Design and construction of Hams Way Footbridge, Worcester

Project credits

Bridge owner	Worcestershire County Council
Structural engineer	COWI
Architect	Moxon Architects
Main contractor	Alun Griffiths Contractors
Steelwork fabrication and erection	SH Structures
Highways and drainage engineer	Burroughs
Environmental consultant	TACP
Flood modelling	Wallingford HydroSolutions
Client's project manager	Jacobs
Category 3 check	Tony Gee and Partners

SYNOPSIS

Hams Way Footbridge is an elegant new pedestrian and cycle bridge on the outskirts of Worcester, UK. The steel bowstring truss bridge features smooth curves and intricate connections and is designed to catch shadow lines along its main members to enhance its lightweight appearance. This article describes the design from concept through to detailed design, including a thorough assessment of the embodied carbon.

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Key facts

Total length	335m
Main span	42m
Bridge type	Steel bowstring truss

Introduction

Hams Way Footbridge **(Figure 1)** is a new pedestrian and cycle bridge forming part of the strategically important Worcester Southern Link Road Phase 4 (SLR4) project in the West Midlands, England. The footbridge replaces a signal-controlled pedestrian crossing of the A4440, one of Worcester's busiest roads carrying more than 30 000 vehicles each day. The new footbridge improves National Cycle Network route 46 from Worcester towards the Malvern Hills by separating cyclists and pedestrians from traffic at the busy Powick Roundabout.

FIGURE 1: Hams Way Footbridge

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↑FIGURE 2: Aerial view of site during flooding

The focal point of the bridge is the elegant trussed-arch main span, supported on dramatic leaning concrete piers to achieve the client's aspiration for a lightweight 'floating' aesthetic. The bridge also features long approach ramps where economy and speed of construction were the main design drivers, while matching the architectural success of the main span.

Constraints

The site has several constraints which were addressed in the design:

- The area is located close to the confluence of the Rivers Teme and Severn and is prone to flooding **(Figure 2)**. During construction in the winter of 2019–20, Worcester was hit by the highest flood since Environment Agency records began.
- The site is archaeologically sensitive as it was the location of the Battle of Worcester, the final battle of the English Civil War in 1651.
- The site is surrounded by a number of historically important pieces of infrastructure, including Old Powick Bridge (original construction 15th century), New Powick Bridge (1837) and Powick Mills, Britain's first hydroelectric power station (1894) **(Figure 3)**.
- The A4440 is a high-load route, requiring a 6.45m clearance under the footbridge rather than the typical 5.7m. This extra height lengthens the approach ramps, which are limited to a 1:20 gradient.

The bridge is one of several new projects in the area, with the overarching objective being to improve sustainable transport links around Worcester. The client's aspiration was for the bridge to be a recognisable 'gateway' structure, while being sensitive to its historic surroundings.

Main-span design

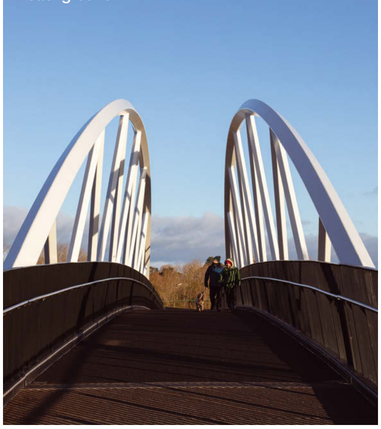
Worcestershire County Council expressed a preference for an arch-type main span for consistency with other footbridges in the region. Aware that 'traditional' steel arch bridges with vertical hangers can fall foul of the Eurocode pedestrian dynamics requirements, the design team proposed a 42m long bowstring truss for the main span. The truss diagonals provide additional stiffness and push the resonant frequencies above the limits for pedestrian excitation. The 6m high trusses lean inward by 7.5° and are unbraced to give a dramatic user experience when crossing on foot **(Figure 4)**.

The chords and diagonal members of the main span are formed from square hollow sections (SHSs) rotated through 45°. These diagonal sections mirror a similar detail on the nearby Diglis Footbridge and are designed to catch light on their upper half with shadow cast on the lower, a visual effect which makes them appear attractively slender.

