Structural design of the new Exhibition Road Quarter at the Victoria & Albert Museum, London

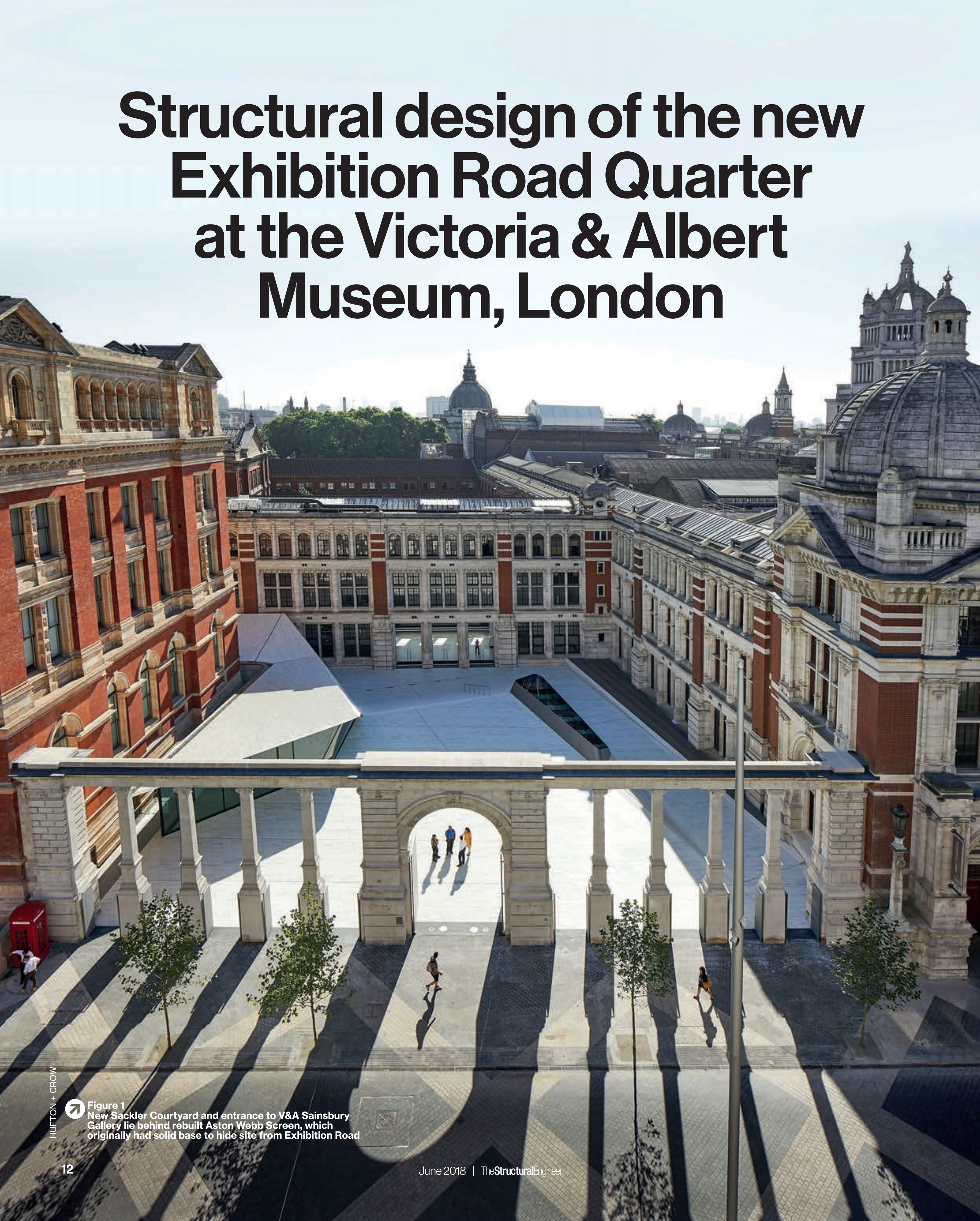

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Figure 1
New Sackler Courtyard and entrance to V&A Sainsbury Gallery lie behind rebuilt Aston Webb Screen, which originally had solid base to hide site from Exhibition Road

Alice Blair
MA, MEng, CEng, MIStructE, MICE
Senior Engineer, Arup, London, UK

Carolina Bartram
MA, MDesS, CEng, MIStructE
Associate Director, Arup, London, UK

Ed Clark
MEng, CEng, FIStructE, MICE
Director, Arup, London, UK

Introduction

Designing deep basements for buildings in historic city-centre locations is always a challenging proposition. The Exhibition Road Quarter project at the Victoria & Albert Museum, London – providing a new entrance, courtyard and purpose-built gallery for temporary exhibitions (Figure 1) – was no exception.

