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The Dinosaur Bridge – innovation in structural form & fabrication using model making and prototyping

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Abstract

While small, the Dinosaur Bridge demonstrates how close collaboration between the design and fabrication team and a rigorous process of modelmaking and prototyping can create a delicate structure that suggests new ways of generating sculptural form.

A team of Tonkin Liu (architects), Arup (structural engineering) and Cake Industries (fabrication and installation) were commissioned by the charitable body that looks after the Victorian Dinosaur sculptures in Crystal Palace Park, London, to improve access for maintenance and educational purposes to the heritage island. By drawing on and abstracting references from the natural world, the team developed a scheme for an eight metre swing bridge that creates a complex sculptural geometry from flat laser cut steel sheet. By cutting a "comb" from a 10mm thick plate, the cantilever struts, deck stiffeners and balustrade posts could all be folded from a single piece. This framework is attached to a triangular and profiled box girder, creating a structure that is visually striking, with sinusoidal forms that act both visually and structurally.

This paper describes the collaborative process of developing the design through understanding and incorporating the fabrication process in the design concept, and working at various physical model scales through to full size testing. The bridge is due to be installed in autumn 2020.

Keywords: structural concepts; planning; fabrication; structural models, moving structures; aesthetics; community funding

Introduction and Project Background

The life-sized sculptures of Dinosaurs [Figure 1] located in Crystal Palace Park, London, were created at a pivotal moment as the first ever "edu-tainment for science". Set in landscapes that attempt to reflect 400 million years of geologic time as light-touch experiential learning, the ensemble has significant heritage value and embodies the democratisation of scientific knowledge. The Dinosaurs were built in Crystal Palace Park in 1854 as it was being developed to surround a re-built and expanded version of the Great Exhibition of 1851 [Figure 2].



Figure 1. The Crystal Palace Park Dinosaurs now [credit: Friends of Crystal Palace Dinosaurs].



Figure 2 Crystal Palace with the Dinosaur sculptures in 1854 [credit: Friends of Crystal Palace Dinosaurs].

To access the island easily, a bridge was required. The Friends of Crystal Palace Dinosaurs, a local charity, instigated a campaign to build a new bridge that would facilitate the restoration of the concrete sculptures of dinosaurs and other extinct animals and open up the island as an educational resource.

Design

Given the limited project budget and strong visual requirements that come from building adjacent to a highly sensitive heritage site, the design of the bridge had to be undertaken collaboratively. Tonkin Liu, Arup and Cake Industries worked together through multiple design workshops to develop a scheme that married form, structure and fabrication, within a miniscule budget.

The bridge is positioned at the southern end of the Dinosaur Islands, in the 'deepest' part of the geological walk through time. This is where the sculptures of the earliest land vertebrates emerge from the metaphorical and actual waters. Inspired by the skeletal structures of fish that dominated the early seas the bridge features a 'linear spine' that supports a cut steel plate from which a series of 'ribs' are folded which support the bridge deck and the handrail. Like a living animal, it moves, rotating into its active or inactive position. The bridge features organic and curved components, similar to geometries found in nature, that are shaped to provide structural support and stability [Figure 3].

