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Saltatur

Node-Based Assembly of Funicular Spatial Concrete

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1 The exhibited structure as part of the Spatial Efficiency Exhibition at the Center for Architecture and Design in Philadelphia, © PSL 2020).

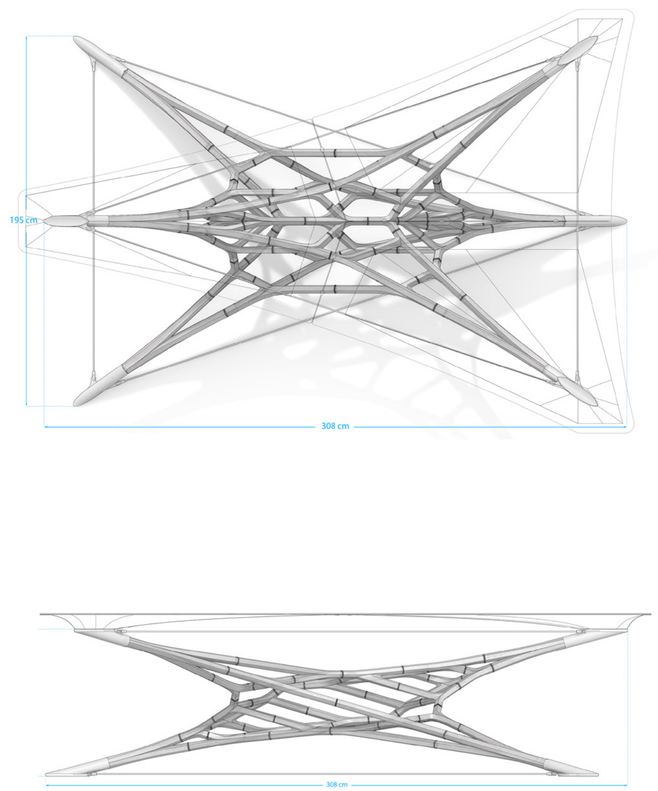
PRODUCTION NOTES

Architect:	Polyhedral Structures Lab.
Status:	Completed
Site Area:	6 sqm
Location:	Weitzman School of Design
Date:	2020

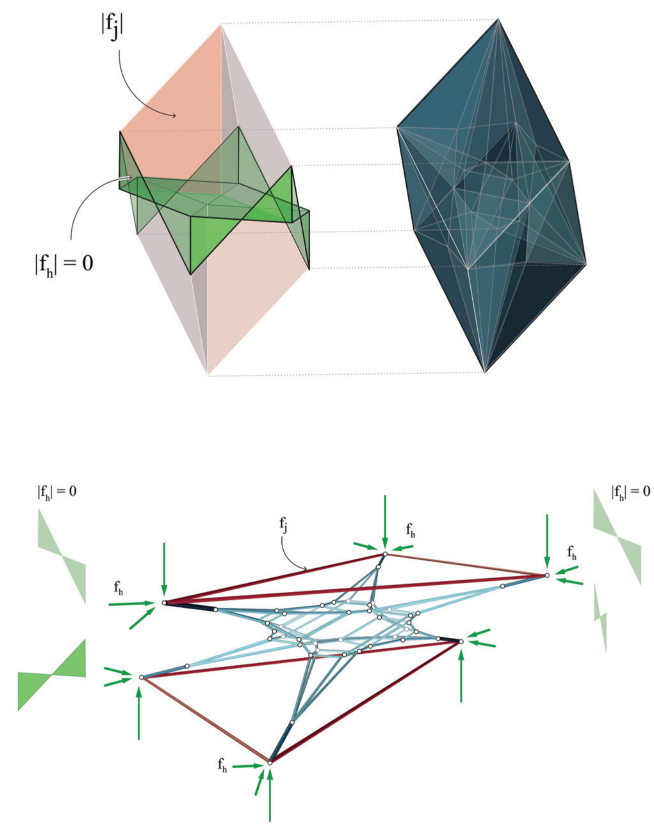
The Saltatur demonstrates innovative research in the design and fabrication of a prefab, discrete, spatial composite structure consisting of a spatial, compression-only concrete body, post-tensioning steel rods, and an ultra thin glass structure on its top in the form of a long-span furniture. Using discrete spatial systems would minimize the volume of concrete and the carbon footprint while preserving the necessary mass for structural performance and specific architectural detailing. Achieving a high level of efficiency in utilizing concrete for spatial systems requires a robust and powerful structural design and fabrication approach (Fig. 1).

