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Computational systems for design and production of complex geometries with large-format roll-bent aluminum plates

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Abstract

This paper describes the process of design and production of the aluminum sculptures that are part of the office building complex "die Welle" in Frankfurt/Main, Germany. The sculptures were executed by Arnold AG. It describes the process in which these complex geometries were designed using parametric tools in 3D modelling, which was then linked to the structural stability analysis in the same parametric system in order to activate structural stability through the geometry of the individual surfaces. The size and complexity of the geometries of each plate was far beyond normal accepted limits for a 4-roll plate bending process. Hence these sculptures show that parametric systems can be used effectively to create objects that may not be possible otherwise.

Keywords: Mathematical modelling, complex geometries, double curved surfaces, roll-bent plates, parametric systems, large format roll-bent plates, conceptual design, form finding, optimisation, metal spatial structures.

1. Introduction

Through the ages of human development, architecture has always given man the opportunity to stretch the limits of material expression. From the idea of a simple shelter in a cave to the modern complex forms with various innovative materials, the journey has been a constant reinvention of techniques of material usage and implementation that stretch the limits of structure and form.

In the history of architecture it is very interesting to note that with the inventions of new materials and processes that allowed a higher structural integrity, a greater freedom was available to the spatial configurations. This resulted in the expansion of the boundaries in spatial structures and also the possibilities of form in architecture. In the 20th century this was particularly visible in the evolution of large free spanning light weight structures that challenged the limits of structural und architectural space. The works of Frei Otto, Felix Candela, Heinz Isler, Antonio Gaudi, etc. are a good example of architects and engineers who expanded the boundaries of form finding processes and stretched the limits of a design where the form and structural stability are integrated into a single entity.

Felix Candela's concrete shells are a good example of integrated design where geometry is integrated into the structural integrity of the form. This process was adopted by some of the authors in the design and construction of "Parapluie" – a shell form that stretches the limits of UHPC using membrane effects [1]. A further investigation in this approach resulted in the Mobiusban(k)d – a seating bench also in UHPC where the design and construction process resulted in innovative techniques of integrated parametric structural design [2] & [3]. To complete the circle, the project “Die Welle”, also done by some of the members of the team of Parapluie and Mobiusban(k)d, expand the horizons of material, structural and geometrical integration in the design and production process. This paper describes the process of design and production of the aluminum sculptures in “Die Welle” and will touch upon the relationships to the aforementioned projects and their influences and relationships between them. (Fig.1)

Figure 1: Felix Candela's Bacardi Plant in Cuautitlán, Mexico 1960 (top left), Parapluie 2012 (bottom left), Mobiusban(k)d 2014 (top right) and the Diving Arch - one of the 6 sculptures at "Die Welle", Frankfurt, Germany 2016 (bottom right).

2. Architectural sculpture

The owners of “die Welle” - a group of office buildings in Frankfurt, were faced with the problem of enhancing the real estate as a form of value addition and thereby enhance the possibilities for the tenants. The buildings are located in a premium location in Frankfurt am Main, Germany but suffered the fate of not being entirely occupied and hence the owners, with the advice of communication and marketing experts, came to the conclusion that the space around the buildings had to be made more attractive and therefore to create a landmark in the courtyard area so that its urban identifiability would increase. The clients approached the authors respective firms with this idea and this led to an interesting process of design and production of the aluminum sculptures.

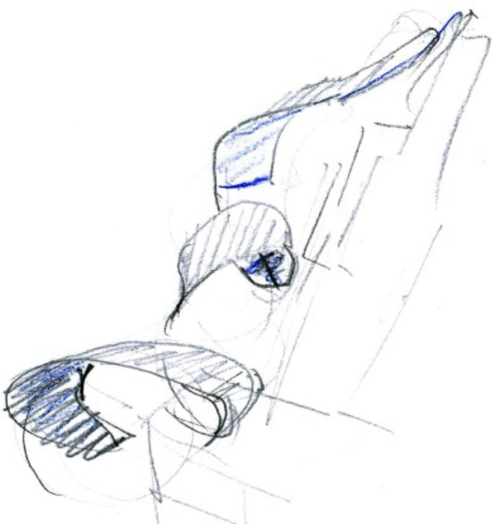

Figure 2: Sketch of the first idea of the band by M. Schumacher

The design was based on the idea of a flowing space (Fig.2) that meanders its way between the structures which then create interstitial spaces that could be used for public areas like terraces for cafés and restaurants. The juxtaposition between the topography of the floor that undulates its way through the space between the buildings and the aluminum sculptures creates an interesting balance between the sculptures and the spaces in-between them.