The deck plate is 10mm thick and is stiffened with flat plate stiffeners welded beneath and two edge stiffeners above, formed by folding up the edges of the deck plate. Cross-beams are rolled universal beam (UB) sections at 3m centres, designed with stiffened connections to the truss chords to provide a degree of 'U-frame' stiffness, stabilising the unbraced top chord **(Figure 5)**.

The top chord of the main span is curved at a relatively tight radius (43.6m). The fabricator, SH Structures, recommended that the SHSs had a minimum wall thickness of 16mm, even though 10mm would have been enough

↙FIGURE 3: Historic structures around site



↘**FIGURE 4:** View along main span showing inclined, unbraced arches, with Powick Mills visible in background

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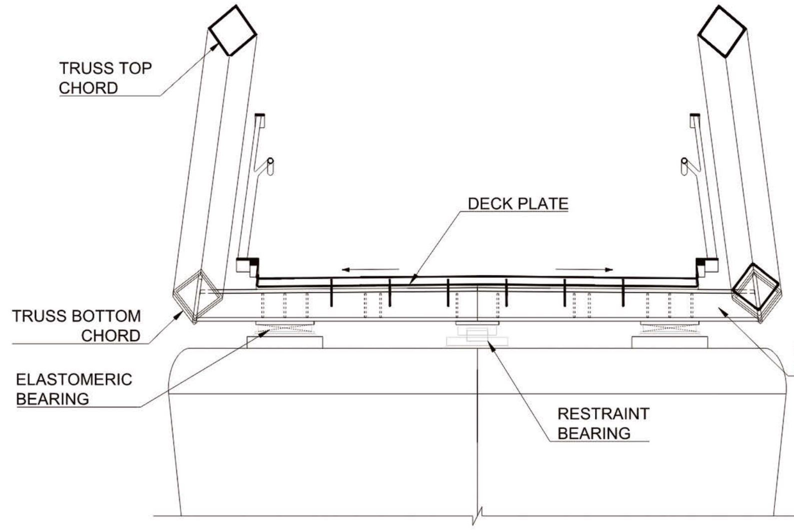


↙**FIGURE 5:** Cross-section of main span

from a strength perspective. The thicker walls were required to prevent local buckling and distortion of the SHSs during the bending process. This is a good example of early input from a specialist fabricator being indispensable in the design process.

At the ends of the arches, the top and bottom chords meet at a tight curve, hiding the supports and giving the impression that the bridge is floating above the piers. This element of the bridge is fabricated from conically curved steel plate, stiffened internally. It was a particular focus of the design with the important architectural detail needing to resist significant forces at the junction of the arch and the hidden bearing cross-beam. Early collaboration between the design and fabrication teams was key in achieving a detail that is efficient in both structural performance and fabrication effort. The finished product is seamless, giving no hint of the complicated engineering within **(Figure 6)**.

To achieve the architectural aim of unbraced arches, the design needed to ensure the elastic stability of the compression chords. Arch bridges typically feature plan bracing of the top chords to improve their lateral buckling performance, but without this bracing the buckling behaviour becomes a much more crucial aspect of the design.

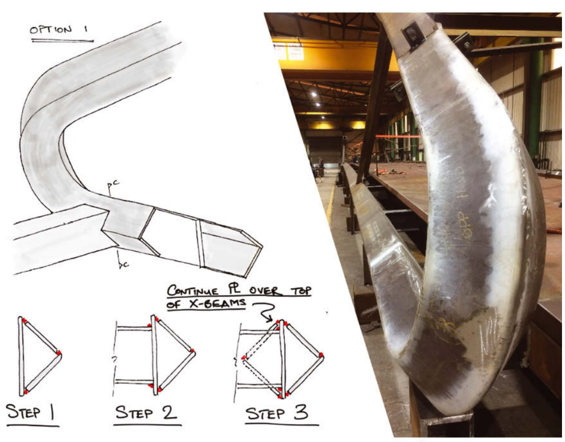
The relatively slender 300mm SHS top chords gain some lateral restraint from the 180mm SHS truss diagonals; however, the diagonals are flexible and do not constitute 'rigid' restraints. To quantify the buckling behaviour of the arches, the design team's finite element (FE) model was used to derive elastic critical buckling modes.

