

# Construction of the ventilation towers at Tottenham Court Road Elizabeth line station

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## NOTATION

FE	finite element
GGBS	ground-granulated blast-furnace slag
GYB	Goslett Yard Box
WTH	Western Ticket Hall

## Introduction

Tottenham Court Road Elizabeth line station is a new station located in the heart of London, adjacent to Oxford Street, being delivered as part of the Crossrail programme. The station is expected to accommodate more than 200 000 passengers every day when it becomes operational in December 2018. The station is of paramount importance due to its strategic location, interchange with the London Underground and future link to Crossrail 2.

Tottenham Court Road consists of two entrances on the east (Goslett Yard Box) and west (Western Ticket Hall) sides of Soho Square, each of which has a ventilation tower equipped to ventilate the 250m long new platforms and running tunnels located 25m below ground (Figure 1). The ventilation towers are two of the largest overground structures on the entire Crossrail project, and presented a vast array of challenges due to their locations as well as their technical complexity.

Following the award of the contract to Laing O'Rourke, discussions were held about changing the design of the superstructures to precast concrete. However, due to the design process that would have been required to alter the concept, and lead time for bespoke precast elements, there was not sufficient time to alter the construction methodology. Therefore, a traditional *in situ*

concrete approach was used. In fact, due to the precise planning and coordination of this approach, it resulted in a more economical solution than the precast option.

## Eastern ventilation tower (Goslett Yard Box)

The ventilation tower in the Goslett Yard Box is part of a five-storey *in situ* reinforced concrete superstructure and five-storey substructure (Figure 2). This will connect the existing London Underground station with the Elizabeth line platforms, and will also be used for services and ventilation.

It was realised at an early stage that to facilitate the successful completion of the entire Tottenham Court Road scheme, significant changes were needed to the construction sequence of the Goslett Yard Box. One of the main programme drivers at the station was to ensure the tunnel fit-out programme was not adversely affected due to its position on the critical path.

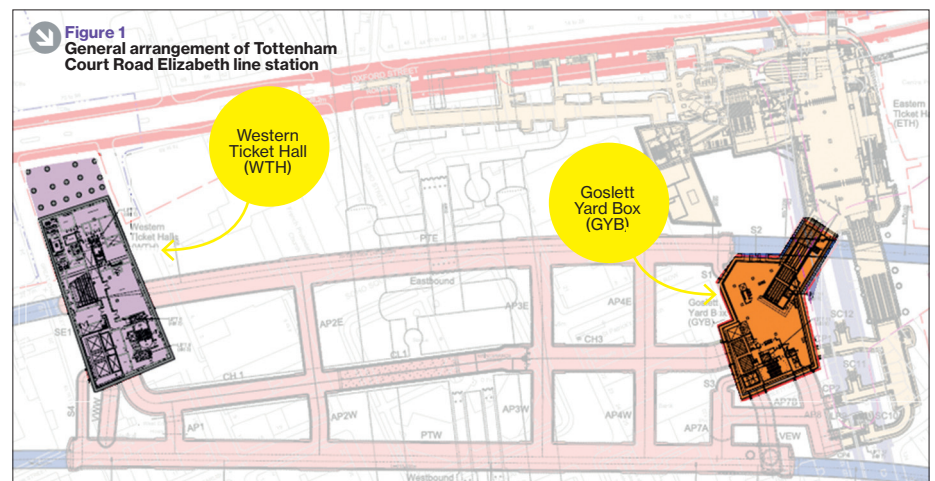
There were only two access points into the tunnels and one of these was through the Goslett Yard Box. This access point was known as the Goslett Yard Box mole hole. It was therefore imperative for the scheme's success that this was left open for as long as possible.

