

Design of Canary Wharf Elizabeth line station and Crossrail Place oversite development

Tim Worsfold

MEng, ACGI, CEng, MICE

Associate Director, Arup, London, UK

Michael Bryant

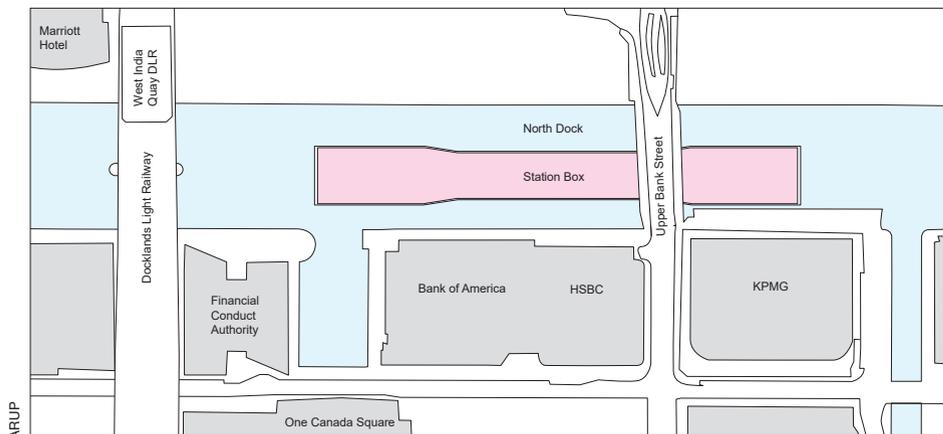
BSc, CEng, MICE

Operations Executive, Canary Wharf Group, London, UK

John Crack

BSc, CEng, MICE, MStructE, MSM, MBA

Associate Director, Canary Wharf Group, London, UK



NOTATION

ETFE	ethylene tetrafluoroethylene
MEWP	mobile elevating work platform
OSD	oversite development

Figure 1 Overall plan showing proximity of Canary Wharf station to major neighbouring buildings

Figure 2 View from West India Quay station of almost-complete station and retail superstructure, showing proximity of tall office buildings

Introduction

Canary Wharf was the first station on the Elizabeth line to be constructed, and the first to be let as a design-and-build contract, with developer Canary Wharf Group. Innovative design and construction techniques enabled the station box to be completed four months ahead of the development programme. Construction of the Crossrail Place retail and leisure oversite development (OSD) proceeded concurrently with that of station. The OSD included a number of features aimed at increasing future flexibility for the developer and tenants. A timber gridshell roof completes the development, partially covering a large roof garden that is open to the public. The OSD opened in May 2015, nearly four years ahead of the planned station opening.

Canary Wharf station

The station site is located on the north side of the Isle of Dogs in the London Borough of Tower Hamlets, and is within the West India Dock (Figure 1). The dock was decommissioned in the 1970s and is no longer





Figure 3
Giken silent piling rig in operation. Rig sits on already-completed piles

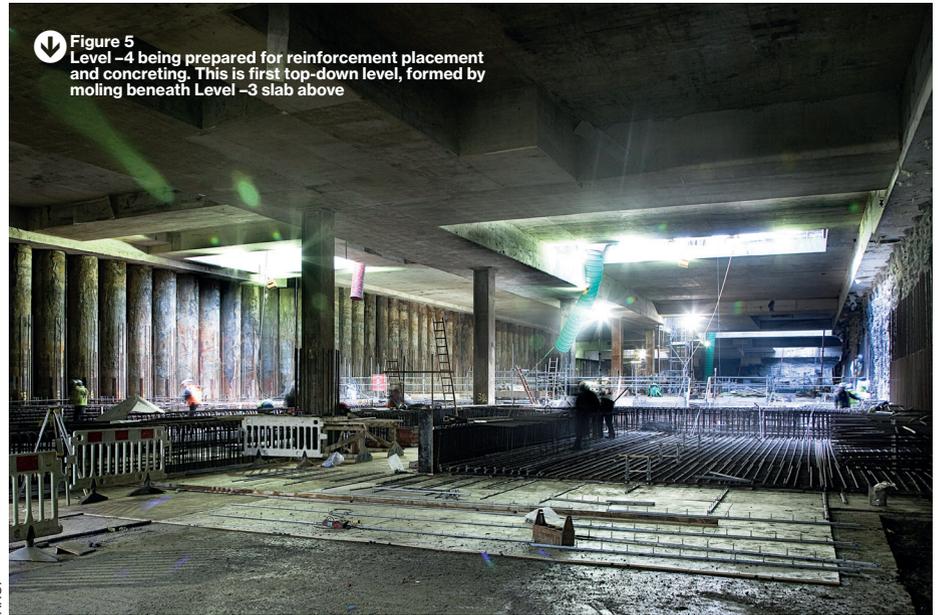


Figure 5
Level -4 being prepared for reinforcement placement and concreting. This is first top-down level, formed by moling beneath Level -3 slab above

