Shaping Forces

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DOI
10.20898/j.iass.2018.196.884

Publication date
2018

Document Version
Final published version

Published in
Journal of the International Association for Shell and Spatial Structures

Citation (APA)
Smits, J., Eigenraam, P., Gkaidatzis, R., Visser, D. R., Wong, K., & Wassermann-Fry, S. (2018). Shaping Forces: Review of two Bridge Design Methodologies towards Architectural and Structural Symbiosis. *Journal of the International Association for Shell and Spatial Structures*, *59*(2 (n.196)), 152-164. https://doi.org/10.20898/j.iass.2018.196.884

SHAPING FORCES; REVIEW OF TWO BRIDGE DESIGN METHODOLOGIES TOWARDS ARCHITECTURAL AND STRUCTURAL SYMBIOSIS

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Editor's Note: Manuscript submitted 13 December 2017; revision received 11 March 2018; accepted 23 April. This paper is open for written discussion, which should be submitted to the IASS Secretariat no later than December 2018.

DOI: https://doi.org/10.20898/j.iass.2018.196.884

ABSTRACT

This paper investigates the symbiotic relationship between the architectural appearance of a bridge and the structural design. The research is done by reviewing and comparing the design methodology employed by the first author in the conceptualization of two of his bridges; an early work from 1997 and a recent work from 2017. The review of the early work describes a design methodology that could be described as intuitive design, whereas the later work is the result of computational from-finding and optimization. Parallels are drawn and the historical development of the toolbox of the architect and the engineer is described. The paper analysis the way the two designs were achieved by looking from the perspective of the architect and that of the engineer, two disciplines that nowadays closely work together on the design of a bridge. The paper concludes by identifying the key design considerations to achieve a beautiful yet structurally sound bridge. The question whether beauty can be the sole result of a rational design process towards the most efficient form according to the laws of mechanics, is addressed. This paper demonstrate the belief that when it comes to the design of a bridge, architecture and structure, form and force, are involved in an interdependable and symbiotic relationship.

Keywords: *Bridge design, Architecture, Structural design, Optimization, Parametric design, Form-finding, Concrete, FRP*

1. INTRODUCTION

Over the past two decades architects have found their way into the practice of bridge design, a field of expertise that was formerly considered the sole domain of structural engineers. Ever since the 90's a strong growth of the involvement of architects in bridge design has taken place. The beginning of this new era of architectural bridge designs is clearly marked by the realization of the Alamillo Bridge, built for the '92 Seville Expo, by the world famous architect and engineer Santiago Calatrava. His design for a cable stayed bridge stands out for the massive pylon which, by its backward inclination, formed a counterbalance to the forces from the cable stays, thus creating a bold demonstration of the forces at play. At the same time the Alamillo Bridge was a defiance to traditional bridge designers demonstrating that the easiest way to design a cable stayed bridge was not necessarily the only way, and that structurally sound solutions can also be found in a not-so-straightforward approach. Ever since the Alamillo Bridge a closer collaboration between architects and structural engineers has resulted in many beautiful and well-integrated bridge designs all over the world. The downside to this development is that at the same time a lot of farfetched bridge designs have also seen the light of day.

What are the key design considerations to achieve a beautiful and yet structurally sound bridge? Does a structure always need to follow the most efficient form, according to the laws of mechanics and/or finance? Or is there such a thing as symbiosis between Form and Force, a way of working that ensures that the final result becomes greater than the sum of its parts?

Two bridge designs from the author, one marking the beginning of his career in 1997 and the second one only recently accomplished, demonstrate the belief that structure and architecture are involved in a symbiotic relationship. One cannot be successful without the other. Just how successful this interaction is, forms the subject of this paper.

2. SHAPING FORCES

In 1997 W. Zalewski and E. Allen wrote the book ‘Shaping Structures’ for students of Architecture and structural engineering. In the preface it is written that ‘The essence of structural design is to shape each structure to respond effectively to the forces that it must withstand and to the human activities that it nurtures’ [1]. It is interesting to compare Zalewski’s theory with the well-known trinity Venustas, Firmitas and Utilitas described by the influential Roman architect/engineer Vitruvius (80-25 BC) in “de architectura” [2]. Zalewski’s theory addresses both force and utility, or as Vitruvius would put it, Firmitas and Utilitas. However, the aesthetic dimension, Venustas, has been left out of the equation. Or rather an assumption seems to have been made that a structure that responds effectively to the forces and to human needs is intrinsically beautiful.

The title Shaping Forces is based on the well-known adage ‘Form follows Force’; the assumption that an architectural design that follows a path of structural logic also holds a greater aesthetical value. But what exactly is structural logic, and how can it be achieved? There are of course many design methodologies that lead to a structurally logic bridge.

One method is to pursue a minimal use of materials for the required program and load case by following the path of the loads to the foundations in such a way that the least amount of material is used. A very popular approach among academics and professionals nowadays is achieved through computational design using advanced parametric form-finding and optimization software like Grasshopper, Karamba and Kangaroo [3].