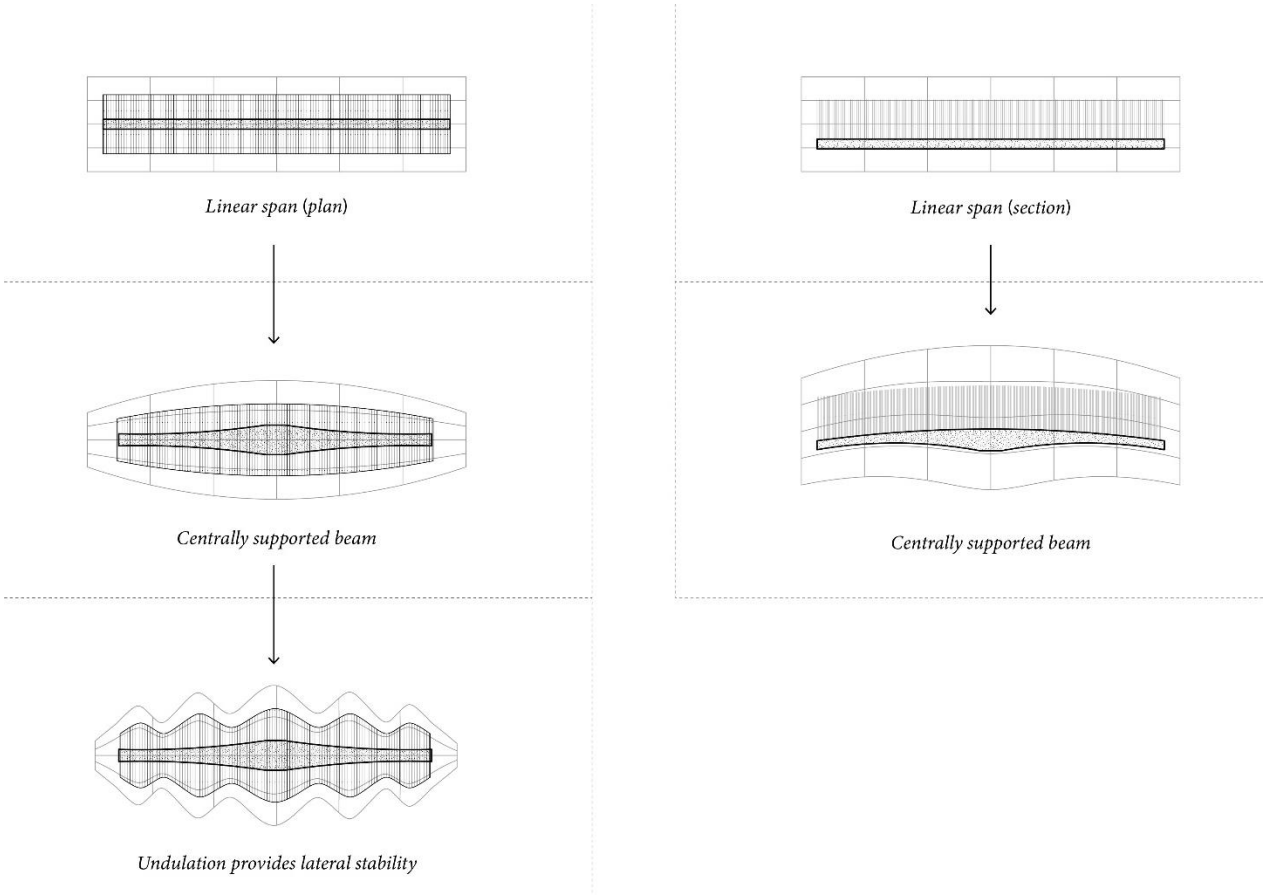


Figure 3. The development of the form from a straight horizontal bridge to one where the form provides strength and stability; load is concentrated towards the centre of the bridge's spine beam and an undulating geometry provides strength and stability to the handrail. [credit: Tonkin Liu]

Model making and prototyping

The major innovation within the design of the structure involved the use of a folded comb [Figure 4] that acts as both the deck plate, the struts supporting the edge of the deck, and also the balustrade post. A series of models were used by Tonkin Liu to test the structural principles of the 'comb' concept during early design stages. The first model that explored the deck was a simple paper model that made an unfolding comb. This was followed by a quick straw model [Figure 5] that tested the notion that a curving profile would add stability to the balustrade and deck. The models demonstrated compression in the downward struts and tension in the deck.