in use as a commercial port. The station box is 260m long and 25–30m wide. The dock water is 9m deep and the station base slab is approx. 18m below dock bed level. The station box sits within 10m of four existing office buildings which are up to 40 storeys high (Figure 2).

Station box design

The developer was a leading advocate for the introduction of the southeast spur of the Elizabeth line, which included a station at Canary Wharf. The developer and designer worked strenuously to minimise the environmental impact of the station construction on the Canary Wharf area and maximise the value the project would bring.

The early reference designs developed by Crossrail Ltd had a station box well over 300m long and involved fully or partially filling the dock.

With over 20 years of local knowledge in the design and construction of more than 30 buildings in Canary Wharf, the developer and designer were able to develop several

schemes to construct the station box within a drained coffer dam without the need to import material to fill or partially fill the dock.

Relative to the reference design, the depth of the station box was reduced to minimise impact on the adjacent buildings and the centreline was relocated to minimise effects on the Docklands Light Railway viaduct (Fig. 1). The developer and its technical advisers worked to reduce the cost of the station while maintaining functionality: this included reducing the length of the station box to approx. 260m; the width of the box was also reduced over the central section. Access to future developments to the north and existing developments to the south was explored. The space above the box was also developed as a retail area.

Station configuration

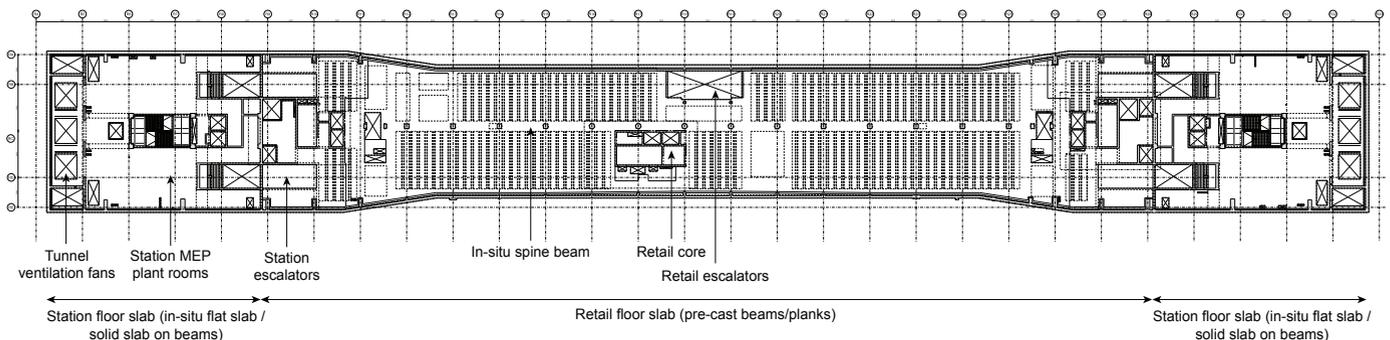
The north, east and west retaining walls were formed from 310 Giken tubular piles of 1214mm diameter, installed using two Giken silent pilers (Figure 3). Reinforced concrete piles were formed by boring through the

bottom of the tubular piles and the whole pile was then reinforced and concreted: the detailed analysis, construction methodology and monitoring is explained in Yeow *et al.*. The southern station retaining wall was formed by a line of 1180mm diameter hard-firm secant piles at 875mm centres from the dock bed. This saved a year on the construction programme from Crossrail's original proposal. To allow for flexibility in the future OSD, there are 105 tension piles of 1200mm diameter along the station; these are spread across the base slab footprint and are for the permanent groundwater case only. In addition, 30 plunge-column piles of 2100mm diameter facilitated the top-down construction.