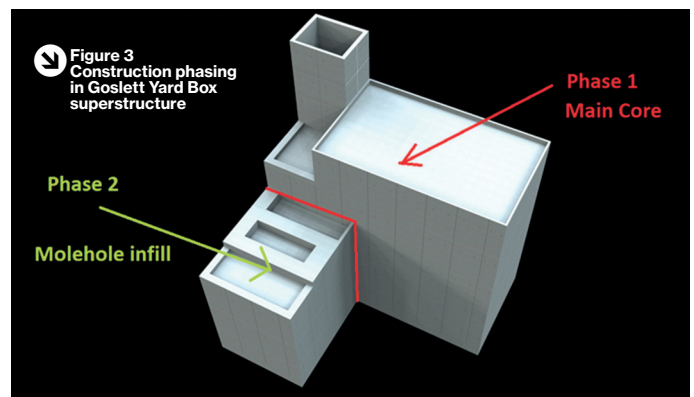
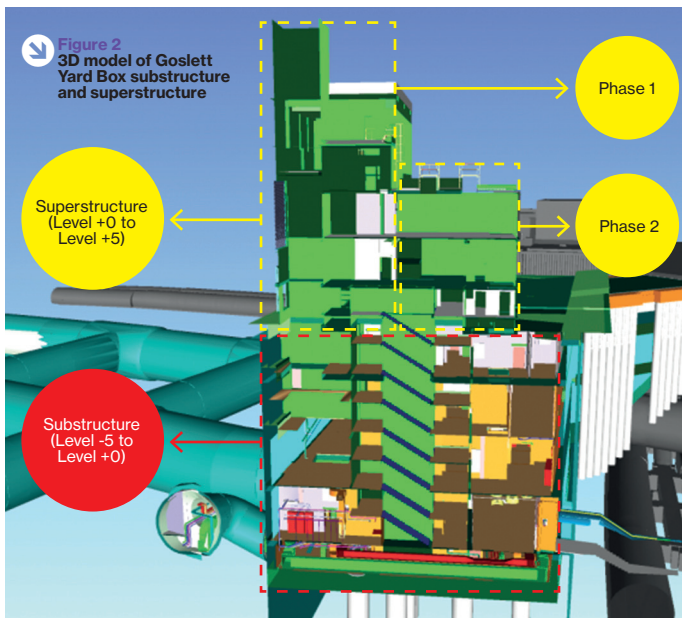
The construction of the superstructure was split into two phases (Figure 3). The major challenges in the construction of the Goslett Yard Box superstructure were the interface around other construction activities, architectural finished concrete and strict programme requirements.

## Construction phasing

One of the main project milestones was the handover of rooms within the structure to the fit-out contractor, known as Key Date 3. This served as a sectional completion for the project. Splitting the structure into two phases created two major benefits:

- The mole hole (Figure 4) allowed access to





the tunnels, which could then be left open for another five months.

- All the major rooms, above ground, required for handover at Key Date 3 were within phase one.

**Architectural finished concrete**

At the Goslett Yard Box the designer had specified that the external walls would adhere to a strict architectural specification for the concrete finish. This requirement was set by Westminster City Council as part of the planning permission, due to uncertainty around the construction of the oversite development in the near future, and was

1). Working closely with the Laing O'Rourke materials laboratory and the concrete supplier, an innovative concrete mix was developed, achieving both the structural and architectural specifications (Mix 3F). This particular mix included a higher amount of limestone filler, which increased workability, reduced the number and size of blow holes, and achieved the desired finish. It was subsequently approved by the architect.

A major concern when working adjacent to Oxford Street was the regularity of the concrete supply. Significant time was invested during initial trials to ensure that the concrete had a four-hour working-life

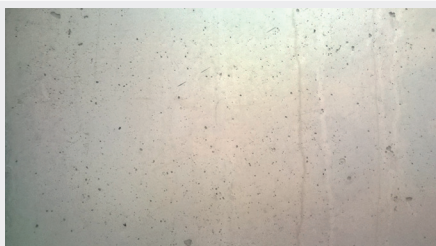

specified within the Works Information.

