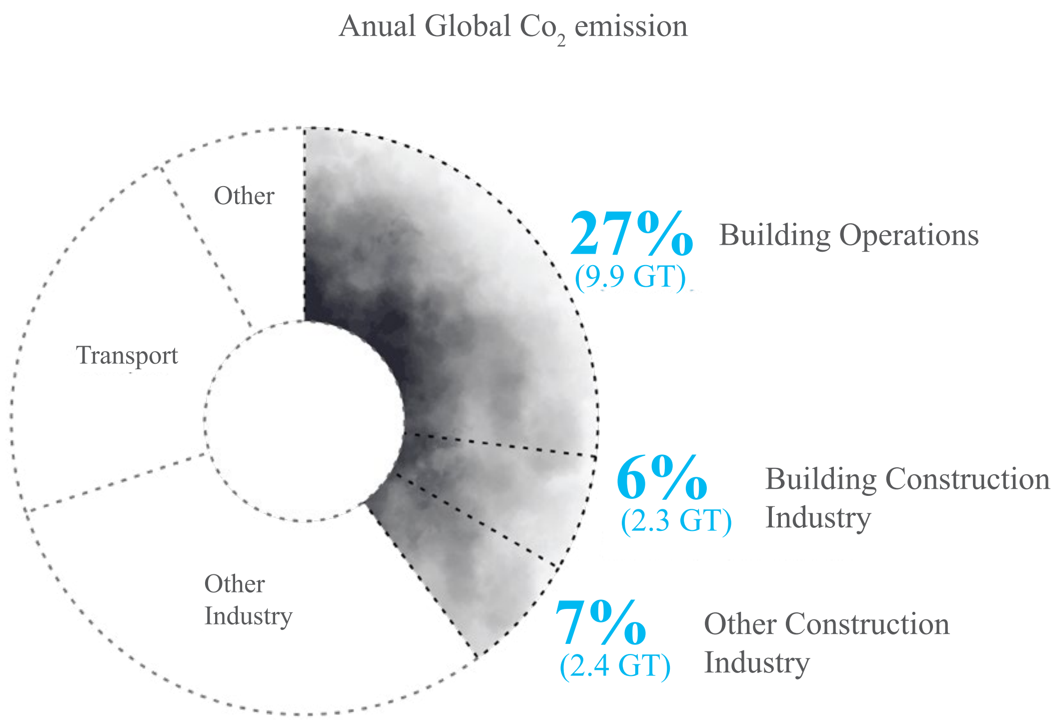
Research / Teaching Portfolio

Mostafa Akbari

Fall 2023



Preface

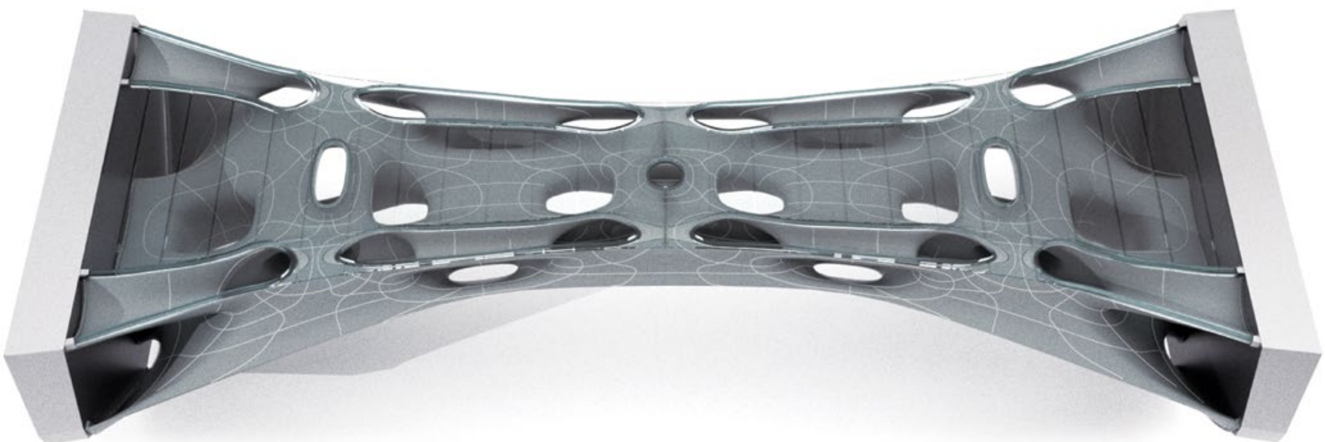
The Architecture and Construction Industry collectively account for over 40% of annual carbon emissions (Data source: IEA 2022, Buildings, Paris). The projects showcased in this portfolio are dedicated to reduce the carbon footprint of architecture. This is achieved through strategies such as minimizing material usage in the design phase of the structures, automating fabrication processes, and adopting bio-based materials. These efforts collectively propel us towards a more sustainable future.

This portfolio primarily features projects aimed at fostering a more sustainable future through the creation of environmentally responsible solutions with a particular emphasis on innovative structures. To achieve this goal, the author focuses on minimizing waste during the design phase, utilizing bio-based materials for construction, and implementing automated fabrication processes to save time, energy, and labor resources. The research conducted lies at the intersection of Computer Science, Digital Fabrication, Structural Design, and Material Science, and the author endeavors to apply this knowledge across diverse disciplines, media, and scales, ranging from micro to macro.

The overarching objective is to enhance the relationship between design and science by drawing inspiration from nature to develop novel design and fabrication technologies. The author's research interests encompass computational design, structural computation, material computation, inventive construction techniques, 4D printing, graphic statics, geometry-based structural design methods, form-finding approaches, lightweight structures, and more. The research is categorized into three main sections: Ph.D. research, collaborations, and pre-Ph.D. research.

Finally, the portfolio represents a group of students work from the courses that the author has taught.

https://www.mostafaakbari.net/



1 Shellular[1] Funicular Structures (SFS)

Contribution: The author is solely responsible for conducting this research, under the guidance of Prof. Masoud Akbarzadeh.

Shellular Funicular Structures are highly efficient lightweight designs developed within the framework of Polyhedral Graphic Statics. Unlike other cellular structures, such as strut-based ones, these structures can withstand forces three times greater. The performance of strut-based cellular polyhedral funicular geometries in Polyhedral Graphic Statics (PGS) relies heavily on the system's buckling behavior when the edges of the form diagram are directly converted into structural members.

Additionally, the spatial configuration of the nodes poses significant challenges during fabrication. This innovative design approach was developed as part of the **author's Ph.D. research** and has a wide range of applications, spanning from macro-scale applications in architecture and structural design to meso and micro-scale applications in tissue engineering, material science, and aerospace engineering. [4 - 8]

[1] For the first time, this terminology was used by a group of scientists in 2015. [2]

Figure 1.1. A shellular funicular structural bridge as a design manife-station for the research.