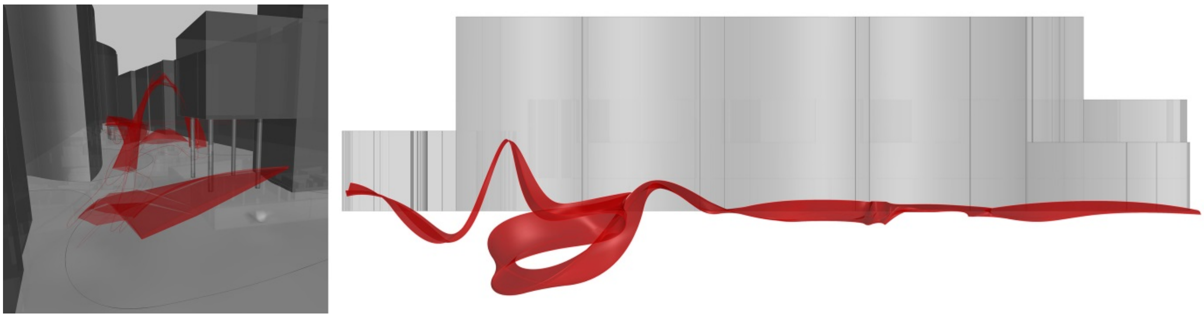

Figure 3: The idea of a continuous band that expresses itself as individual sculptures above ground. The geometrical continuity between the sculptures expresses the unbuilt (underground) elements.

The starting point of the design was the idea of a band that weaves its way across the space between the buildings (Fig.3). This band would relate to the communication design concept of "Glory, Joy and Chill" by various expressions in form. The office buildings named "die Welle" which is German for the term wave, mainly due to the form of the high-rise structure part of the ensemble which has a wavy form in floor-plan. The design for the space between these buildings thus plays with this terminology and the new concept to create an iconic statement in the space.

3. Integrated parametric design

The design idea as a sketch was visibly a complex form and conventional architectural tools of representation were not adequate enough to express the idea entirely. To make the design process more intuitive and have a better control on the form, it was necessary to transform the idea into a parametric design system. A parametric design system is a 3D mathematical model based on the various parameters of the design. The basic aspects of such a system are:

1. Constants (relating to the design geometry and existing aspects in the site)
2. Variables (the values that allow adjustments to the design)
3. Interrelationships between the constants and variables
4. Hierarchies between the interrelationships
5. Boundary conditions (aspects from the site that restrict the design)

A parametric system is hence a combination of the design ideas imbibed into a geometric system with the aforementioned aspects as the basis of the system. The effectiveness of such a system is dependent on the possibilities offered by such a system to test various alternatives under different conditions so as to have a better understanding of the design. This also allows an integration of aspects such as structural stability and optimisation of material usage.

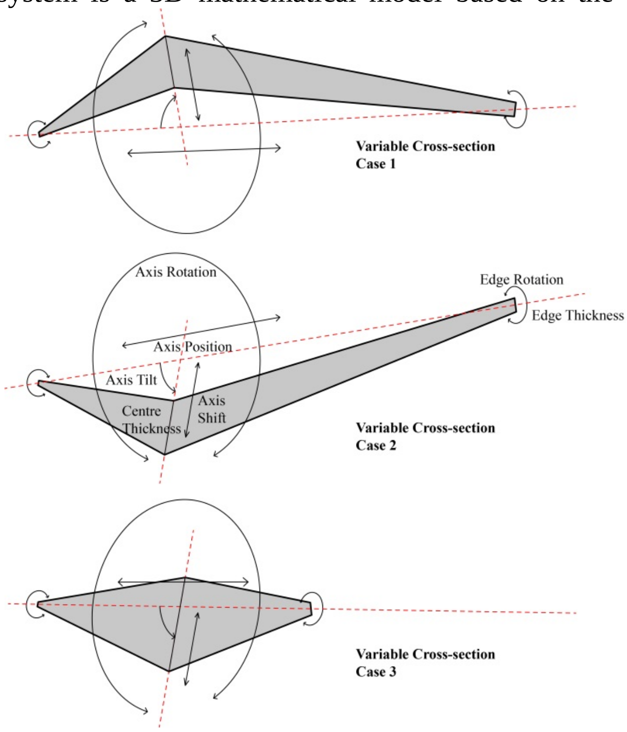

Figure 4: Concept for the cross-section system to be integrated in the parametric design system

3.1. Form generation based on a parametric cross-section system

Since most 3D geometries can be expressed as a mathematical model, a parametric system to design the aluminium sculptures was considered as an advantageous approach so that the aspects of production could be incorporated at the design process itself. The system was designed on the idea of a variable cross-section system. The basic principle of this system is based on creating a cross-section whose individual aspects like edge thickness, centre thickness and their rotation, tilt and shift could be individually controlled. A series of varying cross-section would then generate the form (Fig. 4 & 5).

