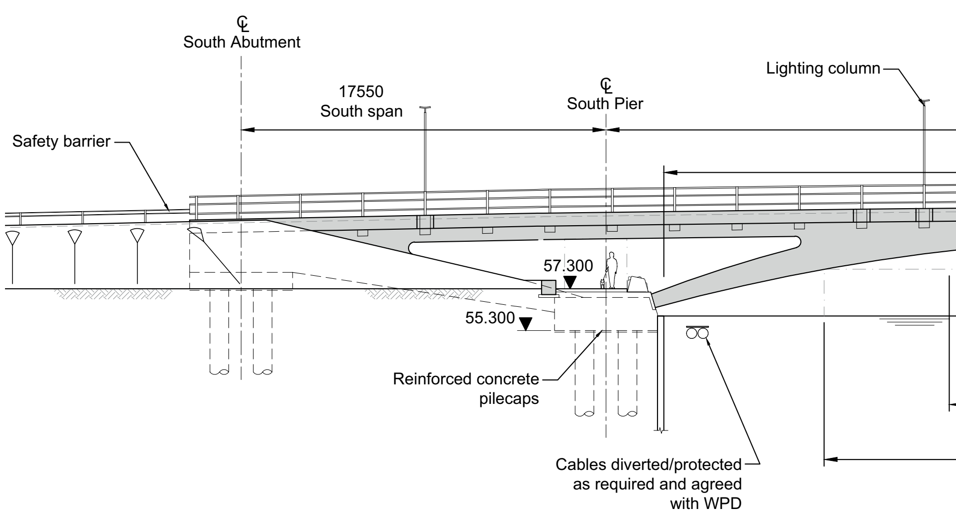
Steel-concrete composite flat arch bridge

As part of a new University Campus development in the city of Northampton (UK), a new road access bridge was required (photo 1 and 2). The aspirations and the planning requirements were set to keep the character of the existing landscape while creating an appropriate landmark structure for the new campus. The client's specimen design included a concrete flat arch bridge spanning 49 m with a shallow rise of 3.7 m above the navigable river. An alternative design was developed using a steel-concrete composite structure solution for the deck. The awarded tender solution includes 220 tons of welded steel plates to form a shallow and flat arch structure.

The bridge design had to address a number of site specific challenges as listed below:

- accommodate a road alignment that would tie-in with Bedford Road Junction and the new campus;
- span without any support in the River Channel (48.5 m min) and provide 18 m wide navigation channel with 3 m clearance above normal water level;



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1 Steel-concrete composite flat arch bridge
2 Aerial view - November 2016
credtis: Commission Air
3 Reference design - elevation

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- provide a clearance envelope beyond the navigation requirements to meet the flood risk design criteria with a 1 in 200 years return period;
- minimize disruption to the extensive number of buried services (11kV cables across the river, 33kV and 132kV in the North bank);
- maintain river navigation during construction period;
- minimal disruption to the river to maintain the ecology and biodiversity;
- create a safe and pleasant pedestrian/cycle environment along the river banks;
- address cost, statutory authority and build ability issues.

Reference design scheme

The client's engineer proposed an 89.7 m long structure comprising a single 49.0 m skew span concrete shallow arch structure supported at each river bank with 17.55 m approach span on each side connecting to the bridge abutments (fig. 3). Comparison of the shallow arch bridge in Northampton with other, similar span arch bridge structures is given in table 1.

Table 1 Arch bridges – comparison of similar spans (road bridges)

