ES11516

Leeds Station Southern Entrance

Ian Besford
Mott MacDonald

Jon Svikis
Mott MacDonald

Learning Objectives

- Discover the workflows required to integrate Rhino, Revit, and Robot Structural Analysis
- Learn how to use Robot Structural Analysis for second-order buckling analysis
- Appreciate how Navisworks can be used to engage with the site team and used to explain complex interfaces
- Appreciate the challenges of working in a confined site

Description

Leeds Station Southern Entrance (LSSE) is a signature new gateway entrance to the existing station in Leeds, United Kingdom. Constructed over the existing river between 2 residential tower blocks, and supported from the existing station structure and Victorian masonry arched viaduct, the site constraints alone make this a challenging scheme. When combined with the multiple curves of the architectural form, it presents a unique set of engineering challenges.

This class will be a case study covering how we've successfully used multiple Building Information Modelling (BIM) tools (including Rhino software, Grasshopper software, Robot Structural Analysis software, Revit software, and Navisworks software) to engineer a scheme that would be impossible without today's technology and to bring the existing and new build elements together seamlessly.

We will discuss the project constraints, the workflows used, and some of the challenges we overcame in design and construction.

Your AU Experts

Ian Besford *is an associate structural engineer at The Mott MacDonald Group with over 15 years of experience gained across multiple sectors. This experience included the then-pioneering use of digital modeling and visualization tools from the start of his career. Ian was instrumental in driving adoption of modern processes and technology across his team's delivery, leading to him taking the role of Building Information Modeling (BIM) champion for structural engineering. These skills and processes have most recently been applied to the Leeds Station Southern Entrance for which Ian is project director responsible for Mott MacDonald's delivery.*

Jon Svikis *is a Senior Structural Engineer at Mott MacDonald with over 10 years of experience in the design and delivery of complex structural engineering schemes across a range of sectors. As project manager for Leeds Station Southern Entrance he has been responsible for the design and delivery of the engineering scheme utilising a range of BIM tools and processes.*

Introduction

About Mott MacDonald

Mott MacDonald is a $2bn engineering, management and development consultancy. We use our ingenuity to create lasting value for all we work with – customers, communities and staff.

Our global business is multisector, spanning buildings, communications, defence, education, environment, health, international development, industry, mining, oil and gas, power, transport, urban development, water and wastewater; and it's multidisciplinary embracing planning, studies and design, infrastructure finance and technical advisory services, project and programme management, management consultancy, strategic asset management, forensic engineering and expert witness.

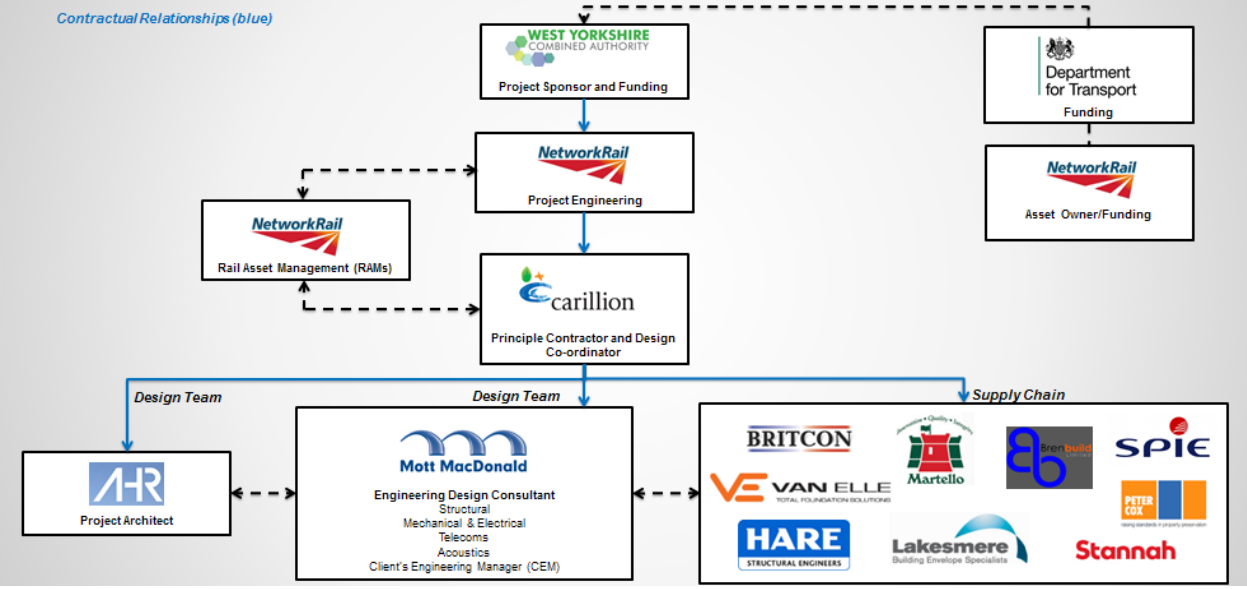
About Leeds and Leeds Station

Leeds is the third largest city in the United Kingdom after London and Birmingham. It is located in West Yorkshire and falls under the administrative remit of the West Yorkshire Combined Authority (WYCA). It was established over 1000 years ago and became a key industrial hub at the core of the Victorian railway network. That railway network enters Leeds from East and West along a masonry viaduct which cuts the city in two. The station is located to the North of the viaduct and opened on its current site in 1938. The station is the second busiest in the United Kingdom outside London (the first being Birmingham New Street, itself the subject of a multi million pound makeover). The station accommodates approximately 900 trains per day and over 100,000 passengers. This represents an increase of 25% over the last 5 years and traffic projections over the next ten years suggest this could increase by a further 50%.

The New Southern Entrance

The new southern entrance is designed to improve access to the station from the south of the city, reducing both journey times and congestion on the main station concourse. The new entrance is expected to benefit approximately 20% of the passengers currently travelling through the station. The new southern entrance has a striking architectural form and is intended to be a landmark structure for the region, highly visible and representative of the ongoing investment and regeneration in Leeds.

Mott MacDonald is working for Carillion Rail who are principal contractor for the scheme and are delivering it for Network Rail. Network Rail are both part funder, operator and client and are delivering the scheme for WYCA and Leeds Metro who are co-sponsors. The design team comprises AHR Architects, Mott MacDonald undertaking full engineering services including rail systems, telecommunications, structural engineering and building services engineering. The Carillion supply chain is extensive and shown in the organogram.



The scheme has had a considerable gestation period. The concept was developed in 2010 and received planning via the Transport and Works Act in early 2012. Mott MacDonald then worked with Leeds Metro to guide the scheme through a public enquiry before detailed design commenced in 2013. Construction commenced 2014 and the station will be operationally ready on January 2016.

