A model railway station: implementing a 'kit of parts' solution to Custom House – the only above-ground station on the Elizabeth line's central section

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NOTATION

DfMA	Design for Manufacture and Assembly
DLR	Docklands Light Railway
ETFE	ethylene tetrafluoroethylene

Synopsis

The new Elizabeth line station at Custom House was a unique opportunity for design and construction. It is the only above-ground station on the central section of the line and will welcome millions of visitors to London's largest conference centre, ExCeL, as well as providing vital connections for the Borough of Newham.

A joint team from Crossrail Ltd, Atkins, Arup, Allies & Morrison, and Laing O'Rourke collaborated to develop the striking station design, creating a beacon for both the Elizabeth line and the local community. Faced with many constraints, a 'kit of parts' strategy was developed for Custom House's construction, including prefabricated and standardised components.

This approach – where much of the station was built off site – minimised work on site, drove down programme times and costs, and reduced the impact on the local community. The approach also led to Custom House's excellent health and safety record – one of the best of any Elizabeth line station to date.

Introduction

The new Elizabeth line station at Custom House was a unique opportunity for design and construction. As the only above-ground station on the central section (Figure 1), it embodies the Elizabeth line's vision and identity.

The station will welcome regional and international visitors to London's largest conference centre, ExCeL London, and create an important transport interchange with the Docklands Light Railway (DLR) and local bus services. It also provides a focus for the regeneration of the local area, the London Borough of Newham.

The station development is made up of two parts: a new 24-hour public route from Custom House to ExCeL and the Royal Docks; and the Elizabeth line station itself, an elevated concourse ticket hall above an island platform.

Overcoming constraints

The Custom House site (Figure 2) presented a number of constraints:

- The existing DLR runs south of the main site, for the full length of the station. As an operational railway, it meant that constraints were imposed on contractors working adjacent to the boundary.
- The north boundary of the main site lies along the footpath to the south of Victoria Dock Road. This is a busy main road, carrying normal traffic, buses and pedestrians.
- A public right of way across the site enables pedestrians to travel from Victoria Dock Road to the DLR station and ExCeL, located to the south of the DLR station. This had to be maintained at all times, including access for people with restricted mobility.
- Although the majority of the site was clear of utilities, there were a number of major services running along the southern footpath of Victoria Dock Road, including a 600mm diameter intermediate pressure gas main and 12in. cast iron water main.
- A line of high-voltage cables overhangs

Figure 1
Stations on central London section of Elizabeth line

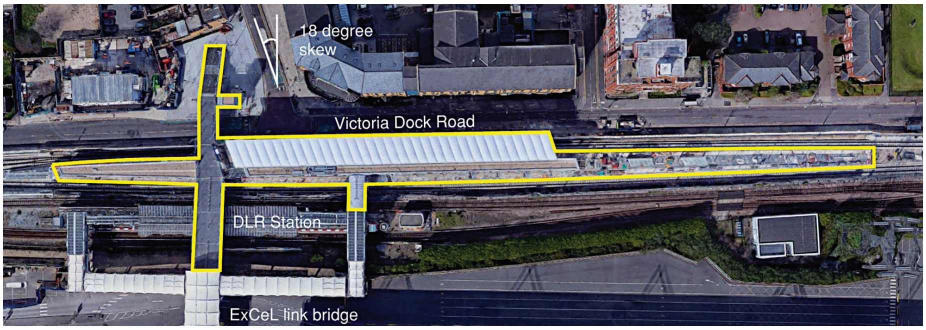

Figure 2
Plan of Custom House station showing 18° skew of site derived from 'urban grain' (relationship between Freemasons Road and Victoria Dock Road)

