

The Parametric Bridge: Connecting Digital Design Techniques in Architecture And Engineering

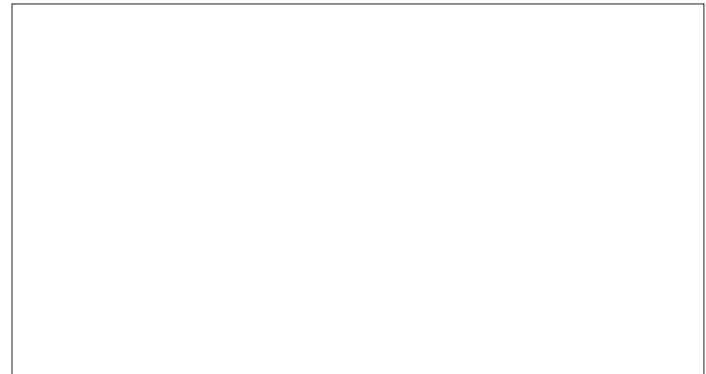
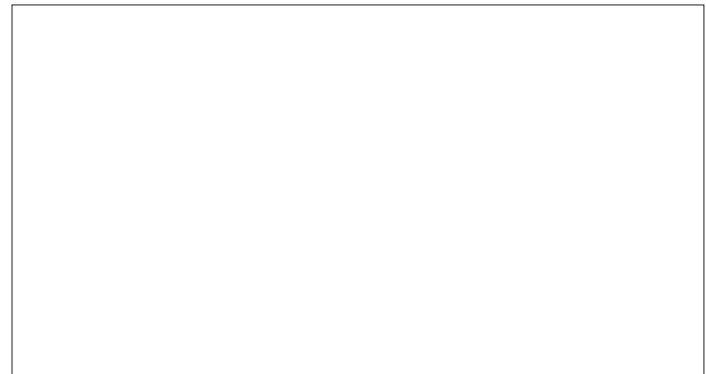
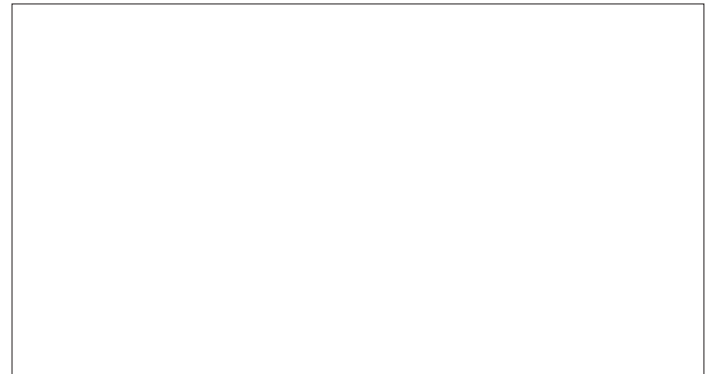
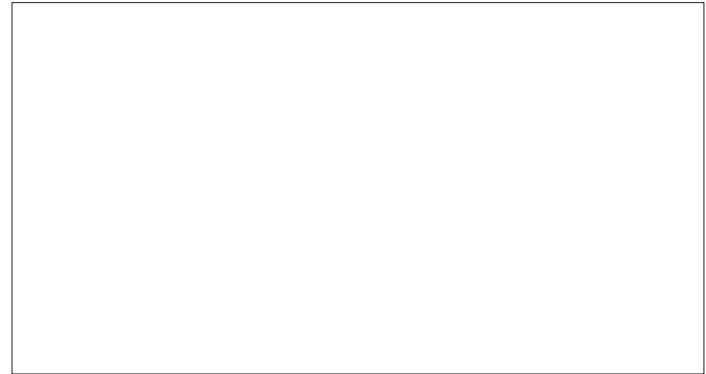
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Abstract

New design opportunities that are facilitated by cross-disciplinary collaboration in both practice and research are available through the use of high level design software that simultaneously offers real time access to both analysis and design geometry in shared three-dimensional digital models. Here we present a collaborative research project between architects and structural engineers for the design of a pedestrian bridge, conceived to test current digital design processes in architectural and structural engineering practice with those in research through the use of models of parametrically defined associative geometry.