The Existing Station

(KEY BELOW)

	Railway
	Existing station concourse
	Existing entrance
	Multi-storey residential accommodation
	River
	New entrance location
	Site compound
●	Bridges
●	Tower crane location

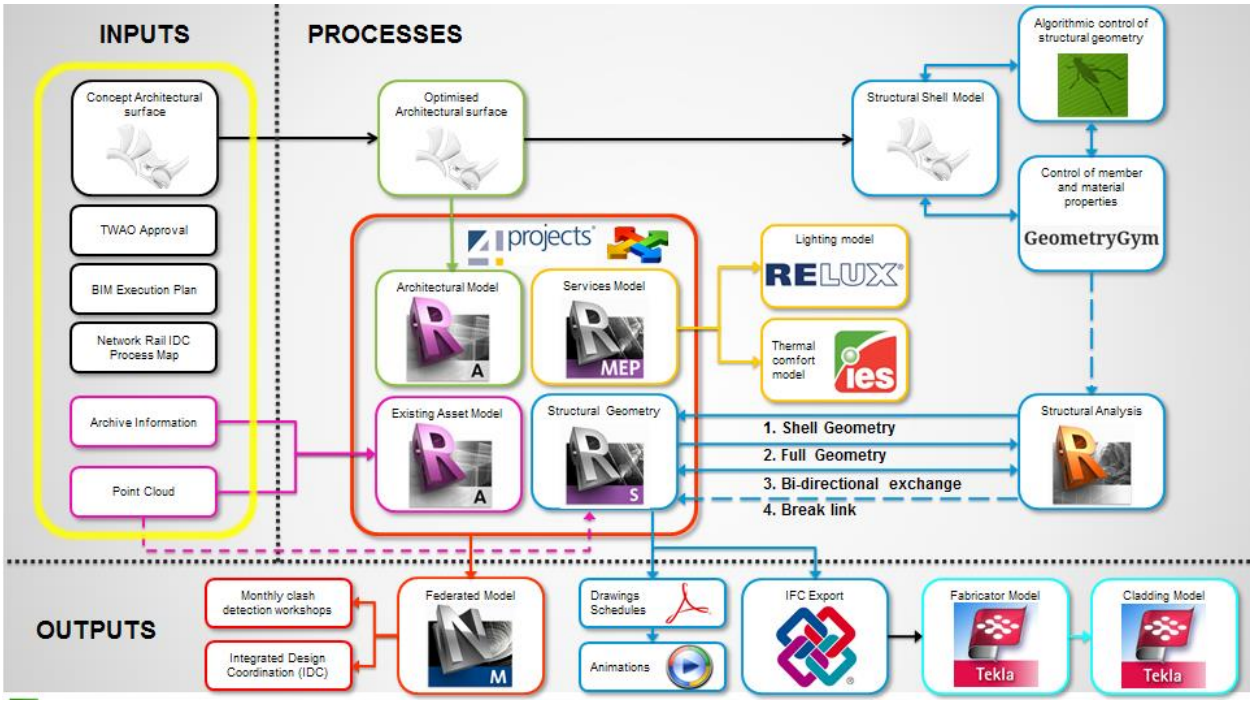
Execution Planning

Workflows

Key to the successful delivery of this scheme was planning the design and information exchange process. This process map captures the process we went through.

Each discipline is represented by a different colour, architecture in green, building services in orange, structural engineering in blue, fabrication in cyan and federated outputs in red.

It can be broken down into three sections, the inputs, the processes and the outputs. We will talk through each of these in turn.



BIM Execution Planning

Key to successful delivery of a BIM project is ensuring a robust execution plan is in place at commencement. The LSSE plan was authored by Carillion in conjunction with the whole project team. It encompassed the following items:

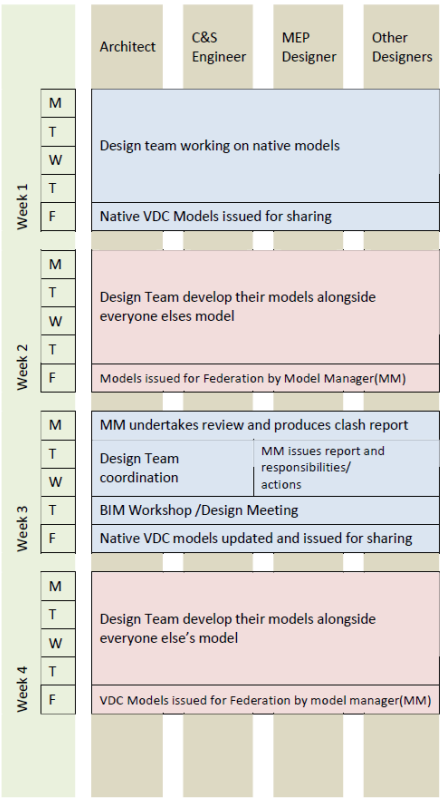
BIM scope – what purpose are we using BIM for

Naming Conventions

Volumetric responsibilities - Who models what? For example masonry and screed. Experience has shown this is key – we encountered multiple clashes because both us and architect modelled screed.

LOD – Define the required level at the right time.

Model management process – It is critical to agree timescales and process for model exchange. Our process is shown right and operated on 4 week cycle with bi-weekly exchange. The federated model was issued fortnightly and monthly reviews with team took place at DTMs.

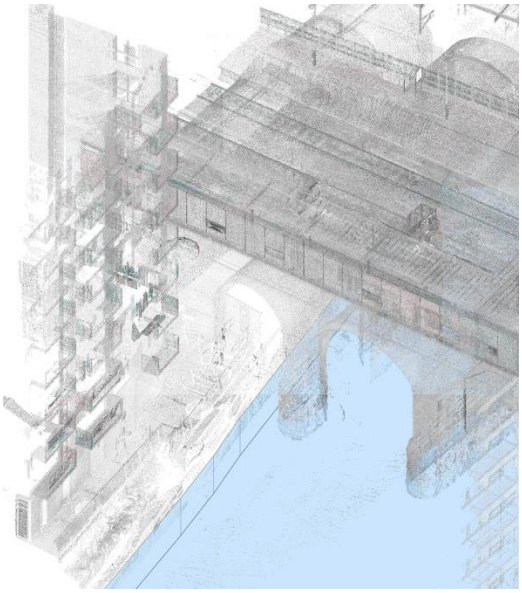


Important lessons learned from this included:

- Do follow the exchange cycle
- Do make it clear the status of information in the model
- Do talk outside of the model exchange process – its no substitute for communication in the real world
- Don't fudge things – don't overlay 2D information to hide inaccuracies in the model
- Don't add any information which isn't validated (particularly relevant with existing asset information
- Don't be afraid of trying things!

Capturing Existing Asset Information

As with many existing assets, existing information was available in multiple disparate places. Limited as-built information was available in archive of several elements, this was of variable quality and reliability. We took this information and supplemented it with geometry from a point cloud survey. This gave a geometrically accurate base for existing information. This was supplemented and validated with intrusive surveys and testing, including taking core samples of the viaduct masonry piers and barrel vaults, validating the existing roof steelwork sizes and thicknesses via traditional dimensional survey and ultrasonic measurements. Foundations verified via trial pitting, measurement and coring.