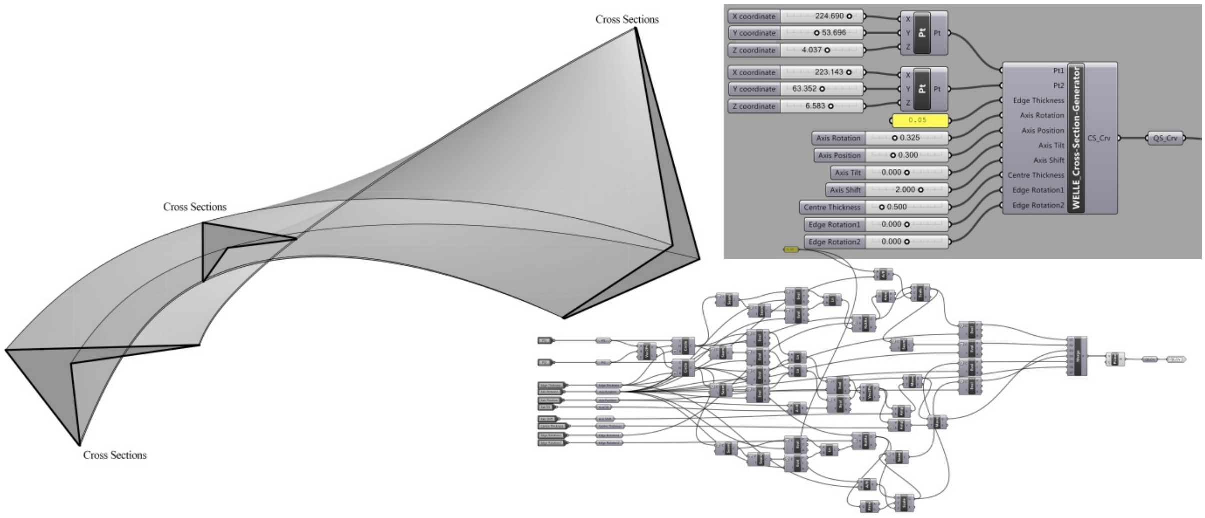

Figure 5: Diagram showing the parametric cross-section generation system on the right and the 3 cross-sections that generate the geometry on the left.

The system used to create the overall form could then be modified based on various aspects such as surface geometry of the resulting element, structural stability, etc. This enabled the possibility of testing and analysing various geometries during the design process. Since it was possible to get a constant feedback of the results of various changes it made the task easier to change the geometries only where it was necessary, thereby reducing redundancies.

The parametric system was developed in a visual programming system based on RhinoCeros 3D and Grasshopper. Into this system, Karamba, a plugin for Grasshopper developed by the structural design consultant for the project – Bollinger+Grohmann Ingenieure, Frankfurt am Main, Germany, was also used. By using the same base system to design the cross-section of the geometries and since these cross-sections generate the overall geometry; it was possible to maintain a mathematical logic in the surface. To explain this aspect in more detail, one can look at the work of Felix Candela, well known as one of the pioneers in the world of thin-shell concrete structures. One of his major contributions is the use of simple mathematical principles like hyperbolic-paraboloid *hypar* to generate complex roof forms for his buildings (Fig.6). The advantage of such a process was the ease of producing the formwork which was based only on straight panels and yet the curved form could be easily constructed. In 1952-1953, Candela worked on a number of umbrella structures that were based on his earlier study of a paper by F. Aimond [4]. Candela's umbrellas were created by joining four straight-edged *hypar* surfaces and by placing several umbrellas side by side, he could make a large roof covering. Many of his experiments in the umbrellas built in 1952 and 1953 led to his designs for some of the churches and industrial plants built in Mexico between 1953 and 1960 [5].

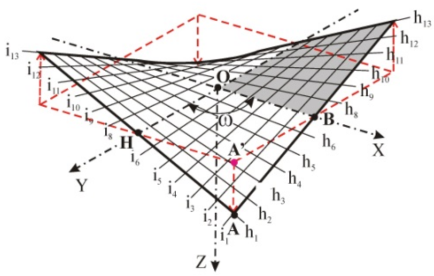

Figure 6: The hyperbolic paraboloid (hypar)

3.2. Form and materiality

After the formulation of the first sketched ideas, the question of the materiality came up. The discussion entered with the material possibilities of concrete cast in-situ structures, concrete prefabricated elements joined on site, stainless steel, wood or aluminum. Architecturally, for the site in the middle of Frankfurt, a robust but elegant solution had to be achieved. The theme of a band meandering between the buildings should be continuously visible.