Station structure

The station structure is a mixture of *in situ* reinforced concrete and precast concrete (Figure 4). The station features an offset central line of columns which extend through

Figure 4
Example of below-ground floor plan



ARUP

the building and are founded on the base slab at Level -6. These columns support a central beam running the full length of the station. At Level -4 this beam is designed to span twice its normal span under accidental load conditions, in case a column below should be lost due to a train derailment. Longitudinal beams also run along the north and south sides of each floor.

Level -3 was the first level to be cast as part of the top-down sequence, and a beam and slab floor structure was adopted, with moling holes incorporated for excavation access below. Level -4 is a solid slab spanning onto the central spine beam (Figure 5).

At Levels -2 and -1, connecting the three longitudinal beams are precast beams at approx. 1.5m centres. Precast lattice planks span between the beams. An *in situ* concrete topping connects the precast elements and completes each floor diaphragm. This arrangement reduced the amount of formwork needed.

Level -1 completes the box structure, with horizontal forces from earth and water pressure being resolved through this level. In some ways, the building can be thought of as a concrete ship, with the Level -1 to -6 substructure being the 'hull' and Levels 0 to +3 being the 'superstructure' (Figure 6). Without the superstructure, the high surrounding water levels and relatively large air volumes inside the substructure would mean that tension piles are needed to hold down the box in the dock.

The longitudinal elevation of the station shows that, in common with tunnelled/mined Elizabeth line stations, the station areas are confined to the platform spaces, plant rooms at each end, and station entrances. Considerable space is available below water level for retail at Levels -2 and -3, as well as at Level -1 between the entrances (Figure 7).

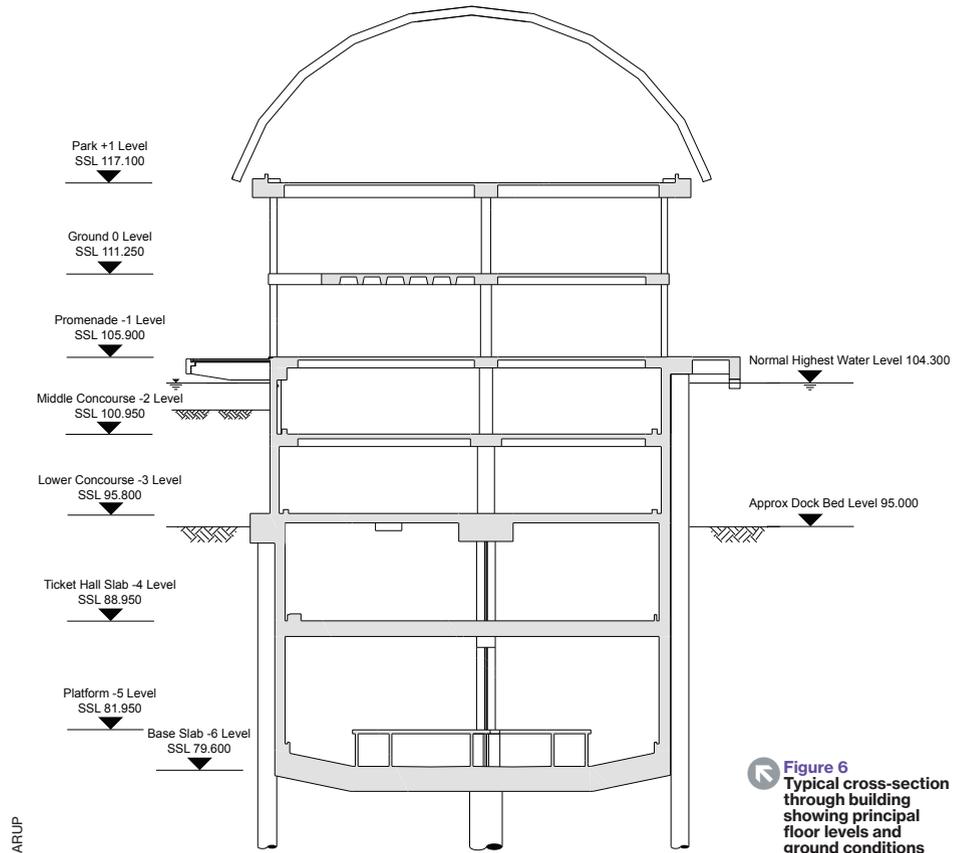


Figure 6
Typical cross-section through building showing principal floor levels and ground conditions

Relationship between station and OSD

The development agreement between Canary Wharf Group, the Secretary of State and Crossrail required Canary Wharf to construct the station within a stated time frame. However, it also allowed the developer the freedom to develop the OSD at any time to suit market conditions. The long programme duration for Crossrail, coupled with the market uncertainty that followed the 2008 financial crisis, meant that a solution had to be developed whereby the station design and construction could proceed without Canary Wharf having to commit to

a particular OSD scheme or, for that matter, any scheme at all.