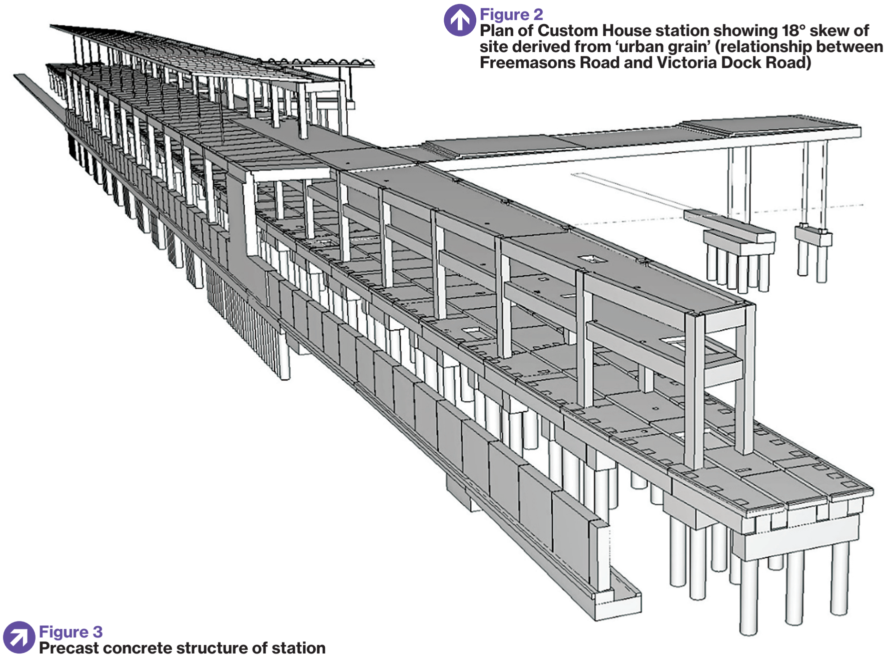

Figure 3
Precast concrete structure of station

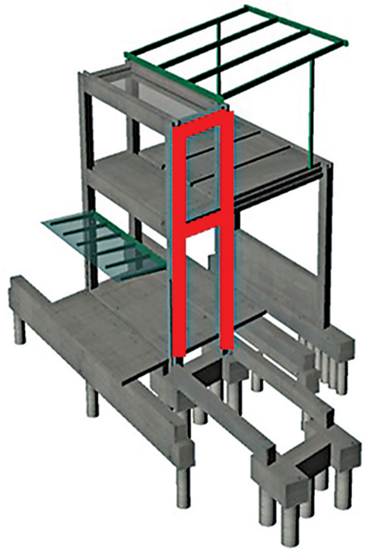

Figure 4
A-frame component highlighted in red

the DLR to the south of the site, stretched from pylons to the east and west of the station. While not overhanging the main station site, they were close enough to be a major source of risk to any lifting operations on the site.

'Kit of parts' approach

The strategy for the construction of Custom House station included prefabricated and standardised structural components, with a 'kit of parts' forming the platform, columns, concourse slab and roof.

This unusual and innovative approach had a number of advantages:

- Work on site was minimised, driving down programme time and preliminary costs, and reducing the impact on the local community.
- Off-site manufacture took place during the Olympic 'blockade', further reducing programme pressures (during the 2012 London Olympics the road network needed to be clear – this did not affect construction of Custom House as much of the work took place off site).
- There were fewer deliveries and vehicle movements around the site, lessening the impact of traffic, noise and air quality on the local community.
- Construction activity was shifted from site to factory, improving working conditions and reducing health and safety risks.
- The more controlled conditions of the factory ensured more consistent and higher-quality production.
- The need for applied finishes was reduced, decreasing programme time, simplifying procurement and potentially lowering costs.

"THE CONTRACTOR CONVERTED THE PRECAST CONCRETE FRAME DESIGN TO FULL DfMA"

The development of a precast concrete solution (Figure 3) brought benefits to both the design and construction phases of the project. It used repetitious units, manufactured in factory conditions to a high standard and consistent finishes, which were delivered to site in batches to coincide with the construction programme. Swift installation by crane was made more acute by adjacent live railway overhead power lines and the restrictions this could have on the construction sequence.

As the project's main contractor, Laing O'Rourke utilised its Explore manufacturing facility in Nottinghamshire to fabricate the major components, which were then delivered on a 'just in time' basis to the site for positioning and commissioning.

The contractor converted the precast concrete frame design to full Design for Manufacture and Assembly (DfMA), splitting large A-frame elements (Figure 4) to be more easily transportable and adopting mechanical connections between the primary components.

This approach is revolutionising construction in the commercial building sector, but this was one of the first applications in a major rail infrastructure project. The seamless integration of the 'virtual' design model and the off-site manufacturing plant allowed the team to create highly precise, major structural elements, delivered exactly when needed. This innovative strategy has great potential for railway infrastructure projects in the years ahead.

Design idea

With Custom House being a new above-ground station, the team had the opportunity to design it as a free-standing building rather than an interior fit-out. This provided scope not only for more architectural expression, but for the station to serve as a beacon, both for the Elizabeth line and the surrounding community (Figure 5).