There are multiple design innovations in various phases of the realization of this project, from conceptual structural design to fabrication. This project impeccably combines efficiency, elegance, and economy in one product whose fabrication technique opens a new horizon for the future of construction of large scale systems. The entire volume of concrete used for this structure is 0.06 cubic meters distributed in 4.44 cubic meters (3.1m x 0.8m x 1.9m) of space. This volume makes the relative density of this structure as small as 1% percent (0.013), which demonstrates the ingenuity in the design and engineering of an efficient load-bearing, expressive system (Fig. 2).

A node-based assembly was considered as a method of construction. To avoid the possible spatial collision of the branches of the nodes during the assembly, an innovative detailing was developed that allowed fixing the members in their exact locations in the structure without using a conventional male-female connection details. Although the concrete structure has been designed to act in pure compression, some of the members will experience tensile stress in the cases of asymmetric loads,



2 The force diagram (top) and its corresponding structural form (bottom).



3 The force diagram (top) and its corresponding structural form (bottom).

especially during the assembly process. The proposed bespoke steel connection transfers the tensile force between the concrete members effectively.

The ultra-thin (4mm) glass structure on the top was formed into a funicular geometry as a discrete structure to span 3.75 meters. The glass can carry the applied loads as a three-hinged discrete arch with a particular detail connections preventing the horizontal movements of the glass parts (Fig. 2).

STRUCTURAL FORM-FINDING

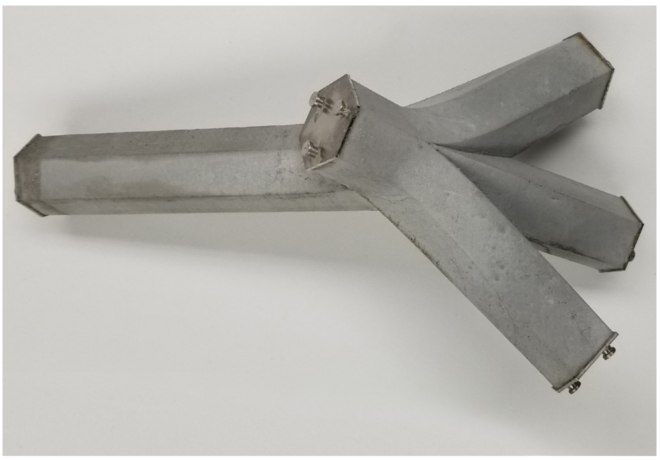
The structural geometry is a spatial funicular form with combined compressive and tensile forces which was designed using the methods of 3D Graphic Statics. There is a creative twist in the topology of the structure, allowing the bottom members of the geometry to have a hundred-and-eighty-degree turn compared to the top members in plan and elevation. This twist induces a rotational symmetry in the structure that reduces the number of bespoke elements by half without resulting in a highly-symmetrical appearance (Fig. 3). Particular technique was used to create the tension ties on the top and bottom of the structure. The structural form was initially designed as a compression only system. In the next phase, we geometrically controlled the areas of the faces related to the horizontal applied loads, f_h, in the system. As a result the trapezoidal faces of the global force polyhedron turned into self-intersecting faces with a total signed areas of zero (Fig. 3). Consequently, the external forces in the form disappeared and the normal of the internal face corresponding to the ties flipped. This change in the direction of the normal for the internal members results in tension force, f_j, in the ties at the top and the bottom of the structure.