In this project, the digital model's architectural design geometry was constrained by the bridge's fabrication methods and linked with its engineering analysis. Iterations of the design geometry were then optimised or 'solved' to produce variations according to the design parameters offered up for change.

The shift of the professions from the plane to digital space exposes the possibilities of new design techniques with the exchange of design parameters potentially operating as a digital dialogue between the disciplines—a kind of digital version of Antoni Gaudi's funicular hanging model—a metaphor of the digital space that has been developed for this project.



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1 Introduction

This paper describes work undertaken for a parametric solution to an Arup bridge design. Concurrent with the design and construction of an actual bridge, the research was conceived as an attempt to test current design processes in architectural and engineering practice with those in research through the use of models of parametrically defined associative geometry. This approach sponsored a collaborative study across the disciplines of structural engineering and architecture through a system using a single digital model that shared geometrical constraints linked to its fabrication method, and material and loading analyses which could then be iteratively regenerated or optimised towards targeted solutions. The use of a single model significantly differentiates the research from other investigations into architect/engineer collaboration such as Klercker (2002).

Cross-disciplinary and *collaboration* are both widely used terms with an inferred interdependence, and both have positive as well as negative connotations. With ever increasing specialisation in design, much is to be gained from developing ways of breaching the traditional barriers of disciplines (Gann 2000). In distinguishing our research as collaborative we recognise that in fact it is more likely to be *co-operation*, the premise of the relationship between professionals, occurring across disciplines far more often and equally deserving in research (Kvan 2000). It is interesting to note though, that much research in cross-disciplinary thinking presupposes that the disciplines to be bridged are those already within a professional coterie. While this is in no way to be discouraged, there is much potential in drawing from outside sources. Our project used high-end software intended for the manufacturing and aerospace industries which necessitated a renewed approach to the design from both disciplines. This process of technological transfer facilitated a system of parallel and mutually dependant actions which were cross-disciplinary yet not essentially of either discipline.

In broadening the framework of the interaction entailed in this research project it has been helpful to review terms which approximate the activity in research from other fields. In interaction design “joint activity,” a close-coupled interaction which is procedurally based might be useful in describing the

“collaborative” result of our visual optimisation. While “mixed initiative,” a responsive dialogue between human and machine, might better describe our ‘cross-disciplinary’ system, expanded in this project to interact discipline to discipline via machine. In that context the declarative process used to inform the parametric model is the common language local to the project, and the exchange of design parameters, the digital dialogue between the disciplines—a digital version of Antoni Gaudi’s funicular hanging model, a metaphor for the digital space that has been developed in this project.

The research was undertaken in both Melbourne and London. The parametric model was developed in Melbourne, remotely from the project team and the periods of intensive collaboration were undertaken “on site” in London. This was partly due to the infancy of design spaces for online collaboration and partly due to its secondary role as a forerunner for an “embedded” research strategy where well equipped mobile post graduate students will spend part of their project based research collocated in practice, the other reflecting outside it.

1.1 Project description

The project is for the pedestrian bridge at the new Selfridges store in Birmingham UK. Future Systems are the architects. The bridge links the store with an adjoining carpark, over a busy road, which circumscribes the larger inner urban development known as the Bullring, in which the store is located (Figure 01). The curved and seamless bridge is a difficult form to realise. Arup London Group Four was supplied with a digital model by the architects, and a fabrication method was sought through the tendering process. A revised model was then built which conformed to the selected fabricator’s requirements. It was transformed into an analysable mesh by Arup’s Advanced Technology Group and analysed in Arup’s structural analysis package, a procedure taking one person working exclusively, three months to complete. While it could be expected subsequent iterations would not take as long, a considerable investment in time would still be required, and at a significant cost.

The aim of the research was to investigate the above process with a parametric model, so that in close to real time, iterations of the bridge could be generated thereby realising the design space that using explicit modelling would have been rendered opaque and unexplored. The project was undertaken with Arup London Group Four and facilitated by Arup Research and Development.

2 Parametric Design

The architectural historian Robin Evans noted the resistance of form to the architectural medium imposed upon it. He contrasted the rejection of perspective by modern painters with the adoption of standard orthographic projection in architecture and detailed near extinct traits such as stereotomy to illustrate the richness in translation through representation (Evans 1995). In this regard



Figure 01. The bridge in on site March 2003, without canopy.

the use of the computer to augment the description of form is well founded where that form resists conventional architectural description.