In addition to the system-wide equipment and wayfinding signage that is part of the Elizabeth line brand, the architectural design had to recognise Custom House's other ambitions: in terms of place-making, fitting into the urban setting of Newham, and its role as an ambassador for the capital's new rail transport system.

Robert Maxwell, Allies & Morrison's lead architect for Custom House, has described it as 'an urban temple' (Figure 6), elaborating: 'At its simplest, the form of the building laid out at the southern end of Freemasons Road produces a tripartite architectural composition. The plinth, or base, consists of a continuous monolithic wall needed for asset and vehicle collision protection; the principle facade, or middle, the colonnade capped by the edge and balustrade of the concourse; and the roof, ETFE [ethylene tetrafluoroethylene] pillows supported on slender steel columns' (Figure 7).

The shape of each of the structural columns is a parallelogram rather than orthogonal, with a rotation of 18°. This is derived from the relationship between Freemasons Road and the urban grain of the neighbourhood with the Victoria Dock Road that runs parallel to the railway lines (Fig. 2). This rotation is also combed through the floor finishes and steel superstructure supporting the roof.

At platform level, folded planes were introduced to the precast concrete soffit panels supporting the concourse. These fold in alternating directions to provide a simple vaulting pattern that is enhanced and lifted by edge lighting.

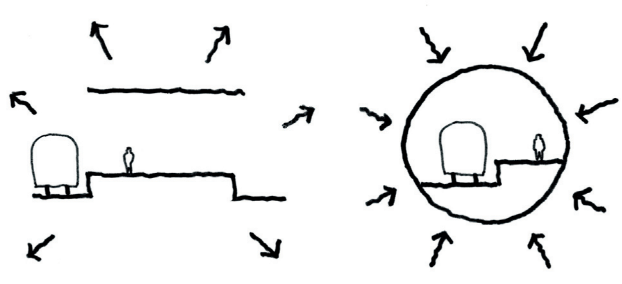

Figure 5 Unconstrained by underground setting, Custom House can serve as beacon for Elizabeth line and community, with transparent views and iconic architecture

The arrangement of the station produces a simple legible route from the entrance to the train doors (Fig. 7). The upper level is intentionally generous and open in feel to aid orientation and route selection for passengers. This open aspect enables observation and passive surveillance for both those approaching and within the station.

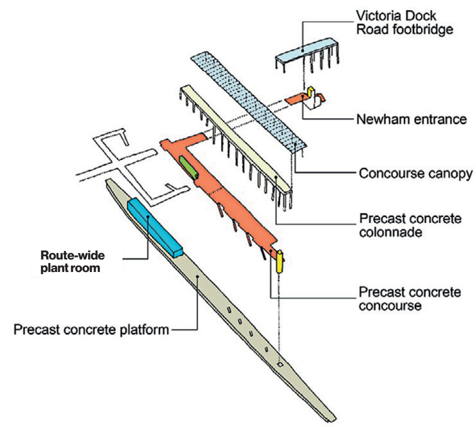

Figure 7 Exploded view of station's form

Design solution

Making good foundations

The made ground on the site is underlain with approx. 4m of alluvium, which includes peat layers. The station and track bed structures require piled foundations as a result of the unacceptable predicted settlements associated with building a ground-bearing structure on soft peat material. Piles were up to 25m long, with diameters of 450mm, 600mm and 750mm. The foundations are designed to bridge over the services running below the site where required, with continuous flight augured (CFA) piles and *in situ* concrete pile-caps supporting the superstructure.

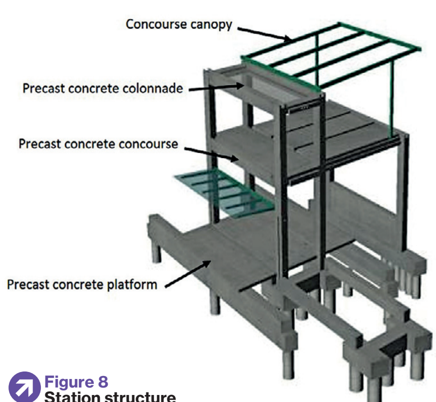

Figure 8 Station structure components

Platform

The platform structure comprises precast concrete panels spanning onto a system of primary beams supported on the *in situ* pile-caps and piles (Figure 8). Typically, there