MATERIALIZATION

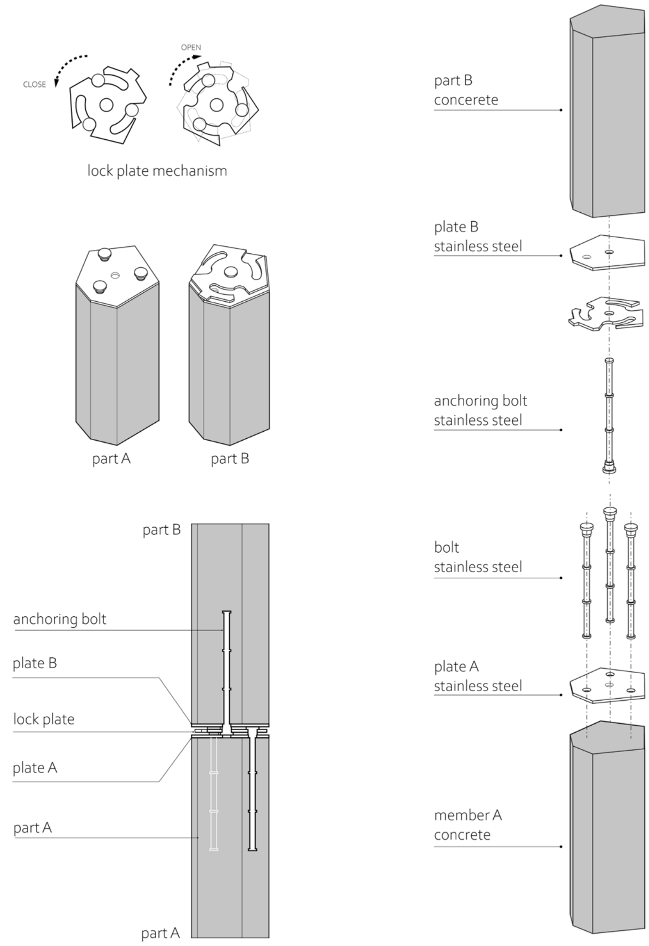
The long-span component on the top of the table is made out of 4 mm glass segments assembled to form an ultra-thin compression-only shell (3780 L x 2540 W x 70 H (mm)) sitting on a discrete spatial concrete structure with the dimensions of 3100 mm (L) by 1950 mm (W) by 75 mm (H). The concrete body consists of 24 (48 in total) unique spatial nodes with the diameter ranging from 40 to 80 mm, each proportional to the magnitude of the internal forces. Self-consolidating, high-strength concrete with carbon fiber reinforcement was used to improve the tensile capacity of

4 The top view of the compression body.

5 The metal detail components and the PLA molds © PSL.



6 A spatial node with its steel connections after demolding © PSL.



7 This is ACADIA-Figure Caption (photographer name, date, © if applicable).

the concrete. Although the concrete structure has been designed to act in compression, some of the members will experience significant tensile stress in the case of asymmetric loads, especially during the assembly process. To address this challenge, particular steel connection detail was developed to transfer the tensile force between the concrete parts.