These buckling modes were used as initial imperfections in a series of geometrically non-linear (large displacement) elastic analyses to BS EN 1993-2 Annex D. The initial imperfections were scaled by the values outlined in Table D.9 for the worst-case buckling curve d (i.e. 140mm for a half sinusoidal wave buckling mode and 190mm for a full sinusoidal wave buckling mode).

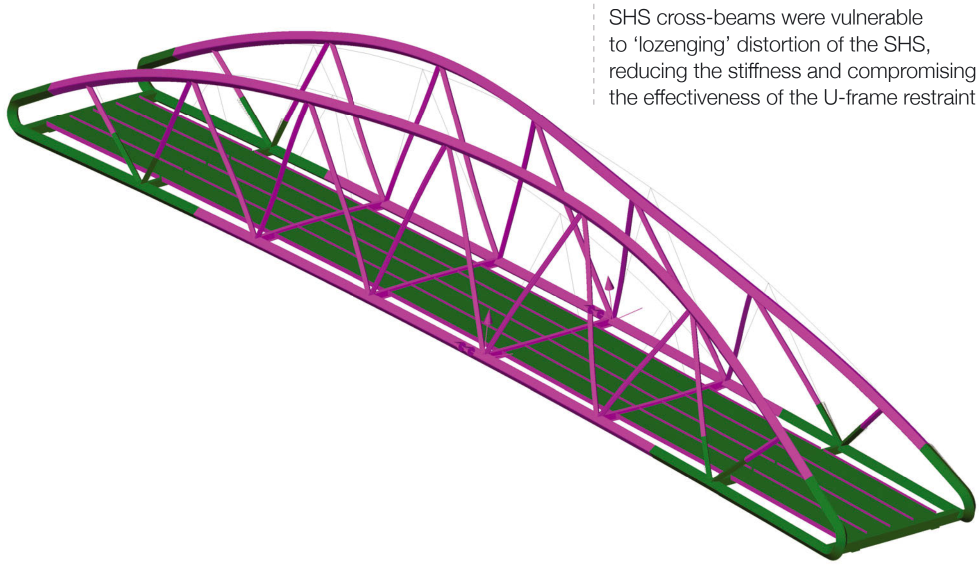
These non-linear analyses enabled direct calculation of the second-order stresses in the truss members to demonstrate adequate capacity. Hand calculations and approximated codified buckling checks were used to cross-check the results of the non-linear analyses.

The main analysis model in LUSAS software **(Figure 7)** used beam elements for the chords and diagonals but further studies were carried out to consider the effects of connection flexibility. It was discovered that the welded connections between the UB cross-beams and the SHS cross-beams were vulnerable to 'lozenging' distortion of the SHS, reducing the stiffness and compromising the effectiveness of the U-frame restraint

↘**FIGURE 6:** Fabrication of end curves – concept and reality



↘**FIGURE 7:** Eigenvalue buckling analysis of main-span steelwork in LUSAS



provided by the diagonals. This was resolved by inserting plate diaphragms at each connection point, preventing the lozenging displacements and guaranteeing a stiff load path through the connection.

When a rotated SHS connects to the wall of another rotated SHS, the resulting joint is known as a 'bird beak' connection[1]. This type of connection was found to perform better in terms of strength and stiffness than an equivalently sized connection where the walls meet perpendicularly. This is due to the in-plane contribution of force transfer and equivalent reduction in out-of-plane bending effects in the wall. However, the bird beak connections fall outside of the Eurocode provisions for hollow section connections and they were instead designed to the CIDECT *Design guide for rectangular hollow sections (RHS) under predominantly static loading*[2] and validated against FE models of the joints, which showed good agreement.

The FE analysis showed significant stress concentrations at the bird beak connections **(Figure 8)**, but limited local plasticity was found not to compromise the stiffness of the joints. Footbridges are not generally fatigue-sensitive, but fatigue studies were performed for both pedestrian live load and wind-induced dynamics.

Although the main span did exhibit some natural frequencies below 5Hz (the limit for triggering Eurocode checks), these were predominantly lateral displacements of the top chords. The first vertical mode was found to be above 5Hz. The main span therefore performed well under pedestrian dynamics, validating the early-stage design choice of adopting stiff diagonal members in preference to vertical hangers.