A series of trials with various concrete mixes was undertaken to agree a benchmark (Table

window. The extra effort spent at this stage reassured the site teams when completing concrete pours that cold joints were significantly less likely as a result of traffic congestion in the area around the site.

To meet the Key Date, a climbing formwork system was used. To achieve the rigorous architectural requirements, which included a regular tie-hole pattern arrangement and specified construction joints and ply lines, a bespoke climbing shutter was used (Figures 5 and 6), with the *National Structural Concrete Specification* 4th edition (NSCS4)<sup>1</sup> used as a guide. Due to site constraints, the shutters were made off site and delivered to site ready for the pours. In addition, the formwork was designed to withstand the concrete pressures imposed by a fast rate of rise (in accordance with CIRIA Report 108<sup>2</sup>) to facilitate concrete pumping. To minimise construction joints, additional anti-crack bars were installed to facilitate larger concrete pours by limiting thermal cracking.

**TABLE 1: DEVELOPMENT OF CONCRETE MIX TO ACHIEVE ARCHITECTURAL REQUIREMENTS**

	Trial No. 1	Trial No. 2
Mix	Original Concrete Mix 3B	Concrete Mix 3F
Additional information	Concrete mix for slabs and walls in Tottenham Court Road with 55% GGBS	Special mix for architectural finish concrete with 55% GGBS and 60kg/m <sup>3</sup> more limestone filler than Mix 3B
Strength	C32/40	C32/40
Finished surface	Excessive blow holes in struck concrete surface	Reduced number and size of blowholes
Workability	Moderate workability	Improved workability
Photographs of struck surface		

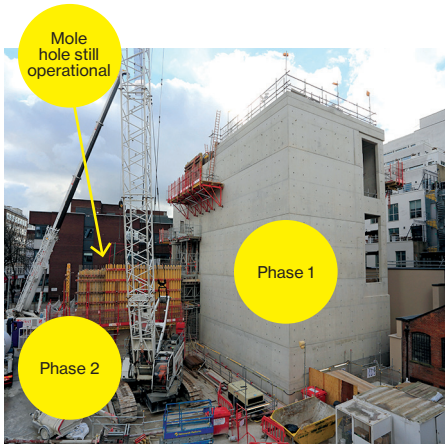


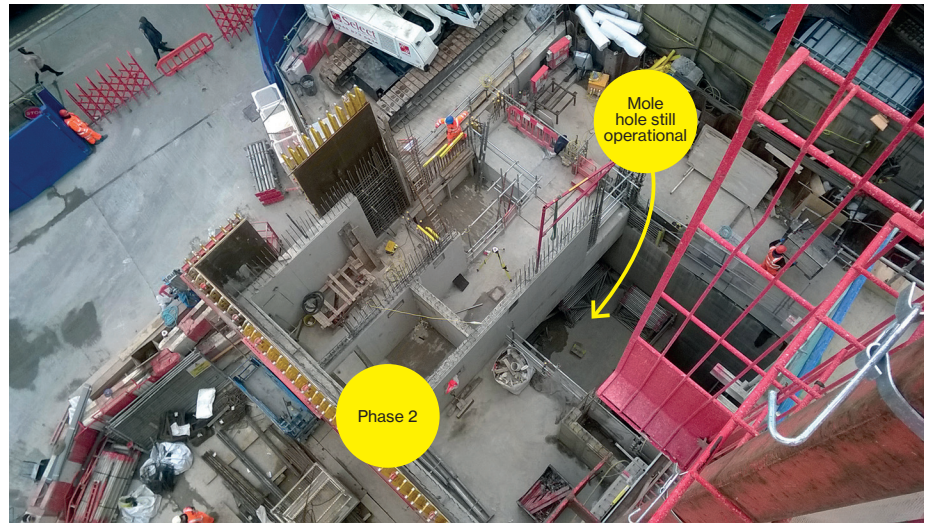
Figure 4  
Phase 1 and 2 under construction  
with mole hole operational

Installation of the climbing formwork was a high-risk operation as it required working at height. A detailed visual risk assessment and method statement were written so that everyone could be briefed and to facilitate greater understanding. In addition, the area was classified as restricted access and a specific safety induction was required for all visitors to ensure their health and safety.