With the possibilities of the parametric design the sculpture was adapted to the different material necessities to examine the changes in the sculpture. As an example the edges of a design in concrete had to have a thickness of 5 cm to have enough coverage for the reinforcement. Today wood structures can be protected by Polyurethane (PU) for greater longevity. Wood can easily be milled three dimensionally and being sustainable, it seemed therefore to be a good choice. The size of the sculpture would have pardoned the softer appearance of the PU. Cast in-situ high performance concrete met very well the requirements of durability and surface quality. It could support the elegant character of the sculpture and all parts touching the ground would have been unproblematic. To build such a 17m high sculpture in one piece, scaffolding and the formwork almost as difficult as a wooden sculpture itself, would have been necessary (Fig.7). To build the sculpture from many prefabricated elements was set aside since the flow of the wave would have been optically disturbed by the visible joints. Stainless steel would have perfectly matched to all demands but not the budget. The material price in addition to the complexity of three dimensional bending of the plates and the large welding warpage in stainless steel made a solution not affordable. Aluminum combined qualities of all the other solutions. It could be crafted by hand like wood, it is durable, it has a solid appearance, it can be welded like stainless steel to achieve a seamless structure, and it can be prefabricated in pieces so as to reduce the construction time on site.

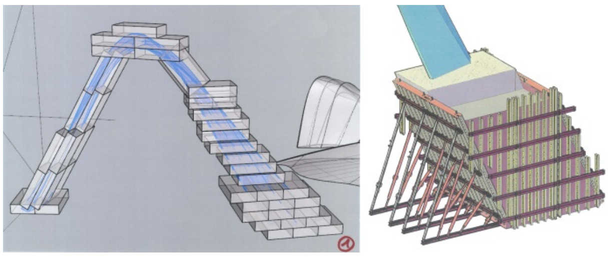

Figure 7: Formwork and scaffolding for a cast in-situ high performance concrete construction of Glorious Arch, approx. 17m high

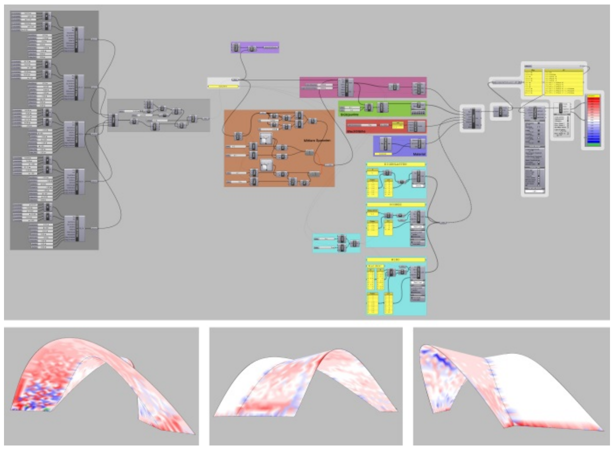

Figure 8: Integrated parametric system with the design and structural analysis system in Grasshopper & Karamba

For the sculptures AlMg4.5Mn grade aluminium plates 6000mm x 1500mm with a thickness of 15mm were used. Using the parametric system and the Karamba plugin one could analyse the structural integrity of the sculptures and fine tune the forms to enhance stability through the geometry and not only the material thickness (Fig. 8). The resulting analysis could be used to optimise the geometry and the distance between the two surfaces. The reason to reduce the distance between the surfaces to its minimum was to reduce the lengths of the pins that were distributed in the space between the surfaces to create structural stability between the two surfaces.

The geometry was optimized structurally in Karamba and then in RFEM to meet all requirements even in the detailing. A connection of the upper and lower plates was introduced to stabilize the cross sections. This middle stiffener, welded to an edge where warping form welding would occur in any case, was introduced to achieve an load bearing I beam cross section in all arches (Fig.9).

