requirements and VMS (variable message signs) proposals. Detailed signage proposals were produced for each level of car parking both for vehicles and for pedestrians accessing the lifts to the various areas above.

In addition, Arup advised the architect on internal pedestrian movement requirements between the levels and within each level. Daily footfalls were determined and converted into hourly profiles for each level. Based on experience elsewhere, shared trips for various level uses were established. A pedestrian flow model was built using *Saturn* software and spreadsheets, and applied to *FRUIN* pedestrian planning software to determine the levels of service at key locations throughout the building. This enabled Arup to advise on entry widths for doorways, escalator numbers, corridor widths, and staircase requirements.

Detailed highway designs were provided for the adjoining network, which also integrated with proposals for nearby land usage. Integrating Arup's proposals with the bus station and railway station was very challenging, as the area available for the bus station was very limited (Fig 49). Much consultation was required with the local highway authority, ZDM, other developers in the area, and local bus operators.

Façade engineering and stone selection

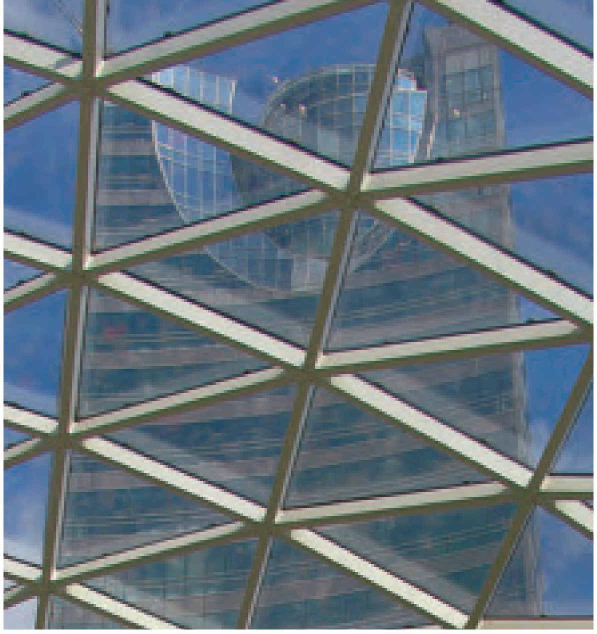
Working closely with the architect to enable the concept design to be realized into a readily procurable building envelope, Arup's façade team used its knowledge of manufacturing techniques and procurement options to fine-tune the geometry to allow repeatability of panel size on the curtain walls for the three office buildings, and for the "icon" feature at the top of the "Skylight" tower (Fig 11). For the cinema foyer's "popcorn windows" (Fig 50), the team helped the architects to rework a complex design with tricky interfaces into a robust and readily installable system that was aesthetically acceptable, controls staining from water run-off, and allows easy glass replacement.

Arup's extensive knowledge of materials and building envelope physics also helped with the optimum specification of envelope materials. The resulting documentation reduced the normal tender stage risks, due to the clarity of design intent, performance requirements, and co-ordination with structural and mechanical systems.

In 2002 Arup stonework specialists became involved in pre-tender design discussions with the architect, who visualized three different types of coloured stone as part of the external cladding. Notably important were technical assessment of the materials, the guidance on sensible panel sizing and thickness, the methods of fixing the stone to the structure, and various detailing issues such as water run-off and staining, as sandstones are relatively porous and susceptible to deterioration through frost damage or visual degradation from biological growth. The stonework package went out to tender on the basis of using three sandstones and a granite.

In 2004, the curtain walling sub-contractor asked Arup to help assess and select the stone, as it had limited experience in projects with stone cladding. The team visited eight quarries - three in south-west Poland for yellow sandstone, two in the Beskid Śląski region in south Poland for green sandstone, and three in the Mainz region, south-west of Frankfurt, for red sandstone – and assessed them for extraction methods, achievable panel sizes,

50. "Popcorn windows" on the cinema foyer façade.



