Planetarium Sorrow

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Abstract: The Planetarium Sorrow was a project that involved parametric design, combined with new materials, manufacturing and construction considerations and perhaps most of all aesthetics. The project is an art piece temporary exhibited at the 2013 FIAC exhibition in the Jardin des Tuileries, developed by Bollinger + Grohmann in collaboration with architects and artists Berger&Berger. The piece resembles a geodesic dome, left with no function whatsoever and minimised to its very minimum. The starting point was a geodesic geometry with some 270 elements, which needed to be reduced to about one third. Culling elements according to which could best be left out, led to a design with a big hole in the top, and therefore not an aesthetically pleasing solution. The aim of the design team was to digitally engineer a way to achieve solutions that had "randomness". Various approaches where tested and compared, to in the end find the most optimal solution regarding weighted parameters of aesthetics, internal stresses and structural performance, and erection process. The project also included design and manufacturing of 3D-printed connection as well as new and innovative magnetic connection methods. The dome is manufactured with bars of 3 different lengths and customised 3D printed nodes. The project is 6 by 4.5m and weighs only 73kg and fits into two boxes so that two people can easily transport it. The art piece was after the exposition bought by a collector and is to be rebuilt soon elsewhere.

Keywords: Parametric Design, Computational Design, Holistic Design, 3D-Printing, Magnetic Connectors.

Figure 1. Architect's Rendering of the Structure Before Start of Collaborative Design Development

Site and Boundary Conditions

Since 1974 the French organisation FIAC (Foire Internationale d'Art Contemporain) has held an annual art fair in Paris, where galleries from around the world exhibit their upcoming art and artists. In recent years the fair has been continuously expanding in size, with expositions growing out of the Grand Palais into the Jardin des Tuileries, the garden in front of the Louvre Museum. Through Paris based Galleri Torri, artist and architect brothers Berger&Berger were asked to participate in the 2013 exhibition.

Their idea was a broken dome: the Planetarium Sorrow (see figure 1). The design concept was a geodesic dome with random elements removed. The geodesic dome was invented, first patented and built by Walther Bauersfeld in 1929 for a planetarium for the optical company Carl Zeiss in Jena, Germany. After The Second World War the Americans acquired all of Germany's patents, and it was allegedly through Bauersfeld's old German patent that Buckminster Fuller found the Geodesic principle and started to redevelop dome structures - for later to acquire his own American patent on the principle. Berger&Berger contacted the engineering consultancy Bollinger+Grohmann to participate in the development of the art piece in everything from overall stability to erection methods.

The geodesic dome is the geometric principle of recreating a sphere using straight elements, thereby creating triangles or heptagons and hexagons. The higher the number of subdivision, or "frequency", the closer the geodesic structure is to the original sphere. The overall size of the dome was decided in accordance with the context of the site and the budget. For the Planetarium Sorrow Berger&Berger had already chosen a geodesic dome with a frequency of 3, with 3 different nodes connecting 5, 5, or 6 elements. The dome was to be around 4.5 meters in diameter and 6 meters high. This design requires approximately 270 elements of 3 different lengths to recreate a full sphere. The sphere was cut slightly below its middle point and rotated around its center point to create the feel of randomness, see figure 2. Berger&Berger chose to use ceramic tubes with an enameled finishing. Berger&Berger had prior to the integrated design process bought 120 tubes of 1,5 meters with a diameter of 2 cm. They were made of Alumina Alsint 99,7%, a ceramic material (see figure 3), and by an enameling process the tubes would obtain a white glossy finish. The elements of the dome were therefore given beforehand and were the first fixed boundary.

Figure 3. Ceramic Tube Before Enamelling

To evoke the feeling of randomness, the basic geodesic geometry was slightly rotated around its center point. Berger&Berger had decided on an initial geodesic sphere with 270 elements, which was supposed to be reduced to around 115. The number of elements was the second boundary condition.

Removing random elements brought along another boundary condition; almost all nodes were to become a different shape. In a regular geodesic dome three different nodes connect either 5 or 6 elements. When removing elements of the regular geodesic dome the design of the nodes becomes more complex; nodes could in principle be connecting 2, 3, 4, 5 or 6 elements. A solution to manufacture some 50-60 different node connections had to be found, as well as a way to make the node-connections with a similar finish to the enameled ceramic.