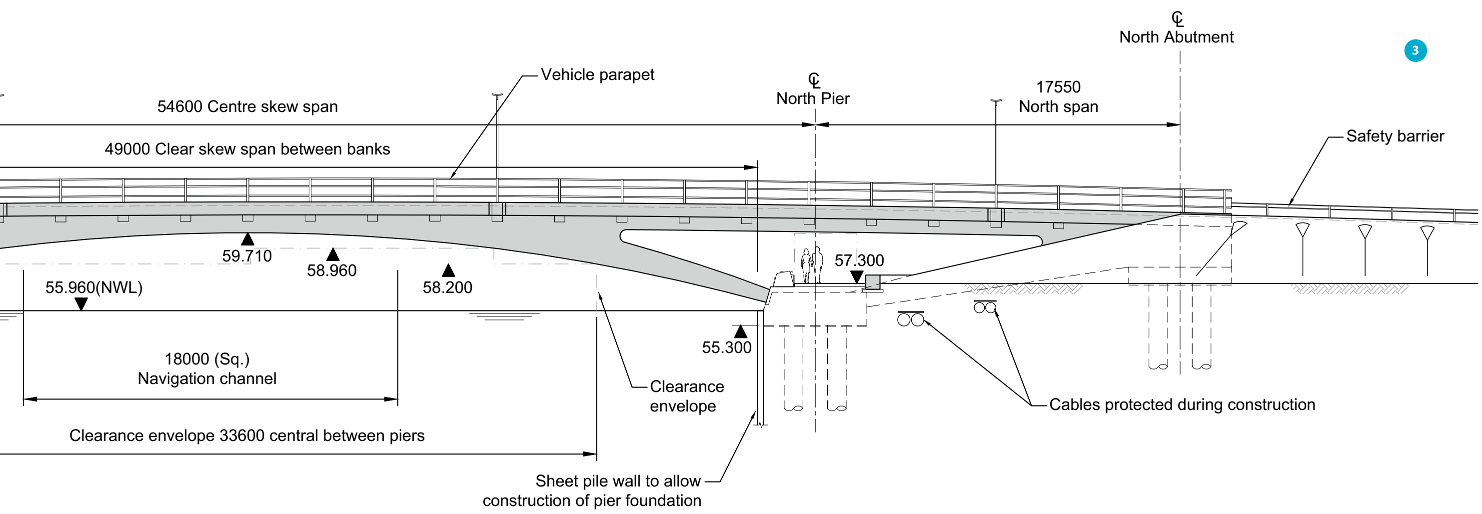
bridge	Tavanasa	Vessy	New Runnymede	Northampton
Year constructed	1906	1936	1979	2016
Span (arch) [m]	51.0	56.0	54.6	50.3
Rise [m]	5.57	4.77	6.96	3.61
Span/Rise	9.2	11.7	7.8	13.9
Structural depth[1] [m]	0.83	0.83	1.80	1.19

[1])*Structural depth at mid-span*

The proposed structure included a concrete ladder deck with deck beams supported on precast concrete arch ribs and forming balanced cantilever frames spanning from piled foundations on each bank (fig. 4).

Tender design

The constraints imposed by the planning documentation do not allow any deviation from the very flat arch requirements with a span to rise ratio of approximately 13. However, the geometry of the



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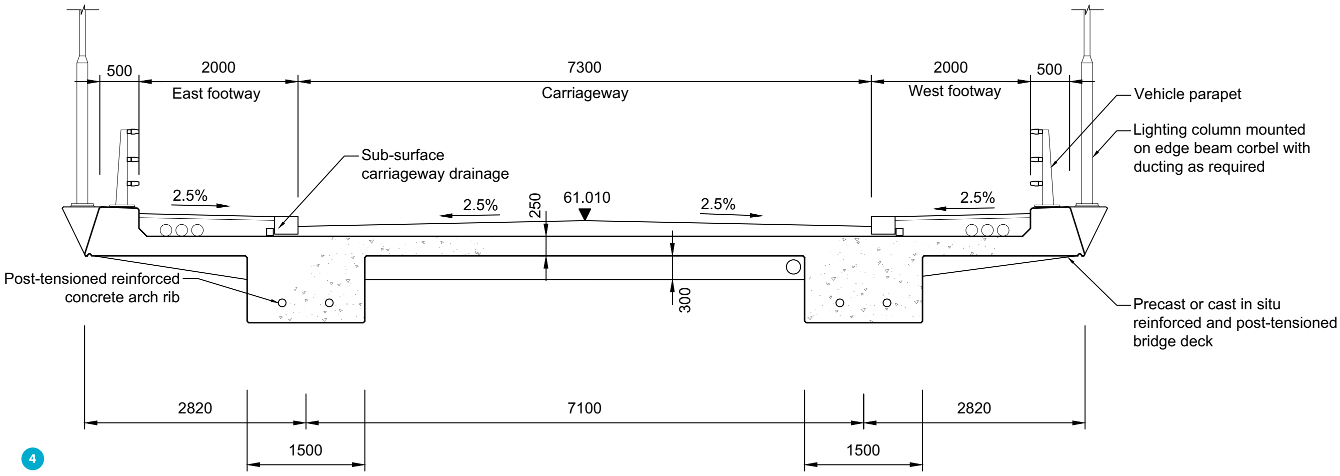