51. The “Skylight” tower through the atrium roof.

52. The five construction zones.

stone availability, and production quality and output at their works. All this helped the subcontractor agree a realistic visual range for each stone with the supplier and architect.

Construction

Enabling works

The first major task was to relocate the bus station onto the front platform deck of the railway station. The enabling works included strengthening the station structure, new roads and bus platforms, and two rows of cantilevered glazed canopies (Fig 49). Also needed were relocation of two enormous air exhaust ducts from the station, numerous service diversions, and demolition of several old viaducts and other structures within the site boundary. All this allowed the whole site to be handed over to the main contractor at the end of 2002.

Construction sequence

This was carefully developed by Skanska to minimize the overall programme. The lines of the previously-described movement joints in the basement and retail levels delineated five zones (Fig 52). Skanska chose to start in zone 3 (under the cinema) and zone 5, then zone 4 (under the “Skylight” tower), then zone 1, and finally zone 2. When concrete construction had reached level 3 in zones 3 and 5, and the atrium roof erection had started, the concrete slab at level 0 was still not complete in zone 2. The structural concrete works were practically completed in May 2005, while the cinema steelwork, above level 3, had not yet begun, due to revised permit issues. Cinema steelwork erection began in August 2005 and was completed in May 2006.

Construction methods

At the peak of construction the programme necessitated over 1000 workers on site. Skanska used up to seven tower cranes, including one on tracks at level 0, with temporary props down to the foundations. Apart from the atrium roof construction described earlier, several other unconventional construction methods were used, including temperature control of large concrete pours, the use of special formwork, and the partially post-tensioned beams referred to above.

Temperature control was crucial for the raft foundation, and for the transfer slab at level 3. Due to the scale, areas of the raft were cast in different seasons – some in winter, some summer. The raft concrete was poured in bays up to 650m^2, using a special low-energy mix with furnace-ash cement replacement, and the concrete was wrapped in thick thermal insulation until it had cooled. The temperature was closely monitored in each pour to ensure that the maximum temperature gradients were not exceeded; despite the summer heat, no internal cooling was required.

Arup’s careful reinforcement detailing for the sloping car park surfaces, together with a thorough curing system, resulted in crack-free concrete for the car parking areas. For the level 3 transfer slab, due to a shorter overall casting time and the longitudinal shape, gaps were left in the slabs to allow for short-term shrinkage.

Special formwork was needed for several unusual elements such as the banana columns. An automatic self-climbing formwork system was used for the core of the “Skylight” tower, and a semi-automatic one for the “Lumen” office block cores.

International working

A key feature was the close co-operation of the design team, despite being spread over 20 different offices. The project could not have been accomplished without the internet, which enabled designers in six countries to work closely together; Arup's designers in Birmingham and London were linked to Jerde in Los Angeles, Epstein in Chicago, Tebodin in Holland, RWDI in Canada, and Waagner Biro in Austria, as well as the Warsaw offices of all the consultants, the client ING, and all the contractors. From the outset, Arup had a resident project manager and two assistants in the site office. During the first 28 months of the contract, Arup issued over 5400 structural and reinforcement drawings and 360 sketches - an average of nine drawings a day. The Arup team was closely involved at every stage of construction, reviewing over 1000 submittals from Skanska, to ensure compliance with the specification.

From 1998, when the first workshop was held in Jerde’s offices in Los Angeles, frequent design workshops, often lasting several days, brought together all of the design team. These were key to establishing a collaborative partnership approach, and a vital source of inspiration, creativity, problem-solving, and trouble-shooting, enabling complex issues to be addressed and resolved as rapidly as possible. They also proved a vital way to communicate the design with ING. Particularly with complex elements such as the atrium roof and the transfer structures, these workshops allowed Arup to explain the design issues and reassure ING as to the feasibility of design and construction.

Arup exemplified the design-sharing approach for the atrium design, by making available free software to the whole team. The *GSA* viewer enabled the team and the specialist contractor to view the same set of data, including the geometry and all the loading data as well as the results of the analysis. This proved invaluable in the design workshops as well as in detailed design.