Three dimensional digital models in architecture are not yet well established beyond visualisation tools. Digital modelling, simultaneously and interactively, as an immersive editing process in practice is virtually unknown. Parametric design however, through the association of geometry, allows form to be controlled through the definition of parameters and application of constraints, which when manipulated can generate families of forms (Burry 1999). In proposing strategies for design structure in digital environments such high end software, developed for the aerospace and manufacturing industries, offers as many challenges as well as opportunities in its adoption to architectural design. In cost alone it is out of the reach of most architectural practices and being antithetical in approach to explicit "one off" modelling (Wittenoom 1999), it requires at the outset the development of an initial declarative schema, which then drives the design.

Research into applying parametric techniques to architecture has been led by Burry through the ongoing construction of The Sagrada Familia Church in Barcelona (Burry 1993). Here the process is informed through the research into the codex of ruled surfaces Gaudi developed during his final twelve years. Similarly the complex digital modelling undertaken by the architectural office of Gehry Partners LLP (Calif. USA) is determined through the primacy of the physical modelling methods used in the office. Glymph et al. (2002) show how Gehry Partners has used parametric design to describe freeform glass structures. In our research a number of suites of parametric modelling software are utilised, and parametric techniques are often applied through programming. This project uses CATIA by Dassault Systemes, software developed originally for aerospace, but now

used widely in the automotive industry. Parametric modelling in CATIA has been introduced in its current incarnation, version 5. In addition, CATIA offers a range of analysis methods and a set of tools for manipulating the information known as *Knowledgeware*, all exploited in this project.

2.1 Building the parametric model

The purpose of the parametric model for the bridge was to constrain its geometry to the fabrication methods selected for its construction. The bridge's underside or tray is steel, and the canopy is polycarbonate supported by steel hoops at varying angles from the deck which rises and falls gently to suit disabled access. The successful tender for the bridge was based on bending steel tubes (side tubes at the deck's edge and a main tube on the underside), in two directions to achieve the three dimensional curves that form the bridge's tray. The tubes were then to be cut down along their bi-tangent intersection and the sides infilled with steel plate. This method was preferred to another proposal which would have approximated the tray's surface to facets (Figures 02 and 03).

The hierarchical database of the parametric model was constructed by first interrogating the explicit model, supplied by Arup from Rhino NURBS modelling software, to gain an understanding of the geometry. Three guiding curves were extracted from the edges of the tubes in the original model and resided at the top of this database, so the parametrically variable tray could be varied to suit different tube sizes while maintaining the bi-tangency of the sides within the boundaries of its perimeter. The polycarbonate canopy followed suit, depending on the successful regeneration of the tray but also operating within its own fabrication constraints.

At any point along the tray an intersection made with the surface by a plane normal to the curve will be found to be circular in profile and of the same dimension as the ends, confirming the topology of a tube.

Bi-tangent lines between these tubes form the underlying structure of tray's sides. A ruled surface was placed between the tubes (Figure 04), which was then developed with little deformation. The benefit of describing a surface in this manner is that, materially dependant, the surface can be then cut out of a flat sheet and rolled or offered up to position. (Fully developable surfaces are those which can be unrolled onto a plane without deformation, a cylinder being one of the easiest to visualise.) The steel hoops share the same principle but at each instantiation are unique. In this case a parametric feature was designed to regenerate itself for the varying conditions each time it was repeated. The hoops vary at increasing angles along the bridge length and are made from steel flats laser cut and fabricated into T-sections (Figure 05). However, the T-sections are not perpendicular, as the flange is always parallel to the polycarbonate (providing an even surface for fixing) while the web is in the plane of the rotating axis.

The guide for the hoops was the polycarbonate top which was defined in a manner not dissimilar to the tray, although without any explicit geometry. The centre line of the deck was found about which a 2700mm radius tube was extruded. The bi-tangency was then found between the outside tubes of the tray and the tube to establish the surface. Intersections with this top guiding surface were made with the ability to move up and down the bridge and vary in angle.