The new Sainsbury Gallery is situated in a 15m deep basement on a site bounded by Grade I and II* listed buildings with unusual and fragile facades. Artifacts sensitive to movements and vibrations are housed in these buildings, and the museum had to remain open throughout the works.

The structure that supports the courtyard is the roof of the basement; this is a 'folded plate' steel structure spanning 36m across the site to create a 1100m^2 column-free gallery below ground. Expressed steel transfer beams and columns support an existing museum building as the main entrance staircase passes underneath. Access to the gallery is via the porcelain-tiled entrance courtyard, known as the Sackler Courtyard, the world's first public space to be paved in this way.

Sophisticated three-dimensional (3D) analysis, digital design and optimisation methods, together with early considerations of buildability and construction sequence, were important to understand the structural actions, and reduce the risks during construction, of this ambitious project. These techniques allowed the structural design to be visualised, understood and communicated in a way that enabled architects, engineers, the client and contractors to participate in its development.

Working with Amanda Levete's architectural practice AL_A, Arup provided multidisciplinary design services from competition stage through to completion of construction. This article discusses the key structural engineering challenges of the project.

Competition brief

The Sainsbury Gallery is in what used to be called the Boilerhouse Yard. Sir Aston Webb, who designed the principal museum buildings, originally intended this to be a courtyard, but when it instead came to be used for the museum's boilers and coal deliveries, he designed a solid rusticated wall, now known as the Aston Webb Screen, with Portland stone columns and an entablature above to hide these back-of-house areas from neighbouring Exhibition Road. When the boilers were removed, the space continued to be used as a servicing hub for the museum (Figure 2). The site slopes in both directions and the buildings that were on and around the site were founded at levels that varied by up to 6m.

The V&A's design competition brief asked for a large column-free gallery, with a minimum floor-to-ceiling height of 5m, to be built on this site within a scheme that would reveal the facades of the surrounding buildings to visitors. This meant the gallery and associated facilities would have to be largely underground. AL_A's winning scheme comprised a courtyard, cafe and shop at ground level, the gallery one level below, with back-of-house facilities beneath the gallery floor for storing and preparing exhibits (Figures 3 and 4).

At competition stage, various configurations, materials and systems were considered for the gallery roof. The eventual choice was a folded, almost origami-like structure, spanning over the exhibition area, which defined the architectural character of the space (Figure 5). This versatile geometry was developed to reconcile the differences in levels across the site, and creates the significant structural depth required to span across the 36m site while providing a feeling of much greater headroom than the 5m minimum.

The roof was profiled to create an efficient structural system that would support both the courtyard and an additional mezzanine, as well as prop the retaining walls of the column-free gallery space below. It was perforated with large skylights to allow daylight to penetrate the basement areas.

Access to the courtyard was created by opening up the Aston Webb Screen: retaining the columns and entablature but opening up the solid wall, with new piers between the courtyard and Exhibition Road.

Structural design

Turning the folded plate concept from a competition-winning idea into a buildable reality was just one of many structural engineering challenges presented by this project. When the design moved from competition to concept stage, the client and design team explored the brief and design in detail to clarify what the fundamental elements of the project were and to balance the architectural scheme and client brief against the pragmatic and economic requirements.

It became clear that the team needed to maximise the internal floor area of the basement, so the structural and

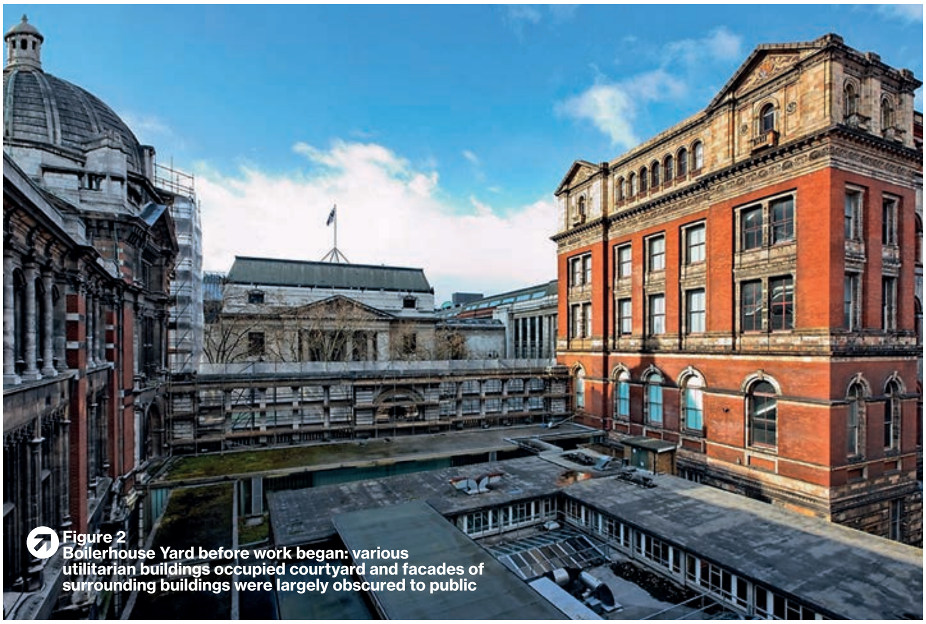

Figure 2
Boilerhouse Yard before work began: various utilitarian buildings occupied courtyard and facades of surrounding buildings were largely obscured to public