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4 Reference design – deck cross section
5 Alternative tender - structural arrangement
6 Alternative design – abutments load path

aesthetic window on the riverside walkways enable to shorten the extent of the side spans and the overall deck length can be reduced to 64 m. The reference design ‘piers’ are thus being replaced with larger abutments and wing walls on each bank (fig. 5).

The setting-out of the foundation is derived from the layout of existing buried utility cables to prevent the need for any diversion. The North abutment is to be constructed in stages with the use of precast concrete elements in order to span the existing cables. For maintenance benefits, a fully integral bridge was chosen. The overall length of 64 m and the 20° skew remain in line with the geometrical range recommended in the UK for integral bridges. The depth of the arch is shaped with a curved intrados to provide the required stiffness and meet the clearance enveloped above the river. Deeper girders are provided at the arch-deck intersection zones tapering down to a shallower section at mid-span and also towards the springing levels. The deck structural depth of the side span is constraint by the road alignment and the clearance to the river side walkway. The bending moment, shear and axial force distribution is shared between the deck and the arch in proportion to their relative stiffness. The overall overturning moment to the abutments is reduced by the stabilising effects from the granular backfill material preventing any net tension in the piles.
The horizontal pull-out forces from the deck and the integral connections are anchored into reinforced concrete buttress walls within the abutments and the loads are transferred into the pilecap via strut-and-tie models in the combined reinforced concrete counterfort-wing wall systems (fig. 6).

The resulting net effects at the base of rigid pilecaps are resisted by the piles transferring the load effects into the ground. A review of various deck cross sections alternatives concluded that a ladder type deck option using steel main and secondary

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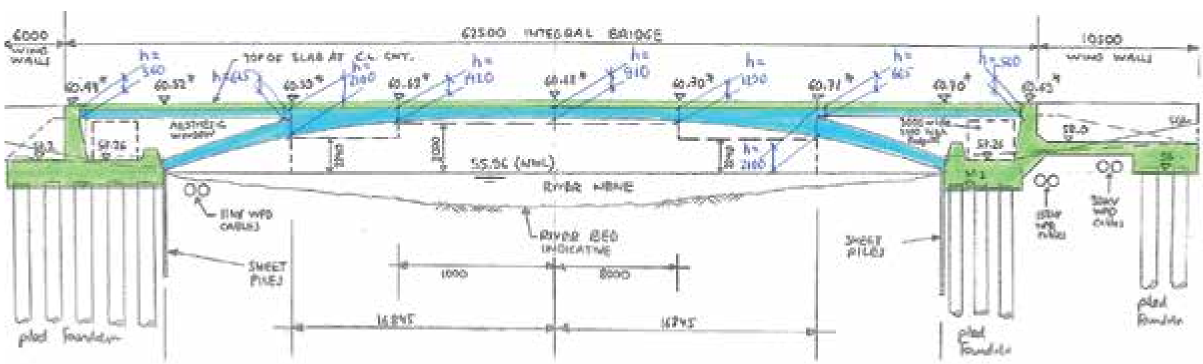