The major engineering challenge of the climbing formwork was its temporary support in the large openings in the external walls (up to 5m x 6.5m). Two options were considered to overcome this problem: the use of temporary reinforced concrete beams; or the use of temporary steel I-beams. After reviewing both options, it was decided to use steel I-beams fixed on either side of the openings with vertical supports at the anchor points (Figure 7), as this was considered an easier system to install with fewer repairs likely to be required after the beams' removal.



Figure 5  
Architectural  
concrete finish in  
Goslett Yard Box  
superstructure



**"THE MOLE HOLE ALLOWED ACCESS TO THE TUNNELS, WHICH COULD THEN BE LEFT OPEN FOR ANOTHER FIVE MONTHS"**

After reviewing the original temporary works scheme, it was observed that there was a potential area for significant deflections due to the localised forces applied at the external flanges. The team suggested that additional stiffeners should be welded at the anchor points. The temporary works designer then verified this visual assessment by using a finite-element (FE) model and approved the installation of stiffeners.

By spending time in the planning stage thinking about intricate details such as

where construction joints would be located, pour lengths and heights, shutter design and temporary works, it allowed the focus on site to be on ensuring the plan was implemented. This focused approach allowed the sectional completion date to be successfully met at the Goslett Yard Box due to a full understanding of the plan and the key roles everyone played within the team (Figure 8).

#### Western ventilation tower (Western Ticket Hall)

The Western Ticket Hall superstructure is a seven-storey *in situ* reinforced concrete structure, supported by a five-storey substructure, which will accommodate services and ventilation equipment (Figure 9). The construction programme for this structure was limited to just 20 weeks, before it was handed over to the system-wide contractors for installation of the ventilation fans, mechanical and electrical