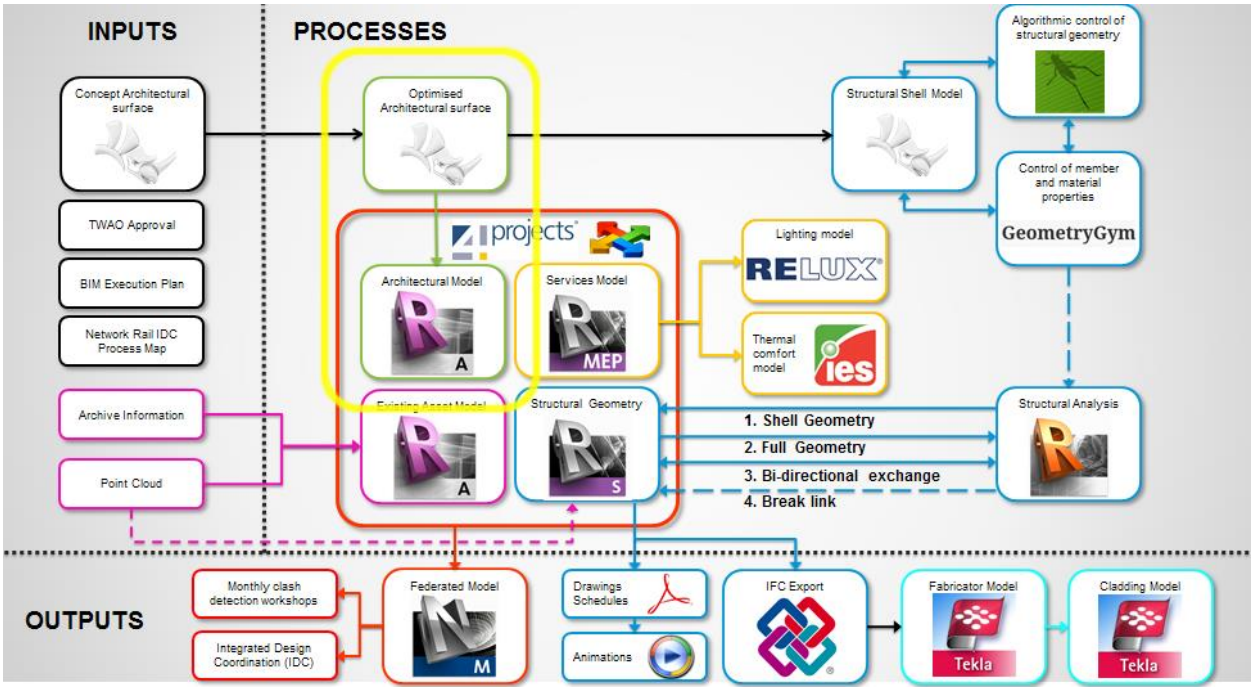
The benefits of the point cloud should not be underestimated in an environment like this. The operational constraints of the railway make traditional survey techniques time consuming and disruptive. The need to close the railway means works can only be undertaken during pre-arranged 8-10 hour possessions and surveys take considerable time. If any information is missing, filling in the gaps is equally disruptive. The point cloud is easy to complete and

accurate. It offers the critical ability to check dimensions without having to revisit site. However they are also large files and are unwieldy to use all the time. They also provide a different aesthetic when it comes to visualization.

In this instance the architect created an as built model form the point cloud in Revit. This was focused on the key interfaces with the new structure and was ideal for visualisations and gross coordination. However it was not good for detailed coordination especially around the masonry elements. Models were created to planar elements and rationalized curves, particularly in the barrel vaulted masonry there was a sizeable discrepancy which could have caused problems when fabricating interference fit elements. In these areas we reverted back to the point cloud for setting out.

Rhino, Grasshopper, Geometry Gym and Robot

Workflows

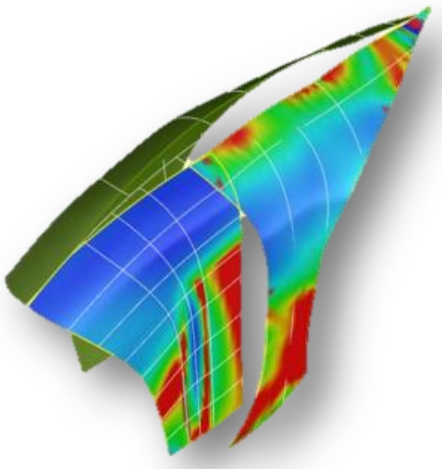


We are now at this section of the workflow and the focus has shifted from capturing the existing asset information to how we create the geometry of the new entrance building. This occurred in two main phases, firstly refinement of the original architectural concept geometry and secondly creation of a structural shell model based on this geometry. This then formed the basis of the authoring model.

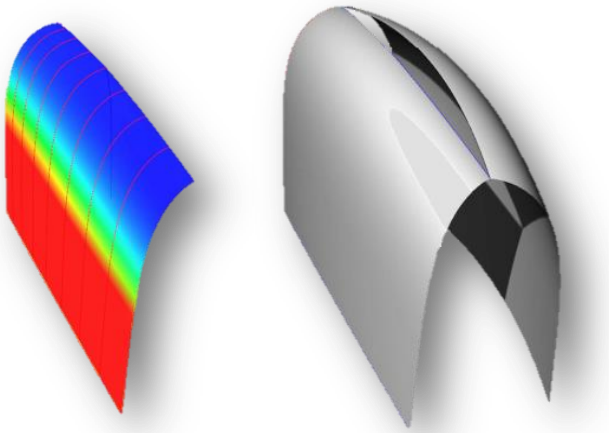
Geometrical Refinement

The original geometric form was developed by the original concept architect. This was developed into the final form using the following process:

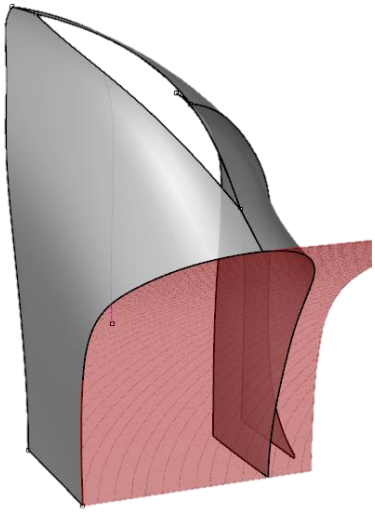
Original architectural surface taken into Rhino.



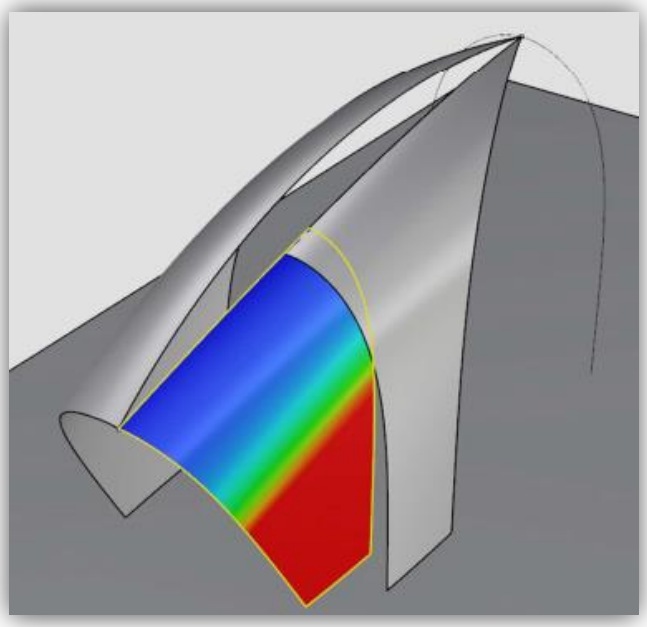
Curvature analysis undertaken on original surface to establish complexity.