One has to acknowledge that these types of form-finding and optimization software are in fact nothing more than a tool to achieve structural logic. The method behind it is not new. An eminent pioneer in this field was Heinz Isler who used his ‘frozen towel’ technique to create poetic natural shells. He states: “One does not actually create the form; one lets it become, as it has to according to its own law.” [4]

Figure 1: *Heinz Islers’ frozen fabric*

Before that Antoni Gaudí used his now famous inverted chain model to find the most efficient vaulted shape for the Sagrada Família.

A third way of deriving architectural form through structural ideals relies on greater design intuition. Instead of letting the form create itself, such as Isler did (Figure 1), a skilled designer with a profound understanding of structural mechanics and a fine sense of aesthetics can accomplish good results. They can shape a structural geometry based on the functional constraints, a befitting architectural typology that fits the context and an understanding of the forces and materials used. It is this intuitive way of determining a structure that is demonstrated in the first case study on the Navel Bridges in chapter 3.

Figure 2: *One of two Navel Bridges in Nieuw Vennep, The Netherlands*

3. NAVEL BRIDGES IN NIEUW VENNEP

The design of the Navel Bridges in Nieuw Vennep, the Netherlands, is a clear demonstration of the authors' conviction that structure and architecture are involved in a symbiotic relationship (Figure 2). The Navel Bridges were designed and drafted in 1999 at his architectural office at a time when he was freshly graduated from both the School of Architecture as well as the School of Civil Engineering in Delft [5].

When planning a new thoroughfare road in a new suburb of Nieuw Vennep, the authorities at first considered making a two-short-span bridge, one span over the canal and the other for a bicycle underpass directly adjacent to the bridge.

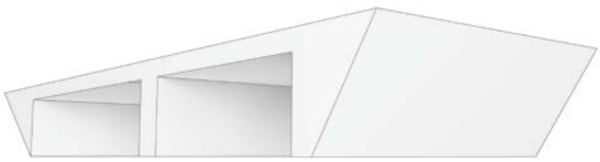

Figure 3: *Initial proposal for a culvert and an underpass*

The short span caused a visual disruption of the recreational water in the park, while at the same time the bicycle passages faced issues of poor visibility on the surroundings.

The first step in the design process was to combine the bridge and the tunnel into one structure spanning both water and bike passage, thus increasing the spaciousness and transparency under the road and improving the perception of the bicyclists of being protected (Figure 3). The chosen material to achieve this span was in situ concrete. This had to do with the specific urban context of the surroundings and the wishes of the municipality to have a sturdy design with little maintenance issues. It was argued that two larger span bridges could be built within the budget if they would be identical (although rotated 180 degrees from each other) and could share the same formwork. An alternative in prefabricated concrete beams was dismissed because both the client and the architect wanted a unique design with a homogenous sculptural appearance that would benefit the identity of the entirely new town.

Second step in the design process was to determine the soffit level underneath the structure, both for bicycles and pedestrians as for boats and ice skaters, to determine the height and alignment of the ceiling. The thoroughfare road was allowed to raise by one meter locally. As it turned out the ceiling needed to be at its highest above the bicycle path, as an optimization between the vertical alignment of the path and the most slender part of the bridge deck.

Figure 4: *Setting the vaulted ceiling*

The resulting elevation of the bridge now showed a vaulted arch with an asymmetrical profile (Figure 4). The asymmetry of the profile determined the static scheme of a clamped connection on the side of the abutment near the water, and a rolling hinge near the bicycle path. Whilst the landing on the side of the bicycle path was relatively slender, a very massive piece of concrete appeared above the water. Therefore, the third step in the design process was to eliminate the surplus of concrete by creating a cavity between the deck and the vault (Figure 5). Sharp inner corners in the concrete cavity were avoided to allow for a fluent flow of stresses, reducing concentrated areas of high stress, and to avoid cracking in the corners. The resulting shape was a combination of a straight, flat slab for the motorized traffic and an arch beneath, which merged with the slab as it rose up vertically. Statically speaking, it is not entirely correct to speak of an arch, as it does not receive any vertical loads after separating from the deck, other than its own weight. One could also see it as a slanted pillar under the deck.

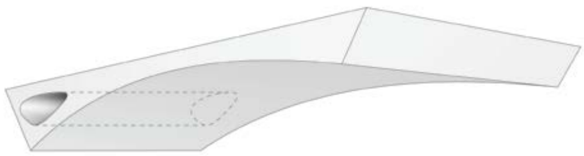

Figure 5: *Taking away the surplus of concrete*

Figure 6: *View on the intersecting cavities in the abutment on the water side. Clearly visible are the rough timber planks in the formwork of the vault and the sides. The cavities on the other hand are smooth inside*

The fourth step in the design process was to further reduce the amount of concrete by tapering the sides of the bridge deck as well as the arch under a 45 degree angle (Figure 7). This resulted in a much lighter appearance, the cavity became shorter and thus more transparent when seen at an oblique angle,

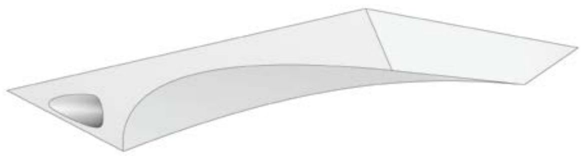

Figure 7: *Tapering the sides*

and daylight penetration under the bridge, on the bicycle path and on the water improved greatly.