DETAIL DEVELOPMENT

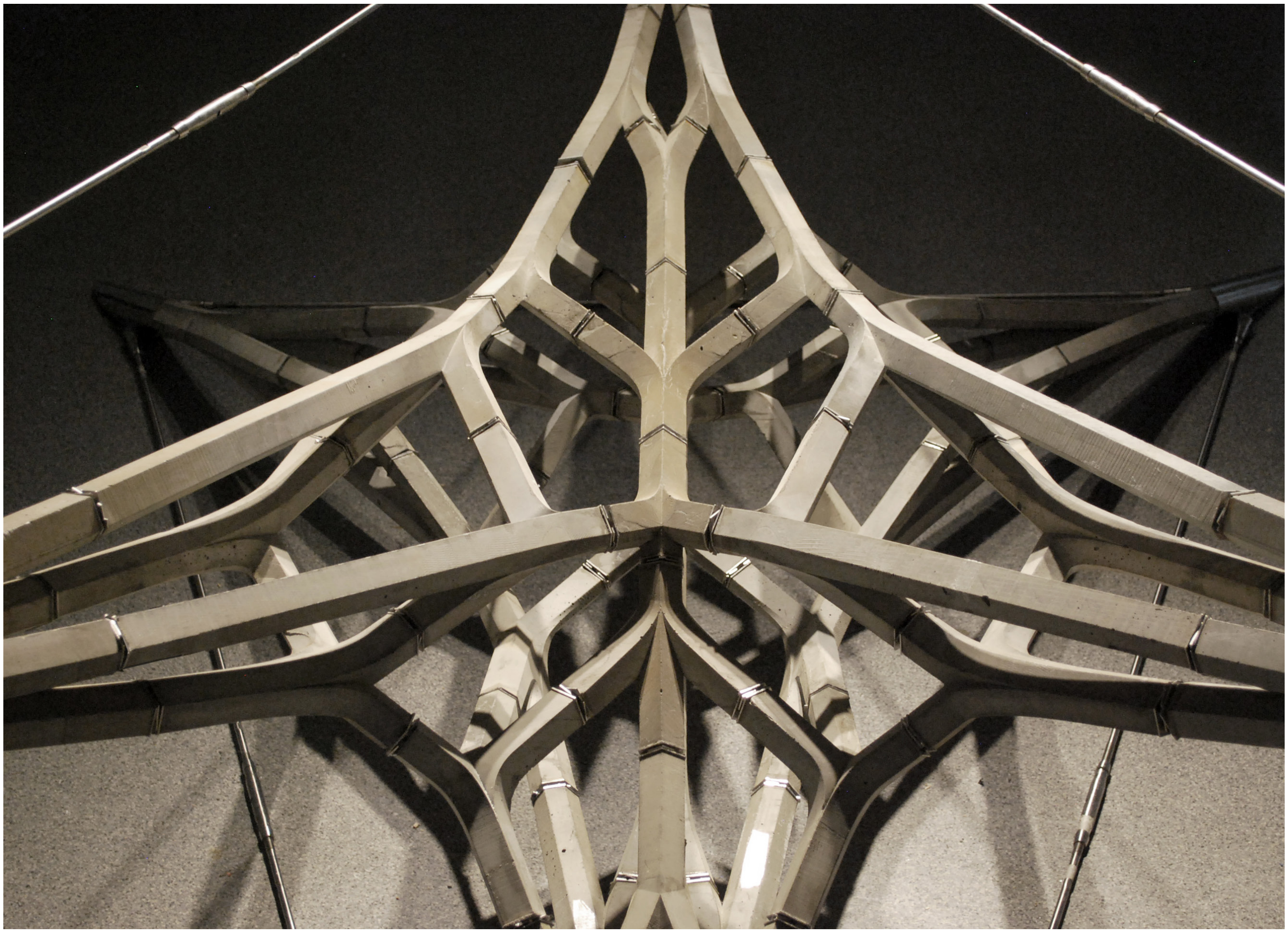
The seven-millimeter (7 mm) connection includes bespoke anchor bolts to engage with concrete and a locking plate rotating around the axis of the bolt on the opposite/adjacent member. Our innovative connection detail allows the insertion of each node with no specific order into the system as longs at least one receiving branch is available. The rotatory lock in the mechanism of the connection provides multiple rotational degrees of freedom during the assembly while fixing the location of the connected branch in the three-dimensional space that significantly facilities the assembly of such complex spatial systems (Figs. 4 -8).

STRUCTURAL ANALYSIS OF THE CONNECTION

Mechanical behavior of the designed connection was evaluated experimentally and later verified numerically. In the first stage, three connections were constructed and then tested using three point bending loading configuration to find the maximum bending capacity and failure type of each connection. Test results showed that the connection can take up to 650 N concentrated load in the worse case loading scenario. The stress analysis of the connection showed that the connection never fails under the existing loads of the table. No crack or failure in concrete was observed at the end of the test, only the rotating plate deformed significantly due to the imposed bending. In fact, the rotating plate absorbs all the deformation in the connection, and it can later be replaced. A detailed, numerical model of the connection was built and analyzed in an FE analysis software, considering all the interactions between concrete, plates and anchors. Numerical models were in a good agreement with the experimental results by predicting the deformation and the strength of the connection (Fig. 9).