Base form remodeled using repetitive simple curvature to simplify the shape whilst retaining the intent. This was necessary due to the constraints of fabricating steelwork – each radius has to be bent separately so the most economic solution is as few and as consistent radii as possible.



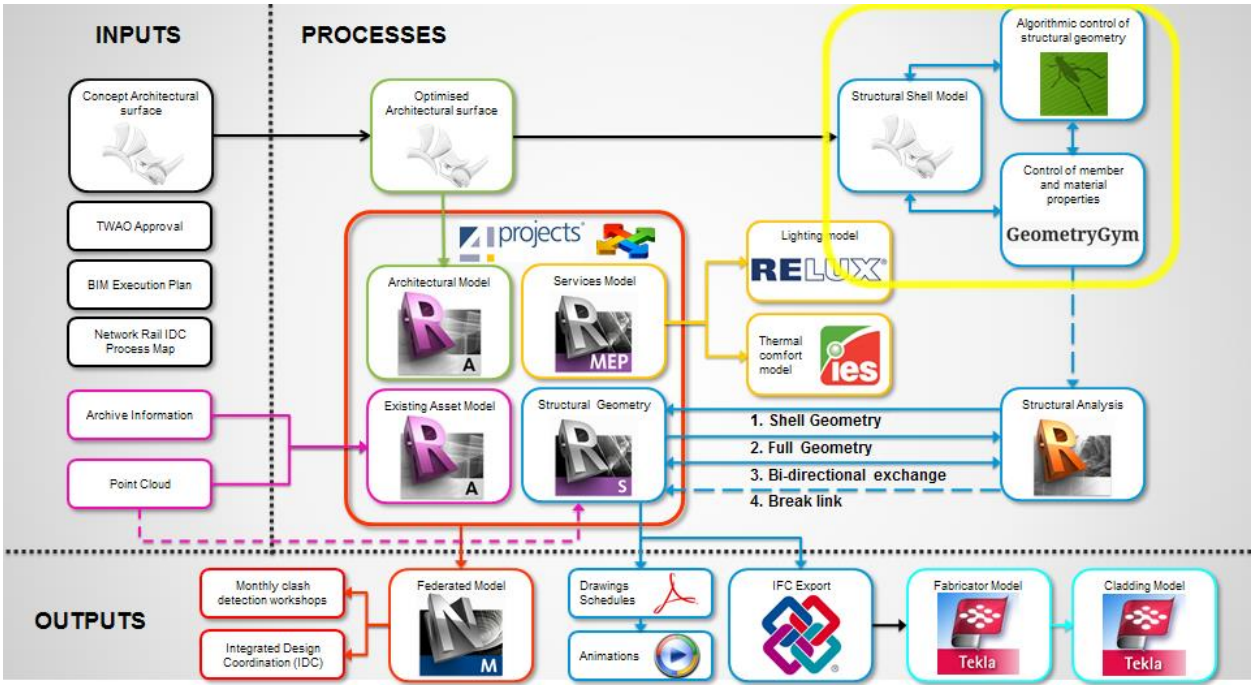
Having established the base shape the structure was regenerated by cutting into the base shape with geometrically defined forms.



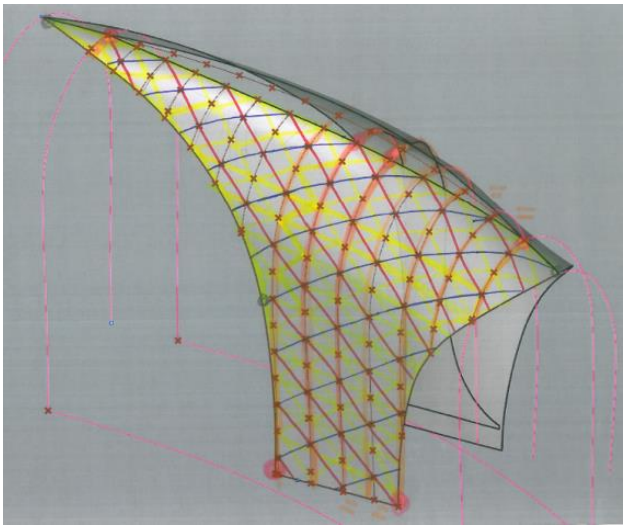
The cut back to the east side was then recreated using the same methodology. Although introducing complexity this was necessary as the shape was restricted by the TWAO approval.

Structural modelling

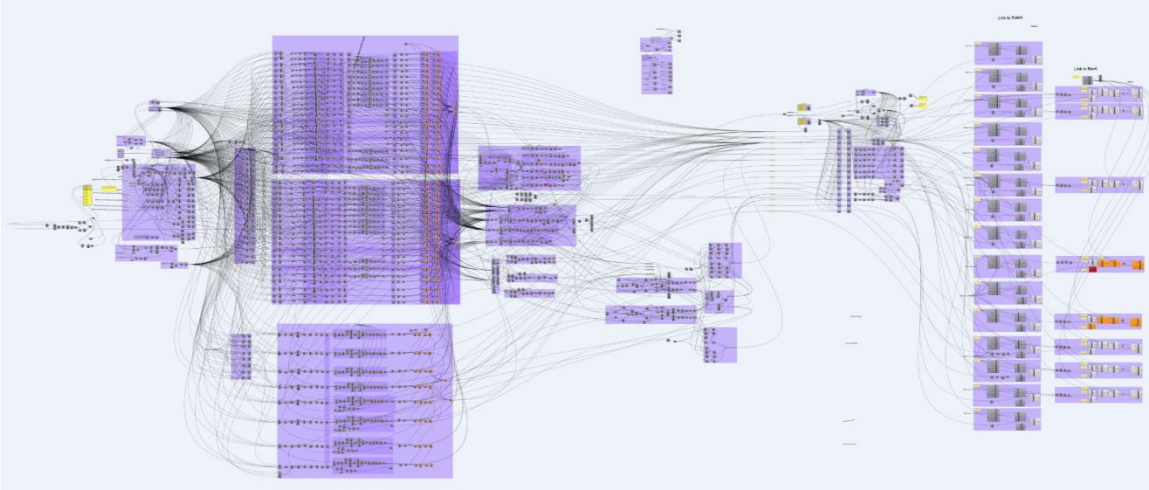
Having developed the architectural form, we moved onto generating the structural frame. This is captured in this part of the workflow.



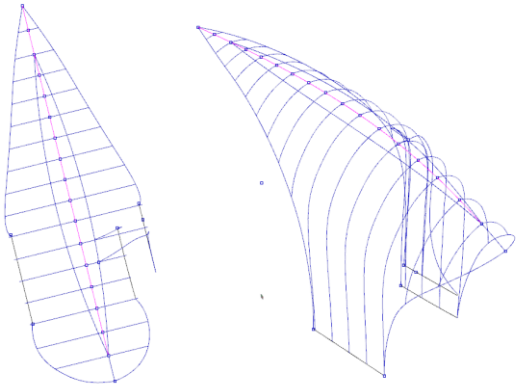
The initial thinking around the structural form at this stage was still conducted manually. Within a BIM workflow there is still a place for pen and paper. We were able to understand and define the fixed points in the structure – springing points of the arch, the nose, the tail, ends of the rooflight etc. These led to some key structural decisions about form. We arrived at a series of hooped steel members looping over the shell which were braced out of plane by a diagrid structure. This has inherent stability and stiffness and was sufficiently aesthetically pleasing that the architect was willing to omit the internal lining and expose the structure. It was also the most structurally efficient solution as one of the key design criteria was to limit the depth of the structural zone to 400mm. This was necessary to ensure adequate space within the building for the escalators to fit whilst also being inside the approved building envelope. The original concept design did not meet this requirement which was a fundamental issue we had to resolve.