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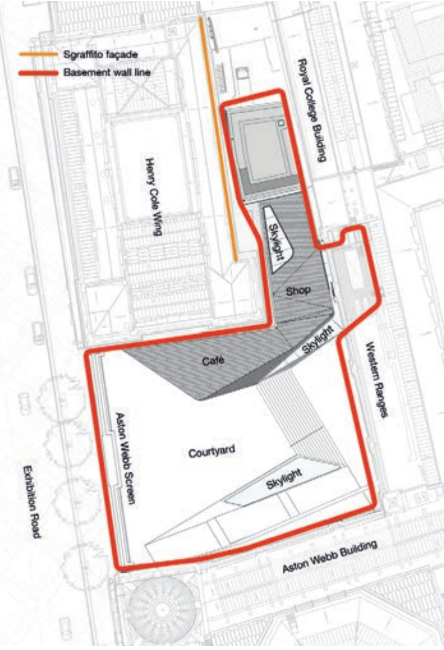

Figure 3 Diagram of 'L' shaped site: museum shop, back-of-house areas and services access are in narrow gap off courtyard

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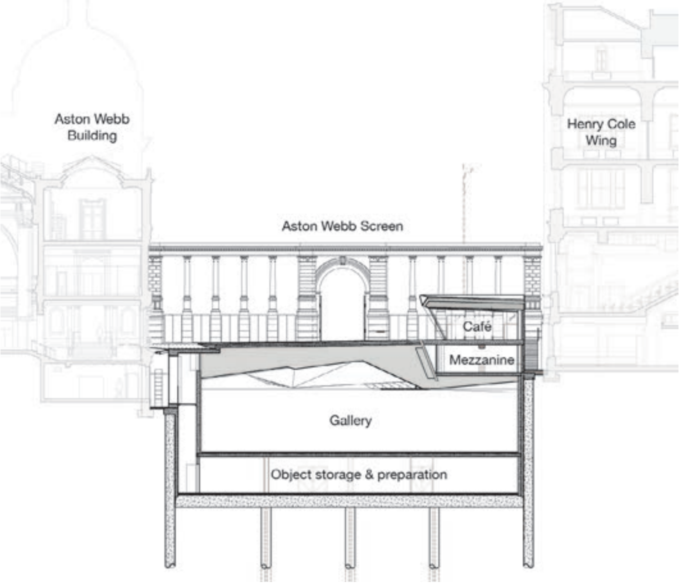

Figure 4 Section of basement with Aston Webb Screen shown in background. Basement extends under Western Ranges (not shown)

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geotechnical design had to consider how close the basement walls could be located to the facades of the existing buildings. The basement also had to extend under the existing Western Ranges museum building, since the stairs to the new gallery had to be located there.

Early consideration of construction sequencing was essential to ensure the museum could remain operational throughout the works and to limit the effect of ground movement on the existing buildings during construction. Other key considerations included how to manage the varying formation levels of the existing buildings and the longer-term effects of ground heave.

Courtyard roof design

The structural design developed during concept stage for the courtyard structure introduced a deep primary truss running along the side wall of the mezzanine that acts as intermediate support for the folded roof. This allowed the depth of structure under the mezzanine to be minimised, and since this was the pinch point for height, it also minimised the basement excavation. After exploring various options, a series of 3D steel trusses was chosen because they were lightweight, simple to connect on site, and provided the most flexible solution for integrating lighting and other high-level services into the gallery ceiling. The mezzanine and courtyard floor slabs, on metal deck, span over the trusses.

At concept stage, simple models were used to review the efficiency of the structural options associated with the geometry: from the lean of the main truss off-vertical, to the depth and different potential geometric forms of the folded plate (Figure 6). The concept design was then transformed into a full 3D geometrical process with AL_A, in order to coordinate and examine the geometry. This was done via a shared Rhino[1] model which used the Grasshopper[2] plug-in to adapt the folded-plate geometry (depth of structure at various locations, widths of trusses) (Figure 7). The model was brought into Oasys GSA[3] for analysis which in turn linked to an Excel optimiser (Figure 8).

The GSA analysis needed to take into account both vertical loads and also the lateral loads the structure had to resist to prop the retaining wall. Due to the slope of the site in both directions and the large openings in the courtyard slab to let in daylight, there was no simple continuous horizontal diaphragm that could be formed to resist these loads.