2.2 Variations and comparison

The constraints were tested and variations made to compare the parametric tray with the original Arup model. With the guiding curves constraining the model's design space, the main tube could be varied between 500mm in diameter up to 1750mm in diameter. Variations were then rapid prototyped in wax and comparatively measured; proportions of tube to plate and dimensional variation from the original (Figure 06). In fact, during the project supply was the most important issue, with the final tube switching from 1050mm diameter to 900mm due to unavailability of the larger size.

The parametric model was developed in Melbourne, with a physical model reviewed in London. Communication during this period was mainly asynchronous, textual via email and often supported with explanatory images. Models, drawings and sketches of details were exchanged, but the overall volume of such material was minimal. In fact the process of distilling written information was found to be invaluable in founding the declarative process which in turn was used to define the parametric schema.

3 Analysis

Speculation about the ability to leverage the finite element analysis and advanced meshing tools in CATIA for use in structural engineering led to an investigation of the single model concept, opening discipline-specific views to the parametric model. Finite element methods are computationally intensive and have only recently migrated to the desktop of engineers. In finite element analysis complex geometries are divided into small elements defined by geometric nodes that can be described mechanically by analytical equations. The equations are linked together in large matrices by the computer in order to describe the behaviour of the complete form. Used for many years in the aerospace industry, they are not commonly applied in structural engineering, as building structures tend to be broken down into two-dimensional planes where elements or sub assemblies can have the rules of statics applied. However, with more complex building forms finite element methods become a critical tool for locating critical stress concentrations.

3.1 Analysing the parametric bridge

In establishing a structural engineering view of the bridge's parametric model, our collaborative process began by passing a portable computer between engineer and architect, constructing

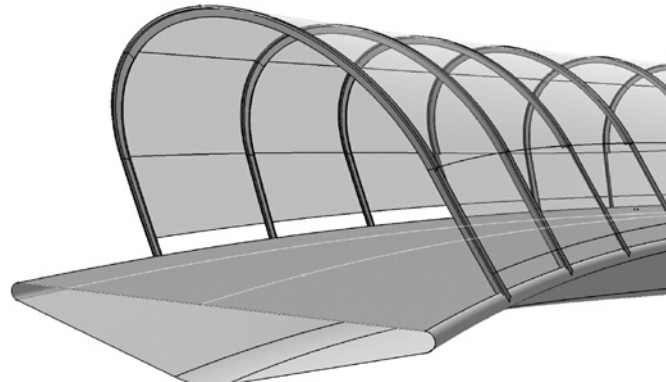


Figure 02. The parametric model.

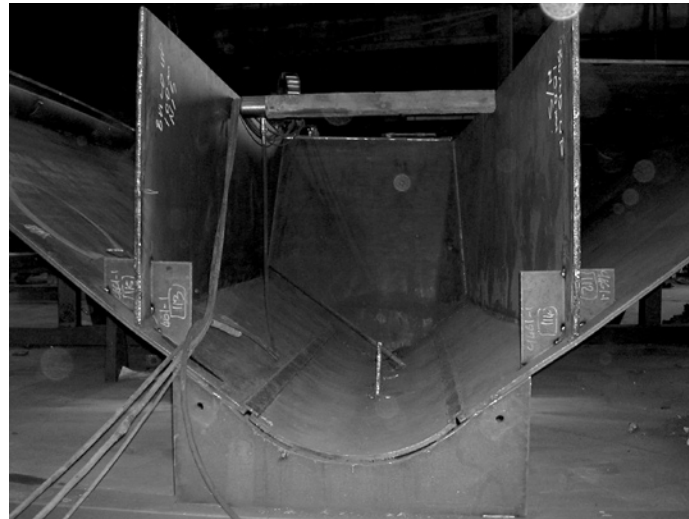


Figure 03. Fabrication method. The bridge's tray in cross section showing tubes under construction. Photo: Ed Clarke (Arup)

a single digital space while sketching and writing ideas to convey each other's principles, toggling views of the model between analyses and geometry, and vice versa.

Arup's in-house structural analysis software is called GSA (General Structural Analysis), incidently an almost identical acronym to CATIA's (Generative Structural Analysis). For this purpose the paper refers to 'Arup GSA' and 'CATIA GSA' so as to distinguish between the two. Comparative results using finite element meshing and analysis require different methods to conventional structural engineering analysis. A one-dimensional beam (stick meshing), two-dimensional surface mesh, and three-dimensional volumetric mesh were used to first corroborate the results between both Arup GSA and CATIA GSA.