Mace, the project manager, was also instrumental in arranging the early involvement of contractors and suppliers to inform the design at key stages before tendering. This was particularly important for the atrium roof, where input from glass suppliers and specialist steel fabricators had a major influence in shaping the design to achieve the most cost-effective solution.

Another reason for the project's success was electronic data transfer, as the complex geometry would have made manual transmission of data a potential source of errors. Mutually compatible software allowed the same set of co-ordinates for the atrium roof to be shared among all the designers. The geometry was originally generated by Jerde in Los Angeles, taken by Arup in Birmingham and developed into a workable structural model, and then transferred to Waagner Biro in Austria, adjusted for fabrication, and fed directly to the workshops in Poland.

See&Share software enabled Arup staff in any office to share their computer screens with each other, or with those outside the firm. Any party can mark comments on the screen in real time with a mouse. This was particularly useful for the atrium design. Trying to describe a 3-D object with 2-D drawings and sketches is extremely difficult, but *See&Share* allows a phone conversation with simultaneous on-screen showing of what is being discussed.

53. Atrium escalator, with "Lumen" office block beyond.

Completion and opening

In summer 2005, as the atrium roof was nearing completion, a film was made about the project by the Discovery Channel. When interviewed about the atrium roof, Eugene Houx, then the project developer and a former board member at ING Real Estate, said: "If I look back at those long days when we were discussing the atrium roof with the people involved, from Arup, Jerde Partnership, and later with Waagner Biro, then those moments now seem to me very special. Because at that moment we were working very hard, and we didn't know if it would come true. But we also realized that it was going to be a very special roof. It had the full engagement, the enthusiasm, the intuition, and the ingenuity of a lot of people - especially the engineers, the architects, and many others. At this particular moment, we can start to see what it looks like. It's becoming reality. It's not a strange idea any more on the drawing board, and we are very happy with the way it looks, and what it is doing for this project. We think the roof has fulfilled several functions. It has become an icon for this part of the city. It might become an icon for Warsaw, a symbol for the new Warsaw, that is renewing, innovative, avant-garde, and looking into the future".

Złote Tarasy opened on 7 February 2007, with 100% occupancy of all retail units, over 200 000 visitors on the opening weekend, and almost 8M in its first six months. The project's success was summed up by Marcel Kooij, Deputy Director of ING Real Estate and President of Złote Tarasy's Management Board:

"ING Real Estate aimed to create the hallmark of the city of Warsaw, a new "living room" and a meeting point for the inhabitants, and thus breathe new life into the capital's city centre. After over half a year since opening, I can proudly say that Złote Tarasy came up to all these expectations. The success of this exceptional retail and leisure scheme should be attributed to several factors, related to its offer, functions, architecture and unique atmosphere. But also the role of Złote Tarasy in terms of improving the infrastructure, influencing the local job market, and stimulating the development of the city's central district must not be forgotten.

"Over 200 renowned Polish and international brands opened their flagship stores in Złote Tarasy, newcomers to the Polish market like Next, MAC and The Body Shop decided to start their expansion in Poland from our project, and over 30 restaurants, cafes and music clubs such as Hard Rock Cafe or Jazz Club Akwarium have opened here. All these examples show that Złote Tarasy is important for both Polish customers and international businesses.

"Every attention was put to the urban planning and architecture. The undulating 1ha glass roof, illuminating the interiors 365 days a year, has already become a Warsaw hallmark. The design team and contractors did a marvellous job in creating this hallmark.

"Złote Tarasy is an important investment for the city of Warsaw. It has revitalized the 3ha area dominated by road traffic and parking next to the Central railway station, created over 2000 new jobs, and has been supporting charities and local organizations. Złote Tarasy is meant to be "the stone in the pond" that triggers other developments in the neighbourhood and helps to create a modern city centre next to the central business district.