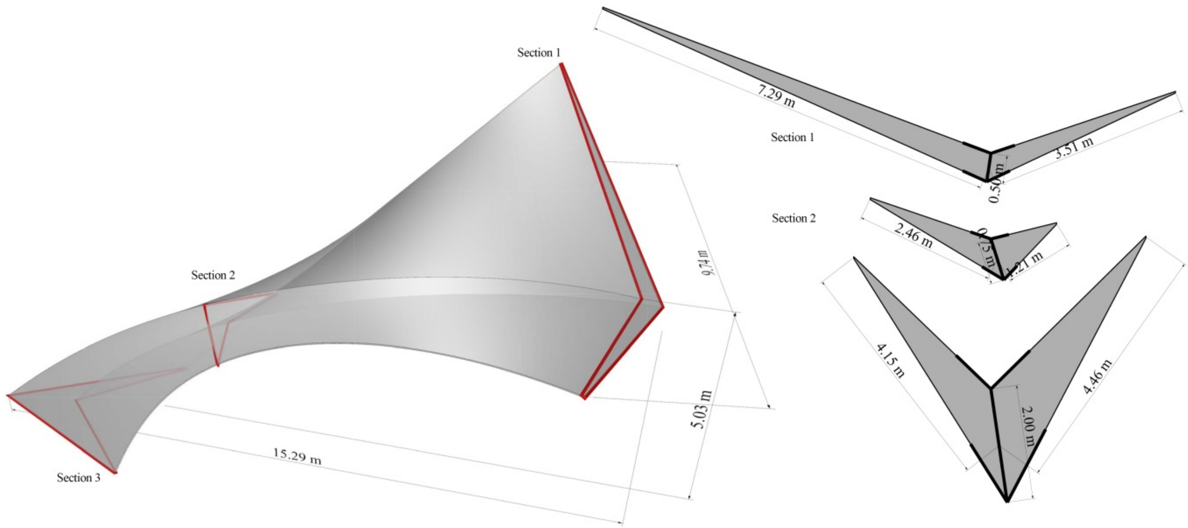

Figure 9: Diving Arch and its cross-sections with the mid-rib as a load bearing I-beam.

3.3. Final Calculations

The final geometry created in Rhino with Grasshopper and Karamba was exported to the software RFEM in which detailed calculations where done including buckling analysis and welding dimensioning. The question was if the 15mm Aluminum plates are able to span more than 5m from the middle stiffener to the edge. Due to the curvature which leads to a shell like load bearing behavior it is able to span the distance (Fig.10).

The overall loadbearing behavior creates normal forces in arch direction which would lead to buckling of the outer and inner plates. Even if the overall load bearing behavior was ensured by the middle stiffener a local buckling would have been visible and not tolerable for a sculpture. Structurally the easiest way would have been to place stiffeners within the cross section but how would they be welded and what would be the visual impact on the outside of the aluminum plates? In a test a stiffener was welded to a flat plate and a warpage line from the welding was visible on the outside. The solution was found when the fabricator came up with the idea of simply connecting the two layers with pins or connectors (Fig.11). From a structural point of view, it did not seem very helpful at the first glance but it was structurally modeled. The connectors were to be welded to the inner and outer plates which produced a bending stiff connection. The structural calculations showed a frame like behavior stiff enough to withstand the buckling in almost every situation.

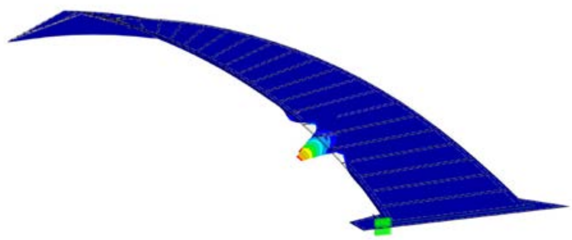

Figure 10: Buckling RFEM analysis of Diving Arch

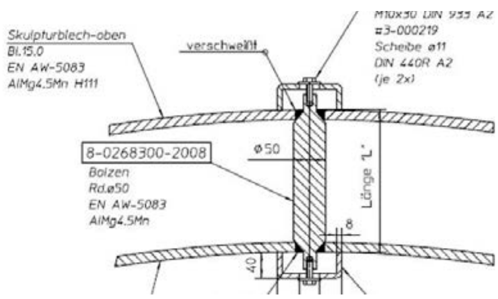

Figure 11: Section detail of a pin connecting the two surfaces

4. Design to production

In the production phase the first step was to subdivide the surfaces into plates in the format of the raw material i.e 6000mm x 1500mm. For this process it was necessary to define the sub divisions such that there would be as little wastage as possible and also have straight lines on the curved surfaces so that welding the plates to each other would be easier. This was achieved by laying geodesic curves on the surface so that the unrolled sub-divided plate would have almost straight edges and would utilise the plate to its maximum. Since almost all the surfaces in the aluminium sculptures were double curved and due to the large format of the plates, it was necessary to first rationalise the geometries so that axes to define the rolling positions could be defined. Geodesic lines are the shortest lines on a double curved surface. This is evident from the theory of general relativity, where light travels in a curved path in the presence of a gravitational field that bends space-time (Fig.12a).

After geodesic lines were defined on the surface of the sculptures, the predefined lines for the rolling axes was used to define the radius of curvature at each edge of the plates. The rolling of the plates was executed with a 4-axis rolling machine, Roccia HR4W 3025. The principle of this machine was based on the two central rollers that lead the plate in and out of the machine. On either side of these two rollers are two other rollers whose axis can be varied on both ends of the rollers individually (Fig.12d). From the 3D model of the individual surfaces the radius of curvature on each edge of the plate was defined on the plate along the axis and this was then used as the information for the load to be set on the rollers to bend the plates to the required amount (Fig.12e). Once the plates were bent to form it was then necessary to check the precision of the bending. Since the bent plates from the rolling machine were also a structural element it was essential that the plates had the form of the final geometry as they came from the rolling machine. The cross-check of the bending process was done by using a table with pins at defined heights. The heights for the pins were extracted from the 3D model and this was then used to check that the plates were rolled precisely.