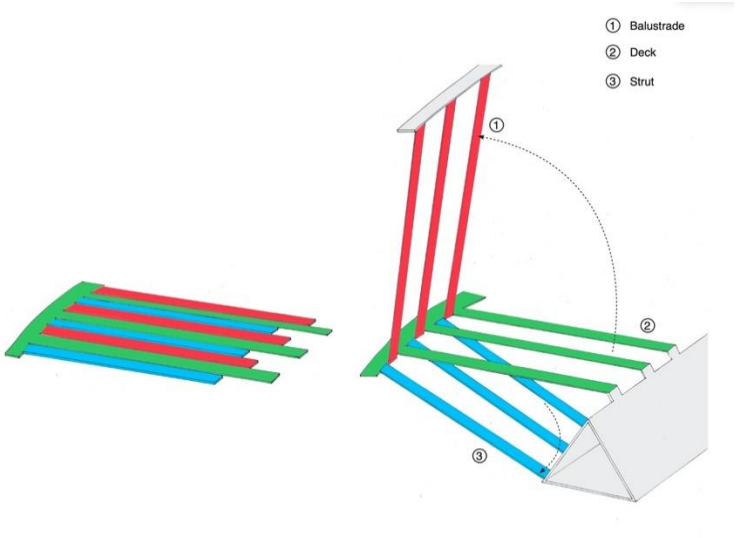


Figure 4. The 'folded comb process' provided deck, strut and handrail elements from a single sheet of steel [credit: Tonkin Liu].



Figure 5. Preliminary model using straws [credit: Tonkin Liu]

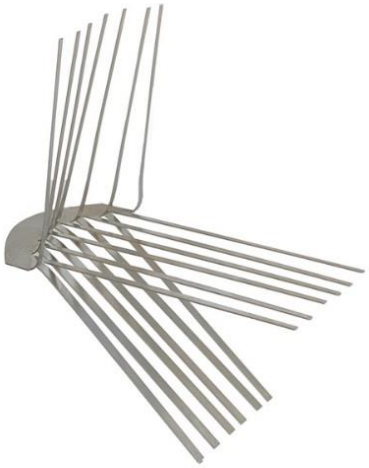


Figure 6. Preliminary model using etched thin metal [credit: Tonkin Liu]

Structural models are quick and easy to put together and demonstrate behaviour in a simple way. Modern modelmaking techniques also make it simple to replicate the process of CNC cutting plate materials [Figure 6] and can create beautiful architectural models that serve multiple purposes – both indicating the final appearance to funders and the public as well as demonstrating the complexities of some geometrical ideas. Tonkin Liu created a 1:20 scale laser etched model [Figure 7] that was exhibited at the Royal Academy Summer Exhibition 2019 (winning the BKI Material Prize). This model was a useful staging post in the design process and led to changes in the overall form, simplifying and slimming the visual impact.

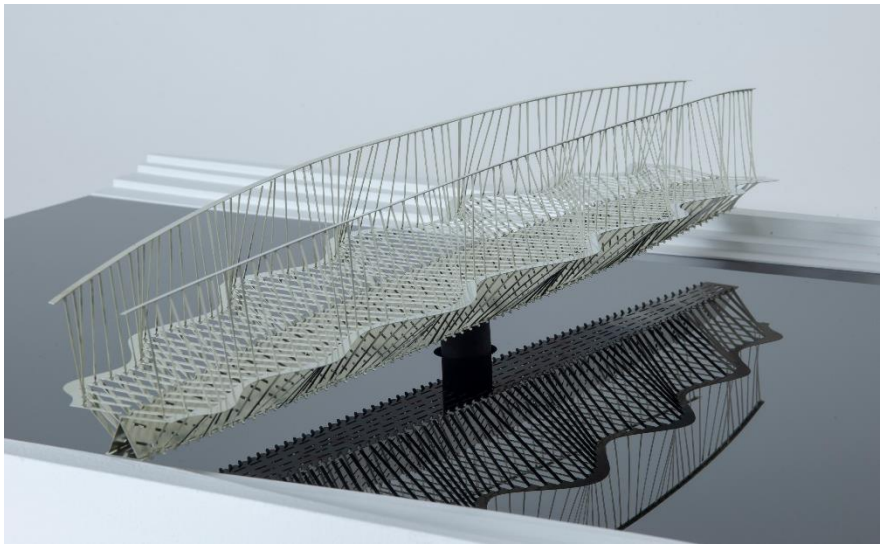


Figure 7. Model exhibited at the Royal Academy Summer Exhibition 2019 [credit: Tonkin Liu]

The folded-comb process was prototyped at Cake Industries [Figure 8] using mild steel sheets to ensure that the process was feasible before it was incorporated in the final design. This prototyping allowed the definition of appropriate tolerance limits and bend criteria to be fed into the Arup structural model to check the buckling and strength capacities of the various elements. It also allowed the fabricator to determine the exact manufacturing process and element spacings to meet the workshop requirements.