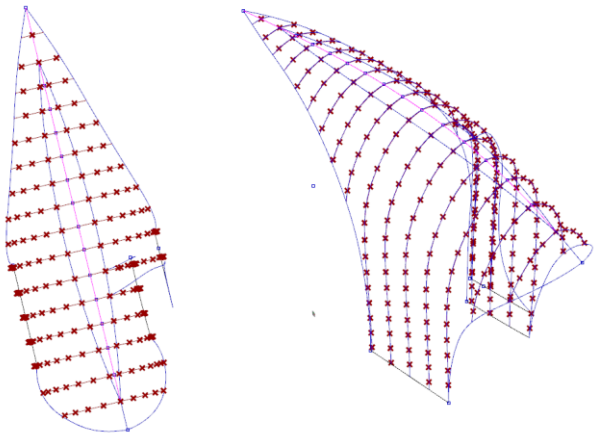
The constraints were hard coded into the structure within the Grasshopper script that was used to generate the structural geometry.



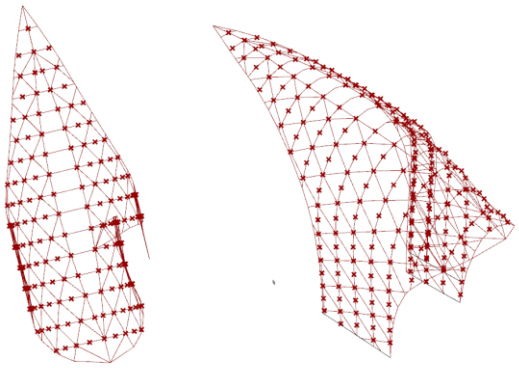
The remaining geometry (residual hoops, diagrid noding and spacing etc) were defined parametrically allowing us to optimize the geometry through iterating the design:



Boundaries defined with gridlines and primary hoop geometry automated to follow surface contours

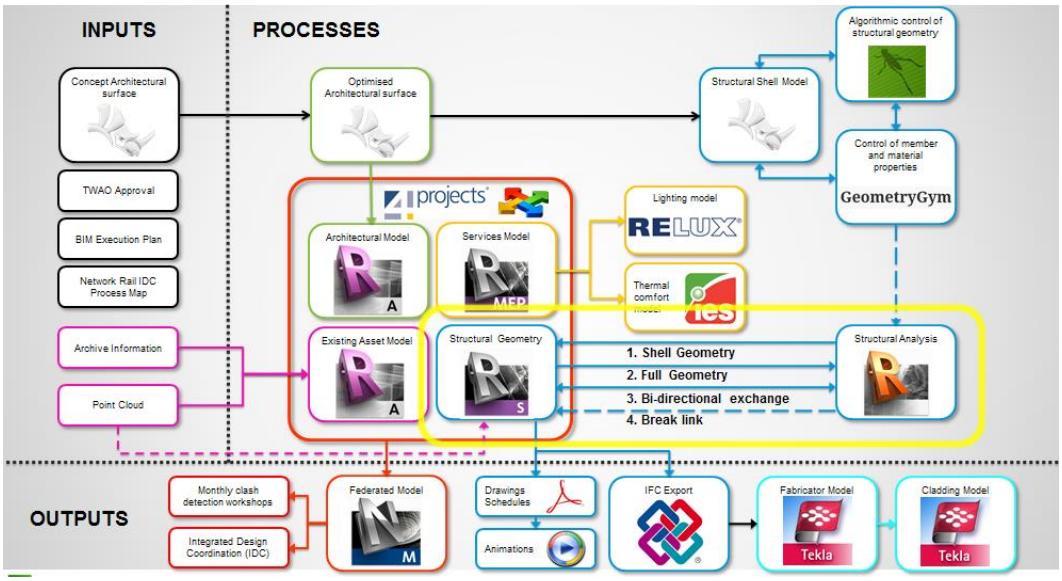


The hoops are then split into note points of variable spacing.



Diagrid members were then created automatically to follow surface. Grasshopper allows the diagrid geometry to be optimised parametrically and Geometry Gym allows member sections, materials and orientations to be defined. The geometry was then exported to Robot, noting that this was a one way trip only making it important to ensure the export was suitable and correct before moving on to the next analysis phase.

The robot model was then pushed into Revit and round tripped using the built in exchange functionality:

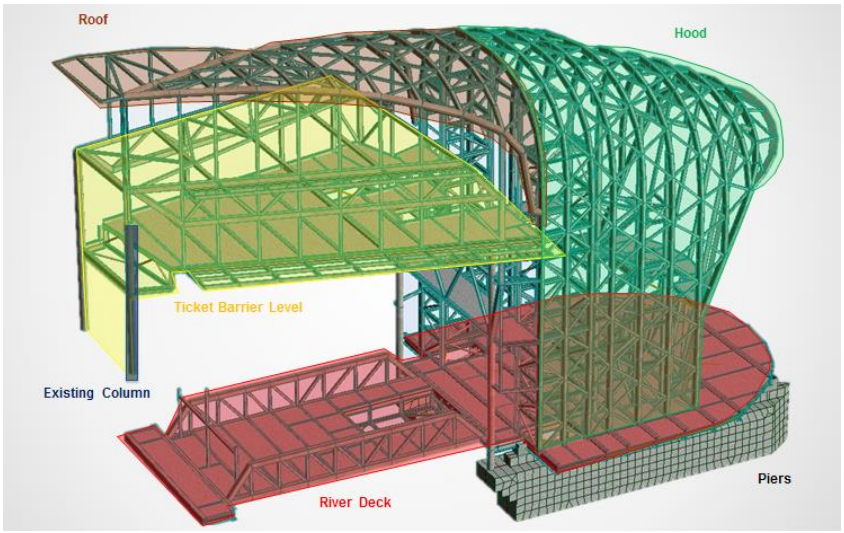


The Round tripping was used to locate the diagrid structure in the correct spatial location. This was then augmented with the other structural members in coordination with the Architectural and building services models and pushed back to Robot to analyse. We also used the functionality in Robot to model the structural frame and to refine the geometry – our experience of the software then (2013 versions) was that the geometry manipulation tools in Robot were superior to Revit. Eventually the structural frame was frozen and analysed and pushed back to Revit. At this point the link was broken as we introduced secondary steel elements which we did not require in the Robot model and the analysis was complete therefore the link was redundant.