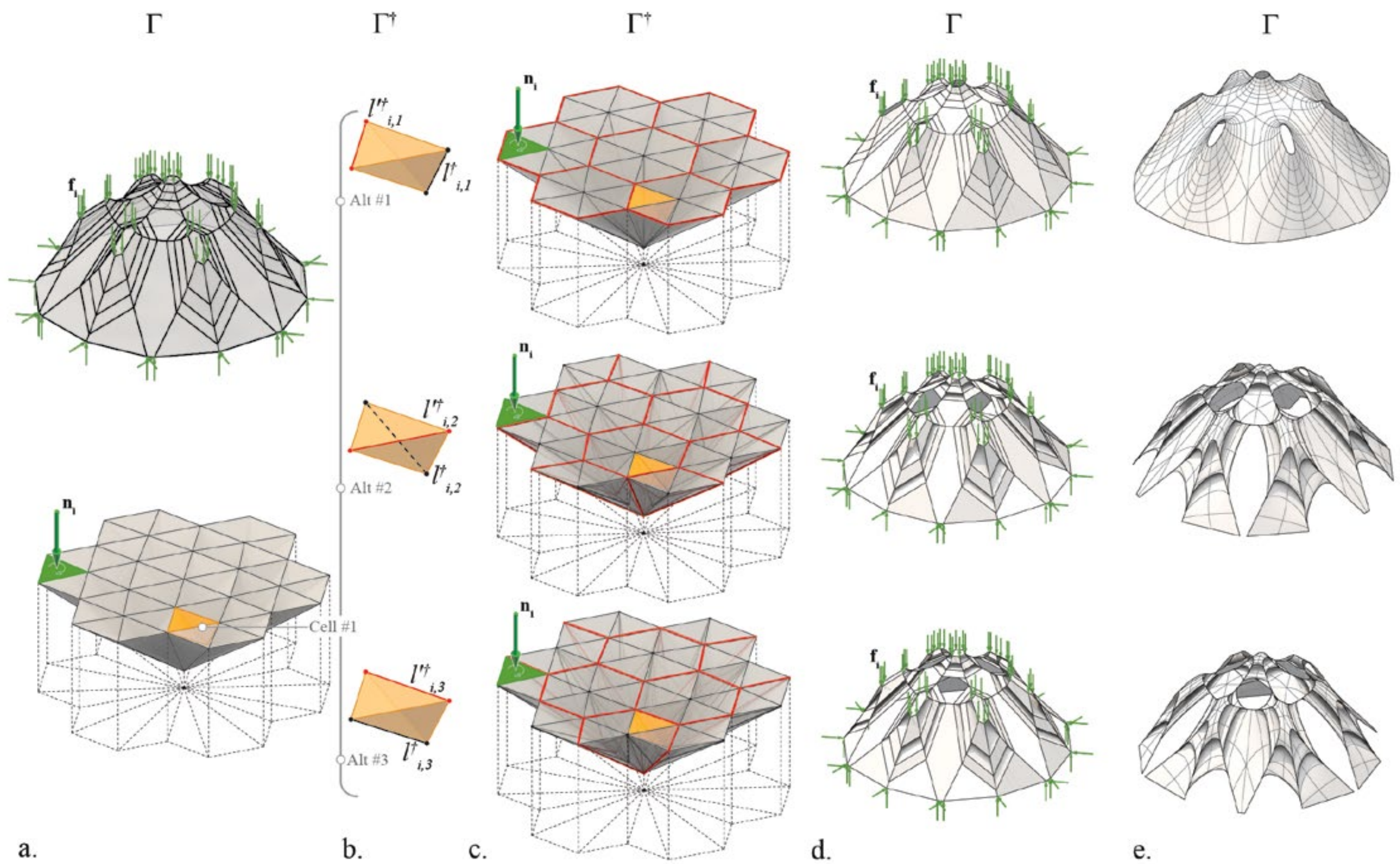


Figure 1.2.

Translating any cellular funicular structure to a shellular counterpart

In this study, an algorithm has been created to convert any strut-based cellular funicular structure into a shellular counterpart. This algorithm has been incorporated into a Grasshopper plugin called **Polyframe**. In this algorithm, the force diagram is divided into a set of tetrahedrons that correspond to anticlastic nodes in the form diagram. The labyrinth graphs, which define the geometry of the shellular structures, are then determined. Because of the geometric flexibility involved, there are three possible ways to design labyrinths as skew edges within a tetrahedron, resulting in three distinct shellular possibilities. Therefore, using this algorithm, users can transform any cellular geometry into three different shellular geometries.

Each of these structures, based on their geometrical properties, can serve specific purposes with varying characteristics, including structural capacity and spatial qualities.

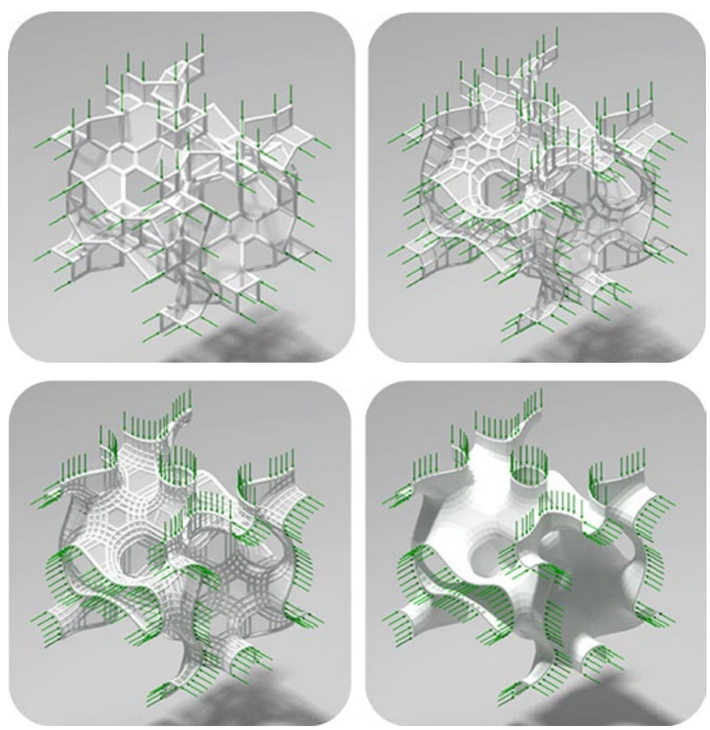


Figure 1.3.

Figure 1.2. Three different possibilities for translating a cellular dome to a shellular version.

Figure 1.3. A group of cellular (left) to shellular (right) funicular structures designed in PGS.