The station design and construction therefore proceeded on the basis of:

- only station entrances and vent shafts being constructed above water level; below-water retail areas being mothballed; various concepts being developed for what to place between the entrances; structure and services being arranged to enable the OSD at an unknown time in the future
- the OSD being developed concurrently with the station box (a retail scheme received planning consent from the London Borough of Tower Hamlets).

The station box structure featured concrete buttress walls up to 1.7m long at regular intervals along each longitudinal wall, upon which the superstructure columns are supported. During design development of the OSD, and after the station structure was substantially complete, the location of these columns was adjusted to enable up to 30% more retail floor area to be accommodated.

This revised scheme required a revised planning application to be submitted; therefore, the station structure and starter bars at Level -1 were configured and positioned to enable any of the 'no OSD', 'original OSD' and 'revised OSD' schemes to proceed.

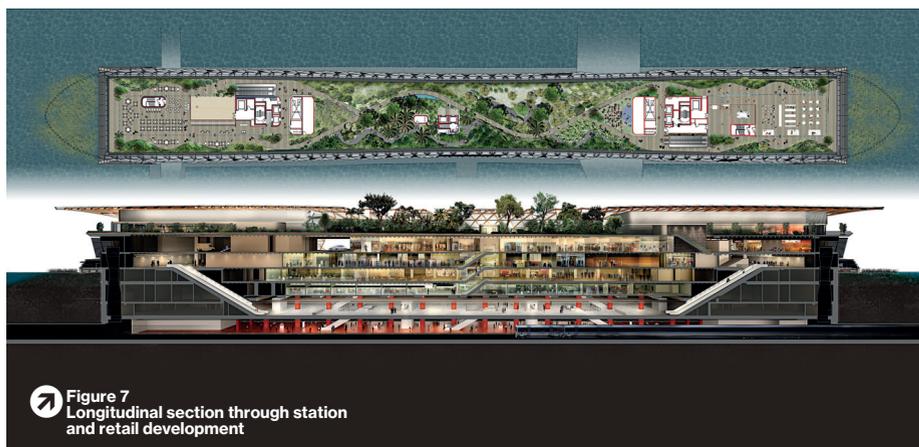


Figure 7
Longitudinal section through station and retail development



Figure 8
Completed park level with clearly visible roof openings to admit air and light to garden. Path is formed on concrete slab that floats over soil beneath, allowing plant roots to extend across roof

CANARY WHARF GROUP

Crossrail Place

The constructed OSD is known as Crossrail Place and consists of retail space within the station box at Levels -3 and -2 and on top of the station box at Levels -1, 0, +1 and +2, with plant rooms at Levels +2 and +3. There is a large roof garden at Level +1. The entire building is capped with a timber gridshell and an ethylene tetrafluoroethylene (ETFE) pillow roof which is 310m long (Figure 8).

The OSD is supported by the station structure below. Building services are entirely independent, enabling each to operate with or without the other.

Structurally, the OSD consists primarily of a reinforced concrete frame with a grid of up to 13.5m x 9m. While the station box structure is continuous, the superstructure is split into three separate buildings via movement joints at 90m centres. However, the roof is continuous. Stability is provided by reinforced concrete cores that transfer horizontal loads to the box below; these cores terminate at the lowest retail level (Level -3), where they are transferred vertically and horizontally.

The structure was designed to provide as much flexibility as possible for both tenants and the developer, while also being cost-effective. At the time of design, there was a

programme and cost incentive to construct the OSD concurrently with the station box, and this required the optimised (wider grid) OSD design to be developed as quickly as possible.