The objective of the structural optimisation was to reduce the overall steel tonnage without introducing unnecessary complications to the fabrication and erection process. Angles of the bracing were controlled to simplify connection geometry and the number of different section sizes adopted was limited. Furthermore, the design moved from initial geometries requiring complex sequencing or significant temporary propping towards fabrication of fully stable elements which

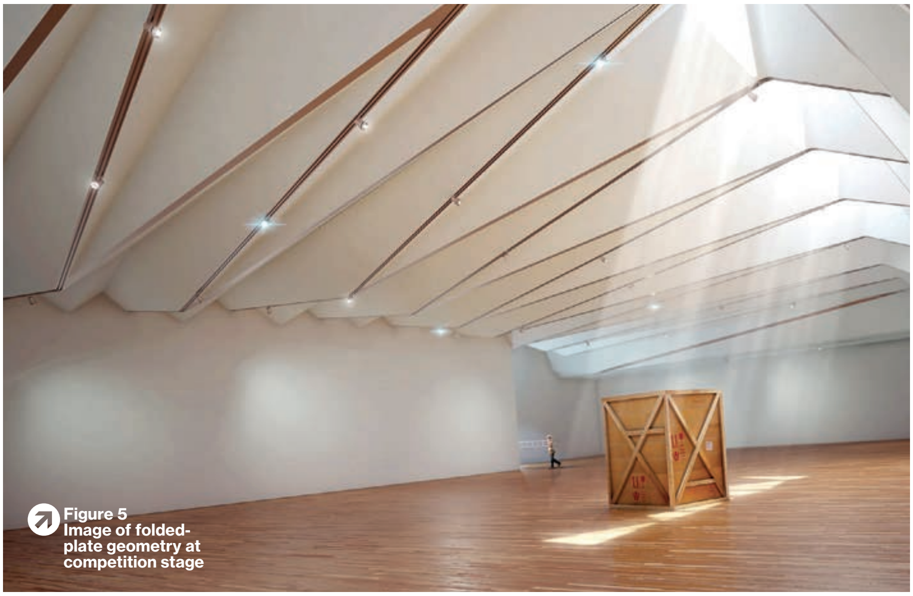

Figure 5 Image of folded-plate geometry at competition stage

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could be installed on site in one lift (Figure 9).

The design process saved approx. 40% of the steel weight of the original concept design.

Basement design and sequence

The achievable floor area within the new building was dependent on the thickness of the perimeter basement wall and how close it could be built next to the existing buildings.

Control of retaining wall deflections during construction was critical because settlement behind the retaining walls could result in damage to the surrounding masonry buildings, which were heavy, yet fragile – these included very fine joints, decorative plaster details, and ceramic and terracotta elements. The pressure from the foundations due to the weight of the masonry buildings close to the top of the new retaining walls was a critical consideration in the way the basement walls were designed.

A hard-firm secant pile retaining wall was selected, constructed using rotary bored piling rigs with temporary casings toed into the London clay due to the presence of perched water in the gravel layer above the clay. In the main courtyard area, the wall is formed from 880mm nominal diameter piles. In the final condition, these piles span vertically up to 11m. In the constrained spaces of the smaller leg of the 'L' shape and under the Western Ranges, the wall thickness is reduced to 600mm.

"SIMPLE MODELS WERE USED TO REVIEW THE EFFICIENCY OF THE STRUCTURAL OPTIONS ASSOCIATED WITH THE GEOMETRY"

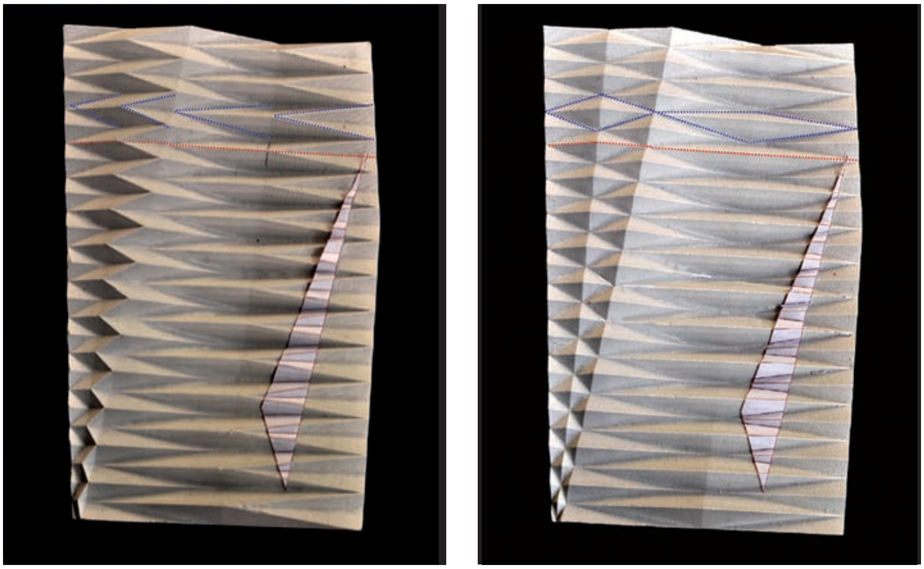
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Figure 6
Physical models for examining different geometries