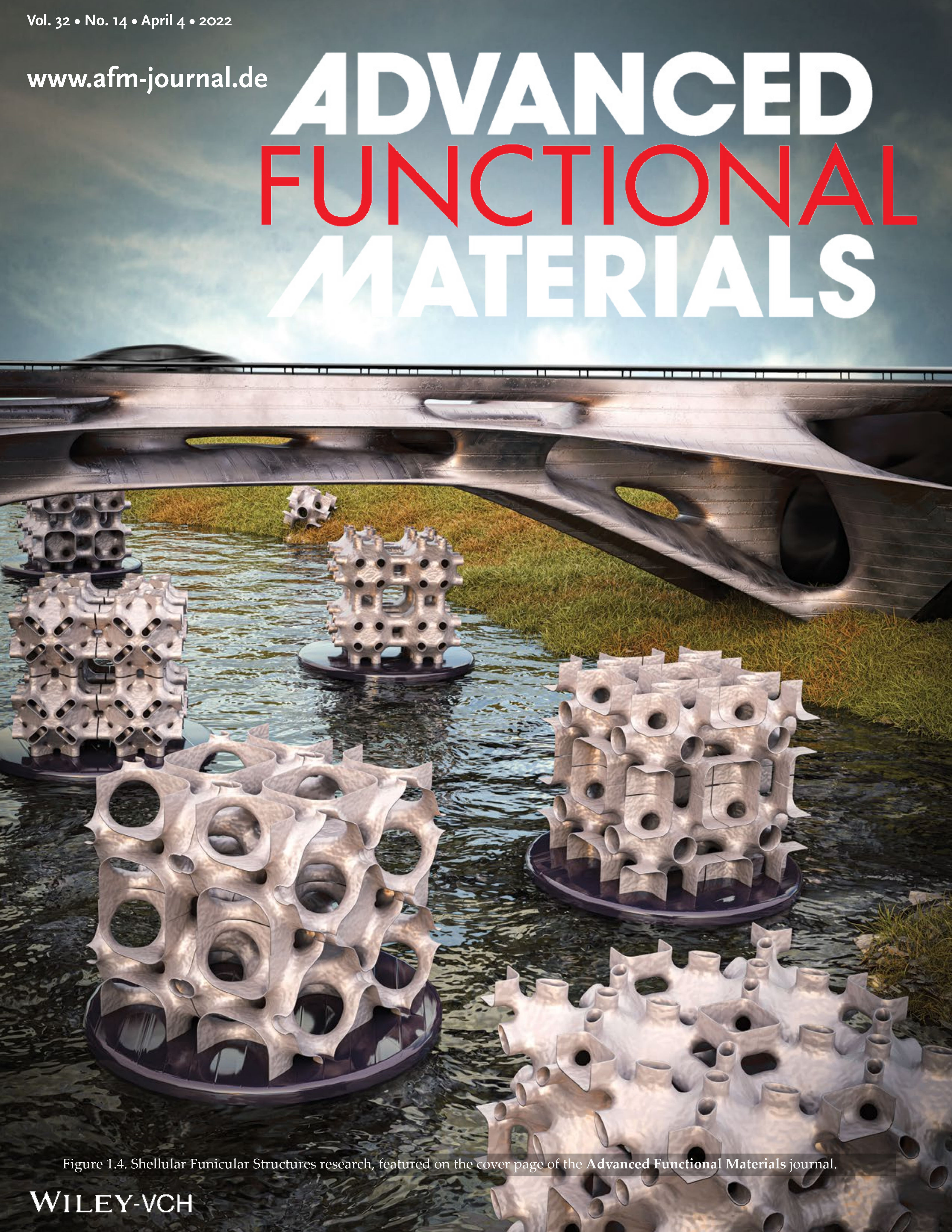


Figure 1.4. Shellular Funicular Structures research, featured on the cover page of the **Advanced Functional Materials** journal.

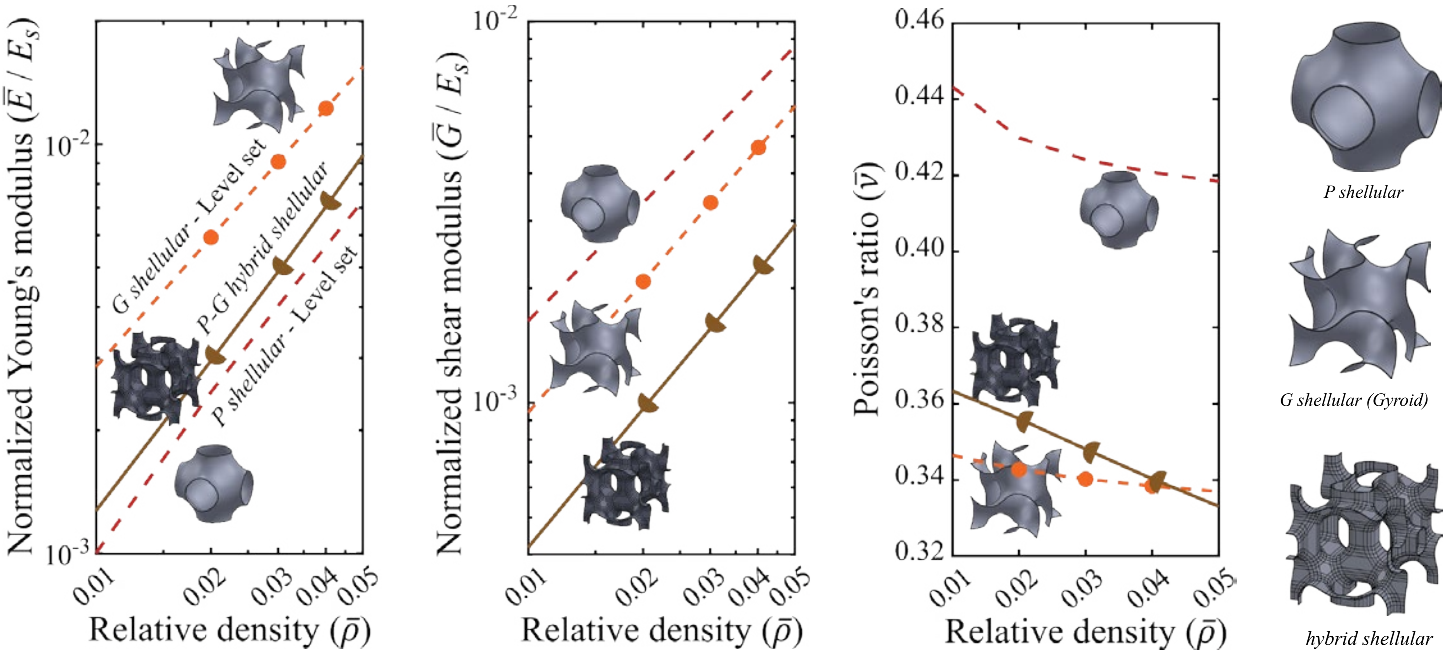


Figure 1.5.

Mechanical Performance

To assess the mechanical characteristics of the designed cellular structures, we employed standard mechanics homogenization on their unit-cells under periodic boundary conditions, yielding numerical values for their effective Young's modulus, shear modulus, and Poisson ratio. When comparing the properties of the P shellular architectures created using this new method with those based on the trigonometric level set equation, we observed a close match in their mechanical properties. Additionally, we examined how these effective properties change as the number of subdivisions (architectural refinement) increases. Generally, more subdivisions result in a stiffer cellular material. Moreover, we evaluated the mechanical properties of a hybrid model that approximates a combination of Gyroid and Schwarz P geometries. In this analysis, the Young's modulus and Poisson ratio of the hybrid model fell between the values of the initial geometries.

In general since strut-based cellular structures are designed for a specific boundary condition, for different boundaries they act as a **bending-dominated** structure while shellular funicular structures have a behavior closer to **stretching-dominated** structures.

Figure 1.5. Comparing effective mechanical properties of an architected hybrid shellular material with P and G shellulars.

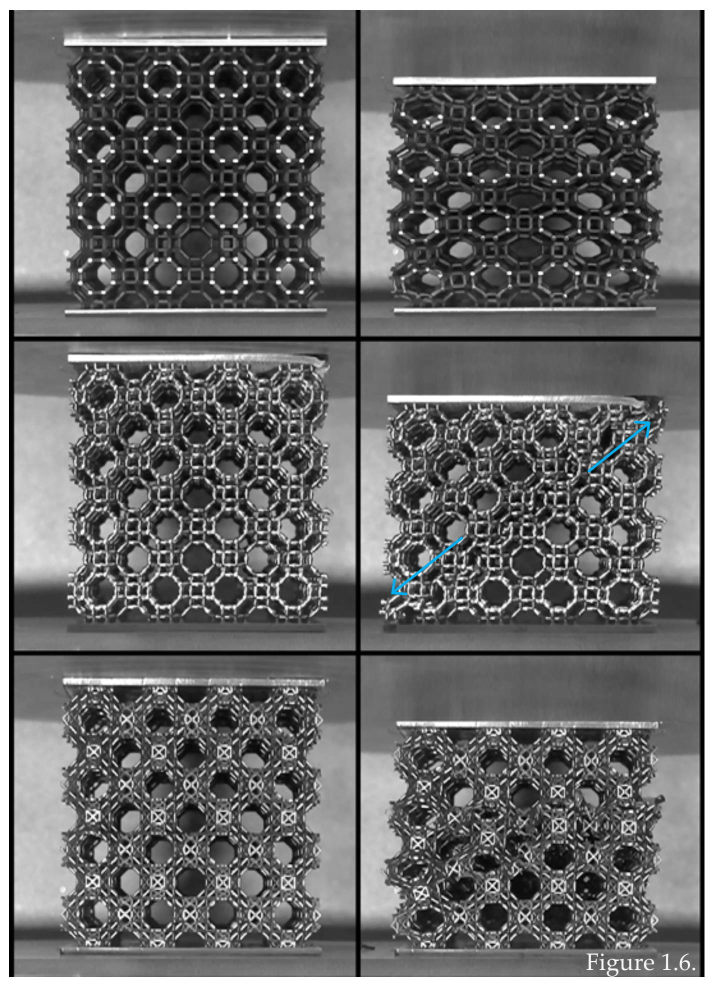


Figure 1.6.