Structural Interfaces and Coordination

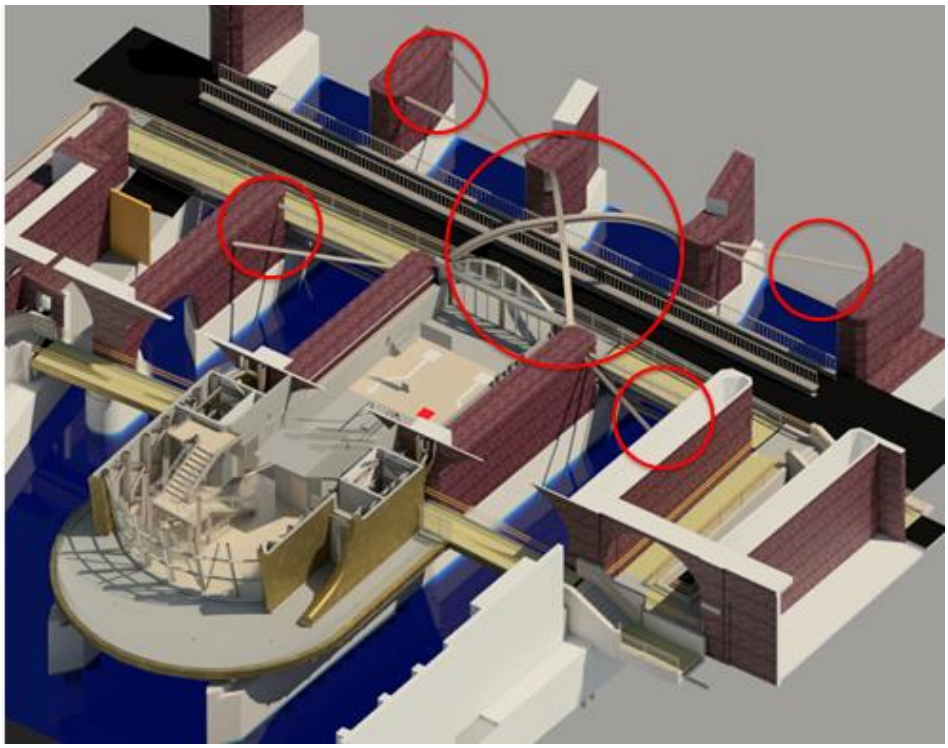
Key Interfaces

The new structure comprises four key parts which interface with the existing structure in several places. Key to resolving these interfaces was the approach adopted.



Interface with existing masonry viaduct

The new structure interfaces with the existing masonry viaduct in several locations:



The new ticket barrier level and roof structure are constructed on top of the existing Victorian masonry viaduct. Substantial additional load is applied to this structure via an existing and new steel column located on platform 15 above. This load is transferred onto the existing quadripartite arch which spans over the river and existing vehicular bridge located beneath the station.

In order to assess the capacity of the existing structure it was necessary to complete a complex second order, non-linear analysis of the masonry viaduct. The point cloud survey and REVIT models were instrumental in the creation of an accurate geometrical analysis model and loading configuration.

Existing strains were recorded on site via state of the art video gauging, which allowed very small displacements to be monitored at various points on the structure using digital video technology.

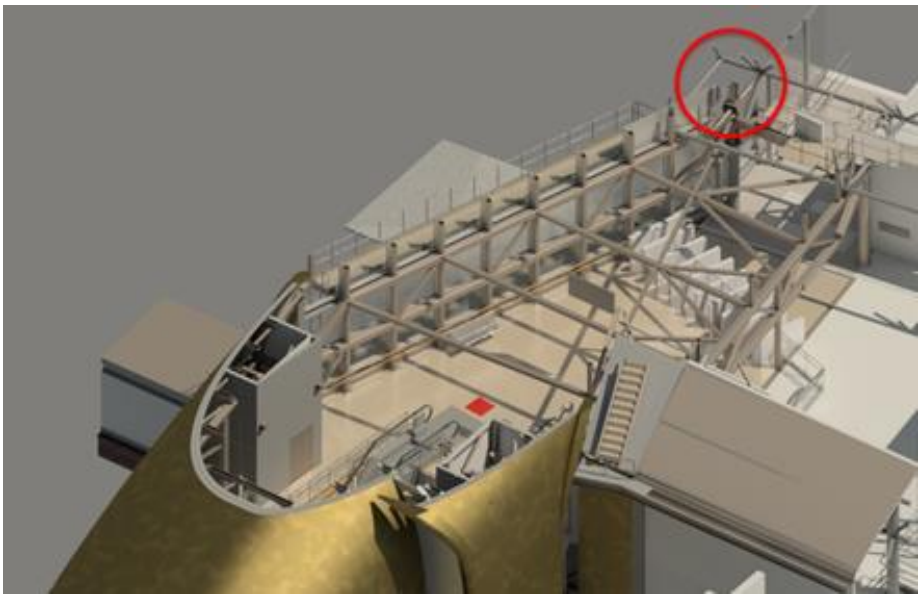
The analysis revealed the requirement for strengthening works. Network Rail's preference for a solution which could be readily inspected resulted in 7.5 Tonne steel arch ribs being installed to the underside of the viaduct, grouted tight to the existing quadripartite vaults and secured to the original masonry piers via 10 number, 1m long anchors at each springing point.

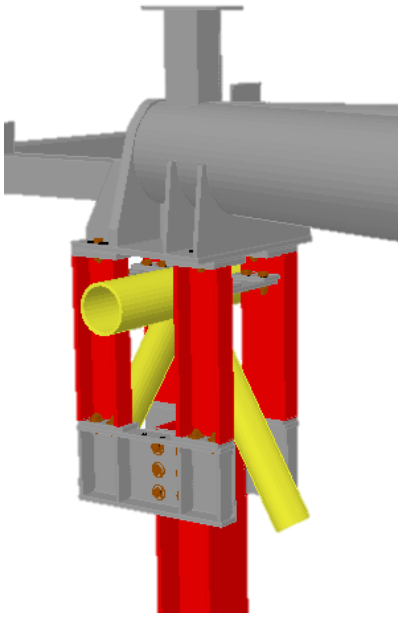
The new steelwork needed to be installed to very tight tolerances. The original point cloud data was used to set out the new steelwork to a high accuracy to ensure that the geometry was fabricated correctly first time, ensuring a tight fit was achieved to the existing masonry structure.

The use of 3D modelling allowed the various construction constraints to be discussed with the contractor in advance of the steelwork erection, allowing a better understanding to be gained of the various constraints imposed on the workforce by the existing viaduct geometry.

Interface with existing roof

The interface with the existing roof was the other key coordination point and was, in fact the key setting out point for the whole structure.





The northern tip of the new roof structure is supported from an existing column which in turn supports a 3D, space frame truss forming part of the existing station roof.

At this location there is a critical interface between the new and existing structures which forms a lynch pin for the setting out of the scheme as a whole. Accurate establishment of the location and setting out of the existing structure was key to the successful delivery of the scheme.