Figure 8. Full scale prototype supporting the team (David Knight, Keefer Erickson, Stuart Chambers, Anna Liu, Mike Tonkin, Matthew Burnett) [credit: Cake Industries]

This loop of design to modelmaking to feedback to prototyping to feedback to final scheme design allowed the design team to become confident enough to implement an innovative and untried fabrication process in the final scheme.

Final Scheme

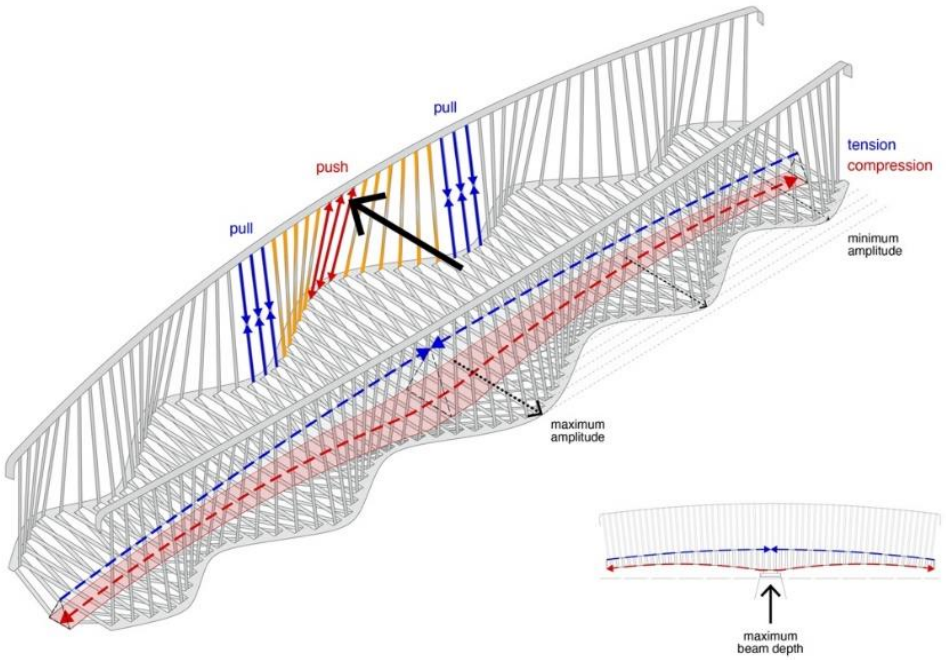


Figure 9. The handrail derives stiffness through the geometry of the comb sections, having a push pull offset along the length of the bridge [credit: Tonkin Liu/Arup]

For the completed Dinosaur Bridge, a single flat sheet of 10mm thick steel was laser cut with a comb pattern. The deck struts (36mm wide) and balustrade posts (31mm wide) were bent out of the plane of this sheet by heating the root of the tine using an oxyacetylene torch, taking care to heat to within the limits for hot working in EN1090-2 (i.e. 600 to 650 degrees). The tine could then be bent by hand to an orientation to suit the final geometry. A 50mm wide deck edge was left attached to the 36mm wide deck cross pieces to tie the system together. A simple expanded steel mesh is incorporated on the deck to create a walking surface.

The spine of the bridge is supported on a single central support that would allow it to rotate on plan, blocking access to the Dinosaurs when spun away from the bank whilst allowing access for maintenance and visitors when in its service position [Figure 9]. In the service position, the bridge does not rest on the banks; it remains supported only by the central support.

The greatest structural forces occur at the central support and the profile of this spine is optimised to be deepest and widest at the centre and to curve upwards and outwards to the two landing points. This curving profile and triangular cross section give the beam maximum strength and stiffness for the minimum amount of structural material as it delivers loads directly to the central bearing. The longitudinal bending forces are primarily taken in the triangular box cross section, but due to the fully welded nature it was important to account for the parasitic stresses that the parapet posts and handrail carry.