The design could have stopped there as a pleasing architectural space under the bridge had formed. However, it was soon realised that further weight savings and greater elegance could be achieved by further opening up the vault and the cavity. The fifth and last step, therefore, was to create another cavity at a 90 degree angle to the first cavity along the longitudinal span of the bridge (Figure 8).

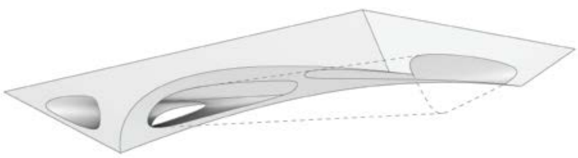

Figure 8: *Creating a longitudinal cavity*

A T-junction of cavities was created, splitting the arched vault into two separate arches and opening up unexpected perspectives through these cavities to the surroundings (Figure 6, previous page).

The bridge was completed by designing matching parapets out of concrete and stainless steel. The bridge was accessible to motorised traffic, so the parapets, which acted as side walls, were required to be robust in design. In addition, the design consciously accommodated for unhindered views of the river for drivers. This was achieved by employing low walls with cavities, which succinctly tied in with the overall design of the bridge. The stainless steel railing was kept light and simple with short posts mounted directly on top of the concrete.

4. THE SHARC, BERLIN 2017

Eighteen years after completing the design of the two Navel Bridges, the author's university team participated in the design competition for a new footbridge for the International Footbridge 2017 Berlin conference, together with the London based offices of BuroHappold (Figure 9). The accepted conference paper focussed on the final product and images, not on the design process itself. The current paper is a review of the used methodology to get to the final design.

The ShArc is a hybrid structure that combines the characteristics of a shell with those of an arc, hence ShArc. The design was created using a computational design methodology by means of parametric software and scripting. The form-finding methods that was used was not limited to optimizing solely the structural behaviour, it was also used to improve the aesthetical and functional design. The iterative design process that was used resulted in a good balance between these three aspects, which interacted in a symbiotic relationship.

Pioneers like Gaudí, Isler and Frei Otto worked on form-finding through physical models such as suspended chain models, frozen textile and soap films. This form of physical form-finding results in one solution for the specific situation. Thereby not taking into account other load combinations that will also be applied during the lifespan of the bridge. The design methodology employed for the ShArc equally started from a unilateral form-finding model, translating self-weight and additional equally distributed loads into a shape that is convenient for the distribution of loads.

The difference however with the methods of physical modelling, described above, is that the authors did not stop when the first correct shape for the constraints was found. The team proceeded

Figure 9: *Artist impression of the ShArc in Berlin, 2017*

to investigate ways to alter the initial form-finding geometry in order to comply better with different load cases, functional requirements and aesthetical requirements. For this purpose, a next step was made by introducing specific additional loads so that the result of the form-finding would include an solution for other loads than equally distributed. This way the curvatures of the sides, the steepness of the slopes and the transparency of the overall design could be controlled intuitively. For this purpose a script was developed allowing for adaptation of the shape of the model, and showing immediate feedback on structural behaviour. The specific steps for the design of the ShArc in Berlin are now further described.

4.1. Conceptual design

Like all designs, this design was based on an initial idea. The concept is to create more than just a bridge from A to B; but rather a bold design that will become a destination in itself and a cultural landmark for the metropolitan city of Berlin. Instead of the two linear bridges with a medium span, as the program suggested, it was decided to create one bridge connecting the three landings resulting in a tripod-shaped bride, located at the confluence of the river “Spree“ and the “Landwehrkanal“, connecting the downtown districts Charlottenburg and Moabit, would serve both purposes (Figure 10).

Figure 10: *Perspective of the ShArc at the confluence of the Spree and the canal*

The goal was to span both the Spree and the canal with one fluent and single span structure, each of the three bridge members being reciprocally restrained by the other two. Another design decision was that the deck of the bridge had to be a fluent arc above the water; shallow enough for pedestrians to be able to walk on top of it, but high enough to allow ships to pass under, and for the arc to act in compression. At the confluence of the three bridge members, the bridge should provide a public platform where people can enjoy panoramic views of the surroundings.