a) Finished structure



b) Architectural elevation

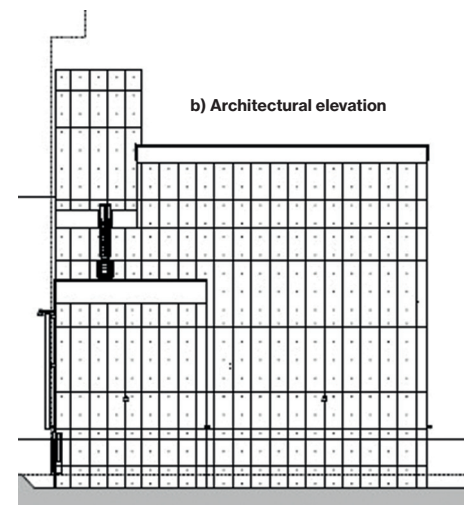


Figure 6  
Temporary support of climbing formwork in wall openings

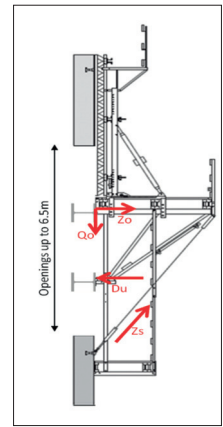
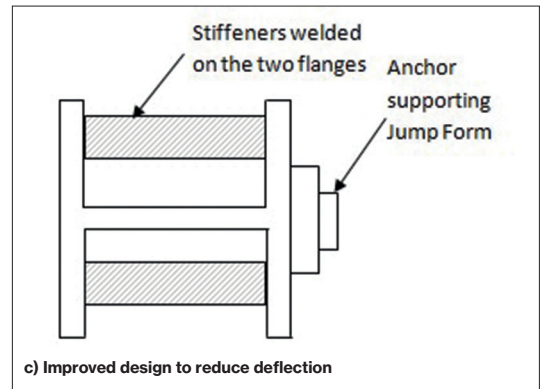
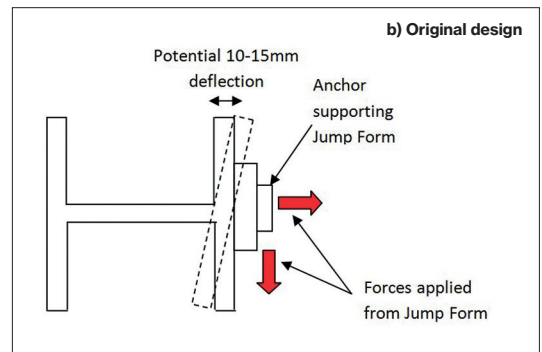
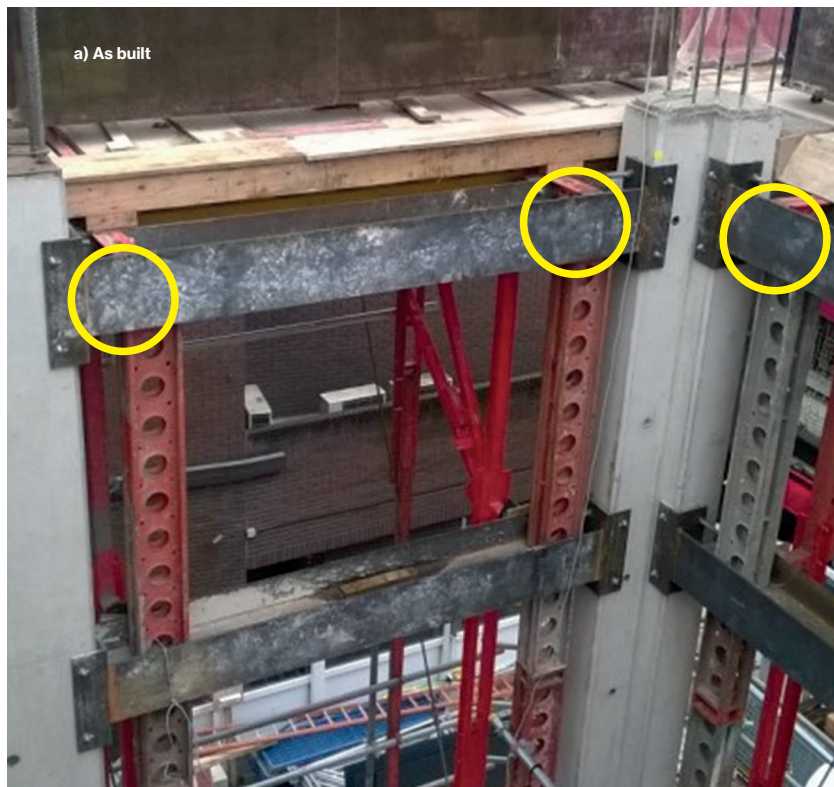


Figure 7  
Stiffeners welded in temporary I-beams to reduce deflections



equipment. As with the Goslett Yard Box, the Western Ticket Hall superstructure had architectural finished concrete specifications, technical challenges, logistical restrictions and strict programme requirements.

### Construction sequence

The construction methodology and sequence were fundamental to achieving the successful completion of the Western Ticket Hall on time and under the strict programme requirements. The selected sequence of works included the construction of the primary walls up to a certain height (using the jump-form system) before the

construction of the slabs could commence. This would enable the construction of the walls and the slabs to occur concurrently and significantly reduce the programme of the works.

For this sequence to be followed, an FE model was developed (Figure 10) to examine the height to which the walls could be constructed prior to construction of the slabs, before excessive stresses and deflections were imposed on the structure in its temporary stages. Following this analysis, a height of 7.2m was specified for the walls before the slab construction could commence.