THE DESIGN OF THE TABLE TOP

The structural form of the glass was developed in conjunction with the concrete body. The structure was designed as a discrete compression-dominated shell in three parts as a three-hinged arch



8 Back view of the assembled structure © PSL.

supported at the corners of the concrete structure. The self-weight of the glass parts matches the design loads for the concrete structure at each support. We used 4 mm regular glass and slumped it into a compression-dominated geometry designed by using the methods of 3D graphic statics. The glass parts meeting at the mid-span are attached to a particular steel connections that sit inside the steel corners of the structure with constrained movement on -xy plane. The glass was connected to its steel connection using Transparent Silicone Structural Adhesive (Figs. 10-11).

ACKNOWLEDGMENTS

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REFERENCES

[1] Akbarzadeh, M. (2016).3D Graphic Statics Using Polyhedral Reciprocal Diagrams. Ph. D.thesis, ETH Zürich, Zürich, Switzerland.

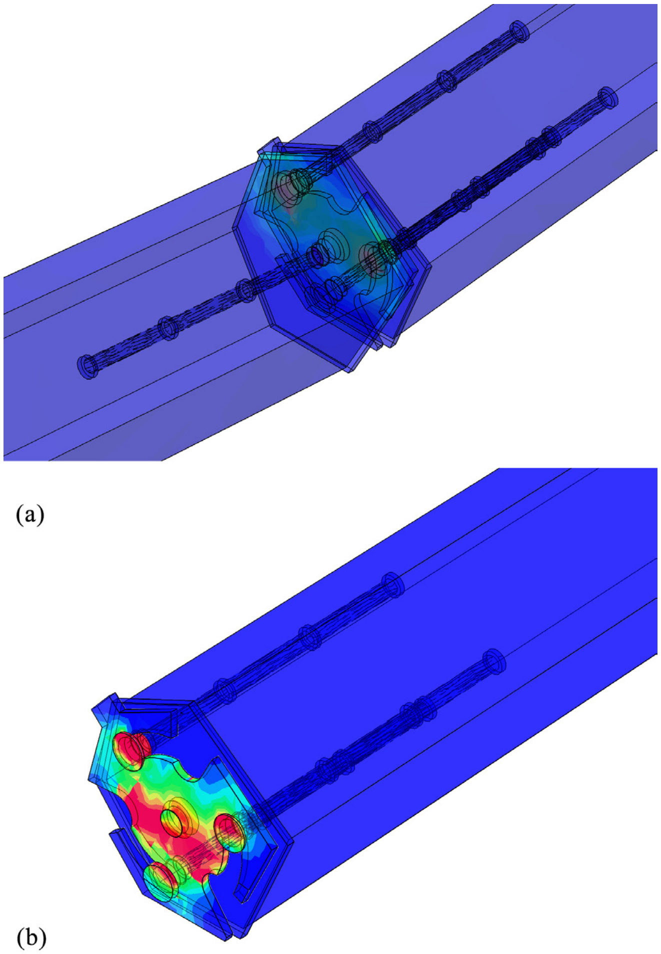
[2] Akbarzadeh, M., M. Hablicsek, and Y. Guo (2018, July 16-20). Devel-oping algebraic constraints for reciprocal polyhedral diagrams of 3d graphic statics. InProceedings of the IASSSymposium 2018, Creativity in Structural Design, MIT, Boston, USA.

[3] Akbarzadeh, M., T. Van Mele, and P. Block (2015). On the equilibriumof funicular polyhedral frames and convex polyhedral force diagrams. Computer-Aided Design 63, 118–128.

[4] Bolhassani, M., M. Akbarzadeh, M. Mahnia, and R. Taherian(2017). On structural behavior of the first funicular polyhedral frame designed by 3d graphic statics.Structures,56–68.

[5] Hablicsek, M., M. Akbarzadeh, and Y. Guo (2019). Algebraic 3d graphic-statics: Reciprocal constructions.Computer-Aided Design 108, 30 – 41.

IMAGE CREDITS



9 The Finite Element Analysis of the connection, © PSL.

10 The glass-steel support connection beneath view © PSL.

11 The glass-steel support connection above view © PSL.

Figure 1-12: © Polyhedral Structures Laboratory, 2020.

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