Once the plates had been rolled, then they were cut to the right contour and the holes for the pins were made. This completed the process of the pre-production of the individual plates. Each plate was identified by a unique ID and all the files and data were labelled with this unique ID in order to have a perfect flow of information and not to have any discrepancies within the process. After the plates had been prepared they were then positioned on the support framework and then bolted together with each other with small strips of aluminium as support which would also be later required as an additional support to the welding process.

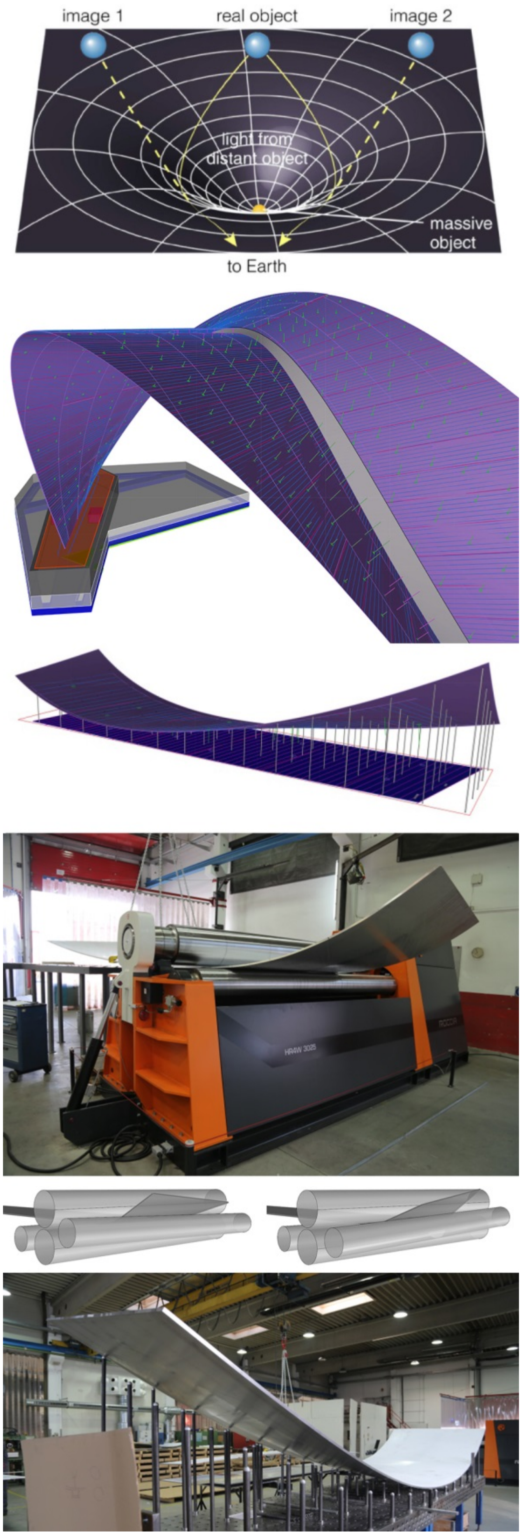

Figure 12: From top to bottom - a) Geodesic path of light in a gravitational field, b) Plate subdivisions of the geometry with the pins and roll axes, c) 3D surface and the unrolled surface for bending information and cross-check, d) Rolling Machine, e) Rolling process, f) Plate geometry check.