The corrosion protection system for all steelwork exposed to the elements was a four-part paint system, with the topcoat being a two-component, chemically curing, acrylic polyurethane coating with a gloss finish. The hollow sections were designed to be fully sealed to avoid corrosion of the internal faces, following the principles of the UK National Annex to BS EN 1993-2.

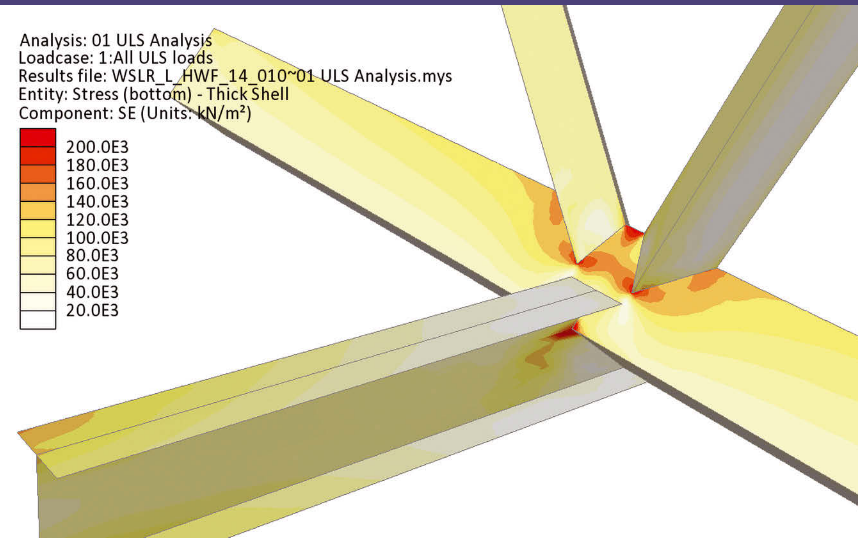


FIGURE 8: Local stress analysis of 'bird beak' connection

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FIGURE 9: Junction of ramp and main span

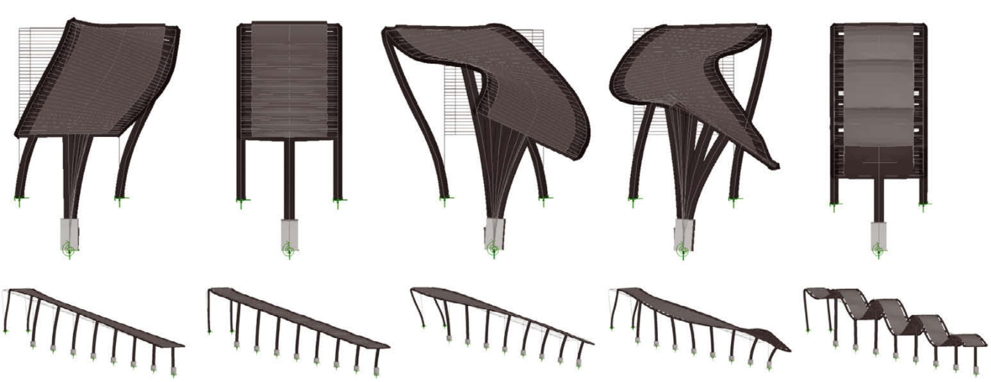

FIGURE 10: First five dynamic modes of south ramp structure

"THE RAMP EDGE BEAMS FEATURE THE SAME ROTATED SHS FORM AS THE MAIN-SPAN CHORDS

Approach ramp design

The main span is reached via multi-span approach ramps **(Figure 9)** as well as a staircase to the north. The total length of the approach spans is over 250m, so an economic solution was required that was quick to construct. A modular approach was adopted using repeated 12m steel spans on single rectangular hollow section (RHS) steel piers. The ramp edge beams feature the same rotated SHS form as the main-span chords, but use simplified flat-plate cross-beams for economy. The ramp edge beams mirror the tightly curved arch end segments at the junction between the ramps and the main span.