Figure 1.6. Load testing 3D printed cellular and shellular samples.

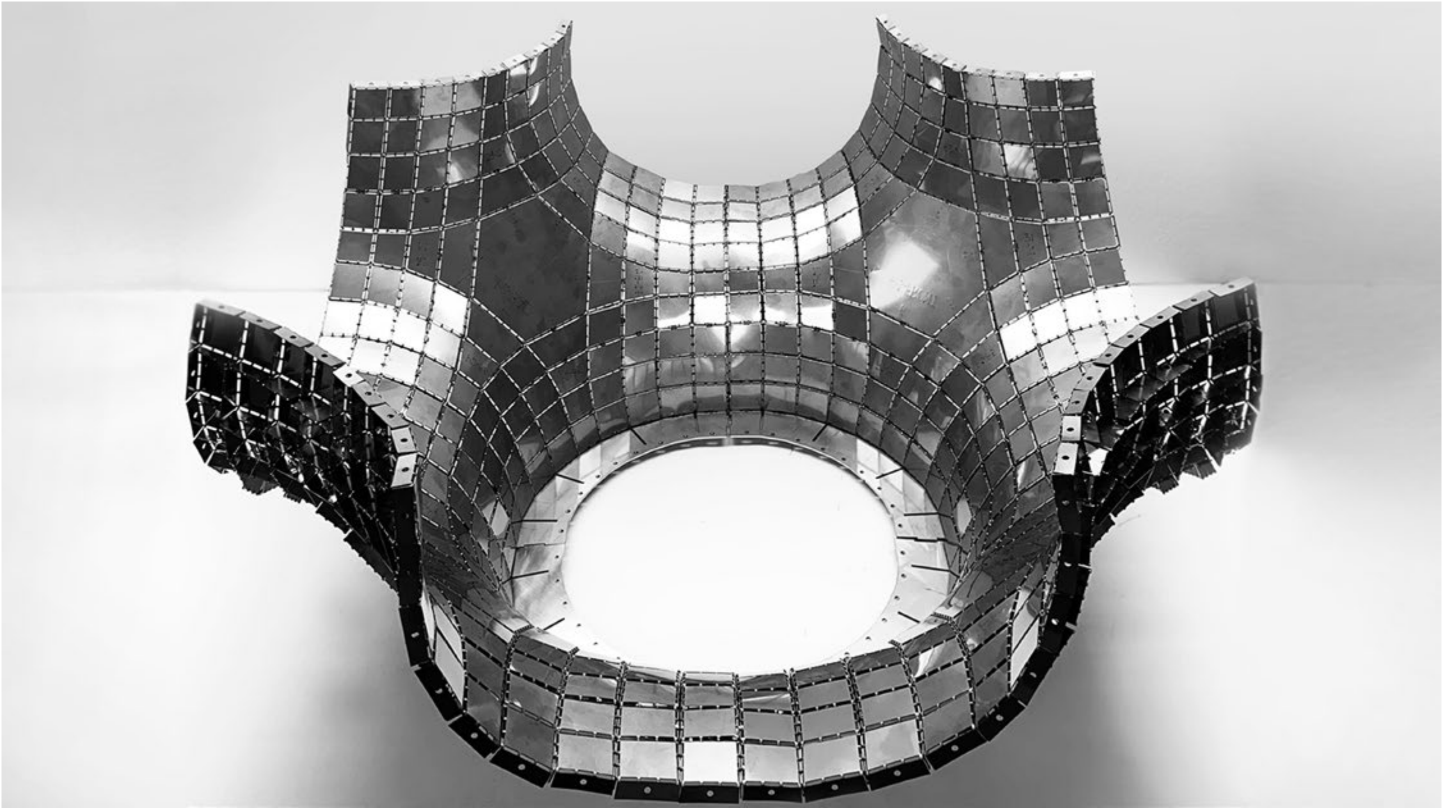


Figure 2.1.

2 Self-folding Origami Structures

Contribution: This research is done solely by the author under the supervision of Prof. Akbarzadeh and Prof. Andrej Kosmrlj from Princeton.

Weitzman SCHOOL OF DESIGN UNIVERSITY of PENNSYLVANIA

Due to the intricate nature of shellular structures, the fabrication process for these designs can be time-consuming and labor-intensive. To address this challenge and streamline the fabrication of shellular funicular structures from a flat sheet of material, this research introduces a self-folding origami technique. Self-folding is an automated method for folding origami structures. In this technique, the origami pattern of a structure is created using both active and passive materials.

Active materials (e.g., wood, agarose) have the property of bending or folding when subjected to external stimuli (e.g., humidity), while passive materials (e.g., Fiber) maintain the structure of the folding pattern without deforming under external influences. The difference in expansion and contraction rates between active and passive materials enables a self-folding process.

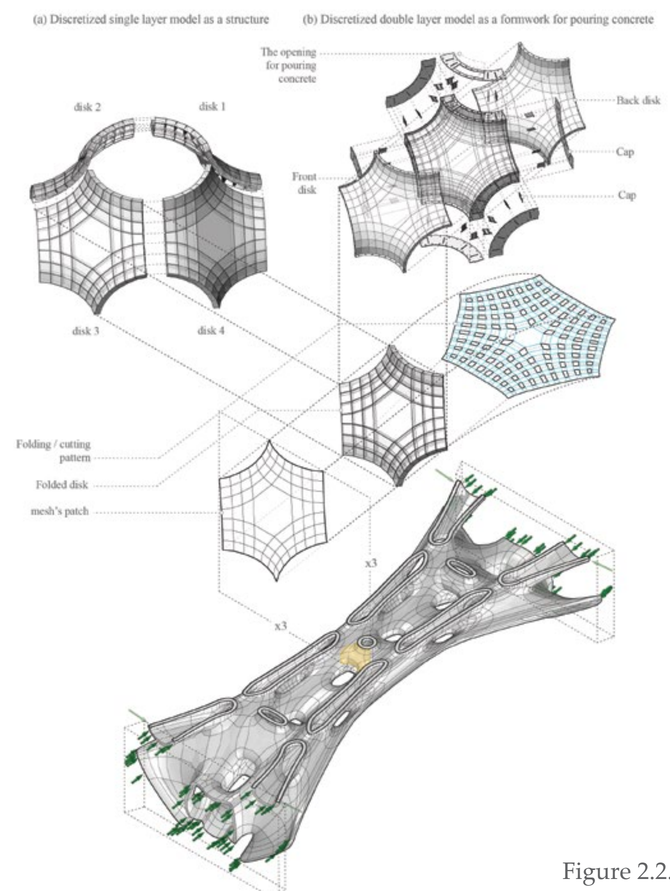


Figure 2.2.

Figure 2.1. A shelllular structure that is fabricated using the tuck-folding technique.