Various floor configurations were studied and it was found that the following scheme achieved the best mixture of flexibility (Figure 9), design/construction speed and cost-effectiveness:

- An *in situ* reinforced concrete structure was used for Levels 0 and +1, featuring longitudinal primary beams and a transverse ribbed-slab structure.
- Removable panels were incorporated into the floor in various places to enable future escalators to be added without major structural work being needed. These panels consisted of precast planks supported by nibs.
- Extensive 'soft spot' zones were incorporated into the floor design to enable future slab removal to create a double-height space, or lift/escalator openings for multistorey combined retail units.
- Most retail entrances were provided with double-height space by default; however, the tenant had the option to infill the space. Steel cast-in plates to the surrounding

columns were provided to enable this to be done without needing major structural work.

- The primary structure was designed to work without the presence of surrounding Level 0 floor areas for restraint, enabling large areas of Level 0 to be removed to create a double-height space if desired.

The mixture of retail or restaurant (or other) tenants was not known at the design stage. While this had relatively limited implications for the structure, it made building services design more difficult due to the much more onerous mechanical and public health requirements for restaurant and leisure use in particular. To address this, a retail/restaurant mix assumption was agreed with Canary Wharf Group. The design did not cater for restaurant use below Level -1.

During tenant occupation and fit-out, restaurant tenants in particular took advantage of the flexibility offered by the building to create the space they wanted. Perhaps surprisingly, although the floor-to-soffit height at Level -1 is 4.6m, many of the restaurant tenants opted to create a mezzanine within their demise. Although this had not been explicitly catered for in design, the floor loading allowances were sufficient to enable this.

Overall, the building has proved to be versatile and has accommodated a wider range of tenants than originally envisaged. As well as more conventional retail units, the building has accommodated 10 restaurants, a number of double-height units (including one involving an unexpected staircase through the top of the box down to Level -1), a three-screen cinema, and even a medical centre.

Roof garden

The roof garden provides a new welcoming public space that works to unite the residential neighbourhood of Poplar and the business district of Canary Wharf.

The landscape architect envisaged this space to be completely different from the rest of Canary Wharf, and to be a glowing beacon among the high-rise buildings at night². The building's ship analogy is extended, with the garden being a reminder of the North Dock's maritime past. Hundreds of plants collectively represent and showcase the many countries visited by ships of the West India Dock Company, which unloaded their wares where the station now sits.

The positioning of the garden above a station provided a number of physical constraints and challenges: shallow substrate depth, weight of planting and an overhead roof structure. These challenges were

embraced by constructing the garden over a slab that acted as a wide tray containing enough soil to support mature trees and plants.

To allow for root growth and drainage of the trees and plants, footpaths had to be elevated on lightweight supporting structures. The structural loading constrains the soil depth to 1.2m generally: deeper zones were created by placing polystyrene void formers beneath the soil. Where the garden spans over Bank Street, a 27m span steel I-beam structure was adopted, with composite floor on metal decking. In this area, soil depth is restricted to 0.6m.

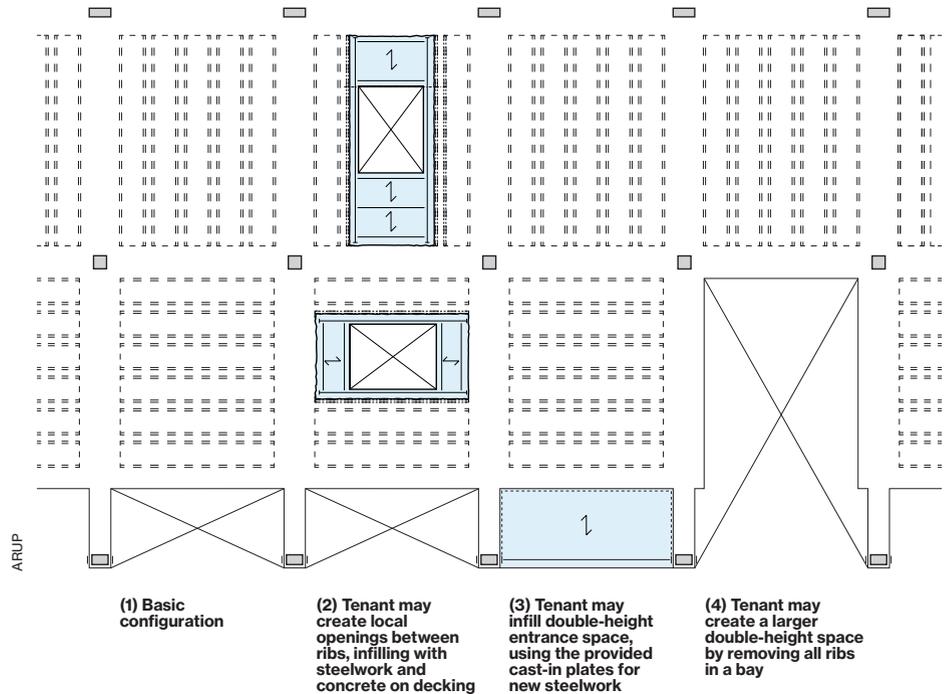
All structures in the roof garden, including the retaining walls, amphitheatre structure, roof access plinths, etc., are designed to be 'free standing' and do not penetrate the waterproof membrane or insulation on top of the Level +1 slab. This enables the garden to be reconfigured (if needed) without disturbing retail tenants below.