The articulation of the ramps was designed to minimise moving parts to reduce maintenance requirements. The ends of the ramps are supported at the concrete abutments on elastomeric bearings. At all other support locations, the ramps are integral with their concrete pad footings. Articulation is accommodated by allowing the steel

↙FIGURE 11: Approach ramp parapet in profile showing sloping posts

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piers to flex and by providing a bare minimum of expansion joints in the deck (one per ramp, at approximately mid-length).

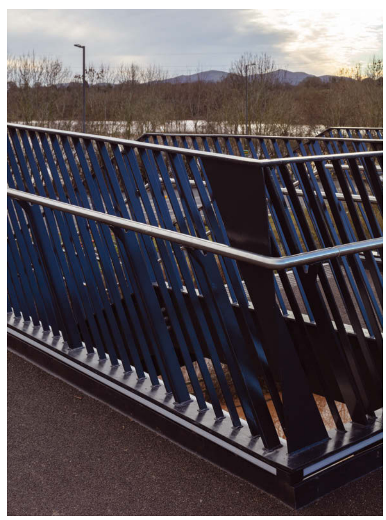
The steel piers were therefore required to be relatively flexible in the longitudinal direction to accommodate thermal expansion, but stiff enough in the transverse direction to provide restraint to eccentric loading at deck level. RHSs were used with the major axis oriented transversely, and the section size was tailored to suit the stiffness required, with taller columns requiring larger sections.

Considering the shallow span-to-depth ratio and the nature of the support conditions, pedestrian dynamic response was investigated in detail **(Figure 10)**. The first five natural frequencies of the taller straight ramp structure were found to be 1.4Hz, 1.7Hz, 2.0Hz, 3.2Hz and 3.9Hz. These frequencies are in the range that can be a concern with regards to pedestrian-induced dynamic response. The first four modes were found to be horizontal modes and the fifth a vertical mode.

The pedestrian dynamic analysis methods outlined in the UK National Annex to BS EN 1991-2[3] (Eurocode 1) address vertical responses in good detail and provide a straightforward method of verifying the accelerations of the bridge deck.

The potential for lateral dynamic excitation of ramps on single-column supports was quickly identified. The Eurocode gives a method for checking that an unstable lateral response due to crowd loading is avoided but lacks guidance on determining lateral accelerations under pedestrian loading,

↘FIGURE 12: Parapet detail at top of staircase



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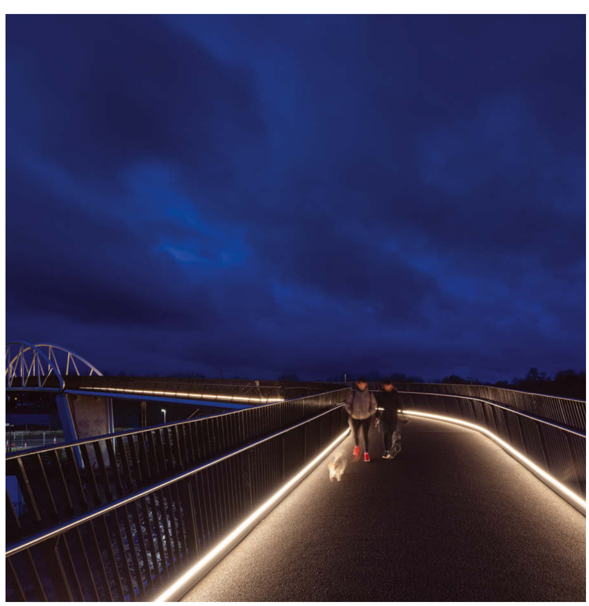
↘FIGURE 13: View from north ramp showing ankle-level lighting



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despite a limiting horizontal acceleration of $0.2m/s^2$ being required according to BS EN 1990[4].

To verify the lateral accelerations, the design team drew on research conducted previously by COWI colleagues. By assuming a simple correspondence between the vertical load model and the lateral load model in which lateral loads are applied at half the frequency of vertical, the amplitude of the first harmonic walking lateral fluctuating load can be estimated as one quarter of the vertical[5], i.e. 70N. This method now forms the basis of the lateral pedestrian-induced response of footbridges in the newly published *Design Manual for Roads and Bridges. CD 353: Design Criteria for Footbridges*[6].

With a combination of the lateral response method outlined above, and the codified method for vertical response applied along both the centreline of the ramps and along the outer edges, the accelerations were kept within the design limits by tailoring the pier column RHS sizes to provide adequate stiffness.