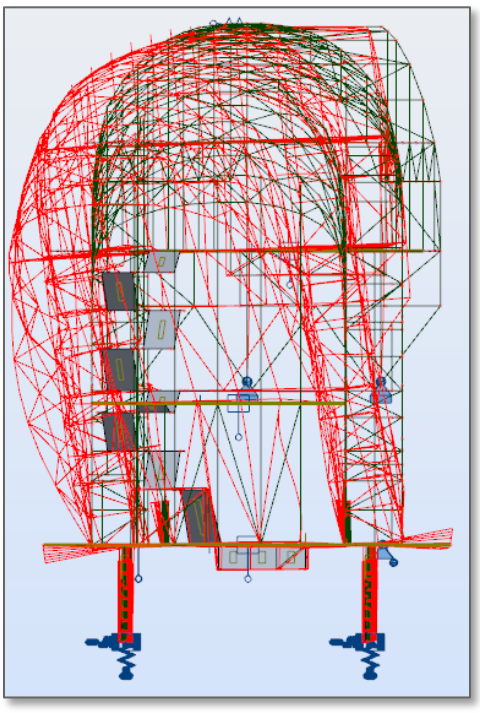
The point cloud survey allowed accurate modelling of these critical elements ensuring the new and existing elements were fully coordinated prior to erection on site.

Roof buckling analysis

The flexible nature of the structural solution required a detailed buckling analysis to be conducted for the design of individual elements, but also the structure as a whole. Robot structural analysis software was used to complete this via two different approaches.

Approach 1 – Buckling analysis conducted directly in Robot Structural Analysis to determine elastic critical load factors, with back calculation of effective lengths and individual element buckling checks to BS EN 1993-1-1 6.3

This approach involved completion of First Order Buckling analysis for selective critical load combinations. The critical load combinations were identified using a degree of engineering judgment. Preliminary buckling analysis undertaken indicated that the critical global buckling mode of the 'hood' was a sway mode of the hoops east to west or west to east. The following combinations were therefore considered to be critical in accordance with BS EN 1990:



- 1.35 x Permanent Actions + 1.5 x Variable Actions
- 1.35 x Permanent Actions + 1.05 x Variable Actions + 1.5 x Wind Actions West to East + Equivalent Horizontal Force (EHF) West to East

- 1.35 x Permanent Actions + 1.05 x Variable Actions + 1.5 x Wind Actions East to West + Equivalent Horizontal Force (EHF) East to West
- 1.35 x Permanent Actions + 1.5 x Variable Actions + 0.75 x Wind Actions West to East + Equivalent Horizontal Force (EHF) West to East
- 1.35 x Permanent Actions + 1.5 x Variable Actions + 0.75 x Wind Actions East to West + Equivalent Horizontal Force (EHF) East to West

Robot 2013 buckling analysis was used to obtain the critical mode shape and corresponding elastic critical load factor for each combination.

Effective lengths of individual hoop elements were then back calculated using Euler formula:

$$P_{crit} = \pi^2 EI/Le^2$$

P_{crit}: Elastic critical load in member (Axial force in member x elastic critical load factor obtained from Robot)

EI: Elastic stiffness of member (Youngs Modulus x second moment of area of member)

Le: Effective buckling length of member

Effective lengths were approximately determined based on the elastic critical buckling factor corresponding to the buckling mode of the element under consideration, the axial load in the member and the stiffness of the element. These effective lengths were then used to undertake buckling checks in accordance with clause 6.3 of BS EN 1993-1-1, utilising standard buckling curves to take account of member imperfections.

Approach 2 – Second Order Analysis with global and local imperfections considered directly within analysis.

BS EN 1993-1-1:2005
EN 1993-1-1:2005 (E)

(7) The effects of initial sway imperfection and local bow imperfections may be replaced by systems of equivalent horizontal forces, introduced for each column, see Figure 5.3 and Figure 5.4.

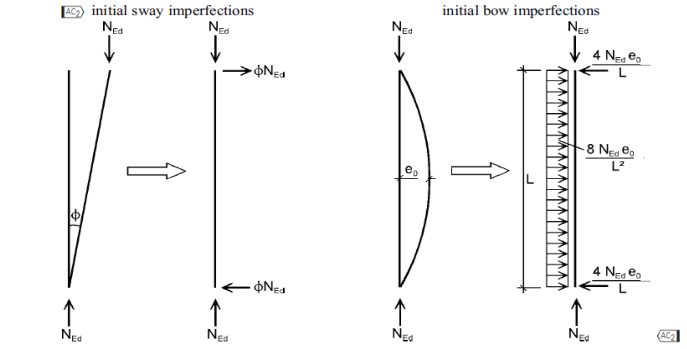


Figure 5.4: Replacement of initial imperfections by equivalent horizontal forces

A P-delta, non-linear second order analysis was undertaken in Robot to account for second order effects arising from changes in initial geometry. Initial global sway and member bow imperfections were allowed for in the analysis to represent the large and small p-delta effects arising from lack of verticality and straightness of individual elements.

Global sway imperfections were considered as a set of Equivalent Horizontal Forces applied at roof and floor levels. These were calculated based on the guidance of 5.3.2 (3a) of BS EN 1993-1-1.

Individual member bow imperfections were represented in the model via the application of uniformly distributed loads (UDLs) to the hoops and other column members. These forces were calculated based on the guidance of 5.3.2 (3b) of BS EN 1993-1-1.

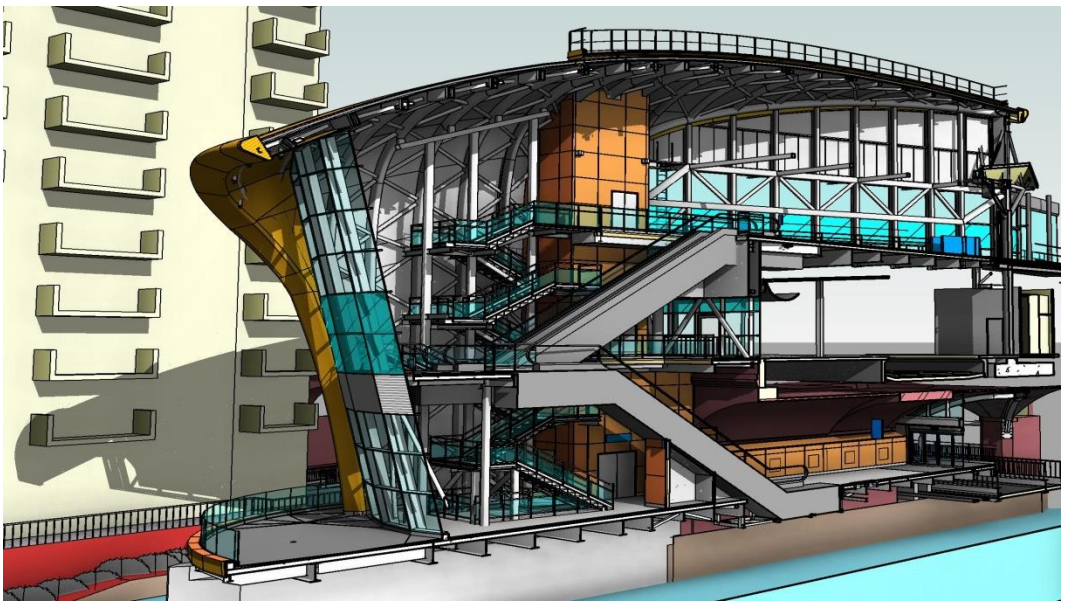
Successful convergence of the analysis for all loadcases meant that no further buckling checks were required to individual elements, as equilibrium had been achieved. Only cross section capacity checks were therefore undertaken using this method.