It should be mentioned that although the materialisation and detailing of the structure is not a subject for this paper, as it focusses on form finding, it was necessary to consider such details in order to conceive a feasible design. The longest span of the bridge is approximately 170m. To achieve the desired fluent and fluid appearance without additional supports, materialisation was rather important. The ShArc is conceived and engineered from a composite sandwich structure material, which is formed from Fibre Reinforced Polymer (FRP) outer layers with a foam or honey comb-core. Sandwich structures can be created from various combinations of outer layer and core materials, enabling flexibility in the design, with the outer layers designed to resist bending and axial stresses and the core to resist shear [7]. For the ShArc, it was proposed to use Glass Fibre Reinforced Plastic for the outer layers and a foam core material. These materials were chosen for their high compressive and shear strength properties, as well as low self-weight [8]. High compression strength also boded well for the arch-like structure incorporated into the design, as pure arches behave in pure compression, and in turn relieving the induced bending stresses in the structure and reducing deflections; through the design process, the optimum arch radius was evaluated, trading off the structural implications and functionality of the bridge. In order to reduce the deck weight further, and to maintain the open character, it was decided to create an opening in the deck at the junction of the three “legs”, directing the flows of pedestrian around the void. Reducing the weight of the deck had structural benefits by reducing deflections and high stresses in these areas. Another advantage of FRP is that it can be easily moulded, which allows the process of creating the curvaceous deck to be considerably easier than traditional materials.

Figure 11: *3D printed Daedalus Pavilion at the GPU*

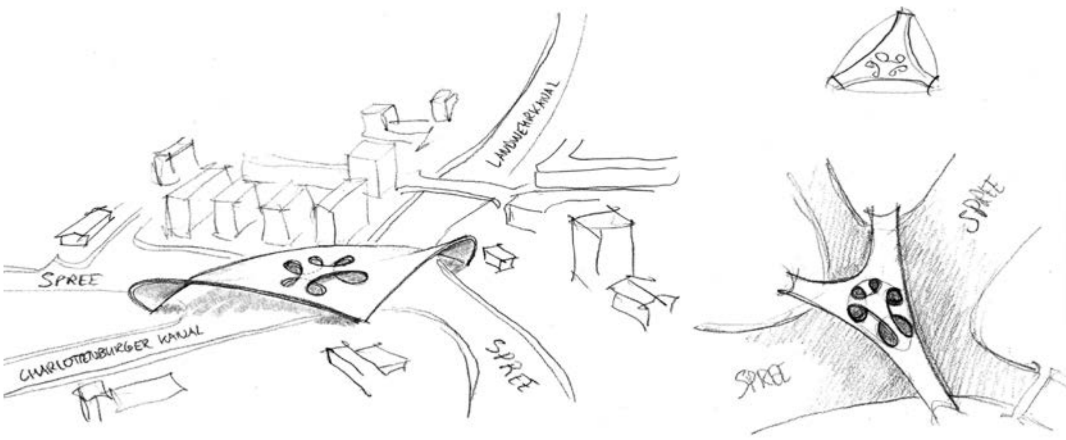

Figure 12: *First sketches for Berlin; introducing a double surface within a shell structure*

Initially the inspiration for the shape came from the 3D printed prototype of the Daedalus Pavilion, presented at the GPU Technology Conference in Amsterdam (Figure 11). The pavilion has an intricate shape with a double layered deck in the central part, consisting of an upper and a lower deck crossing over in a void (figure 12). Although this idea was later abandoned, as it proved impossible to create enough distance between the two decks for a person to be able to walk underneath, it lead to further use of the parametric script as the main design tool. Therefore pursuing the development of the idea proved to be crucial to the process of the design. It challenged the authors to use form finding to manipulate the shapes intuitively in a way that was aesthetically pleasing and not necessary resulting in a structural optimal shape. In this first step this was merely a convenient side effect and later implemented as part of the final design. The shape was manipulated by differentiating the ratio between loads and stiffness in the form finding model.

4.2. Digital form finding

Digital form-finding was used for exploring various possible geometries for this complex bridge. Therefore *Grasshopper* and *Kangaroo* were used. Both well-known and often applied software for form-finding. The first rough model of the desired shape allowed to create a model with surfaces that overlap in the middle (Figure 13). Having physical modelling in mind it would be impossible to create this shape when starting from a single membrane because at the centre there are two layers on top of each other.

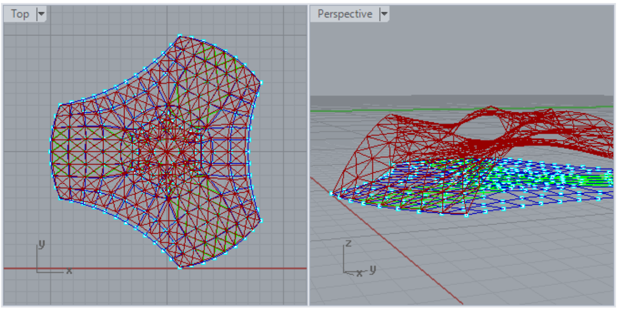

Figure 13: *Initial model for a double surface*

For the initial model two ways to influence the geometry of the structure were applied; differentiating the stiffness within the membrane as if it was non-uniform in different directions but also in different areas of the entire model. A second method was to influence the shape of the structure by including line loads at the perimeter of the model, additionally to the equally distributed loads, which created more curvature within the cross section. This second method was predominantly used to fine-tune the shape of the bridge.