"The mixed-use project is also an integral part of Warsaw's CBD. Highest quality office space is provided by two office buildings rising above the shopping centre - Lumen and Skylight. The Lumen tower gracefully frames Złote Tarasy in the north, while creating a new icon for Warsaw. As the arc of the tower rises, it widens to open the interior of the workspaces up to natural light. Skylight is the distinctive element of the CBD skyline. It fits perfectly into the sequence of hotel and office blocks along ul Emilii Plater and is visible from all the main roads leading to the centre. At the same time its architectural details, such as the icon on the side façade and elegant curves, make it one of the most original buildings in the capital.

"Złote Tarasy is a unique combination of retail, leisure and offices. The centre's popularity among clients and the interest of the tenants proves that we have achieved our goal."

54. The cascade.

Credits

Client: ING Real Estate **Concept architect:** The Jerde Partnership **Executive architect:** A Epstein & Sons International **Project manager:** Mace **Cost consultant:** Gardiner & Theobald **Structural, transport planning, pedestrian modelling, building physics, acoustics and façade engineer, and stonework consultant:** Arup - Darren Anderson, Keith Beckett, Rabinder Singh Bhachu, Christine Blanch, James Bodicoat, Nick Boulter, James Boyes, Tom Brooks, Chris Bruce, Michelle Butler, Duncan Campbell, James Casson, Chris Chan, Wayne Charles, Gurpreet Chawla, Stuart Clarke, Matt Collin, Adrian Collings, Keith Crothers, Zbigniew Czajewski, Piotr Czapko, Marek Dabrowski, Iain Dick, Rafał Duszczyk, Ian Feltham, Damian Friel, Hanna Gadzalska-Syfert, Paul Geeson, Yvonne Griffin, Jagienka Harrison, Christina Jackson, Richard Jackson, Piotr Jez, Tony Jones, Marcin Karczmarczyk, Marcin Kasprzak, Olga Kasprzak, Richard Kent, David Killion, Andrzej Kocmierowski, Zbigniew Kotynia, Radosław Krzeminski, Andrew Lambert, Isabelle Lavedrine, Maciej Lewonowski, Robert Lindsay, Monika Malczewska, Bartek Małetka, Piotr Marszałek, Pieter Mattelaer, Andrew McCulloch, Martin McGrellis, Edyta Miazga, Andrew Minson, Philip Monypenny, John Moss, Edith Mueller, Chris Murgatroyd, Paweł Norek, Andew Norrie, Johnny Ojeil, Paweł Opolski, Raf Orlowski, Chris Parsons, Barbara Pawełek, Ewa Pawlak, Shokrollah Pilwar, Krzysztof Pogłód, David Preece, Barbara Próchniewicz-Pudełko, Piotr Rebajn, Jag Riat, Tomasz Rybus, Neil Scott, Jeff Shaw, Roy Shields, Peter Simmonds, Tristan Simmonds, Annalisa Simonella, Brian Simpson, Andrzej Sitko, Simon Small, Lee Smith, Artur Soluch, Joanna Swiderska, Sebastian Szafarczyk, Sławomir Szumierz, Rob Talby, Ian Thompson, Tim Thornton, Andy Thorpe, Richard Thurlow, Jon Toy, Wiesława Trochymiak, Alan Turner, Martin Vanicek, Jared Waugh, Mel West, Paweł Wewiór, Hilary Williams, Darren Woolf **Sub-consultants:** ProjArt (structural) Billings Design Associates (façades) BPRW (transport planning) Prof Wojciech Wolski/Geoteco (Polish code and technical review/advice: geotechnics) Dr Jerzy Żurański (Polish code and technical review/advice: wind and snow issues) **Site supervision:** SAP-PROJEKT **Main contractor:** Skanska **Atrium roof contractor:** Waagner Biro Stahlbau AG with Zenkner & Handel (atrium design) and Zeman HDF (atrium fabricator) **Sub-contractors:** Exbud (northern half concrete; cinema and “copper houses” structural steelwork) Hydrobudowa 6 (southern half concrete) Freyssinet (northern half post-tensioning) BBR (southern half post-tensioning) Salgeo (piling) Soletanche (diaphragm walling) Permasteelisa (office blocks and cinema façades) Axima (M&E installation) Scheldebouw (curtain walling) **Illustrations:** 1-2, 15, 18, 38-39, 54 Waagner Biro; 3, 5, 14, 24, 52 Arup/Nigel Whale; 4, 6-7, 10, 36, 41 ING Real Estate; 8, 11, 20-22, 25-26, 30, 33-34, 40, 47, 50 Arup; 9, 16, 27, 44-46, 51, 53 inblanco.pl; 13, 19, 23, 31-32, 37; Richard Kent; 12 Tomasz Szymanski/ iStockphotos.com; 17 Jerde Partnership; 28-29 RWDI; 35 Waagner Biro/Nigel Whale; 42-43 Marcin Karczmarczyk; 48-49 Radosław Krzeminski.