Gridshell roof

The park and the rest of the building are enclosed by a distinctive roof, which wraps around the building like a protective shell (Figures 10 and 11). This 310m long timber lattice roof is open in the centre to draw in light and rain for natural irrigation. Timber was an appropriate material to enclose the park – it is organic in nature and appearance, strong, adaptable and is sustainably sourced.

During design development, many studies were undertaken to rationalise the roof geometry and produce a form that maintained an aesthetically satisfying curved shape while minimising the number of elements

Figure 9 Summary showing flexibility built into retail design for tenant modifications



(reducing crane time) and the number of steel nodes that connect each element (reducing cost). Eventually, a form was derived that is effectively a barrel arch structure, tied across the Level +1 slab via the steel embedment plates connecting the roof to the floor.

The roof consists of 1418 beams and 564 nodes. The beam lengths are typically

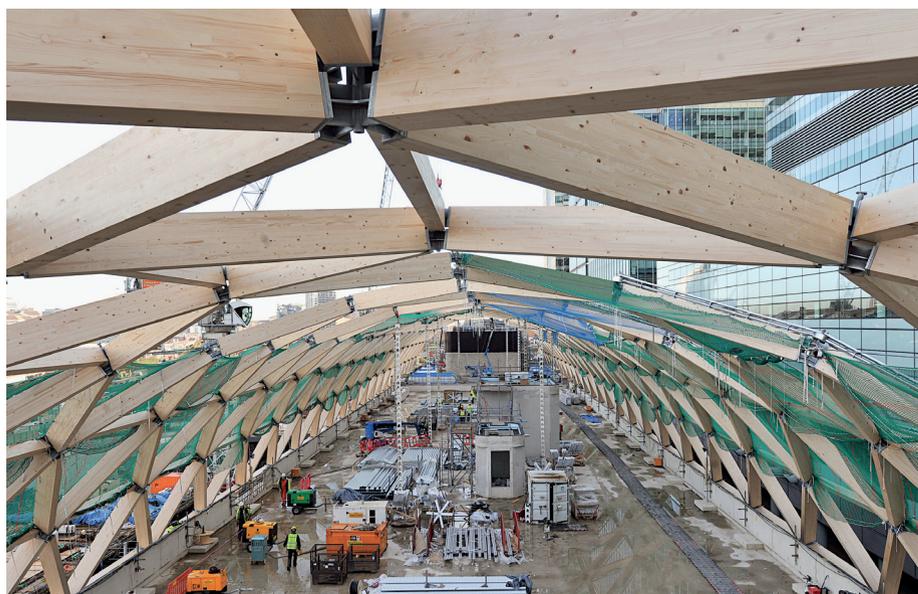
6m, although this varies around the roof, with the geometry subtly adjusted in places to accommodate constraints such as the connecting bridges between Crossrail Place and Canada Square. Over mechanical plant areas, steel beams are used in order to avoid continuously exposing timber elements to damp air.

Structurally the roof is continuous, with moment-resisting connections at each node. This makes the structure highly indeterminate, and considerable effort was paid to understanding the sensitivity of the roof to varying stiffness assumptions given the relatively low ductility of the high-strength screws used in the connections. Load tests of connections were undertaken to assess connection strength and ductility.

A second consideration was ensuring that the roof would be sufficiently durable to give maximum lifespan for reasonable cost. The roof is made of European softwood (spruce) and is protected from rain by anodised aluminium flashings. Additional screws have been placed in various connections with the intention of extracting them at regular intervals in the building's life to assess corrosion, given the building's location in a brackish dock.