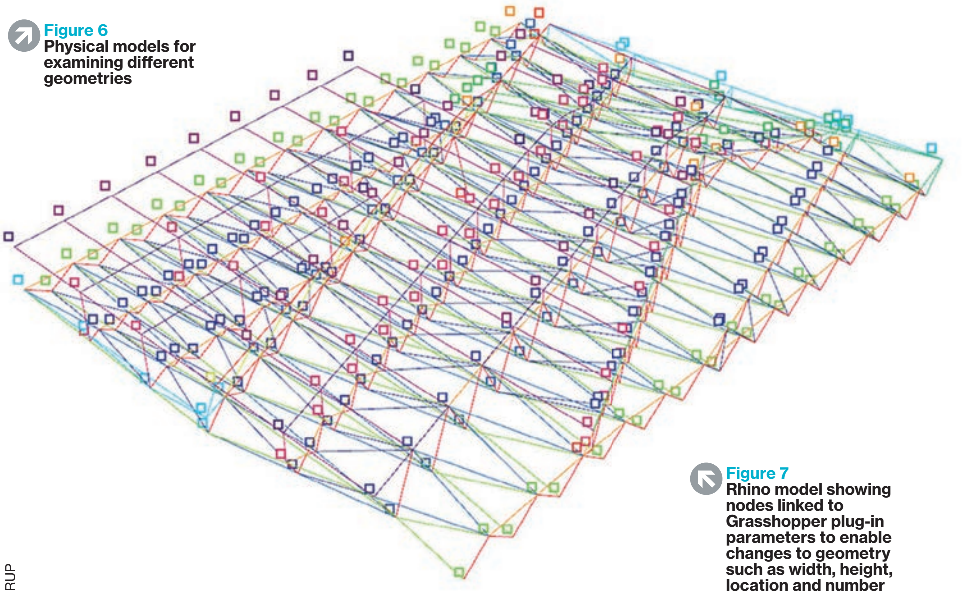
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Figure 7
Rhino model showing nodes linked to Grasshopper plug-in parameters to enable changes to geometry such as width, height, location and number of folds

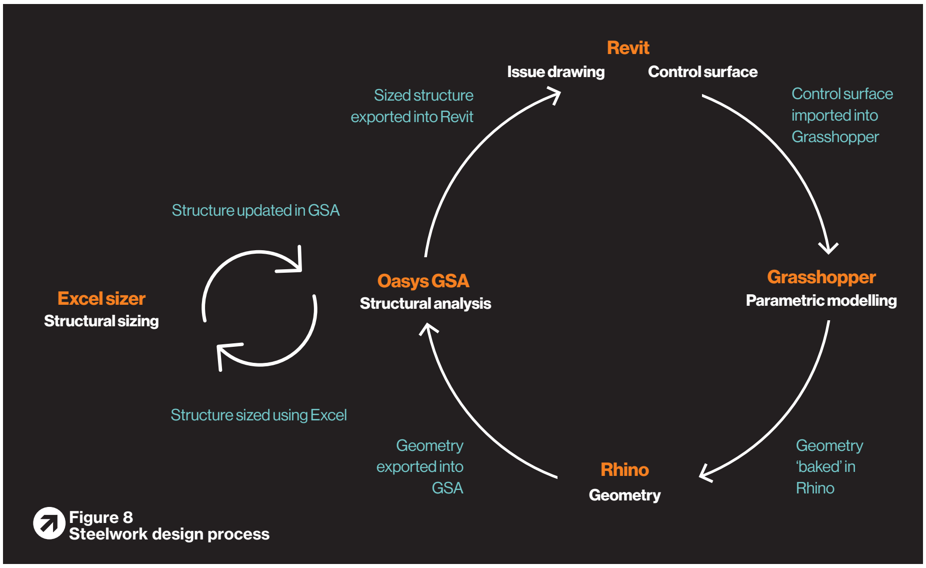

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Figure 8
Steelwork design process

Arup developed a good understanding of what the tightest possible limits were, by combining information from measured surveys of the facades, and trial pits to find the existing footings, with pre-construction advice on clearances required by likely piling rigs. This also meant a high level of detail could be produced for tender so that contractors were fully aware of the risks and the care they would need to take.