The selected sequence had an additional

benefit: the reduction of the noise impact on local stakeholders. Due to the walls being constructed first, a physical barrier was in place between the construction of the slabs and the surrounding buildings, which significantly reduced the noise impact during the construction phase.

### Technical challenges

The construction of the walls ahead of the slabs imposed a major technical challenge: the provision of continuity in the reinforcement between the walls and the beams. The original design specified L-shaped couplers cast into the wall (Figure 11). Due to the significant bending moments

and shear forces, one of the beams required B32 bars cast into a 250mm wide wall, which caused clashes with the jump-form system.

Following extensive research, the Laing O'Rourke engineering team proposed the use of terminators. These are headed bars which provide the same anchorage as L-shaped bars by activating the shear cone and placing the concrete into compression. To prevent concrete pulling-out, which is one of the failure mechanisms of this system, additional reinforcement was added horizontally along the terminators. The advantage of the terminators over the L-shaped bars was a reduction in the anchorage length (due to the headed end) which suited the thickness of the wall and the construction methodology.

This proposal was supported by research papers<sup>3,4</sup> and industry specialists in mechanical anchorage. It was accepted by the structural engineers and provided a solution to a technical problem that could potentially have hampered the construction sequence and put the construction of this ventilation tower at risk.

**Innovative technologies**

In the Western Ticket Hall superstructure, the early concrete strength was monitored using wireless thermocouples – a pioneering



← **Figure 8**  
Team who delivered scheme



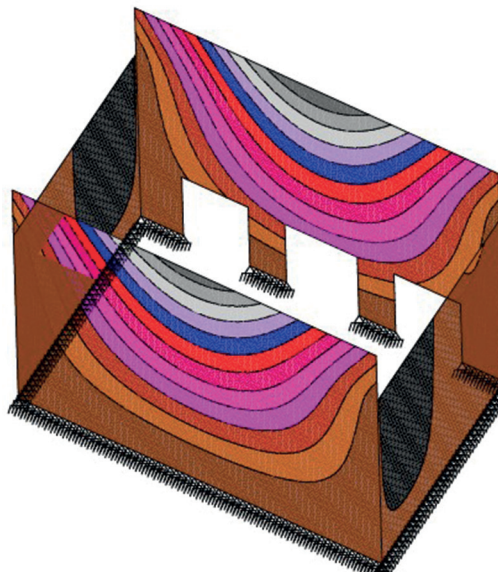
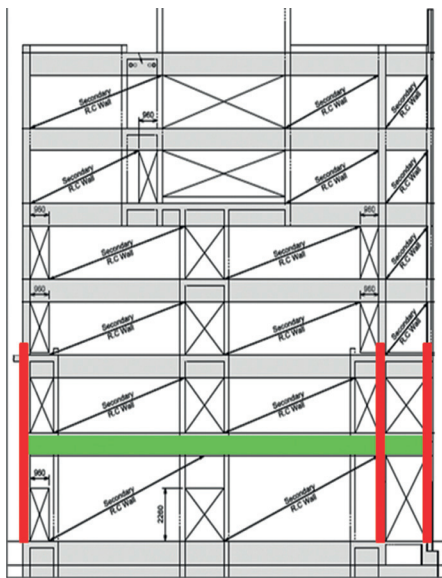
↻ **Figure 9**  
Western Ticket Hall superstructure with climbing formwork

technology. The wireless thermocouples remotely record the temperature of the concrete in real time during curing. The concrete strength is then determined using maturity graphs (cores were taken and crushed to gain compressive strength during trials to ascertain concrete strength). The use of thermocouples was necessary at Tottenham Court Road for the following reasons:

- The concrete mix contained 55% ground-granulated blast-furnace slag (GGBS) to comply with the project specification for