Working with a parametric script provided a great amount of design freedom. It allowed to intuitively modify the model. For example, it became much easier to move the landing areas along the quays in order to create bridge members that were more equal in length, and thus had less steep ramps.

4.3. Physical form-finding

Form-finding within a digital environment proved to be very powerful while allowing for a great amount of flexibility to modify the model. However, for structural purposes it does not necessary provide insight in the structural behaviour. Furthermore numerical models provide quantitative information which does not necessary lead to qualitative information. Therefore, parallel to creating the parametric script, physical form-finding tests were performed using experiments in fabric, paraffin and gypsum (Figure 14). Physical models provide insight. Stiff and flexible parts can be identified quickly by applying loads by hand. Since models are often fragile the weaker parts break when the model is subjected to less gentile pushing. Thereby they are easily identified as well. Also the overall shape provides a reference for the shape resulting from form-finding within a digital environment. Physical modelling provides a context to think about the consequences of different shapes and boundary conditions or where to apply stiffening measures. The cutting pattern for example influences on the resulting shape, as does the positions of the three support points. The type of fabric also influences the shape. A microfiber cleaning cloth was used which has uniform stiffness in all directions.

The results provided a reference for the shape that was form-found digitally, using only a distributed load that represented self-weight. Also, by having a physical model, structurally weak places could be identified quickly. Therefore the model had to be damaged, but multiple models could be made easily. One essential flaw that was particularly demonstrated was that the model had a tendency to become flat in the perpendicular direction of the span. This made it sensitive for asymmetric loading, introducing bending in the structure.

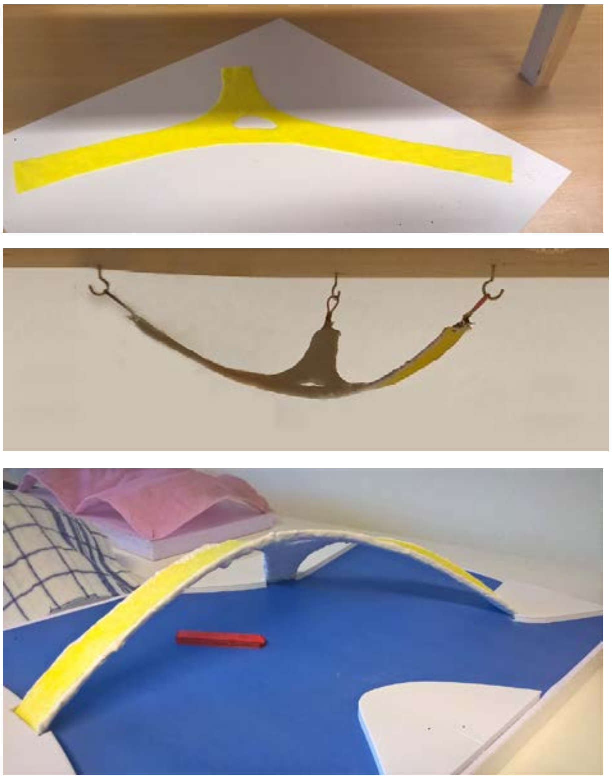

Figure 14: *Form-finding experiments in microfiber cloth and gypsum*

Making a physical model created awareness of the aspects influencing the digital model. E.g. the initial layout, stiffness of the membrane in multiple directions and positions of the supports. Also, a physical model provides a sense of scale to the designer. Something that in a digital model is easily lost.

4.5. Reflection on the performance

Both the physical models and the parametric model demonstrated one weakness in the shape. The shell was initially optimized for one load case only; that of an equally distributed load, the self-weight. However, as different load cases do not result in the same deformed shape, and will deflect according to their own load take-down (Isler), the physical model showed to be weak when subjected to asymmetric loading. Since the model was rather slender it was expected that other load combinations than self-weight could have significant effect. The first models resulted in a rather flat cross-section of the deck along the entire span of the bridge. The flatness wasn't well suited to resist the asymmetric loading; A flat geometry behaves in a beam-like manner, so induces higher bending stresses. Therefore it was required to design for more resistance to bending stresses in certain areas. In other words, the second moment of area of the cross section had to be increased at certain points. This can be done by increasing the structural height. This was applied in a gradual manner reducing towards the supports (Figure 15).

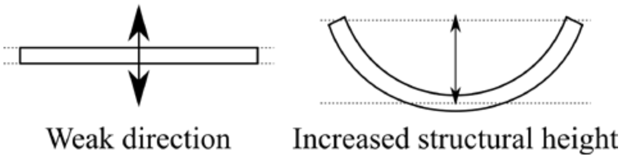

Figure 15: *Schematic cross sectional properties*

Manipulating the shape of the shell also altered the stress patterns throughout the structure. This resulted in two different curvatures for the top and bottom of the bridge. The thickness of the top and bottom FRP layers are able to be adjusted to suit the stresses in the panels throughout the structure.