Parapets

As well as functioning as a containment system for bridge users, the parapets are a major visual feature of the bridge **(Figure 11)**. The plated nature of the sloped elements that make up the parapet means that they appear solid when viewed along the bridge, focusing the bridge user towards the path ahead, yet transparent for views directly out over the bridge to the impressive scenery that surrounds it. The parapets contain thousands of plated elements welded together, as well as hundreds of connection details. In total, they weigh approximately the same as the main-span steelwork.

The stainless steel handrail **(Figure 12)** is supported at regular centres by carbon steel posts which carry the design loads down into a high-strength friction-grip (HSFG) connection and into the edge beam/bottom chord. To prevent bi-metallic corrosion of dissimilar metals, the handrail is isolated from the posts with neoprene isolators. The bottom rail serves a dual purpose: it supports the intermediate parapet posts as well as housing and hiding the lighting box and cables that provide ankle-level lighting to the bridge deck.

Drainage and lighting

Drainage of the bridge is achieved by the transverse crossfall of the deck plate and a longitudinal fall of the bridge. Water flows to the edges of the deck plate and down the bridge and ramps, being picked up at intermediate locations using stainless steel gullies. An 8mm thick polyurethane-based deck surfacing was

FIGURE 14: Site-welding of main-span steelwork

used, which also acts as a waterproofing layer to the bridge deck.

LED lighting is provided at ankle level to minimise environmental impact and reduce glare to vehicles travelling below **(Figure 13)**.

Construction

Minimising disruption to the A4440 was a key selling point of the tender design and the planning submission. The lightweight steel main span was chosen to allow it to be installed during a minimal road closure.

The whole main span exceeded road transportation limits and it was delivered to site in pieces. An assembly 'jig' was constructed close to the main span's final position and the transport segments were site-welded to complete the superstructure **(Figure 14)**. The main span was installed during a Saturday morning closure of the A4440 using self-propelled modular transporters (SPMTs) **(Figure 15)**. This installation method was extremely rapid and enabled Powick Roundabout to be reopened within two hours, before the peak Saturday morning traffic period.

The approach ramps were fabricated and transported in two-span sections with end-plate HSFG bolted connections. Access to tighten the edge beam bolts is from a hidden hatch on the inner-lower face of the diamond edge beam **(Figure 16)**, hiding any discontinuity the panels would have on the appearance of the edge beam.

FIGURE 16: Hidden bolted splice connection within edge beams (cover plates omitted)

FIGURE 15: Installation of main span on SPMTs

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Following completion of the reinforced concrete pad foundations and steel columns, the ramp units were lifted into place, working from the abutments towards the main span. The ramps were designed to be repeatable modular units that could be transported in two-span (24m) lengths within normal road haulage limits **(Figure 17)**.

Emerging technology in design

3D modelling is no longer a new technology, but as our industry becomes more digitalised, the way in which 3D modelling adds value to projects is constantly evolving. Although delivery of the Hams Way Footbridge design was contractually through 2D drawings, a full 3D model of the bridge was created in Tekla **(Figure 18)** and this added great value to the project.

Visualisations of the bridge, created by the architect, were ultimately the greatest driver in allowing stakeholders to make informed decisions at early stages of the project. Sight lines, aesthetics, lighting levels, and health and safety hazards were among the many criteria. Another valuable tool was the ability to convert the Tekla model into a virtual reality representation of the bridge **(Figure 19)**. Nothing puts a client's mind at ease better than being able to walk around a realistic virtual model of the completed structure!

Parametric models were linked to the analysis software and early-stage global static and stability checks could be carried out on many different orientations of geometry and section sizes. This allowed the steelwork to be optimised and prevented any surprises at later stages in the design. Parametric models were also linked to the global Tekla model. This ensured the geometry

FIGURE 17: Erection of 24m section of ramp

that was used in the analysis was exactly what was being communicated to the fabricators. It also ensured the geometry was mathematically defined and could be represented on drawings with a concise set of parameters.