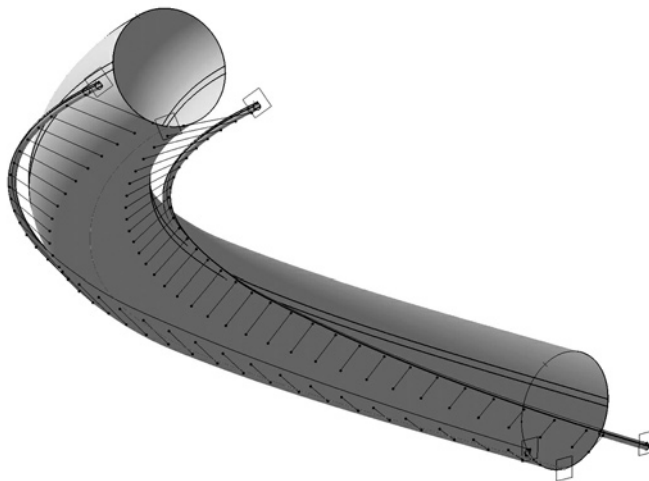


Figure 04. Bi-tangent lines between main and side tubes.



Figure 05. Variations from the same parametric parent. Developed T-Section flanges of the hoops.

For the purposes of the research, the tray and deck of the bridge were determined to be an acceptable approximation of the form for the structural analysis. The bridge's cable restraints were later added. A two-dimensional surface mesh was generated on the parametric model and a finite element analysis performed to determine the bridge's displacement and stress. Through the discipline specific view of the structural engineer, this operation involved the addition to the project of local axes and restraints at the ends of the bridge, linear loads, and the application of material qualities including thickness (Figure 07). A routine of meshing the parametric model and computing the result of the analysis in CATIA GSA then followed any modification of the bridge's design geometry.

3.2 Variations of the parametric bridge

Through the Product Engineering Optimiser, a *Knowledgeaware* function in CATIA, parameters can be optimised to a target value, be it minimum, maximum, or given. Free parameters are then offered for variation and steps and ranges can be set. Two algorithms are used by CATIA, a localised Gradient "hill climbing" method or Simulated Annealing, which adds in some randomness to offer the potential to "jump" the hills and further explore a design.

Consideration was given at this point to the flexibility of the design space. The parametric model had been limited by the design curves, which were explicit and therefore without parametric variability. As already shown, iterating through the free parameters in the geometric model which were related to tube sizes had already mapped the potential variation. In seeking to extend the perimeters of the form and increase the parameters which affected it, the parametric model was rebuilt so the guiding curve for the main tube, the underside of the bridge, was defined by a combined curve (the result of the intersection of the extrusion of two curves). This process was also informed through reviewing the strategy with the architects. A vertical parameter controlled the depth of the bridge and when added with a horizontal parameter, the combined curve freed up the position of the model in space. This operation required carefully re-editing the parametric database to replace the explicit curve with a parametric curve. This was time consuming and is at the limits of redefining hierarchical parametric geometry.

Several scenarios were then designed for optimisation (Figures 08 to 10). Every iteration during optimisation requires the consistency of the model's database. In the bridge's case, this means adhering to its fabrication constraints. Each model outputted could therefore be identified as a tube deformed in two directions with bi-tangential sides of ruled surfaces. The values of each parameter used in the optimisation routine are recorded at each change in a spreadsheet (Table 1. provides an example), and the figuration at each iteration interpreted at a later stage. By simply resetting the parameter's values states can be selectively revisited if so desired.

The displacement analysis results generated from CATIA GSA were used as targets for the following constraint solving optimisation procedures using the engineering analysis to visually optimise the form. The process then, to understand the scope of what might influence a model's geometry and its potential design space, becomes increasingly important in a collaborative sense to all those taking part in the mediation of the artefact.