Figure 2.2. An anticlastic section of a shellular bridge along with its folding pattern for fabrication.

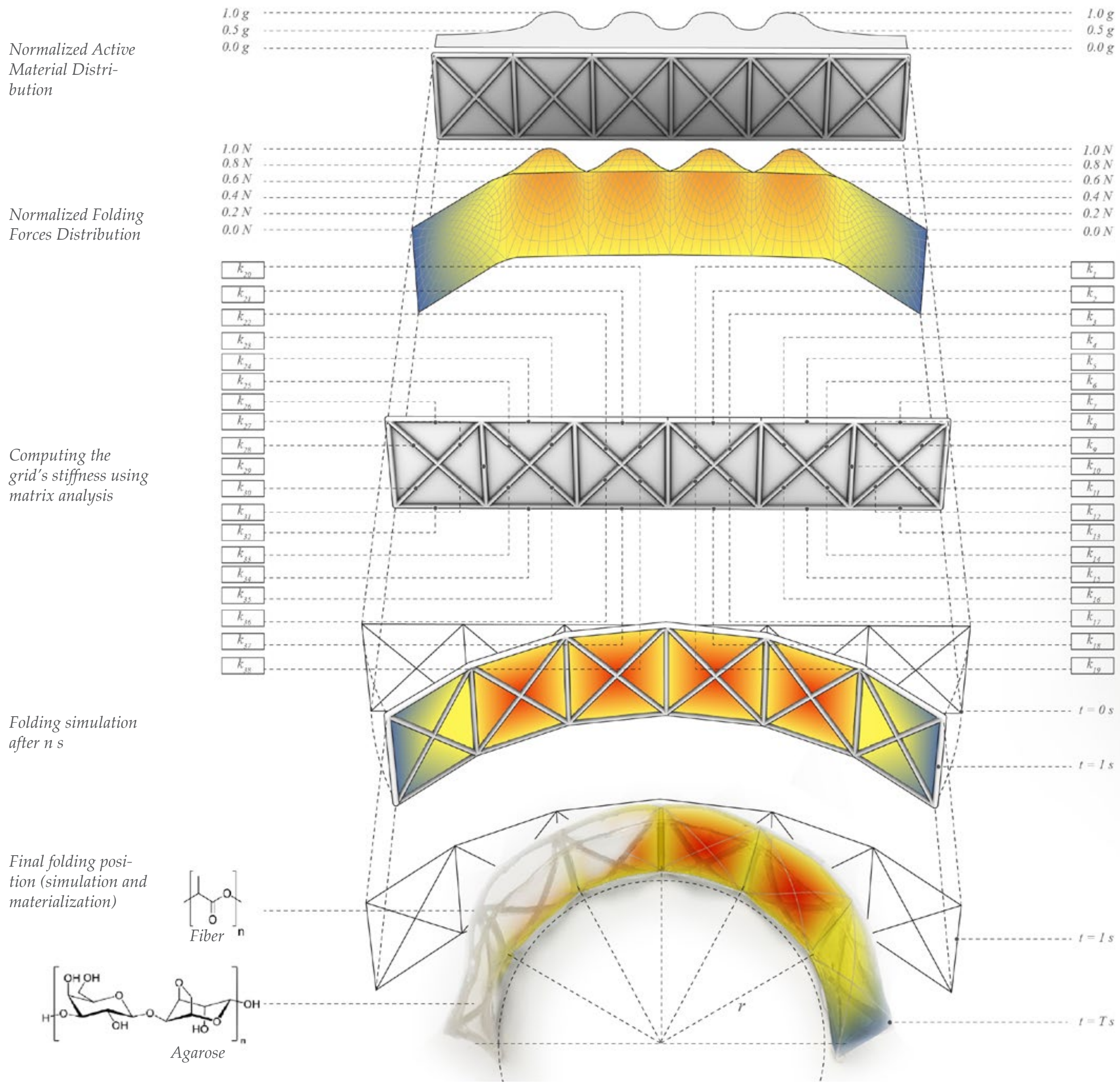


Figure 2.3.

From self-folding simulation to materialization

To bring the computational model into the physical world, a grid substrate (passive material) and agarose (active material) are used. To align the physical model with the computational simulation accurately, the stiffness of the grid substrate needs to be calculated using the Matrix Analysis Method. After determining the stiffness of each grid bar, the folding simulation is rerun to recalculate elastic bending forces. Active material is then added to the grid substrate in proportion to the active bending forces in different parts of the structure. The materialization process involves 3D printing a grid structure using Fiber and casting agarose (a polysaccharide derived from sea kelp) on top. As the agarose's humidity evaporates upon exposure to air, the significant contrast in contraction between agarose and Fiber causes the structure to bend.

Figure 2.3. The process of simulating the self-folding of a grid and materialization based on the folding forces' distribution.