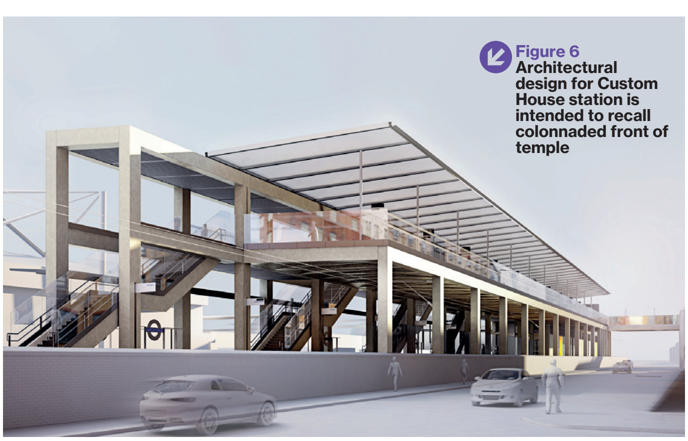

Figure 6 Architectural design for Custom House station is intended to recall colonnaded front of temple

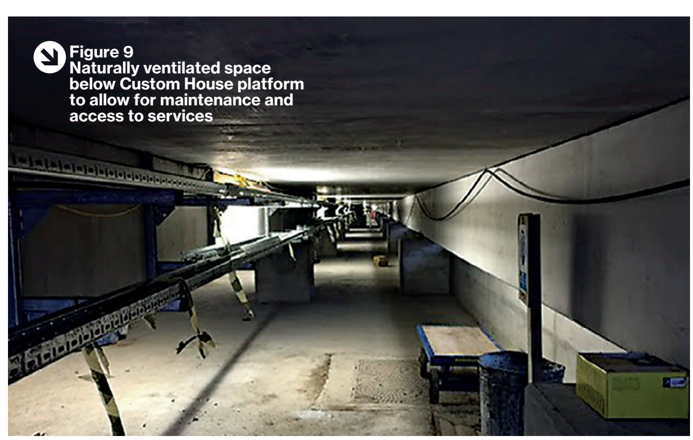

Figure 9 Naturally ventilated space below Custom House platform to allow for maintenance and access to services

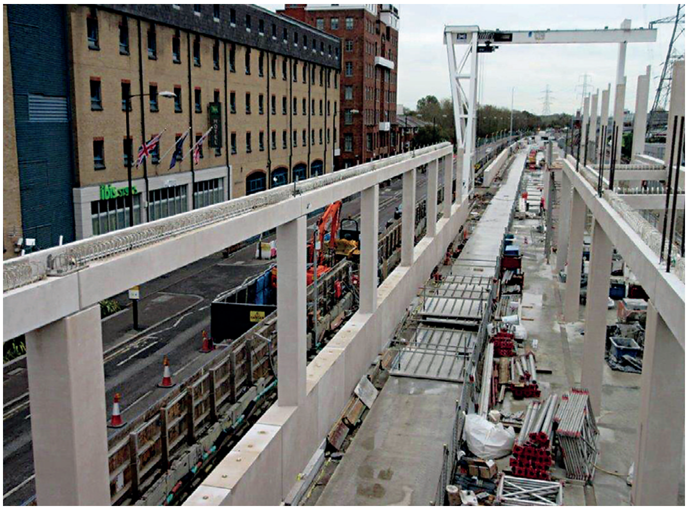

Figure 10 Concourse structure along Victoria Dock Road with precast 'L' beams waiting to receive coffered floor panels

Figure 14 Precast panels with triangular vaulted soffits are used on main span of concourse structure

"THE CONCRETE SUPERSTRUCTURE CONSISTS OF A SERIES OF PRECAST REINFORCED CONCRETE FRAMES, COLUMNS, BEAMS AND FLOOR UNITS"