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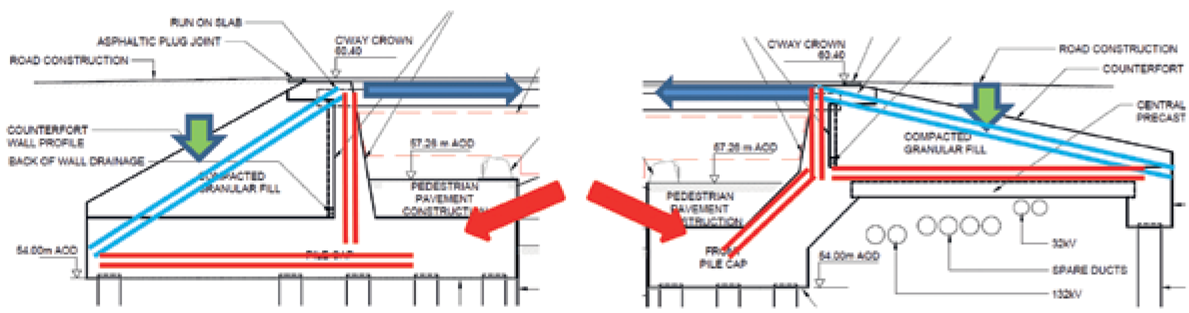
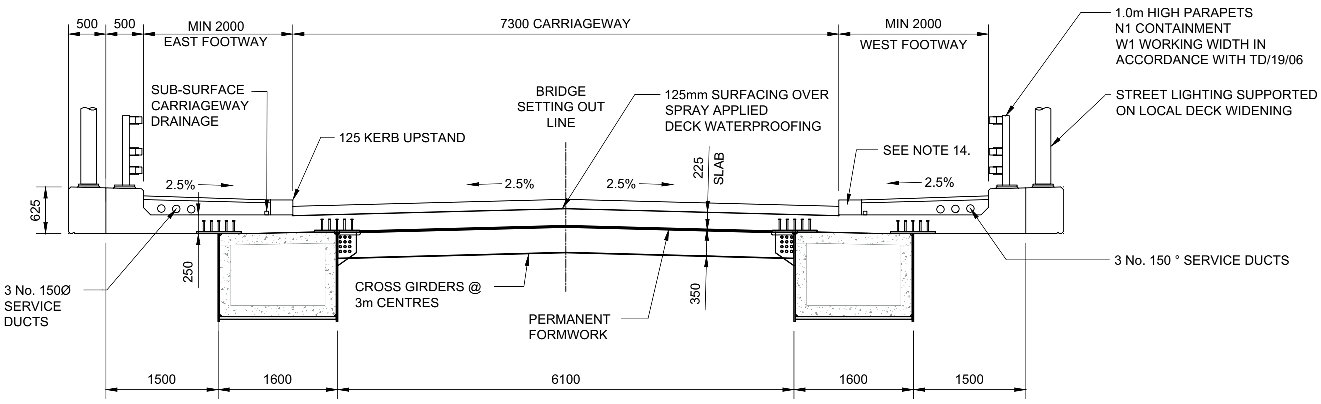


7 Alternative design – deck cross section
8 Extracts from computer idealised FE model
9 First the steel arch installation



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beams offered the optimum solution (fig. 7).

The cross girders are set at 3 m centres orthogonal to the main beams to simplify the connections, the seating details for the concrete permanent formwork panels and the fixing of the deck reinforcement. The 1500 mm deck cantilever allows the adoption of a 250 mm reinforced concrete slab and the girders can be set back to remain relatively in the shadow of the deck slab. Furthermore, it allows the use of modular proprietary cantilever falsework system that facilitates the construction of edge projection of deck slabs. The cross girders are shaped to provide a 225 mm constant concrete slab thickness with transverse cross fall in line with the carriageway requirements. The main design constraints for the foundations are the proximity of a significant number of buried cables and the requirement to keep a 48.5 m minimum clear span between the banks. Sheet pile walls form the river side of the pilecaps and provide a scour protection to the foundations as well as offering a temporary cofferdam during construction. They are set within the minimum clearance from the centre line of any buried cable. Each abutment is supported by 750 mm diameter continuous flight auger (CFA) piles to provide the most efficient and economical solution for the given ground conditions. One of the main advantages of the steel bridge solution is the lighter weight, which means it can be erected from cranes on both banks without the need for extensive temporary works and associated costs.