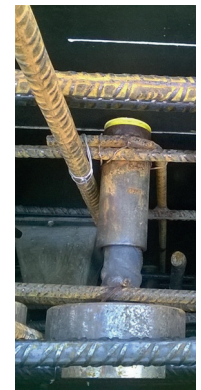
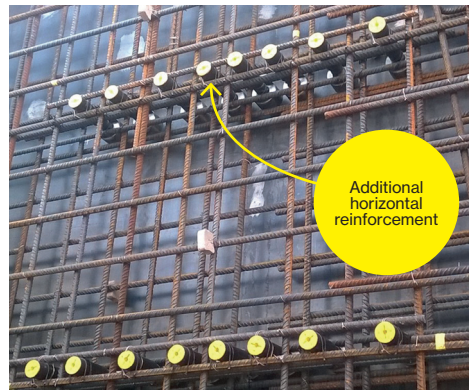
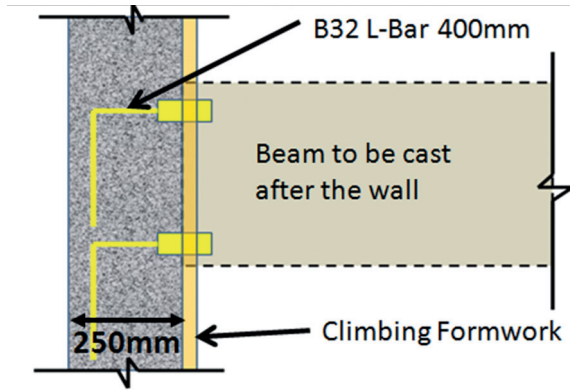
lower embodied CO<sub>2</sub>. The GGBS is used as a cement replacement and results in slower strength gain.

- To comply with the architectural concrete specifications, striking was permitted:
  - for concrete strength greater than 5N/mm<sup>2</sup> for walls
  - when the temperature difference between the concrete and the surrounding air was less than 20°C, in order to avoid cracking from thermal shock.
- According to the climbing formwork design,



LINE	VALUE
1	-0.00074
2	0.00064
3	0.00135
4	0.00202
5	0.00271
6	0.00340
7	0.00409
8	0.00478
9	0.00547
10	0.00616
11	0.00686
12	0.00755
13	0.00824

↻ **Figure 10**  
Construction sequence and FE analysis of temporary structure



**Figure 11**  
Use of terminator for wall-beam connection

the concrete strength had to reach 20N/mm<sup>2</sup> before the platforms could be lifted to the next level.

With the wireless thermocouple, the strength of the concrete could be viewed in real time in a phone application or on the website (Figure 12), instead of a more time-consuming operation using traditional thermocouples. The use of this innovative technology enabled striking of the formwork just in time,

ensuring compliance with the specifications and bringing significant programme savings.

### Logistics and public interface

The central location of the project adjacent to the busiest high street in Europe, with more than 300 000 pedestrians every day and more than 100 buses every hour, imposed a logistical challenge. To overcome this, the construction team employed the latest technology in booking and tracking vehicles to plan and coordinate just-in-time deliveries.

All the deliveries were booked using a logistics management system (Juggler) and discussed in a daily coordination meeting between all the trades working on the

project. This was to ensure that adequate space was available on site, as well as crane availability to offload the deliveries. The vehicles were also tracked using GPS technology to ensure the precise delivery time was known and to prevent clashes with other deliveries or other works on site.

Due to the sequence of works, the internal formwork panels in the Goslett Yard Box had to be sent off site during the construction of the slabs. Instead of sending them to the supplier's yard, they were temporarily stored in a nearby yard owned by Laing O'Rourke. This initiative contributed to a significant reduction of CO<sub>2</sub> emissions (Table 2).