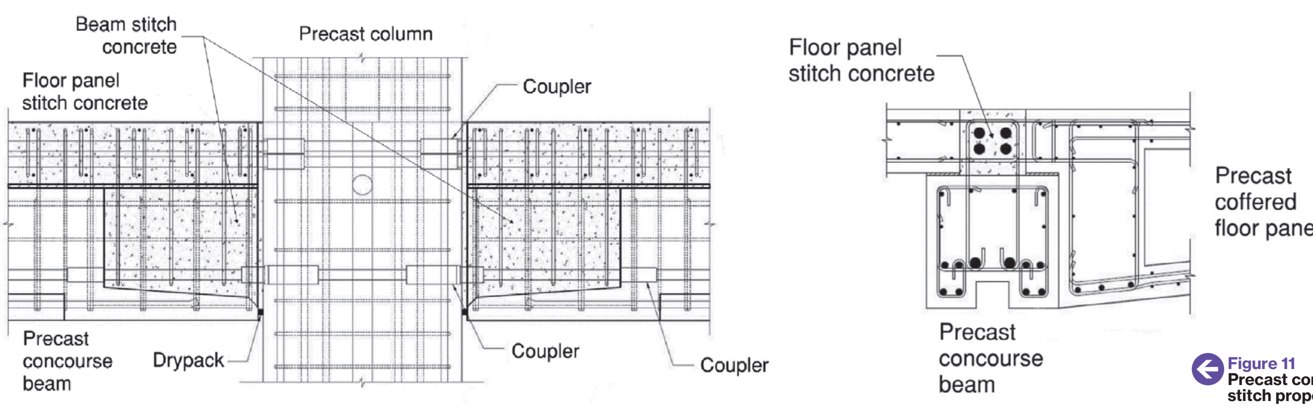

Figure 11 Precast concrete wet stitch proposal

Figure 12 Hybrid mechanical and wet stitch solution for typical beam

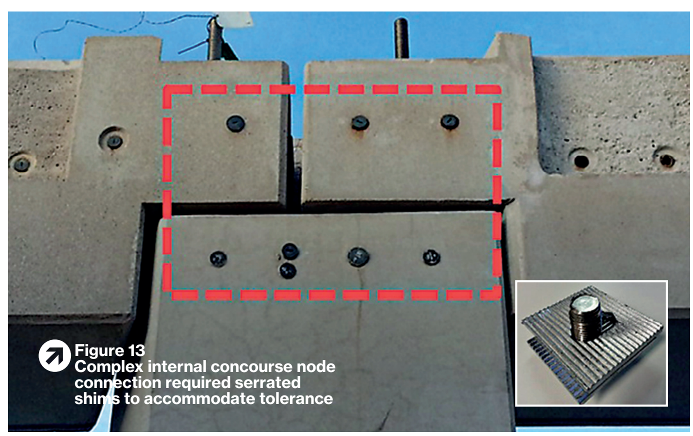

Figure 13 Complex internal concourse node connection required serrated shims to accommodate tolerance

are three or four lines of beams which span between the pile-caps, depending on the width of the platform and the location of the platform drainage channels.

There is a naturally ventilated space below the platform for maintenance of the services running below it (Figure 9). The services include two 11kV cables powering the Elizabeth line, drainage pipes for the roof and concourse drainage, and other electrical and communications services serving the platform.

Main station structure

The concrete superstructure consists of a series of precast reinforced concrete frames, columns, beams and floor units. In section, the beams are either rectangular, 'L' or inverted 'T' shapes depending on the precast floor units they are required to support (Figure 10). All the precast units were designed to be attached together with a hidden *in situ* concrete stitch. The key structural design challenge for Custom House was reconciling the need for the primary precast component connections to be 'invisible', while having sufficient strength and stiffness to transfer the connection forces generated from moment frame action.

The wet stitch proposed by the design

team for this connection (Figure 11) was eventually replaced by mechanical bolted connections (Figures 12 and 13). The advantage of this method was the lack of temporary propping required at the beam ends. The approach satisfied the original architectural intent, except in a few locations where discrete half-joint connections were adopted. This did, however, reap greater benefits in terms of constructability and temporary works.

The main span of the concourse structure consists of precast panels with triangular vaulted soffits (Figure 14) and beams along each long edge, which are supported by east–west primary beams. The profile of the soffit planes was determined primarily by the architectural intent, but also by the prefabrication process in which the release of the finished component from the moulds and the need for void formers within the panel, in order to limit weight, had to be considered.

With the open-plan nature of the station environment, braced or shear wall stability structures were not viable, so the lateral stability of the main station building is derived from a series of portal frames in both directions (Figure 15). Lateral loads are transferred to these stability elements by the concourse and roof structures being wholly or partially stitched together to act as a stiff diaphragm. Wind loading from the north and south is transferred through the structure via the A-frames, and wind loading from the east and west via the precast concrete colonnade.