When work began on site, the piling rigs operated to within 300mm of the buildings at their limits (foundations and cornices) (Figure 10). Success is demonstrated by the

Figure 9 Trusses being installed on site

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fact that the basement wall was constructed to the Arup setting-out without change or any impact damage to the neighbouring buildings.

In the courtyard, a semi-top-down sequence was proposed and adopted to minimise cost and risk (Figure 11). Temporary props were used at the top of the walls across the main box, followed by excavation to gallery floor level using the construction of the gallery floor slab to prop the walls at mid-height since these were stiffer (and less costly) than a second row of props. Moling holes were provided for further excavation below the slab to formation level (Figure 12). In the narrow 'dog-leg' area of the site, construction was bottom-up with four levels of props to control ground movements.

A staged 3D finite-element (FE) geotechnical model was created at scheme design stage to refine the temporary propping arrangement and excavation sequence, and to predict ground movements due to excavation in more detail; it did not include effects of pile installation. The model was created using the geotechnical software LS-DYNA[4], with the advanced BRICK model[5] representing the soil behaviour.

The model showed that two main factors influenced the predicted settlements of the ground outside the excavation and the

> **"WHEN WORK BEGAN ON SITE, THE PILING RIGS OPERATED TO WITHIN 300MM OF THE BUILDINGS AT THEIR LIMITS"**

Figure 10 Piling rigs operated to within 300mm of existing buildings

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Figure 11 Semi top-down construction

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Figure 12
Top-down construction under gallery slab

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existing buildings. The first factor was the secant pile wall design: the stiffness of the wall itself, and the stiffnesses and levels of the temporary and permanent basement props. The second factor was ground heave. This latter effect is particularly significant in the courtyard area where there is minimal gravity load to counteract the long-term heave due to the 18m of bulk dig.

Heave board or sub-slab drainage to reduce pressures under the base slab were ruled out as the FE model showed they could increase the predicted settlements of the surrounding buildings to an unacceptable degree. Instead, a piled raft with heave-reducing tension piles to control deflections was adopted. The 12 piles are located on a grid of 8–9m centres and extend 34m below the raft, with plunge columns installed on each pile to support the 300mm thick gallery floor slab.

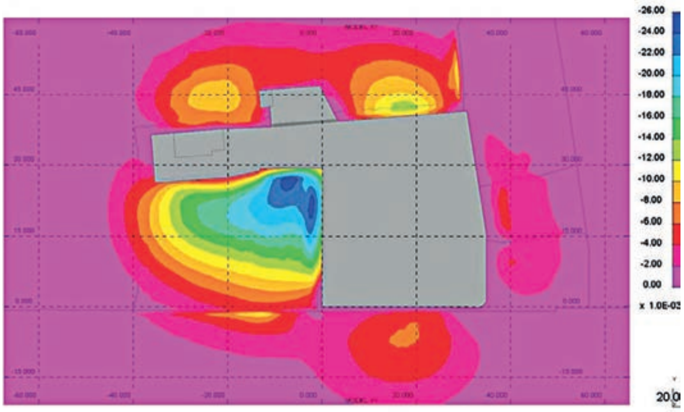

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Figure 13
Total greenfield vertical ground movement prediction from bulk excavation to long term from LS-DYNA model

In collaboration with the Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge, the heave effects will be measured as part of a long-term research project. Fibreoptic monitoring systems have been installed in two of the tension piles and within the basement raft. The development of tension in the piles and bending in the raft will be monitored and calibrated against the 3D models to achieve a better understanding of the phenomenon of heave. This use of fibre optics is a pioneering example of how we can use actual buildings to inform future design.

The 3D FE model was used to consider all aspects of the basement geometry and model key construction stages to predict building movements, and from these predict crack widths and the potential for damage. Because the model showed how important the wall stiffness and levels of the temporary props would be, Arup designed all the piles and defined the assumed construction sequence, stiffness, strength and levels of temporary props in the tender information.

Arup specified a detailed system of movement monitoring which included surveying the building using 3D prisms on facades and BRE levelling studs within the buildings, extensometers in the ground and inclinometers in the secant piled wall. These were all monitored regularly throughout the construction process and tracked against pre-set trigger levels at each location for each stage of construction.

Between the end of piling and the end of construction, the measured vertical building movements were less than 10mm, compared with up to 25mm of greenfield movement predicted (Figure 13). Settlements due to piling installation were in addition to this.