4 Collaboration

Today, the potential of finite element methods recalls an earlier enthusiasm for the graphic methods of statics, an engineering

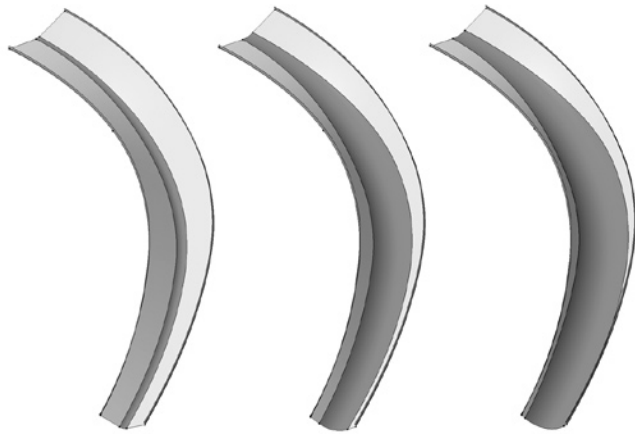


Figure 06. Parametric comparisons.
L-R. 500mm, 1500mm, 1750mm radius main tube

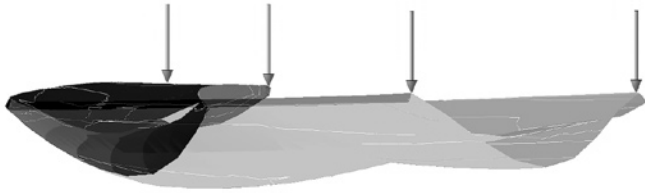


Figure 07. An analysis view of the bridge. Steps taken from a stress animation.

practice developed late in the 19th century. Structural analysis through graphic statics allowed the exploration of forms not easily analysed before its introduction. The funicular hanging models Antoni Gaudi used to arrive at his unique solutions were in fact three-dimensional graphic analyses. He first employed them on the Colonia Guell church (1898, 1908 - 1914), where a scaled model was hung in a workshop creating a dialogue between his assistants who would, upon instruction, shift the bags of lead about to vary the shape, which would then be photographed, turned upside down, and rendered to give effect to the form. This unique process was done with both the interior and exterior of the church (Figures 11 and 12). Not only did this funicular model provide a method of communication between Gaudi and his assistants, but as a structural analysis tool it also provided a forum for cross-disciplinary collaboration.

Proximity and face to face contact, it would seem, are still essential to seed collaborative processes. Two key meetings were held for this project when the authors were in London, one at its inception and one for review. These were followed by periods of research and reflection in Melbourne. Then a final intensive session of collaborative work on the single model was undertaken while collocated at Arup in London.

In our research project, we found that synchronous

technologies, which generally mimic conventional communication, such as web chatting, internet meetings, and video links at best augment the design process. These essentially serve to perpetuate connectedness, and in doing so reinforce the absence of communication tools that support the heterogeneity of complex processes that inform the act of designing.

Collaborating on a single digital model between two separate disciplines demands more than document workflow facilitation. A bi-directional flow of information not normally associated with communication between the disciplines is required. Our team extended beyond architects and engineers; in this project mathematicians and fabricators were also authoritative. A design structure which can be influenced by structural analysis and optimised to target a visual solution adopts and borrows techniques from both disciplines, and yet cannot be expected to be of either discipline. This certainly has implications for the adoption of traditional methods of communication when collaborating.

4.1 Extending the process

The research drawn from this project could be extended in two directions. Firstly, to what extent can the process be adopted to delimit the boundaries of a design space at the conceptual stage? Although the case for parametric design is well founded at a detailed design stage, how might this collaborative process be applied when dealing with the incomplete knowledge inherent at the beginning of a design project? Conceptual analysis tools such as the Evolutionary Structural Optimisation method (Xie 1997) might be useful in establishing a cross-disciplinary dialogue.

Secondly, automation techniques in fabrication could be investigated when linked to parametric databases. How might the intersections of bi-tangency be inscribed onto a tube or could the hoops be constrained to minimize wastage based on efficient cutting patterns?

5 Conclusion

Through the sponsorship of the parametric bridge project we have been able to explore the potential of a digital design model offering cross-disciplinary collaboration between architects and engineers. While parametric modelling might at first be regarded as another specialisation, here we have shown an approach or technique for possibly understanding equally well architecture and structural engineering.