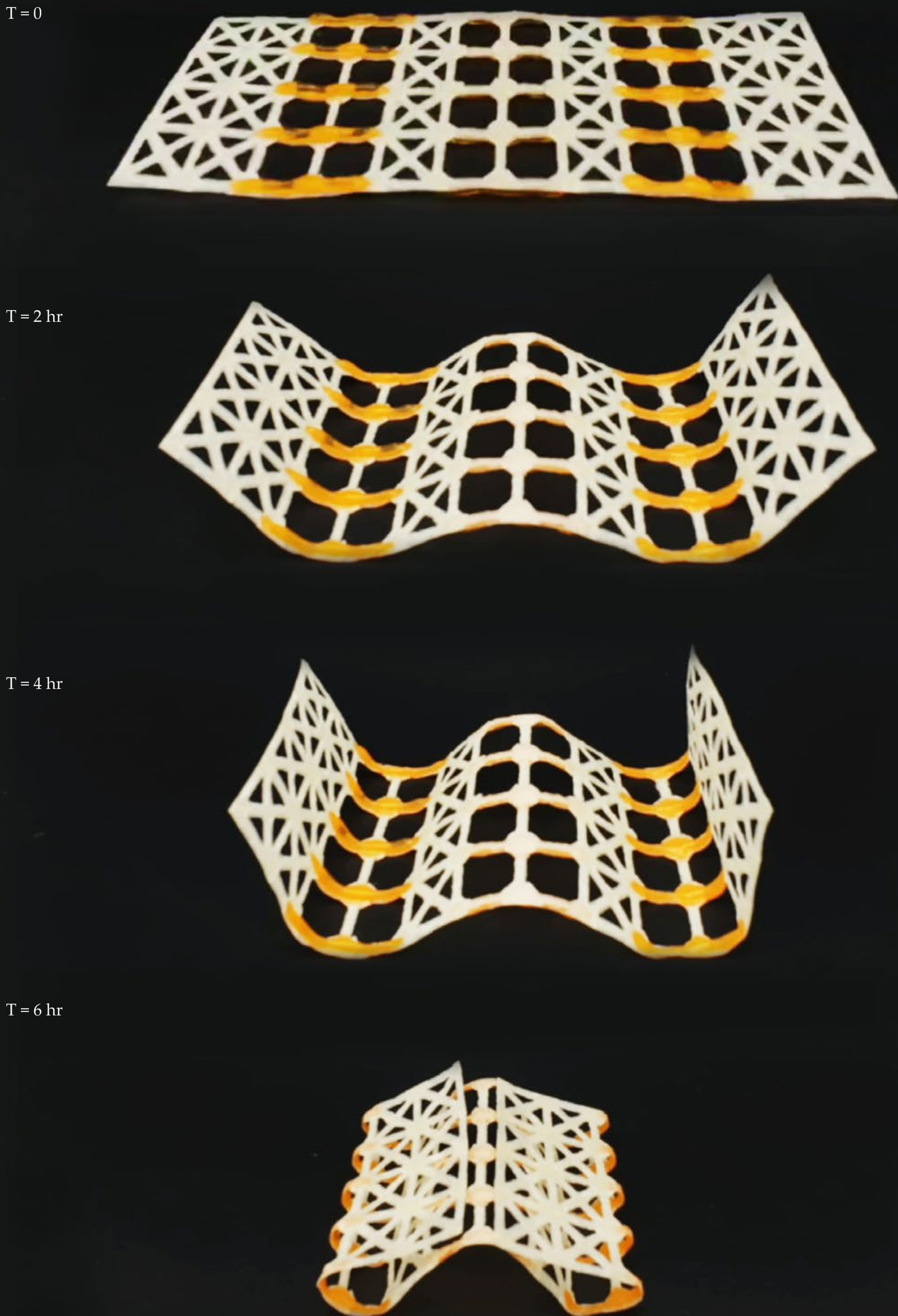


Figure 2.4. Self-folding process of a truss, made from Fiber as a passive material and Agarose as an active material. The folding process is first simulated in the designed software and then materialized accordingly (Structure's length = 30 cm), [Behzad Modanloo Contributed in the printing process of the structures].

Figure 3.1.

3 Saltatur | *Node-Based Assembly of a Funicular Spatial Concrete structure*

Weitzman School of Design University of Pennsylvania

In collaboration with Masoud Akbarzadeh, Ali Tabatabaie Ghomi, Mohammad Bolhassani, Alireza Seyed Ahmadian, Konstantinos Papalexiou, Jingchu Sun, Hanqing Yao

Contribution: In this project the author collaborated on designing the structure, designing the form work, and fabrication from 3D printing and concrete casting to assembly.

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-tensioned steel rods, and an ultra thin glass structure on its top in the form of long-span furniture. Using discrete spatial systems minimizes 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. The entire volume of concrete used for this structure is 0.06 cubic meters distributed in 4.44 cubic meters (3.1 m x 0.8 m x 1.9 m) of space. This volume makes the relative density of this structure as small as 1% percent (0.013), comparable to the volume density of the human's bone structure, which demonstrates the ingenuity in the design and engineering of an efficient load-bearing, expressive system. [3]

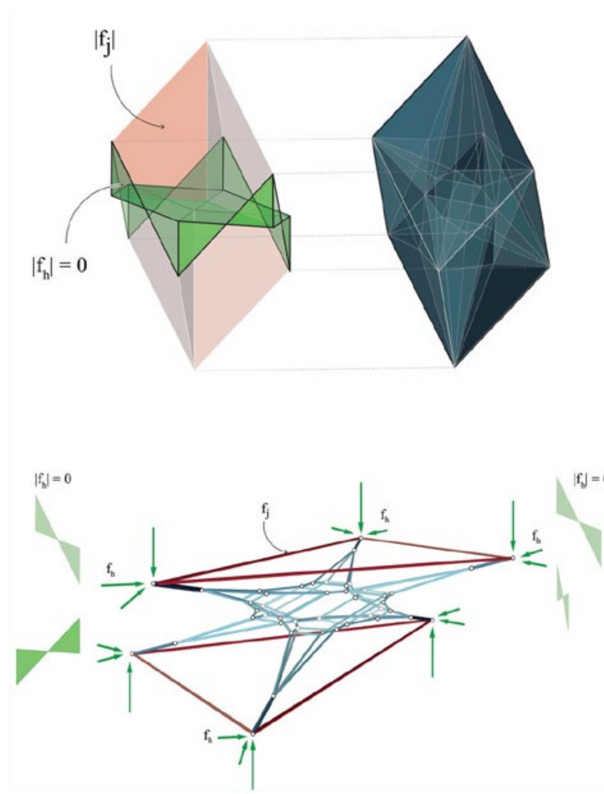


Figure 3.2.

Figure 3.1. Saltature, an efficient light weight strut-based cellular funicular structure madde out of concrete

Figure 3.2. Force diagram of the Saltature (top), and its corresponding form diagram (bottom)

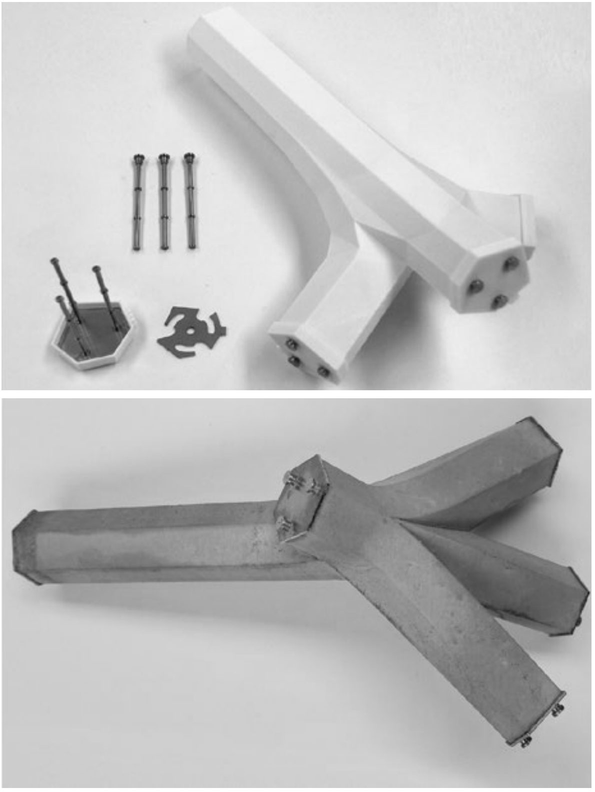


Figure 3.3.

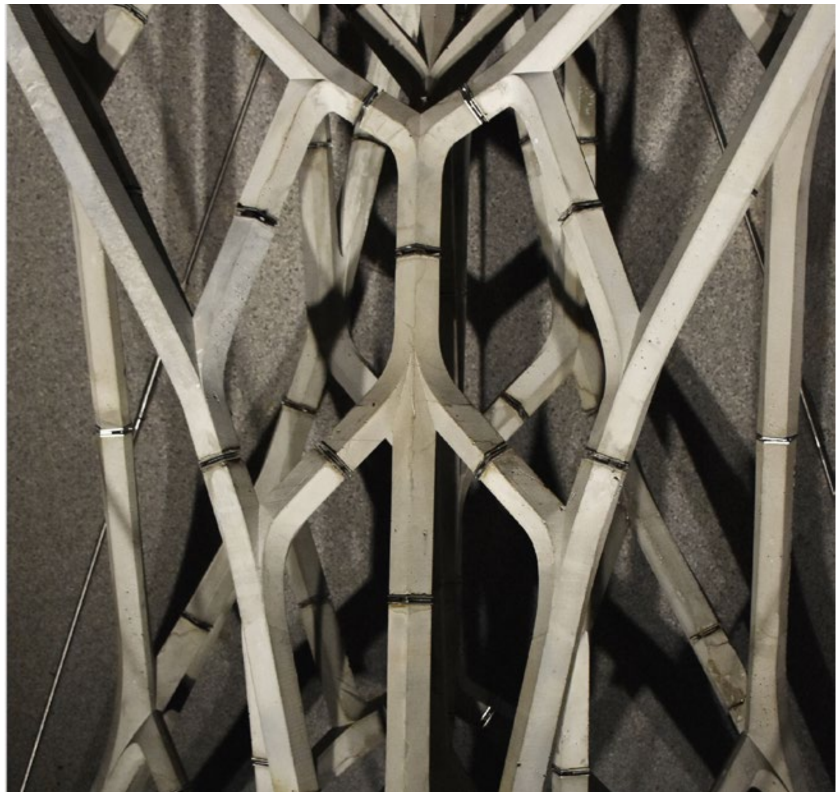


Figure 3.4.