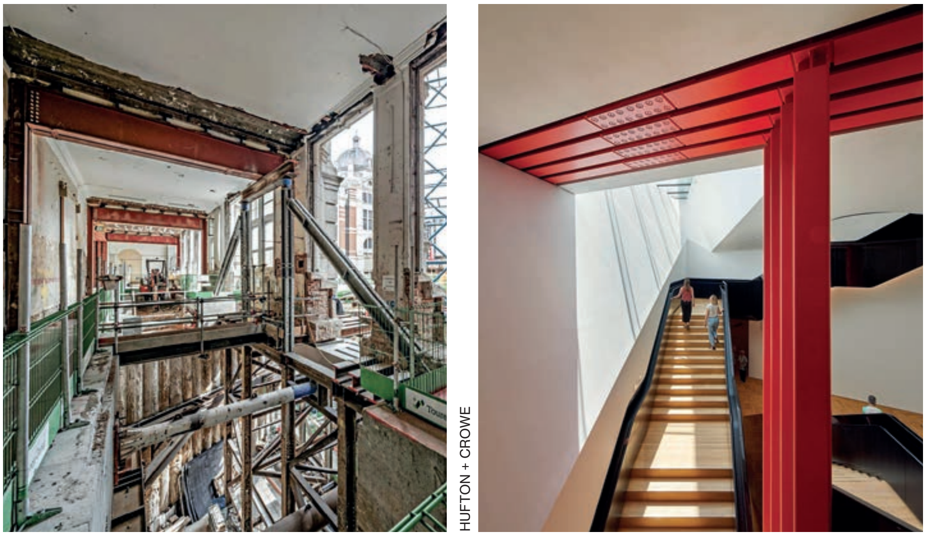

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Figure 14
Construction of stairs to gallery, within listed Western Ranges building, was carefully planned and meticulously executed

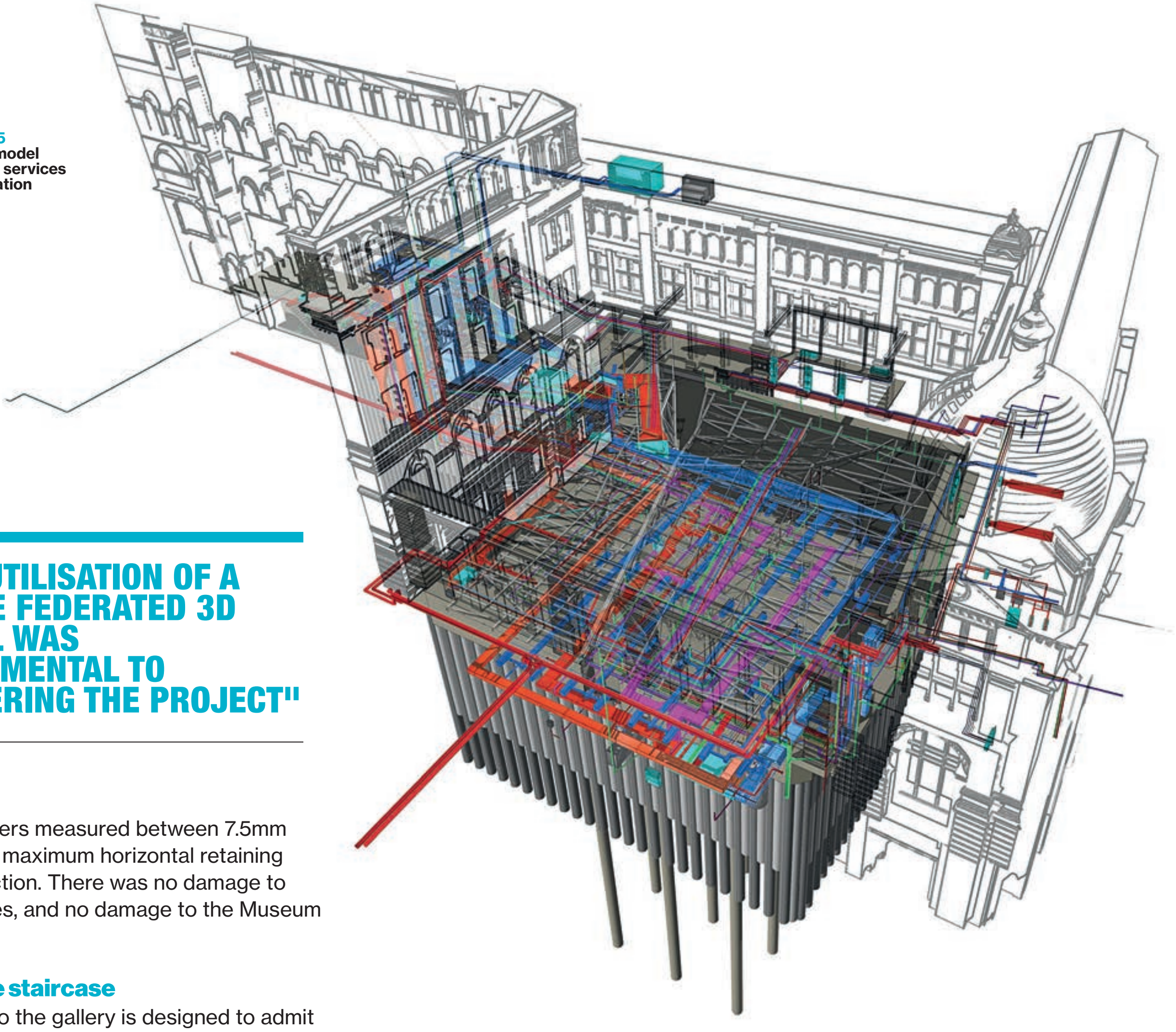

Figure 15
Design model showing services coordination

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"THE UTILISATION OF A SINGLE FEDERATED 3D MODEL WAS FUNDAMENTAL TO DELIVERING THE PROJECT"