This work involved considerable technology transfer, adopting methods from outside the fields of architecture and engineering, and challenging established techniques in each discipline. As the outcome of the research could be considered greater than the input of each contributor, it could be said to be a truly collaborative process.

Iteration	Maximum Displacement (mm)	Cable Restraint Location (mm)	Tube Vertical Location (mm)	Tube Horizontal Location (mm)
23.4008	12798	12798	1484.59	5745.23
23.4008	14385.8	14385.8	1466.18	5739.07
23.4008	13228.7	13228.7	1538.32	5787.56
23.4008	12449.3	12449.3	1441.57	5775.39
23.4008	11784.1	11784.1	1507.41	5824.81
23.4008	12797.7	12797.7	1484.57	5745.18
23.4008	12141	12141	1545.82	5645.9
23.4008	10935.1	10935.1	1515.71	5744.4
23.4008	12797.7	12797.7	1484.57	5745.01
24.1539	13318.8	13318.8	1482.65	5761.29
24.1539	12567.7	12567.7	1439.34	5741.03

Table 1: Example of changing parametric values during optimisation.

Scenarios with three or four free parameters were run for approximately seven hours at a time—not yet a real-time process, but indicative of the processing power required. The location of the bridge's restraining cable was iterated along the length of the deck, and the curve of the main tube was freed horizontally and vertically.

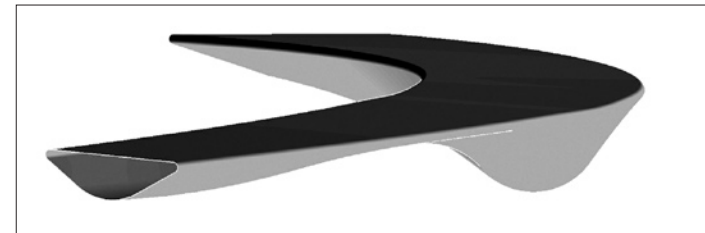


Figure 09. Vertical optimisation (Curve Depth) Geometrical view of the model.

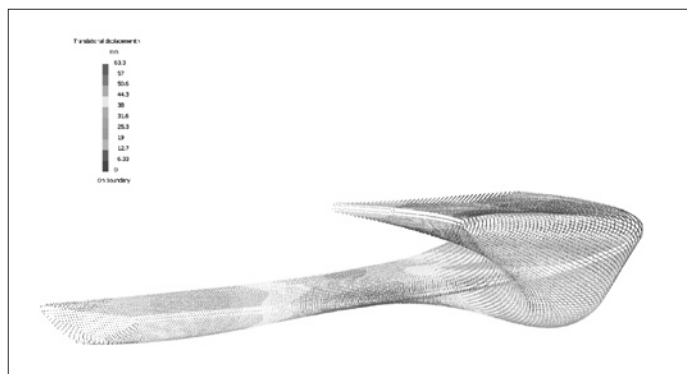


Figure 08. Vertical optimisation (Curve Depth) The vertical parameter of the tube's position optimised to minimise displacement. This generated a distinctly different shape, thinning at one end then swallowing to a much deeper point than the original point. Analysis view of the model.

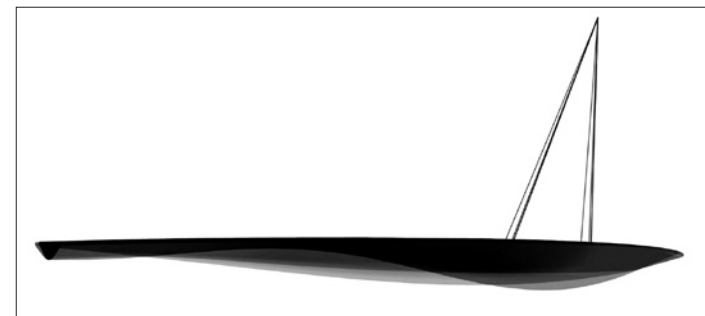


Figure 10. Combined bridge forms. Several iterations of optimised trays overlaid.