Structural form finding / Detail devel-opement

The structural geometry of Saltatur 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. The structural form was initially designed as a compression-only system with tension ties on the top and the bottom, resulting in a self-supporting system.

In order to lock the members in place without moving them, a locking mechanism has been develope, comprising a rotating plate and three anchoring bolts.

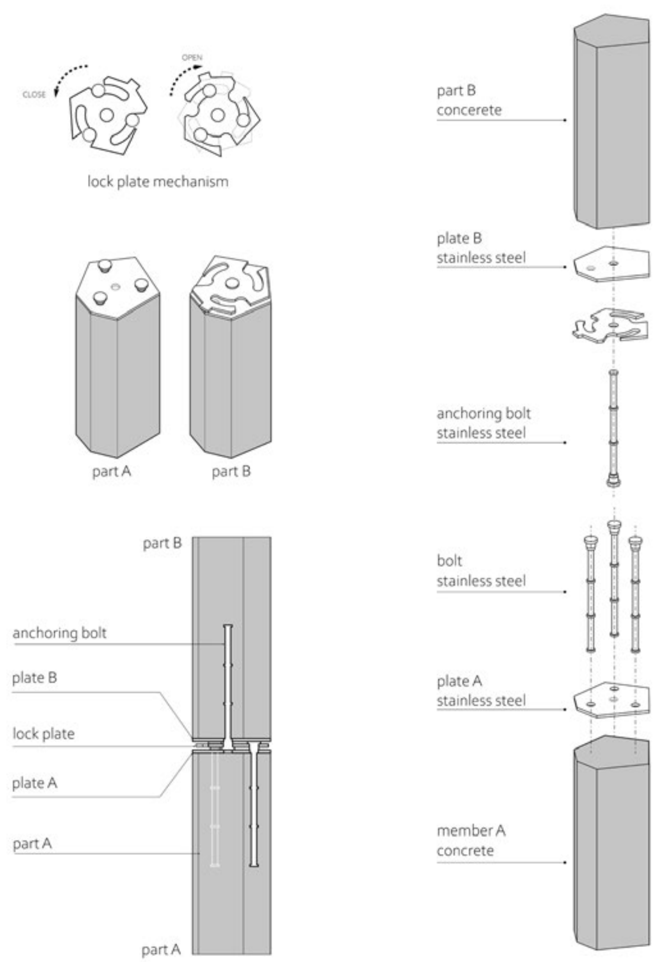


Figure 3.5.

Figure 3.3. The locking mechanism and its details between the spatial members.

Figure 3.4. A spatial node with its steel components before and after demolding.

Figure 3.5. The top view of the structure.

Figure 4.1.

4 Bio-Based Composite Spatial Shell Structures

In collaboration with Farzaneh Oghazian, Ji Yoon Bae, Felecia Davis, Laia Moagas-Soldevila, Masoud Akbarzadeh.

Contribution: In this project the author collaborated in the design and physical experiments from solidifying the knittings to printing material on top of them and fabricating the jig.

Since Shellular structures comprise a single surface, they are suitable candidates to be fabricated using knitting technique, a method by which yarn is manipulated to create a textile or fabric. Using knitting approach, one can fabricate shellular structures with minimum production waste in which the knit can work as a formwork for actual structure or act as a composite structure combined with bio-based materials.

The research proposes a methodology which starts with designig a shellular structure and unrolling it to the XY plane. Next, the shellular pattern is going to be fabricated using manual knitting machine. After holding the knit using a jig, a tension only shellular strcture will be resulted. Afterwards, the structure will be solidified using different biobased material in order to result in a structure that not only can tolerate its own weight but also can take some extra loads. [9]

Figure 4.1. Bio-Based Composite Spatial Shell Structure.

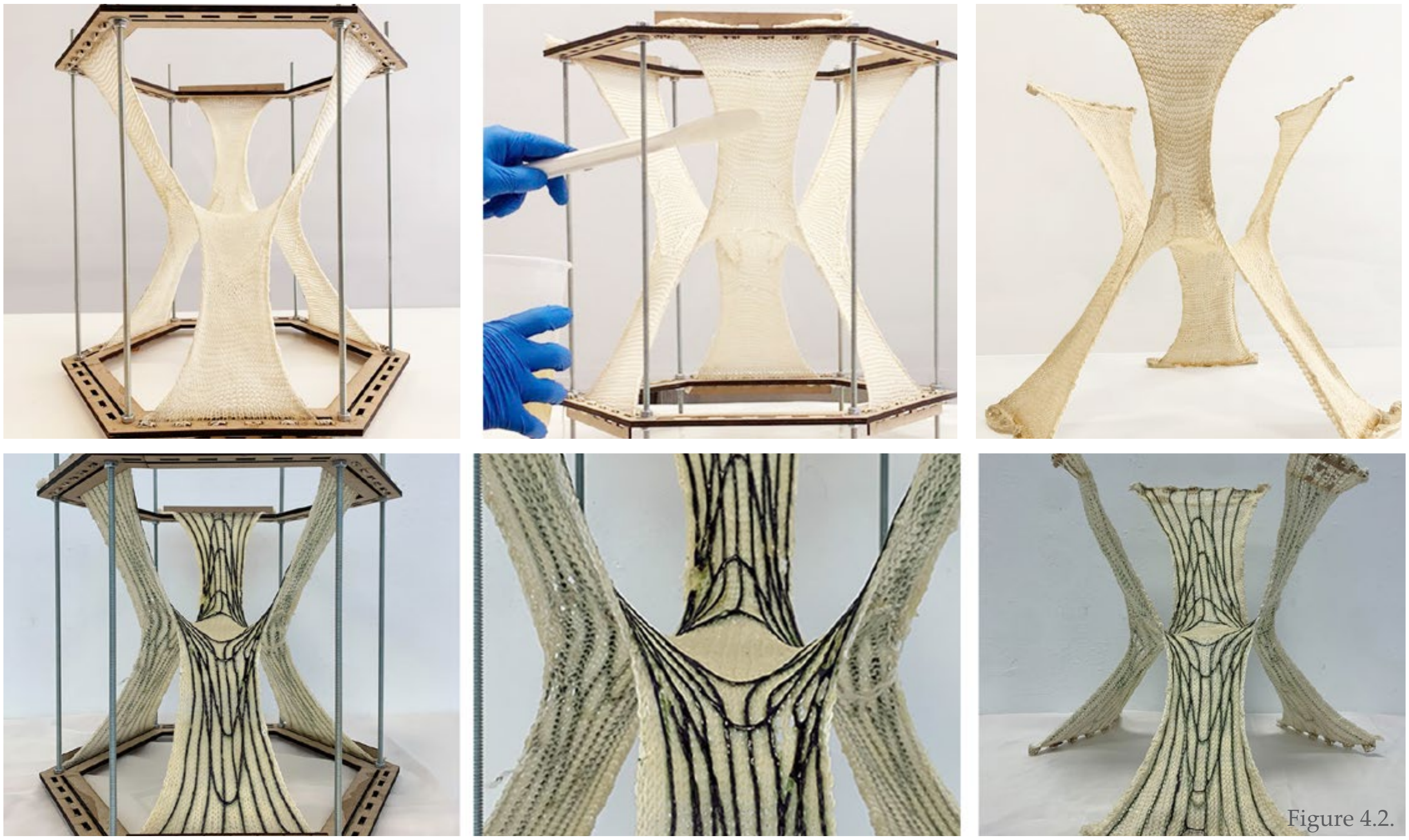


Figure 4.2.