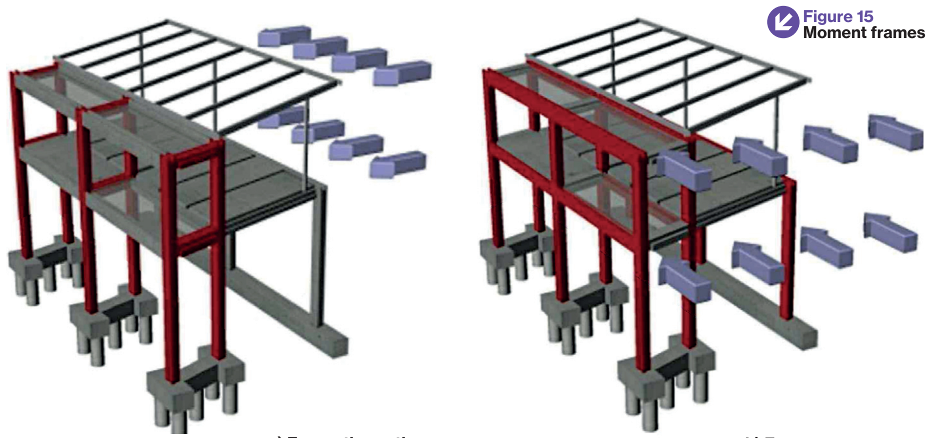

Figure 15
Moment frames

a) For north–south lateral loads

b) For east–west lateral loads

Roof structure

The steel roof structure supporting the ETFE pillows comprises circular columns and fabricated box-section beams (Figure 16). The columns are set back from the edge of the roof structure and are supported at their base by the precast panel beams described above. The roof members are connected by concealed bolted end-plate connections and all visible welds have been ground flush and smooth.

The ETFE pillows are connected on all sides to aluminium extrusions, which also form the watertight seal and gutter. In order to connect these extrusions to the steelwork, discrete L/T-sections are required on top of the steel roof members.

Victoria Dock Road wall

The key challenge in the design of the Victoria Dock Road wall structure and foundations was the limited space available both above and below ground level. With the footpath, and associated services, immediately to the north and the Elizabeth line tracks immediately to the south, the 2000kN and 500kN train collision loads need to be resisted by a 500mm wide linear structure. This was achieved by casting structural steel sections into the precast concrete column/wall units (Figure 17) and having linear pile clusters beneath the columns. As with the precast column bases, the wall units were connected to the cast-in anchor bolts in the *in situ* pile-caps using stainless steel column shoes.

Figure 16
ETFE pillows are supported by steel roof structure with circular columns and fabricated box-section beams

Footbridges

There are three footbridges linking the DLR station, ExCeL arena and the London Borough of Newham to the new Elizabeth line station. All three structures comprise steel fabricated primary box-beams with a composite slab cast on permanent precast concrete planks. Of these bridges, the ExCeL footbridge had the largest span and was the most challenging to construct due to the proximity of the overhead power lines. This was achieved by using two cranes working in tandem (Figure 18).

Construction

Crane decision

Before construction started, a major decision was taken to move from the use of a mobile crawler crane to a gantry crane for erecting the main works (Figure 19). Although common in the shaft and tunnelling world, using a gantry crane is an innovative solution for above-ground station construction.

The primary driver for the gantry crane solution was health and safety. How could the team effectively manage a crawler crane in such a restricted area with so many

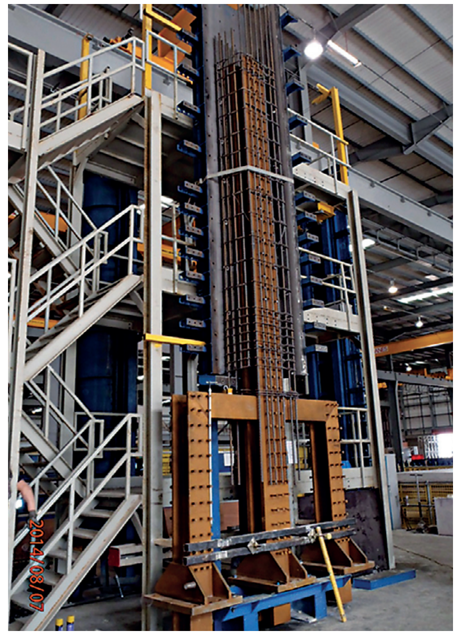

Figure 17 Victoria Dock Road column/ wall structures

variable interfaces? The team decided the answer was that it simply could not. Using a gantry crane significantly reduced major risks such as collapse radii and proximity to the 400kV overhead power line. Another major benefit of the gantry crane was its ability to track back over the structure once erected.