The roof shape naturally requires elements to twist around the roof, and in the final design the twist was taken out at each node. While this made the nodes relatively complicated, it enabled each timber piece to be entirely straight and square-ended, minimising timber wastage – only four timber pieces had to be

Figure 10 Timber roof under construction. Galvanised tubes that will supply air to pillows are visible from this angle, but were carefully positioned so they cannot be seen from eye level. Concrete floor forms roof to retail units below, prior to receiving waterproof membrane and soil for garden



CANARY WHARF GROUP



Figure 11
View from Adams Place showing completed roof and Adams Place footbridge

curved. Three visual grades of timber were used, with the lower visual grades used at greater distances from eye level. The nodes consist of welded steel plates, 364 of which are of unique geometry. All nodes were hot-dip galvanized to maximise their durability.

In contrast to some other large lattice roofs, the roof at Crossrail Place was designed to minimise the amount of propping required during construction. This was achieved by arranging the structure into a series of arches that cross the building diagonally on plan and, when linked together, form a relatively short length of roof that is stable in itself. In addition, the timber beams' moment connections were sized to enable each beam to cantilever off one node in the temporary case, thus avoiding further propping. Once the central section of the roof had been erected, further beams were added progressively towards each end.

The gridshell roof is supported by the Level +1 structure at 6m centres along the building. Typically, Level +1 consists of relatively stiff 1m deep reinforced concrete beams; however, where Level +1 spans over Bank Street, the roof connects to 27m span steel beams which are much less stiff. Analysis showed that the steelwork and roof diagrid combine structurally to form, in effect, a three-dimensional truss. This was a potential problem because it meant that when the roof garden soil load was added afterwards, a significant proportion of the load would end up in the timber diagrid rather than being confined to the steelwork. This would have resulted in substantially larger timber member sizes in this region.

To avoid this, 300t of kentledge was placed on the steelwork before the roof was erected, this weight being similar to that of the future soil. The roof was then erected and the kentledge removed, with the structure deflecting upwards as a result. When the roof garden was built, the added soil returned the roof to the originally erected level, with very little net load in the timber members.

The construction programme for the timber gridshell was approx. six months. Following erection of the main gridshell, the flashings were added along with the ETFE pillows and air supply systems (Fig. 10). The pillows require a continuous supply of air, although the system is designed to generally operate at a lower pressure when possible, with higher pressure only being required for high loading (such as snow load).

Access to the roof is via mobile elevating work platform (MEWP) from the underside, with the MEWP connection pads discretely hidden in the garden planting. At the 30m cantilever ends, access is via cleaning cradles suspended from rails. Access above the roof is via abseiling points which are connected to the nodes.

Sections of the roof can be removed for plant replacement below – an important design consideration was the effects of load redistribution in the continuous structure once a section is removed. The roof has been designed for robustness beyond that required by the Building Regulations, which is relatively

easy to achieve given the load redistribution potential of a diagrid structure.

Summary

Crossrail Place opened on 1 May 2015, nearly four years ahead of the Elizabeth line station beneath it. It adds 100 000sq.ft of retail and leisure facilities to Canary Wharf Group's estate, which now incorporates over 300 shops and restaurants (Figure 12). Crossrail Place is a unique addition to Canary Wharf's social and business community.

Project team

Client: Canary Wharf Contractors Ltd
Architect: Foster + Partners; Adamson Associates International; Tony Meadows Associates
Landscape architect: Gillespies
Civil and structural engineer: Arup
MEP engineer: Arup
Concrete contractor: Expanded
Timber roof contractor: Seele-Wiehag jv

REFERENCES

- ▶ 1) Yeow H., Nicholson D., Bryant C. and Westbury M. (2012) 'Achieving more for less at Canary Wharf Crossrail station, London', *Proc. ICE Civ. Eng.*, 165 (5), pp. 50–57.
- ▶ 2) Mourgue A., Unwin A., Scott B., Worsfold T., Huber C. and Bentley-Smith R. (2015) 'Crossrail Place', *New London Quarterly*, 24, pp. 78–89.

HAVE YOUR SAY

- To comment on this article:
- ▶ email Verulam at tse@istructe.org
 - ▶ tweet @IStRUCtE #TheStructuralEngineer



Figure 12
South side of retail at Promenade Level -1. Water feature is actually flood storage reservoir, making up for dock volume occupied by new station

CANARY WHARF GROUP