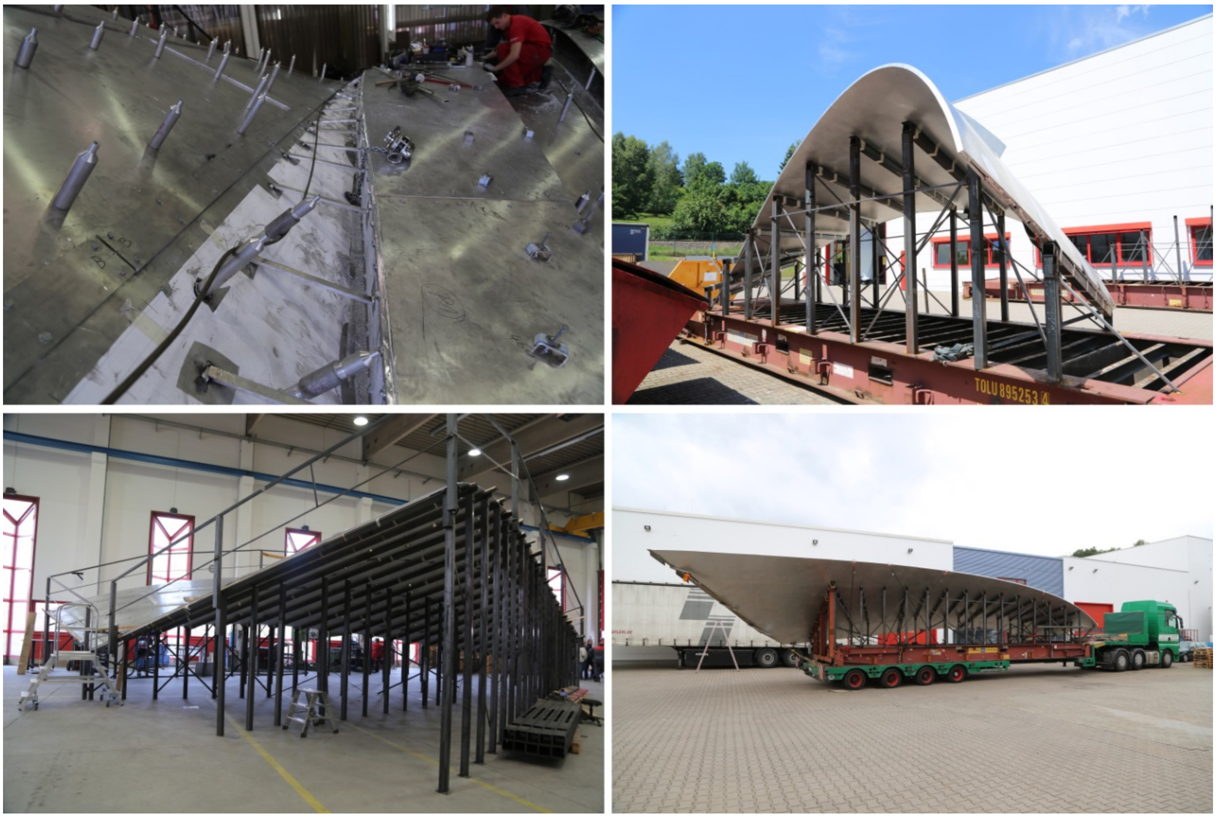

Figure 13: Photographs in the workshop of the sculptures in production and transportation

Figure 14: On site construction of the pieces with gantry cranes.

Once the individual plates were put into position, the pins with their respective lengths were fixed and subsequently the outer surface was mounted on them. The entire form was thus completed and then the individual plates welded to each other. The sculptures were produced in pieces large enough to transport them from the workshop to the site and then the last stages of completion were executed at site (Fig.13).

On site the individual pieces of the sculptures were placed on the respective locations such that the final stage of positioning them as designed was done with as minimal effort as possible. This optimised the effort on-site and also the infrastructure required to position and complete the construction of the sculptures on-site. This approach also required a precise positioning of the sculptures and also a convenient method to hold them in the position. On an average, a single piece was about 8-14 tonnes and was carried on 2-3 hooks by one crane or a gantry crane. Once the sculptures were brought to position the base plates were bolted and the individual parts bolted to one another. While the pieces of the sculpture were still supported by the cranes the welding process was completed so that a structural integrity was achieved and the cranes could then be released (Fig. 14).

This entire process was completed in almost a day so as to optimise the extent of infrastructure used in the process.

5. Conclusion

These aluminium sculptures are a very good example of how one can use contemporary mathematical tools right from the design process to get an effective and optimised result of such complex