The day-to-day interface with the public and the numerous businesses and



**Figure 12**  
Real-time maturity graph using wireless thermocouples

TABLE 2: SAVINGS IN CO<sub>2</sub> EMISSIONS FROM USE OF LOCAL YARD FOR STORAGE OF FORMWORK PANELS

	Storage of formwork panels in supplier's yard in Rugby	Storage of formwork panels in Laing O'Rourke's yard in Westferry Road
Total distance for return trip	270km	22km
CO <sub>2</sub> emissions per km*	1.852kg/km	1.852kg/km
CO <sub>2</sub> emissions per return trip	500.04kg	40.74kg
Total number of trips for GYB construction	21	21
Total CO <sub>2</sub> emissions	10 500kg	856kg
<b>Total savings in CO<sub>2</sub> emissions</b>	<b>9644kg</b>	

\* Data from Environment Agency's Carbon Calculator based on average 15t load per trip

stakeholders around Tottenham Court Road caused both logistical issues and operational challenges during the construction works. Generation of noise and vibration is an unavoidable outcome of the construction works for a complex infrastructure project. To minimise the impact on the local stakeholders, continuous liaison, early engagement and mutual understanding of each other's needs was fundamental.

For example, adjacent to the Western Ticket Hall site there is a school and a recording studio which could potentially have been impacted by noise and vibration during exam periods and music recordings, respectively. The construction team and stakeholders worked closely together so that exam dates and recording sessions were embedded in the construction programme, ensuring that noise and vibration during those times were kept to a minimum. An example of this was all demolition work below ground ceasing during recording sessions, as the vibration generated by the activity interfered with the recording equipment.

### Conclusions

The construction of the two ventilation towers at Tottenham Court Road posed myriad technical and non-technical challenges. The scale of these towers, their onerous architectural specifications, in conjunction with their central location and the strict programme requirements, made these structures complicated projects in themselves. However, with a commitment to succeed and to resolve the technical challenges, the Laing O'Rourke engineering team (Figure 13) worked closely with the client and designers to implement new ways of doing things to improve safety, efficiency

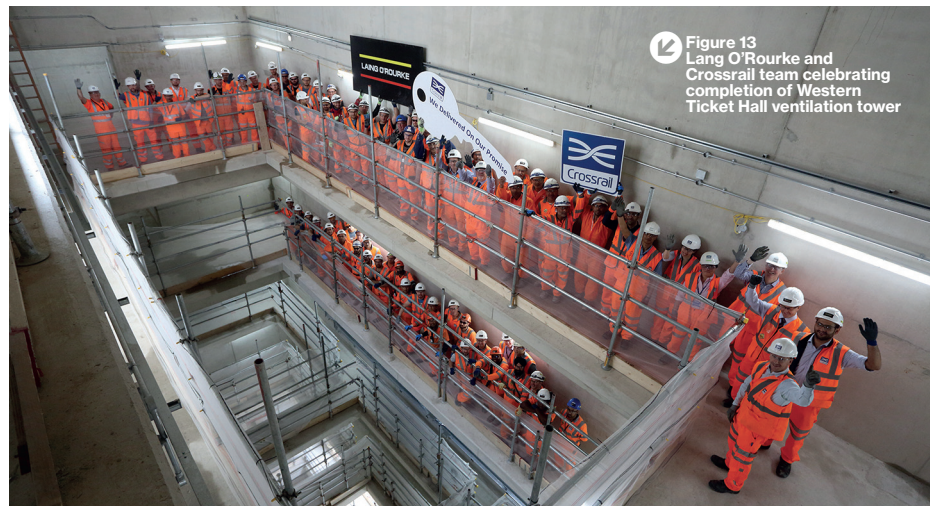


Figure 13  
Laing O'Rourke and Crossrail team celebrating completion of Western Ticket Hall ventilation tower

and productivity.

The interface with the public and the local population imposed logistical and operational challenges to the site. These were overcome through continuous engagement with the stakeholders and the team's aspiration to minimise the impact on them and their businesses.

The experience gained from the construction of these ventilation towers, which is shared in this paper, will be valuable on other projects across the industry and on the future extension of Tottenham Court Road station to accommodate Crossrail 2.

## "EXAM DATES AND RECORDING SESSIONS WERE EMBEDDED IN THE CONSTRUCTION PROGRAMME"

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