Awards

MAPIC Plaza Retail Future Project Awards 2005: Best of Show, and Best Large Retail Development Scheme

Institution of Structural Engineers (IStructE) Midland Counties Branch: Structural Commercial Project 2005 Award for the atrium roof

Architectural Review MIPIM Future Project Award 2006, Retail and Leisure category

European Convention for Constructional Steelwork 2007 European Steel Design Award

IStructE Structural Awards 2007: nominated for Commercial or Retail Structures

MAPIC Awards 2007: Best New Shopping Centre.

Darren Anderson is a senior geologist with Arup’s Façades London Group. He provided specialist input for the building façades, particularly on the stone selection.

Zbigniew Czajewski was formerly a structural engineer in the Warsaw office. He was involved throughout the project, as a structural engineer, then as the design and construction co-ordinator, and finally as Arup Project Manager for the final phase.

Stuart Clarke is an Associate of Arup and now leads the Façades Group in Dubai. He was responsible for the façade engineering.

Ian Feltham is an Associate Director of Arup with the Advanced Technology & Research Group in London. He provided specialist technical input on second-order effects for the structural design of the atrium roof.

Paul Geeson is a Director of Arup and leads the Warsaw office. He was the Project Director throughout.

Marcin Karczmarczyk is a senior engineer with Arup in the Building London Advanced Geometry Unit. Formerly in the Warsaw office, he was responsible for the detailed analysis and design of the atrium roof.

Richard Kent is an Associate of Arup in the Building Midlands Group, and was responsible for the atrium roof concept and detailed design from inception to completion.

David Killion was formerly an Associate of Arup in the Warsaw office. He was the Arup Project Manager for the project until 2004, with the main responsibility for managing and co-ordinating the input of the numerous Arup disciplines and offices.

Zbigniew Kotynia is an Associate of Arup and a senior structural engineer in the Warsaw office. He was the structural team leader for the detailed design of the foundations and substructure.

Maciej Lewonowski is an Associate of Arup and a senior structural engineer in the Warsaw office. He was structural team leader for the detailed design of all the superstructure concrete and steelwork design.

Robert Lindsay is an Associate of Arup with the Gulf Group in Abu Dhabi. He was the structural engineer responsible for the concept and scheme design of the foundations and substructure.

Philip Monypenny is an Associate of Arup in the Building Midlands Group. He was the structural engineer responsible for the concept and scheme design of the superstructure.

Chris Murgatroyd is an Associate of Arup in the Materials Consulting London Group. He provided specialist input on materials and welding for the atrium roof steelwork.

Johnny Ojeil is a Director of Arup in the Infrastructure and Planning Midlands Group. He was the team leader for the transport planning input to the project.

Raf Orlowski is an Associate Director of Arup in the Acoustics Group in Cambridge, UK, and provided the acoustic input to the project.

Andrzej Sitko is a Director of Arup in the Warsaw Office, and was responsible for overseeing the structural engineering design throughout the project.

Darren Woolf is an Associate Director of Arup in the Building London Environmental Physics Group, and was responsible for the building physics studies, including the CFD modelling.