Inclinometers measured between 7.5mm and 15mm maximum horizontal retaining wall deflection. There was no damage to the facades, and no damage to the Museum collection.

Entrance staircase

The stair to the gallery is designed to admit light and afford views of the sgraffito facade and the dome of the Aston Webb building. To avoid encroaching on the gallery space, this stair (and a passenger lift) is accessed from a two-storey basement beneath part of the Western Ranges building, connected to the rest of the basement through the original facade line.

Major temporary works and a specific construction sequence were needed for the stairwell because of the requirement to support the loadbearing wall of the building above, and the restricted working space. A low-headroom piling rig and temporary plunge columns were used. The plunge columns supported temporary steelwork that in turn supported the three-storey masonry facade, internal floors and walls of the Western Ranges building from ground level upwards during excavation.

The permanent structure consists of four steel transfer beams, which span between two sets of four double-height steel columns and the basement walls. The contractor's preferred sequence was to install the beams early until the columns could be built after excavation. Temporary transverse propping of the retaining walls was also needed and threaded through circular holes cut in the webs of the transfer beams (Figure 14).

3D modelling

The utilisation of a single federated 3D model (Figure 15) – initially owned by the design team and then by the contractor – was fundamental to delivering the project given the tight site and complex geometries. The model incorporated a 3D survey of the existing buildings as well as the new construction.

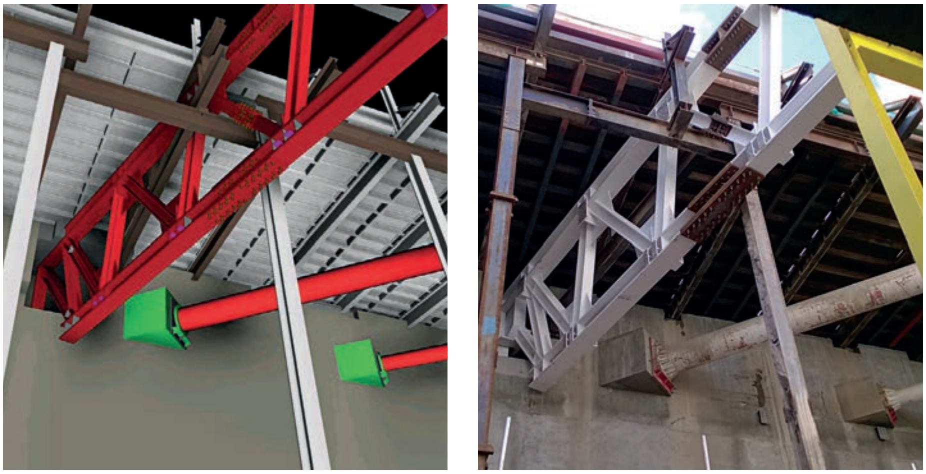

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Figure 16
3D model and actual construction for propping and truss coordination

In particular, the coordination of temporary works with the permanent steel and concrete structure would have been very difficult without the use of 3D models, which were refined at various stages of the construction process (Figure 16). The use of a joint building information model (BIM) allowed the team to review the large temporary props and their relationship to the trusses and other elements of structure at different stages, and to model how they would be removed.

By combining the process of optimisation with a review of construction methodology, the concept-stage structure, which had at one point seemed very complex to build, became one for which the fabrication, structural action at all stages of construction, and installation were well understood. This greatly minimised risks and increased speed of delivery.

Summary

This was an ambitious project from the outset, but the design intent and brief from concept stage were very clear. Best-practice use of automation, optimisation and collaborative digital processes helped the team to successfully understand, design, coordinate and construct this complex building on a challenging site. The project delivered the concept (Figure 17), minimised risk during construction, and combined demanding geometrical and structural analysis with care, pragmatism and understanding to exploit this challenging site to its full potential.

Project team

Client: Victoria & Albert Museum
Structural engineer: Arup
Architect: AL_A
Main contractor: Wates Construction
Basement propping and Western Ranges temporary works design: Wates Engineering
Piling: Keller Foundations
Specialist low-headroom piling: Martello Piling
Demolition, groundworks and substructure: Toureen Group
Structural steelwork: The Bourne Group

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Figure 17
Completed gallery space

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