The central spine beam is supported by the bearing and in turn supported the comb sections, which act somewhat independently of the spine. Out of balance force over the width of the deck are dealt with through torsion in the spine beam, while out of balance force over the length of the bridge are dealt with through the bending strength of the spine beam, transferring the overturning forces to the bearing and foundation.

The handrail derives stiffness through its undulating geometry. Utilising vierendeel action in balustrade sections to transfer the shear force, the handrail system generates a lever arm at its base that allows it to resist the overturning force generated by people pushing or pulling the handrail.

A project of this nature was bound to go through several design iterations until the desired outcome was achieved. To streamline the process Arup generated a parametric script utilising Rhino, Grasshopper and plugin Geometrygym [Figure 10], which allowed the rapid build and test of a multiple analysis models. Parameters such as section size, fabrication thickness, amplitude, repetition of wave form, hierarchy of elements, and so on were varied and studied, with feedback from the physical modelling fed into the process.

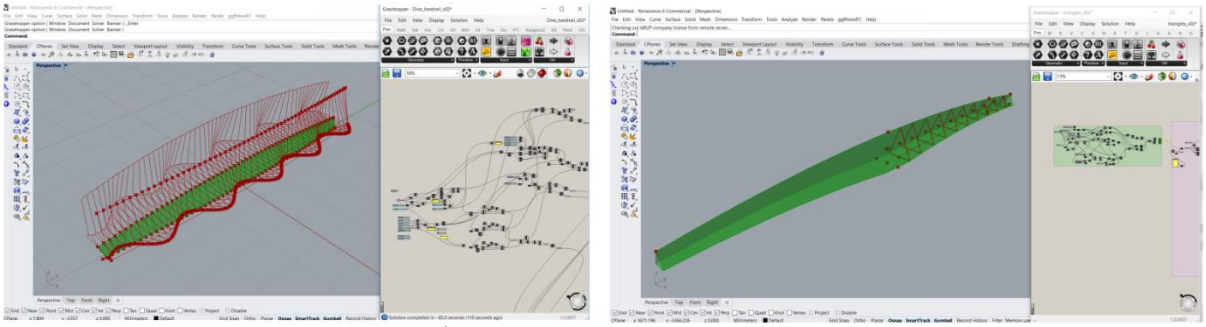


*Figure 10. Grasshopper and Geometrygym used for rapid generation of varying analysis geometries [*credit: *Arup]*

These studies allowed the team to determine rapidly and accurately the most efficient yet visually appealing forms. They demonstrated that for this system there was a delicate balance between the force distribution in elements of the bridge and the regularity of their repetition. It transpired that (similar to a bicycle wheel) by using *many* slender elements all acting together, the bridge could in fact achieve higher resistance than it would if using *fewer* larger elements, where force would ultimately concentrate and overload a single element of the comb.

Whilst there was a desire to utilise the thinnest possible steel plate to maximise buildability and minimise material use, the bending forces induced by a point load on the deck had a significant impact on the stresses of the deck elements. A balance was struck with 10mm as it offered a plate thickness that could still be bent during fabrication but allowed the deck widths desired.

The bridge, having relatively little mass, is highly susceptible to footfall-induced vibrations. The connection detailing from spine beam to bearing has a considerable impact on the stiffness and vibrational performance, commensurate with the depth and thickness of the spine beam. The bridge form was tailored to maximise stiffness to combat these effects.