Kit of parts in action

With the connection design for the 880 precast units (each weighing up to 34t) completed, all hidden within the structural envelope (Figure 20), the next task was to ensure that the team could achieve the architectural finish. Service void dimensions and shapes, chamfers and drip details, and visible joint arrangements all needed careful detailing for the DfMA process. Prototype units were cast to check the manufacturing process was working as expected and to confirm the finish quality.

Due to the size of the units and the number of handling operations required, both in the factory and on site, the lifting solution needed careful planning. With no space in the top of the units for cast-in lifting points, the team developed a bracket that used the permanent works connections. This ensured the units were adequately protected during the horizontal to vertical pitching process.

Going digital

Modelling all of the components at Custom House in three dimensions (3D) provided an invaluable communication tool to aid conversations between teams around buildability, site inductions, logistics, sequencing and health and safety. The 3D model was also linked to the project programme in Synchro[1] to visualise and plan the complex sequence of installation. This was in turn linked to Laing O'Rourke's factory database.

Figure 18 ExCeL footbridge, largest at Custom House, is lifted into place

Figure 19 Gantry crane was used to reduce risk from station's close proximity to overhead power lines

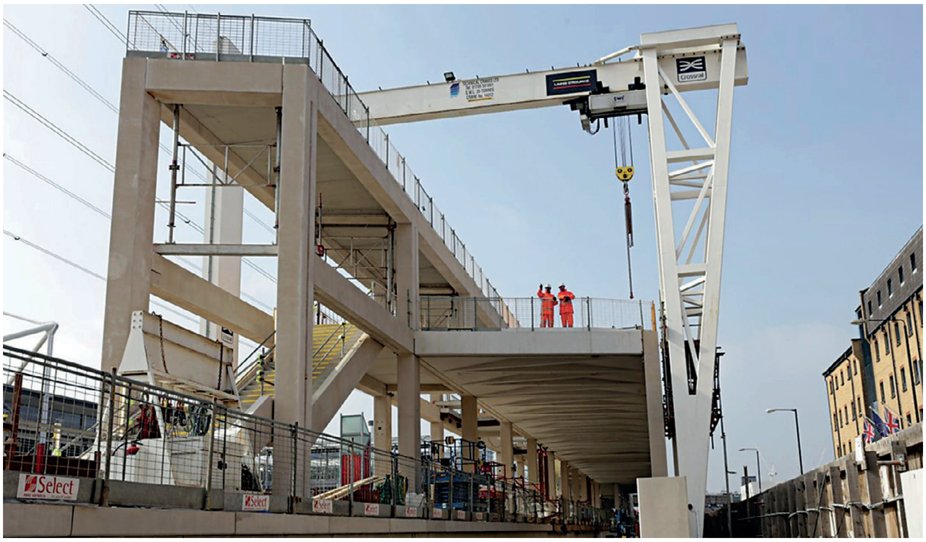

Figure 20
Custom House station used 880 precast units

By using unique QR codes on each component, the team was able to track, plan and record the status of each of the 880 precast components from the design stage through to casting, delivery and installation on site. Once on site, mobile devices scanned the QR code and brought up the necessary quality form to complete. This provided an efficient way to carry out all quality control and health and safety checks, maximising traceability and simplifying the handover process.

Conclusions

Custom House's success resulted in the project winning 'Infrastructure Project of the Year' in the Explore Offsite Awards, and 'Offsite Construction Project of the Year' in the London Construction Awards. Using a 'kit of parts' approach, the close collaboration of Atkins, Laing O'Rourke, Arup and Allies & Morrison developed a solution that was elegant, durable, cost-efficient and safe to erect on the constrained site (Figure 21), with the majority of the fabrication process taking place in a controlled factory environment. The team not only overcame the unique challenges for design and construction presented by the site, but also delivered the iconic 'ambassador' for the new Elizabeth line network they were seeking. A real-life model railway station.

Acknowledgements

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Atkins is a part of SNC-Lavalin's Engineering, Design and Project Management business.

Project team

Structural engineer: Atkins
Client: Crossrail Ltd
Building services engineer: Arup
Architect: Allies & Morrison
Main contractor: Laing O'Rourke

REFERENCE

►1) Synchro Software (2018) *Synchro* [Online] Available at: www.synchroltd.com/ (Accessed: May 2018)

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Figure 21
Custom House station in final stages of construction