Integrated design coordination (IDC)

A key aspect of all Network Rail projects is the concept of integrated design coordination. These are meetings where all parties from all disciplines meet and review a package of drawings around a table. They can be long and expensive, requiring experienced people for a substantial amount of time.

LSSE introduced a new approach for IDCs to Network Rail. Regular project team meetings utilised the federated 3D model for interactive reviews rather than using paper drawings.

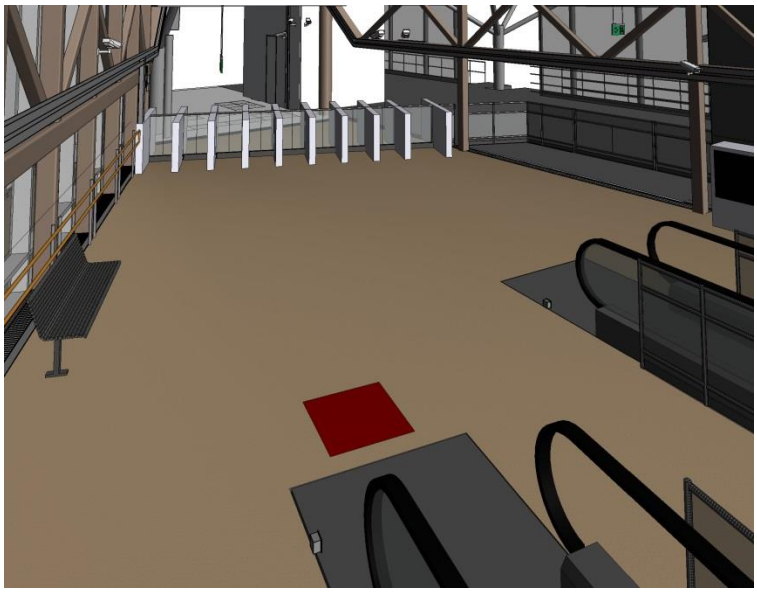
Navis Works was used for clash detection of elements and walk through presentations to the design team allowing clearer understanding. Element clash reports were exported to Microsoft Excel and appended to traditional meeting record forms together with the agreed resolution.



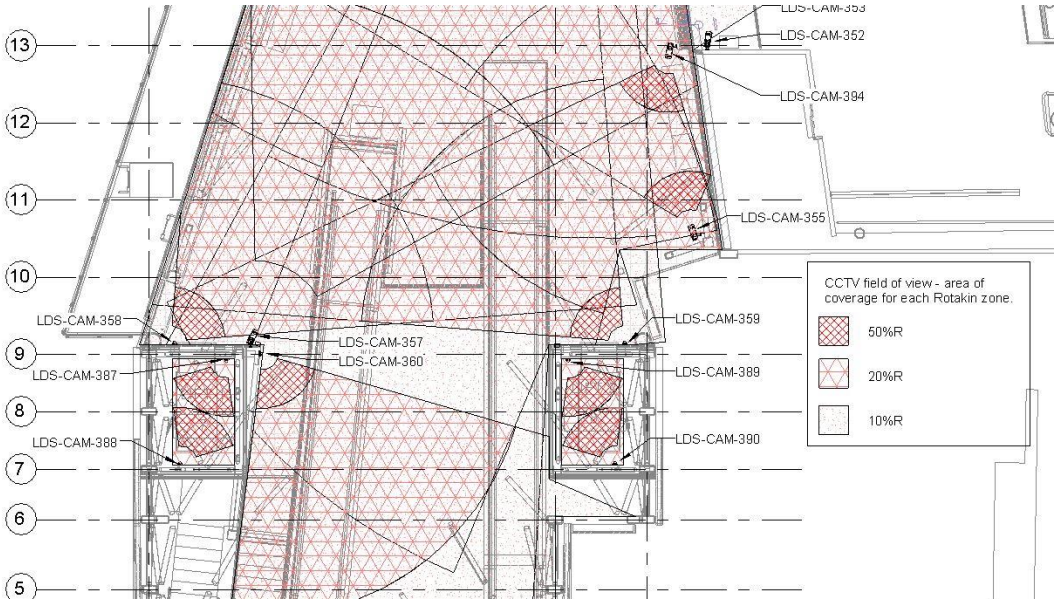
Network Rails asset managers (RAMs) were a key consultee at these meetings and have a keen focus on the maintainability of structures. They require the ability to undertake a touching distance inspection of all bolted connections every 5 years meaning careful consideration had to be given to all details to allow access and avoid concealed bolts. The model was used as a visualisation tool for Network Rail's asset managers. Issues could be clearly communicated in order to obtain project sign off.

Visualisation and CCTV

Station security is another key consideration for Network Rail. In this instance we were able to set up security camera objects within the model with associated views to allow the exact positioning of the cameras to be determined in consultation with the security experts to ensure there were no dead areas.



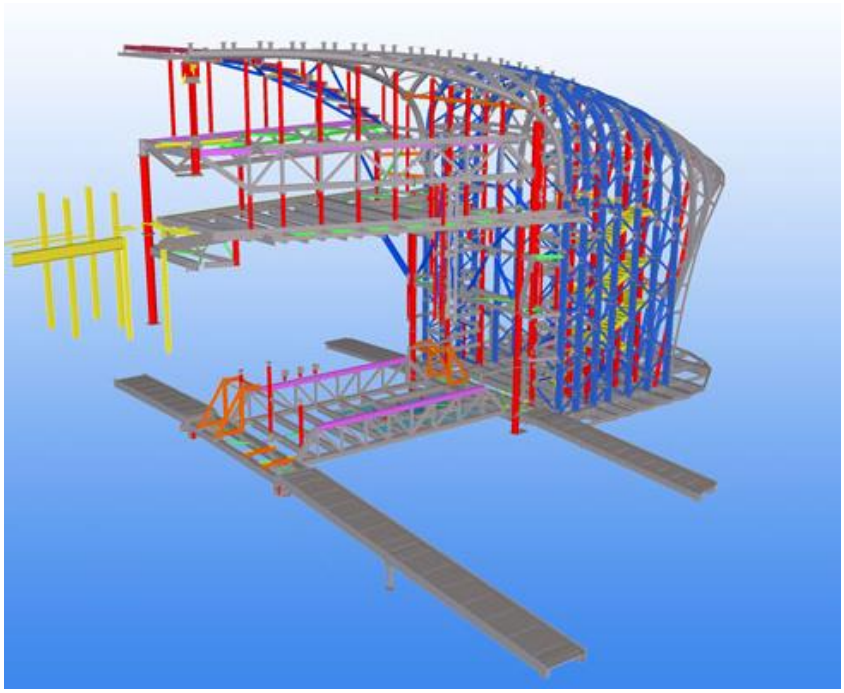
These were then plotted as standard field of view drawings :



Construction

Model Usage

The federated model provided a single source of truth for all the traditional construction deliverables. In addition the structural model was issued to the steelwork fabricator in IFC format for them to base their model on and the architectural model was issued to the cladding subcontractor to produce their shop drawings from. Both steelwork fabricator and cladding subcontractor were using Tekla so despite receiving two separate IFCs from two separate but federated Revit models, they were able to bring their respective fabrication models together in a native Tekla model for coordination purposes.



Site Progress

Site works are well progressed with completion due before the end of 2015. The following section comprises site photos from key points during construction.