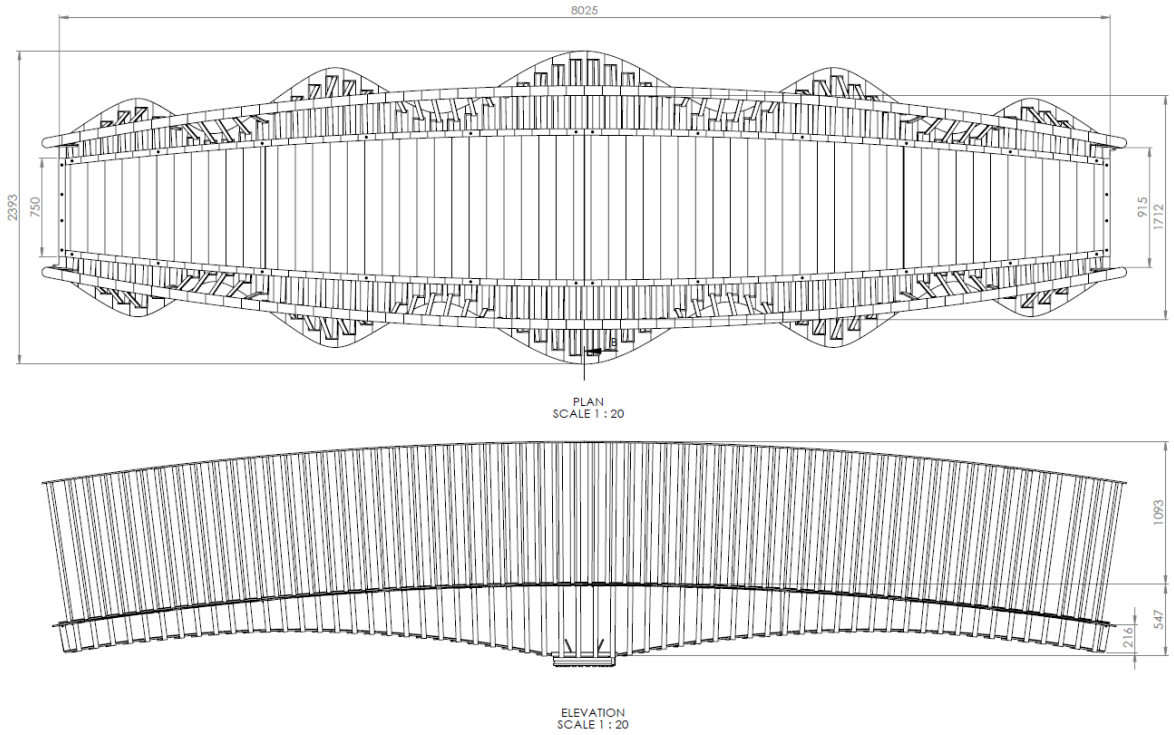


Figure 11. Final plan and elevation from the Cake Industries fabrication model [credit: Cake Industries]

Fabrication and Construction challenges

The fabrication of this project required both the use of modern digital tools and the traditional skills and craftsmanship of high-quality metalwork. The geometric constraints of the form necessitated a full object-based 3D model in Solidworks [design output shown in Figure 11], which generated cutting patterns for flat steel plate to be laser and waterjet cut. The elements that formed the central spine were assembled in a plywood CNC cut female mould (much like fabricating a boat hull) which formed the backbone of the structure and also provided the geometric control for the form of the deck.



Figure 12. Fabrication underway in the Cake Industries workshop: heating combs prior to manually bending [credit: Cake Industries]