Sustainability in design

The global warming potential of the infrastructure we design is rightly coming under increasing focus across the industry in light of the UK's commitments to reach a net-zero economy by 2050, and similar commitments around the world. The production of construction materials and construction activities contribute significantly to our carbon footprint. For infrastructure projects, the embodied carbon in a structure is likely to dwarf the operational carbon emissions and so makes up the bulk of the emissions within the engineer's direct control. We therefore consider it a priority to quantify and manage embodied carbon in our designs.

The IStructE has promoted the following hierarchy for focusing on embodied carbon reduction in construction: i) minimise material usage, ii) specify low-carbon materials, and iii) offset emissions. For Hams Way Footbridge, the design team and supply chain all contributed to these principles:

- The structural form is efficient, with a steel trussed arch for the main span and simple, repeated lightweight steel spans for the approach ramps.
- The steel structure was transitioned to low-carbon reinforced earth ramps (using site-won material) as soon as the flood modelling analysis allowed.
- Structural members were designed to high utilisations, with section sizes varied to suit different situations.
- Steel moment connections were detailed to minimise the number of bracing members.
- Shallow footings were used for the ramps, with footprints optimised to provide only the resistance required.
- Where concrete was used (ramp footings/abutments and main-span piers and foundations) a low-cement CEM IIIA mix was specified (minimum 50% GGBS).
- Concrete elements were standardised to allow reuse of formwork.
- Steel elements were generally designed for off-site manufacture and bolted assembly on site, minimising waste and pollution. SH Structures' facility in North Yorkshire is powered entirely from renewable sources.
- The ramps were designed and detailed almost entirely without bearings, minimising future maintenance and bridge closures.

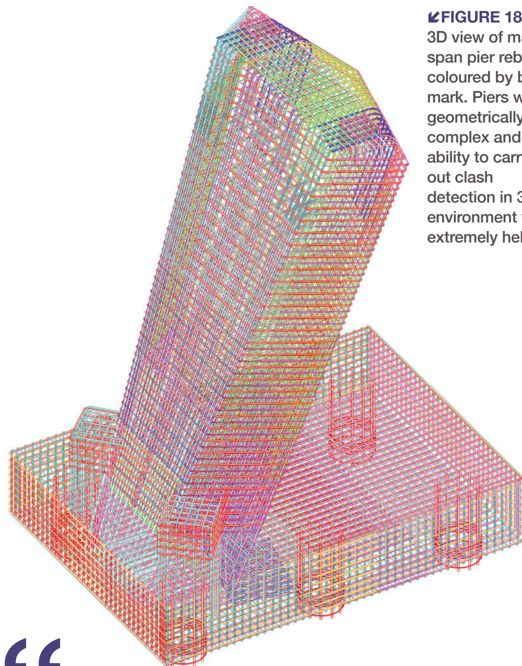


FIGURE 18: 3D view of main-span pier rebar, coloured by bar mark. Piers were geometrically complex and ability to carry out clash detection in 3D environment was extremely helpful

> **"STEEL ELEMENTS WERE GENERALLY DESIGNED FOR OFF-SITE MANUFACTURE AND BOLTED ASSEMBLY ON SITE**

FIGURE 19: View of Enscape VR simulation of bridge as presented in stakeholder meetings. Concrete on nearside pier has been hidden to allow inspection of rebar for constructability reviews

An embodied carbon comparison study has been performed to assess the efficiency of the structure and the relative impact of different components **(Figure 20)**. The method utilises guidance outlined by the IStructE[7] and the Inventory of Carbon and Energy (ICE) database with some amendments to make it suitable for infrastructure projects. It includes lifecycle stages A1–A5, i.e. raw material supply, transportation of material, manufacturing, transport of product to site and construction installation processes. For meaningful comparison with other projects, the total weight of embodied carbon ($kgCO_2e$) per functional unit of bridge (m^2 of deck) was calculated.