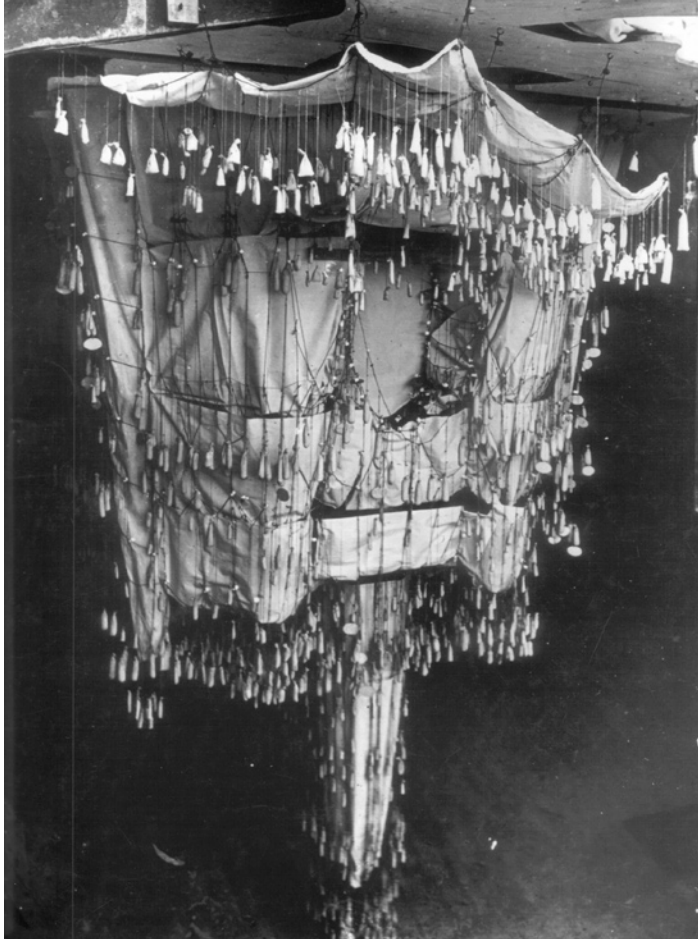


Figure 11. Gaudi's hanging model.

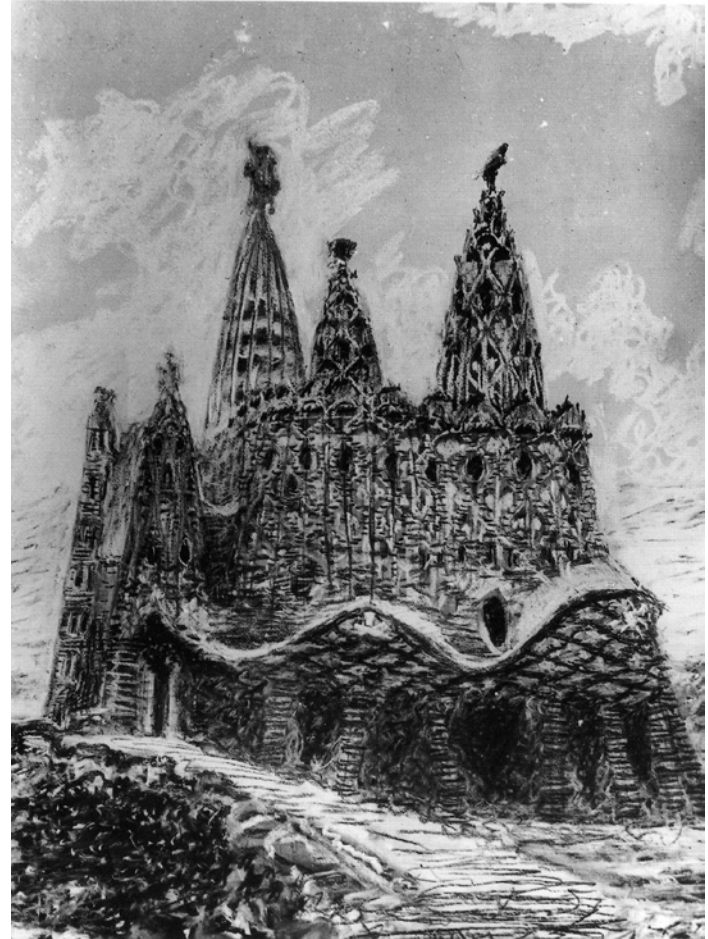


Figure 12. Inverted photographs used to render forms.

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Future Systems are the architects for the new Selfridges store in Birmingham