4.6. Elaborating the parametric model

Based on early findings the parametric model was modified in *Kangaroo* to create more resilience to bending and buckling. In order to increase the second moment of area the sides of the cross section were curved upwards by adding virtual line loads along the perimeter (Figure 16). This unequal distributed load was in total approximately similar in magnitude to the total load of the equally distributed load. Therefore the overall shape of the model was similar but now with a curved cross section.

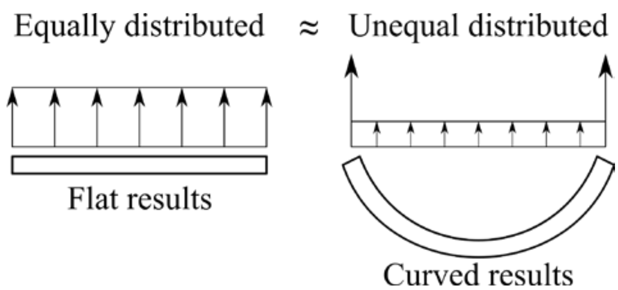

Figure 16: *Schematic load distribution of the cross section*

Another influence on the curvature of the deck was the shape of the supports at the bridge abutments. While a straight line support (and resultant flat deck) only offers limited stiffness, a concave line extends the 'half-pipe' (and more moment-resisting) section through to the pier. This would have consequences for the distribution of stresses which should be taken into account later. For aesthetic reasons the walking surface at the landings changed from sinclastic to anticlastic. By raising the edges the second moment of area also increased at the area of transition.

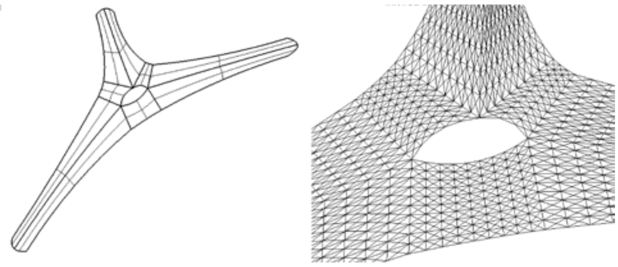

Figure 17: *Subdivision of deck (left) and grid (right)*

For modelling purposes the model was subdivided into nine surfaces, each one subsequently divided in a grid and diagonals (Figure 17). This set-up provided means to differentiate the stiffness in different directions.

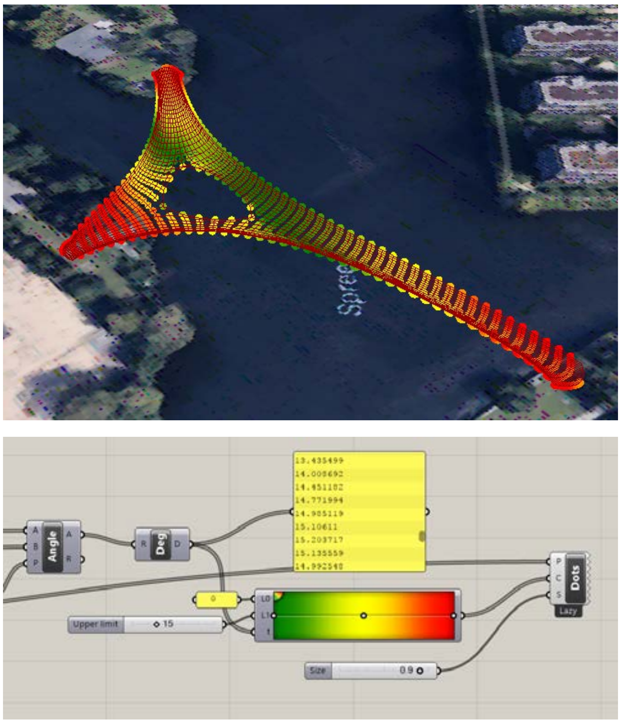

Figure 18: *A grasshopper script was written to monitor the resulting slopes*

While the authors were constantly modifying the geometry, realisation came that one of the most important functional requirements of the bridge, the slope percentage, was also constantly changing. In order to get visual feedback on the slope percentage from the model an addition to the script was made to provide direct feedback on actual slopes Figure 18). This became a useful tool to balance fulfilling requirements of different nature, namely structural, aesthetic and functional.

During the process of form-finding, one of the challenges was to prevent the shape of the bridge from wrinkling. This can be seen in Figure 21. Here the abutment remains fixed while the edges of the bridge are curved up- and inward. This proved to be problematic for both practical and structural reasons. A wrinkled surface would not be a good surface for further modelling. Structurally, a wrinkled surface would not transfer loads in a distributed way. The analytical model therefore had to be tidied up before analysis, rendering the process less efficient. The wrinkling effect could be prevented by changing the properties of the line elements in the parametric model by setting a rest length smaller than the original length. This would be equivalent to changing the length of the springs during the form finding.