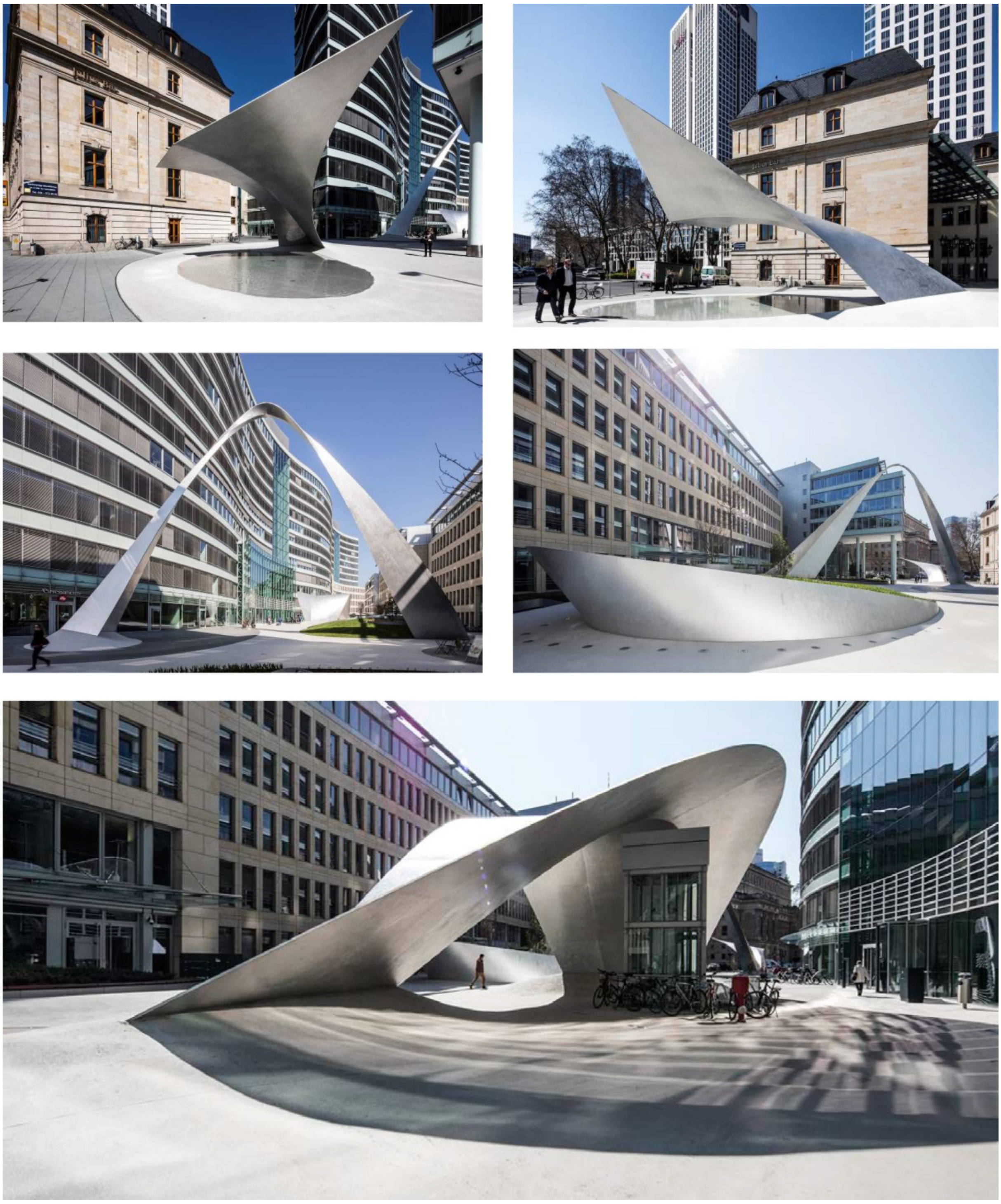

Figure 15: The completed sculptures. Top: Diving Arch, Centre: Glorious Arch, Bottom: Joyful Wave

geometries. In this project it was evident that without the tools it may have been extremely difficult to get the desired results in the time frame provided and thereby helped in optimising the effort and costs involved in creating such complex structures. The success in the project lies at the base of the idea of integrating structure and form into a single entity that helped in creating an integrated design and production process. The sculptures are a testament to the modern idea where the boundaries between architecture, structure and production in an industrial sense dissolve and create a new entity that combines all of them in process and result at the same time.

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References

[1] Eisenbach, P.; Vasudevan, R.; Grohmann, M.; Bollinger, K.; Hauser, S.: Tsuboi Proceedings Award Paper for 2013: Parapluie - Ultra Thin Concrete Shell Made of UHPC by Activating Membrane Effects; *Journal of the International Association for Shell and Spatial Structures* (J. IASS), Vol. 55 (2014) No. 4 December n. 182, (Print Version) 1028-365X; Sergio Pellegrino (Ed. in Chief); p. 201-212.

[2] Rumpf, M.; Grohmann, M.; Eisenbach, P.; Hauser S.: Structural Surface – multi parameter structural optimization of a thin high performance concrete object, in *Proceedings of the IASS Conference 2015, Amsterdam*.

[3] Eisenbach P., Grohmann M., Rumpf M. and Hauser S., Seamless rigid connections of thin concrete shells – a novel stop-end construction technique for prefab elements, in *Proceedings of the IASS Conference 2015, Amsterdam*.

[4] Aimond F., "Étude statique des voiles minces en paraboloide hyperbolique travaillant sans flexion," Publications, *International Association for Bridge and Structural Engineering (IABSE)* 4 (1936)

[5] Maria E. Moreyra Garlock, David P. Billington, "Félix Candela's legacy", *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.*