A fourth boundary condition was related to the assembling. The 2013 FIAC exhibition was only a temporary event from 24th to 27th October, and the sculpture therefore had to be disassembled fast and easily.

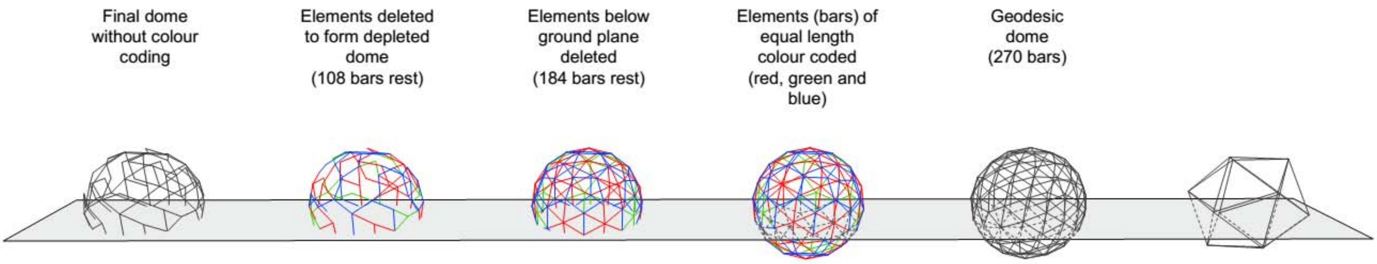

Figure 2. Development of the Geodesic Structure

Form Finding Through Generative Optimisation

To find the optimal structural shape of the broken dome, the internal forces in the elements and in the nodes had to be limited. To search for an optimised solution an algorithm was developed by the use of parametric modeling tools.

Figure 4. Visualisation of Generative Optimisation in Grasshopper using Evolutionary Solver Galapagos

The algorithm was developed in Grasshopper, a graphical algorithm editor tightly integrated with the NURBS software Rhinoceros 3-D. With the use of the Finite Element Modeling (FEM) tool karamba, a live test of the broken dome's stability could be performed. Combining structural analysis made with karamba with the evolutionary solver Galapagos (figure 4), it is possible to computer-generate several optimised designs. Galapagos first produces a given number of random species, then measures each of them against a chosen optimisation parameter and then tries to combine the good genes from each species into mutations.

Computational design is not cleverer than the input it gets. Initially no restrictions were built into the algorithm, and the optimised output did not have the random visual expression which the design team sought. Asking the initial script to take out the elements that it could best do without resulted in a Pantheon-like shaped dome with a large hole in the top. In general the geometries that came out of the initial algorithm had the tendency to be clumped together leaving big holes in the dome.

To achieve the randomness asked for by Berger&Berger, the script was further developed and different approaches were investigated. Some options were made by manipulating the geometric input; for instance by dividing the initial geodesic geometry into zones. Other options were based on a completely rewritten algorithm, which instead of culling elements connected nodes with either 3 or more elements.

The different geometric approaches were tested with different optimisation parameters as total deformation, maximum deformation, normal forces or bending forces.

3D-Printing and Node Design

The design of the nodes was carried out in parallel to the form finding process described above. Berger&Berger had initially imagined the nodes made of steel tubes welded together in the right angles, but it would be hard to obtain a result precise enough with this technique. It would also take a lot of time to produce that many different nodes. Instead 3D-printed nodes were proposed; each node could be different as all the "hard work" of various angles from node to node would all be done digitally.

In collaboration with *Materialise* several test pieces were printed to test strength and finish. Recent years' advances within 3D-printing techniques have made it possible to print new materials, for instance titanium. For budget reasons it was chosen to use a material called Alumide. 3D-printed alumide models are constructed from a blend of aluminum dust and nylon plastic, making it relatively strong but also quite elastic (see figure 6).