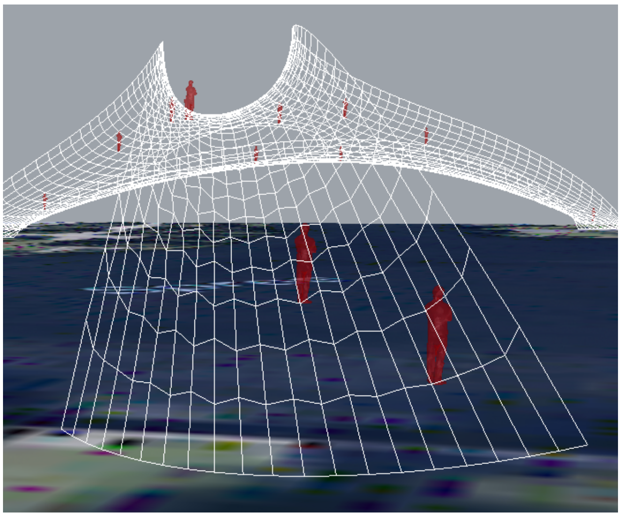

Figure 19: *Wrinkling near the abutment*

Like all shells, slenderness comes at a price. The bridge had the tendency to buckle laterally at the edges of the deck. Stiffening these edges by adding a separate edge beam was undesirable from an architectural point of view. Instead, the edges were strengthened by curling them, very much like a water lily leaf, to create thicker flanges.

4.7. Use of FEM with the Grasshopper script

The parametric set-up that was used allowed direct communication between the *Grasshopper* model and the FE analysis software (*Robot*). This meant that all FE input data could be centrally-controlled via the *GH* interface, and all resultant FE output data (deflections and stresses) fed back to the script.

Relying on a rigorous node and panel-numbering system, each panel is individually selectable and properties controllable, allowing us to assign specific panel thicknesses and loads, model large-scale gradients of loading-scenarios, and effectively analyse a more realistic cross-sectional geometry.

FEM was used to determine areas for perforations. As with the concrete bridge design method mentioned before for the Navel Bridges in Nieuw Vennep, from the FEM analysis we were able to determine the areas of high and low stress. This ultimately indicated the areas where redundant material had been provided, informing the locations and sizes of the perforations. It was essential to implement the numbering system in the script. In such a way the tool could be used for both intuitive modification and structural analysis.

In order to optimize the structure and use the material to its full potential, an iterative *Grasshopper* form-finding process is adopted. The sandwich composition of glass-fibre outer layers with honeycomb interior provide only limited out-of-plane shear capacity. Instead, the doubly-curving geometry of the ShArc allows shear transfer to the curving edges to be transmitted to the piers via the parapets and hull, which we need to encourage the *Kangaroo* relaxation algorithm to converge to.

Weighting functions are developed for each of the utilization factors as follows (Figure 20). This is to promote a high utilization in-plane (approaching 0.8), a low out-of-plane shear utilization and as low deflections as possible. The functions are at this point not academic and mainly serve comparative purposes.

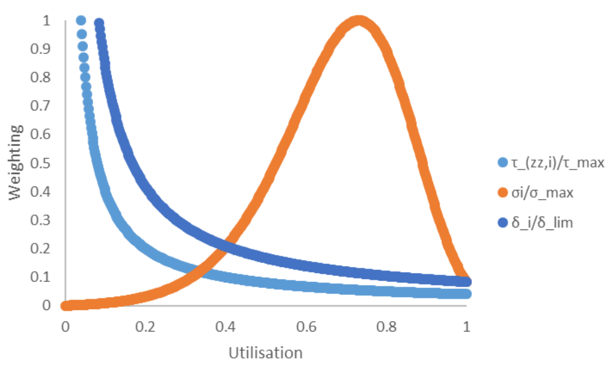

Figure 20: *Weighting functions*

$$f(UF_\tau) = f\left(\frac{\tau_{zz,i}}{\tau_{max}}\right) = \frac{k_1}{\left(\frac{\tau_{zz,i}}{\tau_{max}}\right)}$$

$$f(UF_\sigma) = f\left(\frac{\sigma_{v.Mises,i}}{\sigma_{max}}\right)$$

$$= \left(k_2(1 - \frac{\sigma_i}{\sigma_{max}})\right)^{-1} * \mathrm{e}^{-\ln(\left(k_2\left(1-\frac{\sigma_i}{\sigma_{max}}\right)\right)^2)}$$

$$UF_\delta = \frac{k_3}{\left(\frac{\delta_i}{\delta_{lim}}\right)}$$

$$UF_i = \overline{UF} = \frac{1}{3}\sum(f(UF_\tau) + f(UF_\sigma) + UF_\delta)$$

With:

$\tau_{zz,i}$ = out-of-plane shear at each node
τ_{max} = out-of-plane shear capacity
$\sigma_{v.Mises,i}$ = in-plane stress at each node
σ_{max} = in-plane stress capacity
δ_i = deflection at each node
δ_{lim} = deflection limit
$k_{i=1..3}$ =weighting factors

The average value of the utilization factors is calculated, and used as a utilization factor singular to each node (UF_i). The utilization factors for each node can then be plotted against their location relative to the bridge, either in a 2D plot graph or directly over the 3D geometry. As a result, areas of low material utilization can be identified rapidly and highlighted for required geometric alterations.