For the materials used in this project, the typical A1–A3 emissions factors (based on the ICE database v2.0) were as follows:

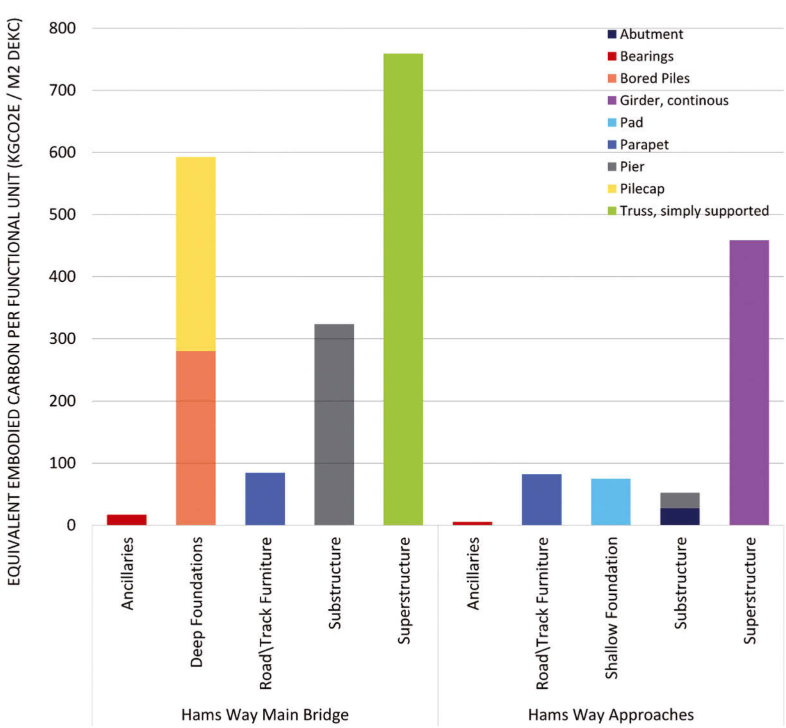
- Fabricated steel plate: $1.96kgCO_2e/kg$ (including $0.3kgCO_2e/kg$ for fabrication)
- Rolled steel section: $1.53kgCO_2e/kg$
- Concrete: $243kgCO_2e/m^3$
- Reinforcement: $1.4kgCO_2e/kg$.

The following conclusions are drawn from this study:

- Unsurprisingly, the longer main span uses more CO_2 per unit area than the approach spans ($1700kg/m^2$ compared with $700kg/m^2$). For optimum efficiency of superstructure, it makes sense to use short spans; however, this is at the expense of additional substructures and foundations. We believe the repeated 12m approach spans with shallow footings are close to the optimum span arrangement for a bridge of this type. It's worth noting that optimum embodied CO_2 closely mirrors the optimum economic solution, with reduced material usage a priority in both metrics.
- The overall estimated embodied CO_2 for Hams Way Footbridge is 815kg per m^2 deck area. This value makes it the best-performing bridge in CO_2 terms of any analysed by COWI so far. This is due partly to the long approach ramps with relatively short spans, but the careful design considerations and material specification listed above also led to a dramatic reduction relative to what could have been.
- 15% of the embodied carbon for the entire bridge can be traced back to the two main-span piers and their foundations. The relative significance of these elements can be tied in part to the decision to adopt inclined piers that achieve a particular aesthetic and meet the client's desire for a landmark structure. Although a minor concession, simple vertical piers could certainly have been lighter. As our environmental responsibilities become stricter over the coming years, this type of compromise may well become unacceptable. Engineers will need to collaborate more closely with architects during the concept phase to ensure that structural efficiency leads the architectural scheme, rather than the other way round.

Comparative studies such as this, as well as transparency and continuous improvement in design processes, are imperative in pushing forward the sustainability agenda in the structural engineering industry. By quantifying the issue and highlighting the priorities, engineers are able to focus their attention on the most CO_2-sensitive design features.

We anticipate it becoming common practice that CO_2e tools such as this are used to guide design decisions from the very start of projects, and that clients will expect as much. Further integration of building information models to track carbon with full transparency throughout key design stages should also be encouraged. The authors' organisation has developed such tools and is now routinely using them to assist with sustainable practices in design projects.



↑FIGURE 20: Summary of equivalent embodied carbon (lifecycles A1–A5) per square metre of usable deck area

Conclusion

Hams Way Footbridge is an excellent example of how an ordinary road span can be upgraded to a 'statement' bridge with a few carefully considered architectural enhancements. Complex detailing was delivered in a clear, buildable and sustainable way through collaboration across the design and construction teams. Digital tools were utilised to effectively communicate design intent with the construction team, as well as to the client and many stakeholders of the bridge.

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