Figure 5. 3D-Printed Node with Magnetic Female Connector Part Glued Inside

A magnetic screw solution originally developed for connections in wood was proposed instead – a solution called *Invis Lamello* (figure 5). As ceramic - like wood - is a non-magnetic material it was possible to glue in a male connector part inside each tube and a female part in the arms of each 3D-printed node. The male parts have magnets placed around the thread, and with a special magnet "bit" for a screwing machine, the thread can be turned when it is placed inside a ceramic tube. Another advantage of the system was the ability to completely hide the male thread inside the tube, so the last element of a triangulation can easily be placed.

Figure 6. Photo of 3D-Printed Node Connection

Choosing the Final Shape

The generative form finding process resulted in some thirty different optimised options, some more optimised for internal forces and others had a limited deformation. Each option was calculated in karamba with continuous elements rigidly connected to each other. The parametric modeling did not take into account the varying stiffness between the 3D-printed nodes and the ceramic tube elements. This assumption was purposely made before the final design of the nodes was found, so in order to equitably compare options developed later in the process, this error was not corrected along the way. All options therefore contained this fault.

To test the impact of the stiffness difference between nodes and elements all options were calculated in RSTAB - a commercial FEM structural analysis program - with the correct material properties. One could imagine that the impact of the error would vary from option to option; an option where less stiff nodes placed in areas with a concentration of forces would not perform very well compared to other options.

The deformation found through karamba calculations was compared with one found in RSTAB. The factorial difference between deformations should lie within the same area, otherwise the impact of the less stiff nodes was too high and the options had to be excluded from further comparison. It was to verify that the optimised form was still optimised when taken the less stiff nodes into account. The final solution was intended to still work as a dome, though the geodesic geometry was broken up. A dome structure primarily has normal forces, and higher bending moments would cause higher deflections. It was chosen to leave out the 75th percentile (figure 7).

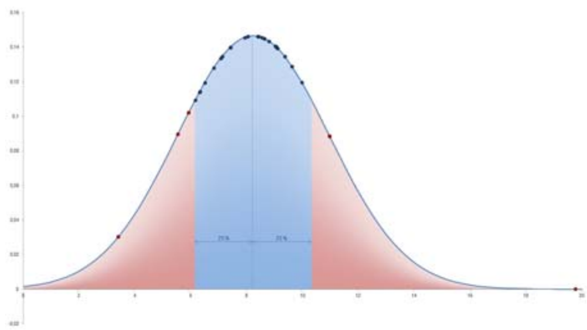

Figure 7. 25^{th} Procentile of the Developed Designs was Kept for Further Study

Finally the von Mises stress was calculated for both the 3D-printed nodes and the ceramic tubes for various load cases - some loading situations even included the weight of pigeons. The maximum stresses were compared to find the option which could spread the forces in the most optimised way. The option with the least amount of internal forces also responded to excitation with the least amount of energy, and was in that sense the most optimised form of the some thirty different options initially found.

Figure 8. Photo from During Construction at Jardin des Tuileries

Prototype

To solve eventual construction problems or questions before the assembling a 1:5 scaled prototype model was made. All 57 nodes and 122 elements of the chosen option were 3D-printed in-house and assembled in the office of Bollinger+Grohmann. The prototype helped clarify erection sequences and assembling methods. The team of architects, engineers and builders could discuss the process of assembling around the model. The 3D-printed prototype helped all to reach a greater understanding of the complex geometry of the broken geodesic dome during the actual erection process (figure 8).

Conclusion

Through a collaborative process the art piece Planetarium Sorrow was developed by the use of cutting edge technologies. From a set of given boundary conditions, the design team developed a solution optimised in the dynamic 3D-modelling software Grasshopper, and the FEM plugin karamba. The final design was the most optimised design for the given aesthetic requirements set out not only by the artists but the engineers as well.

The Planetarium Sorrow consists of 122 ceramic tubes with three different lengths and a diameter of 2 cm.

Innovative methods were used for the design of the nodes and the connectors. The derived solution used newly developed 3D-printing material with strengthening aluminum dust to create custom made, high strength 3D-printed nodes.

Invisible magnetic connectors, originally developed for high-end furniture in wood, were used for the creation of a seamless transition between ceramic tubes and 3D-printed nodes.

The final result was exposed for two weeks at the 2013 FIAC exhibition in the Jardin des Tuileries (figure 9).

Figure 9. Photo of the Planetarium Sorrow Exhibited at Jardin de Tuileries