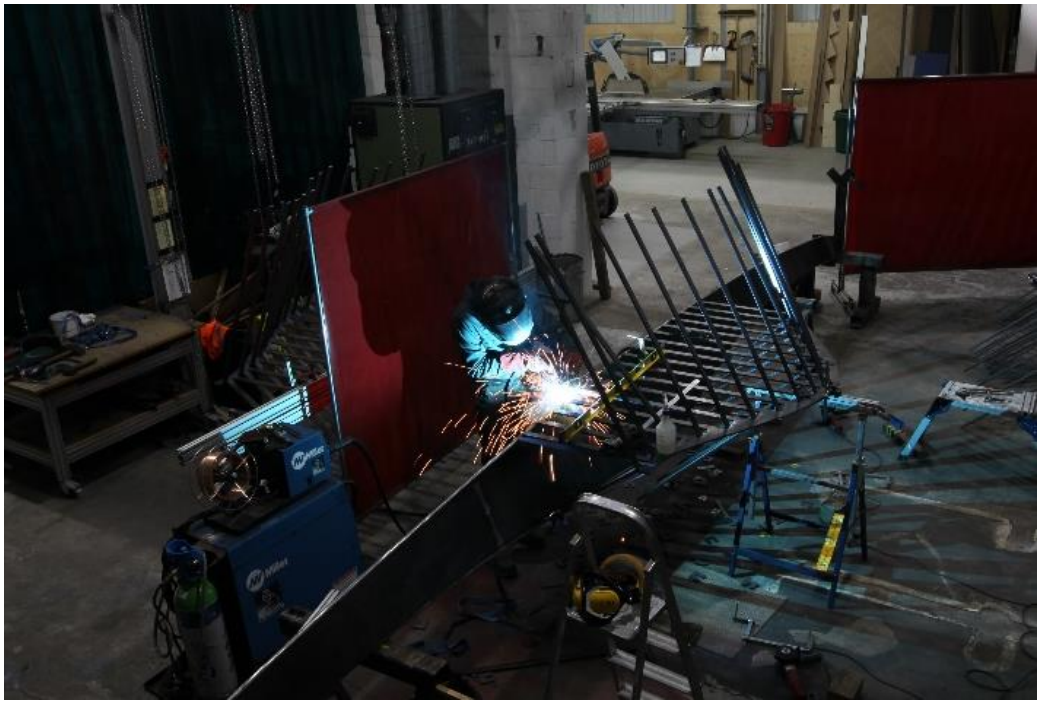


*Figure 13. Fabrication underway in the Cake Industries workshop: welding deck to the spine beam; [*credit: *Cake Industries]*

The deck combs were formed using a manual two stage process. Deck struts and balustrade posts were bent to an intermediate position [Figure 12] to allow the segments to be offered up to the central core [Figure 13], before a secondary process was used to bend the tine to exactly the correct location at the bottom of the spine beam or where it intersected with the handrail line. This

process allowed the craft skills of the makers to focus on forming smooth curved lines within the structure rather than concentrating on absolute dimensional accuracy [Figure 14].

Cost

This project was undertaken by the design and fabrication team as a charitable exercise, working closely with the client who are a local volunteer organisation dedicated to looking after the Crystal Palace Dinosaurs. The funding for the project was raised from charitable grants and local people through a crowdfunding process and therefore the design and build budget was necessarily constrained, with under £100,000 being available to construct the bridge. Donations of time and fabrication space by Tonkin Liu, Arup and Cake Industries made up the shortfall in cost.

Galvanising

With an overall form that consists of small thin elements, designing for the durability of the structure was a key process. Stainless steel was considered as a possibility but was precluded by the minuscule fabrication budget. Instead, the visual and protective finish for the structure was applied in a single action by hot dip galvanising the entire structure [Figure 15]. This required the use of the largest galvanising bath in Great Britain, located in Chesterfield and operated by Joseph Ash.

Considerable design effort was put into ensuring that the overall height of the structure including the integral parapets and handrail was smaller than the width of the bath (1700mm). As the final height was only 60mm smaller than this, additional measures had to be put in place by the galvaniser to prevent the presence of impurities on the surface of the bath discolouring the final finish. This include the provision of additional operatives to scrape the bath surface and "air lance" the piece as it was removed from the bath. Drainage holes were provided throughout the core to allow free drainage of zinc through the structure. It is expected that no further maintenance to the finish will be required for the lifetime of the structure.



*Figure 14. Transportation from the fabrication yard to galvanisers, showing sinuous form [*credit: *Cake Industries]*



*Figure 15. The bridge after hot dip galvanising [*credit: *Cake Industries]*

Conclusion

Model making and prototyping paid a critical role in the success of this project, and allowed the use of an innovative fabrication method to drive the design of a bridge structure. In the same way that the Dinosaur sculptures are a representation of current knowledge, models enable a stage to be set for further research and development. The process of repeated loops between virtual and physical model making with the addition of full-size prototyping gives the entire project team confidence in the outcome of the design and in this case has resulted in a bridge [Figure 16] that provides delight as well as creating a structure that adds to the story of the Crystal Palace Dinosaurs.



Figure 16. Rendering of the Final Scheme [credit: Tonkin Liu]

SEI data block

Owner: Bromley Borough Council
Client: Friends of Crystal Palace Dinosaurs
Architect: Tonkin Liu
Structural Engineer: Arup
Main Contractor, fabricator and temporary works: Cake Industries
Plate cutting and profiling: M-Tec
Galvanising: Joseph Ash Galvanising
Piling and foundations: Capital Piling
Lifting subcontractor: City Lifting