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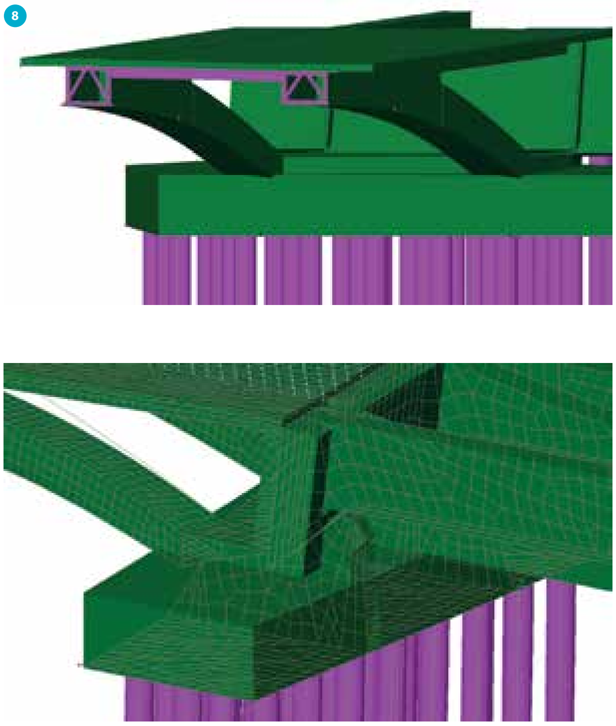

Detail design

During late spring 2015, the contract was awarded to Volker-Fitzpatrick based on this alternative proposal. The detail design phase started in early summer 2015 by setting an idealised 3D finite element model to include the steel-concrete composite superstructure (arch ribs, deck girders and slab) and the reinforced concrete abutments. A series of computer models with shell and beams elements were produced to extract the stress build up within the composite sections model considering long term, short term and staged construction effects from arch ribs erection, deck girder installation, backfilling behind abutments and the concrete deck castings sequence (fig. 8).

The concrete deck slab connecting to the integral abutments was also designed as a concrete tension member with consideration of tension stiffening effects in line with EN1992-2 in order to control crack widths at serviceability limit state.

10 Steel arches and tie beams completed

The soil-structure interaction analysis and pile load derivation was computed by close calibrations between structural/global models and separate geotechnical analyses. Upper and lower bound pile stiffness were used for the global analyses of the bridge. Combined with a pile test on site, the detail analysis confirmed the tender design solution and offered a ten percent reduction in pile length for the 63 CFA piles.
The main steel girders are shaped with a variable depth and a constant width of 1600 mm. A stiffened steel box section was generally adopted except for the tie beams where a pair of 560 mm deep plate girders was designed to respect the pedestrian clearance on each banks. The combined arch-deck section is an open top steel box section keeping steel continuity of the web and the bottom flange. At its deepest, the girder is 2150 mm. The lower part of the arch is 600 mm deep at springing levels and it tapers up to 1400 mm before the arch meet the deck. It was decided to infill them with self-compacting concrete (SCC) grade C32/40 with slump-flow class SF2. Similarly, the 15 m long central portion of the span where the depth of the steel is shallower than 1200 mm, a 150mm thick concrete lining was specified to the inside faces of the steel box with lightweight expanded polystyrene void former in order to protect the steel against corrosion. The benefit of concrete lining in midspan and SCC infill within the lower part of the arch is that it provides additional robustness against accidental vessel impact actions. Stability of the arch girders and resistance to buckling was analysed using a 3D finite element analysis model and reviewed with hand calculation methods. As individual arches where assembled on site, a temporary bracing arrangement was required until the tie beams could be connected to the abutments and cross girders installed.

Construction

Piling started on the North side in December 2015 and the reinforced concrete pilecaps and abutments were completed by July 2016. With the backfill completed, the construction site could start preparing for the main steel lift with one 500 t capacity mobile crane set behind each abutment. In August, the main girders were delivered to site in 25 m long, 37 t sections. Each half arch could then be lifted individually and lowered into the predefined concrete pocket within each pilecap allowing the central bolted splice connection to be completed using tension control bolts and accessed using a mobile elevating work platform on a floating pontoon (photo 9).

The same operation was repeated for the adjacent arch girder and then followed with erection of the lighter tie beams (13.5 t each) and cross girders.

The concreting phase could follow with completion of the abutments and the parapet edge beams allowing installation of the road restraint systems. With the main structure finalized, the road pavement, footway verges and expansion joints could be installed and the bridge construction was completed by the end of 2016. ☒

PROJECT DETAILS

client University of Northampton
design and build contractor VolkerFitzpatrick
civil and structural designer Tony Gee and Partners
highway designer Peter Brett Associates
independent checker Ramboll
client's Engineer CH2M
project manager MACE
bridge architect MCW
landscape architect LUC
steel Fabricator Briton Fabricators
piling contractor Van Elle
temporary works designer Tony Gee and Partners

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