Shown are node utilization factors (UF_i) along the y-axis, with their relative position to the centre of the bridge shown along the x-axis (Figure 21 and 22). As can be seen between A and C, significant improvement can be made to make the material fully-utilized. A low point is shown at C, close to the centre, where the high stress concentrations associated with the piers are not as typical. The slight arch of the bridge and wide deck width presumably prevent the high flexural stiffness's typically associated with the mid-spans of structures.

The step at B is a result of an averaging function that we used to avoid the high local stresses at the corners where the two tracks meet around the opening, which we deem will require constructive mitigation and so deem to be unrepresentative.

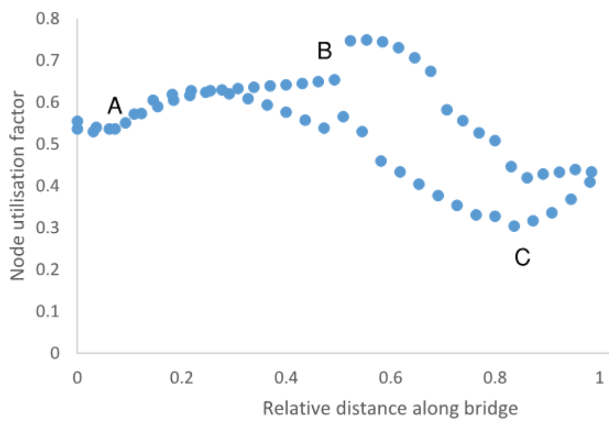

Figure 21: *Node utilization against relative position*

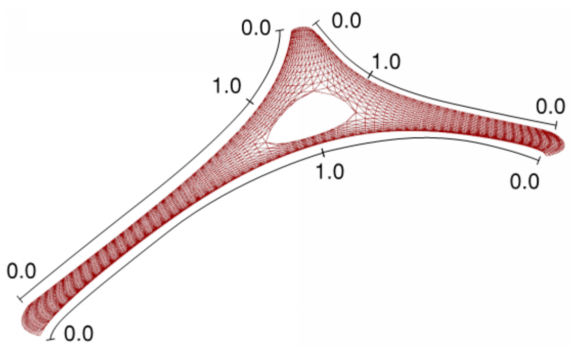

Figure 22: *Relative node positions*

Future scope for research include expanding the number of utilization factors to include factors such as susceptibility to dynamic excitation, material quantity, gradient of the bridge deck and visual prominence/ height of the bridge above the water.

Ultimately, a global fitness criteria is to be created ($UF_{glob,j}$), which provides a reading for the working efficiency of a specific geometry for all affecting parameters. As geometric input parameters are altered, the resultant utilization factors can then be tested for their improvement to the global utilization ($UF_{glob,j+1} > UF_{glob,j}$?) and the change retained or discarded as appropriate.

With sufficient computing power, this approach can be extended to the use of an evolutionary solver, with the geometric variables as input parameters and $UF_{glob,j}$ as the fitness criteria. As the analysis runs through multiple iterations, it is expected the analysis will converge toward a material and structural optimum.

5. CONCLUSIONS

1. In order to achieve symbiosis between architecture and structure in integral bridge design architects and structural engineers must be willing to overcome the current division between the work of the architect and the work of the structural engineer and get rid of the classical hierarchy.

2. A pure and self-contained form of bridge design is possible when the designer observes a degree of self-restraint to stay within the boundaries of the forces at play. A bridge design must follow the laws of static, allowing minimal manoeuvre space for frivolity. This way each design visualises its own display of forces, showing nothing more than itself.

3. At the same time it is important to acknowledge that a bridge design cannot be simplified as a mere display of forces. A coherent design is just as much influenced by thorough response to the boundary conditions imposed by the context, the choice of material, the building process and the maintenance and financing of the bridge. A beautiful optimization design has little added value to society if it is impossible to build, maintain or finance.

4. Today, the need to carry out experiments and physical tests with scale models is put into question with the ability to use the computer as a tool for optimization and a way to search for new forms. But how useful is the computer really? In an interview with Juan Maria Songel in 2010 Frei Otto stated “The computer can only calculate what is already conceptually inside of it; you can only find what you look for in computers. Nevertheless, you can find what you haven’t searched for with free experimentation.” [6]

5. Although the tools have changed over the last 18 years, the methodology and the design parameters have remained the same.

6. Just like design methods in the pre-computational period, computational design allows for intuitive design. Through parametric models and graphic scripts, an interactive design process can be created that is open to both architects and structural engineers.

7. Parametric design allows for exchange of disciplines in a multidisciplinary process.

8. A parametric model allows control over aspects that are hard to influence in a physical way.

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