Local and global impregnation of the knitting structure

For impregnating the knitting using the bio-based materials, two different methods have been chosen. In the first method the whole knitting structure is soaked in Chitosan. In this process, Chitosan has been applied to the whole surface of the structure using a spatula. This type which is called the global impregnation resutls in a self-supporting structure (Fig. 4.4). The local impregnation method includes printing fibroin-based material on top of the stress lines in the knitting pattern. In this method, first a computational simulation has been run in order to result in the stress line patterns resulted from the loading condition. At the second stage, using a 3 axis CNC system, a fibroin-based bio-material has been printed on the stress lines, increasing the structural performance of the system in the places that we have maximum forces.

Figure 4.2. Putting the structure in tension and solidifying it using Chitosan (top), and impregnating the structure locally (bottom).

Figure 4.3. Local imprennion of the structure using bio-based materials.

Figure 4.3.

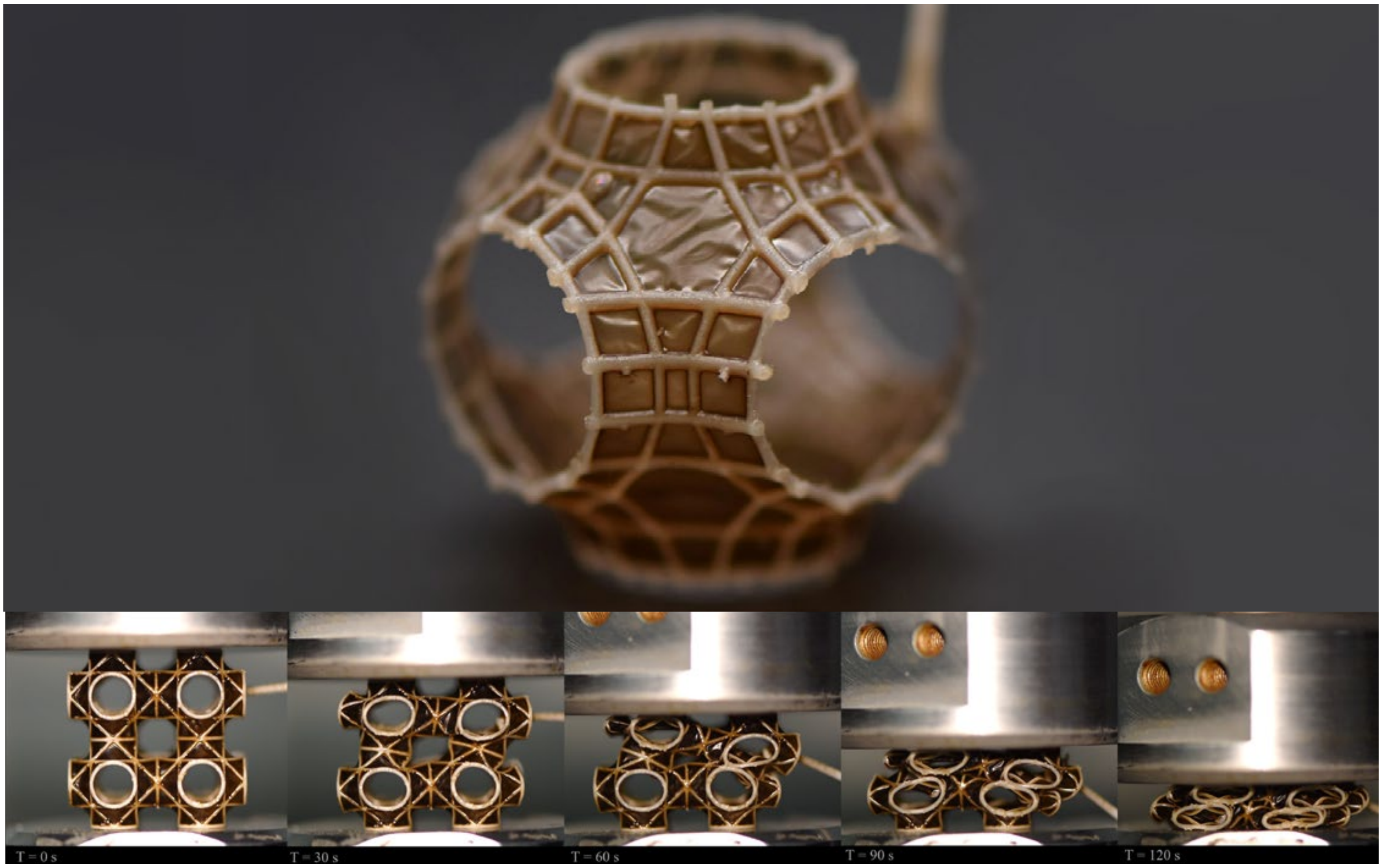


Figure 5.1.

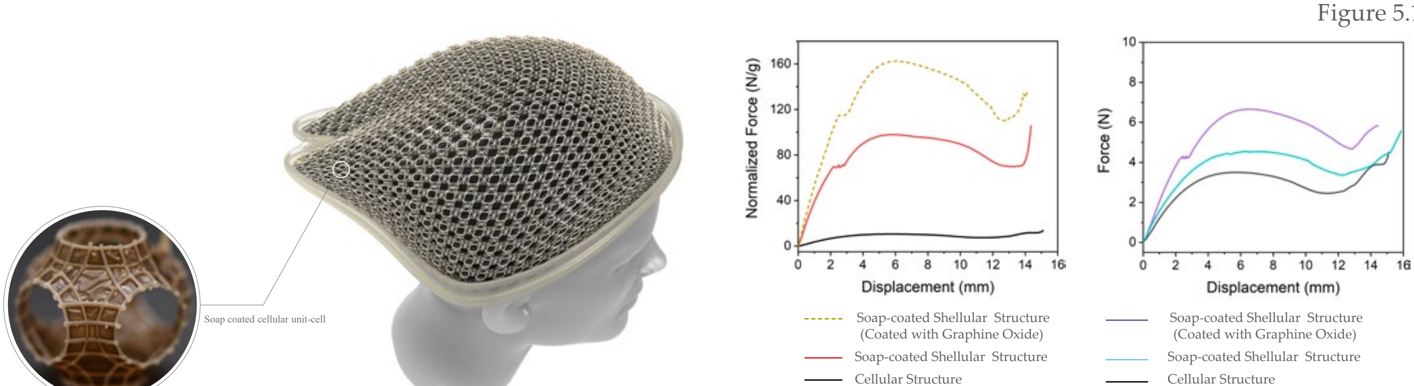


Figure 5.2.

5 Soap Coating Cellular Structures

In collaboration with Yinding Chi, Yuchong Gao, Mohit Patel, Kunhao Yu, Pt Brun, Masoud Akbarzadeh, Shu Yang

Contribution: In this project the author collaborated on designing the structure, fabrication and structural analysis of the members.

In this research, the wireframe of a shellular structure approximating the Schwarz P surface that is designed in PGS is soaked into the soap solution. The wireframe is 3d printed using plastic material. Two different solutions have been used in this experiment. The first one is a mixture of Polymer and Graphine Oxide (GO) aqueous and the second one is Polymer aqueous solution. These solutions will fill the faces of the polyhedral structure with a soap film, improving the structural performance of the structure. In fact, the strut-based cellular structures that are designed in PGS do not have the desired shear capacity and adding the faces will improve the shear capacity of the sdtructure.

Figure 5.1. A soap coated cellular structure reinforced with soap film/ Graphene Oxide.

Figure 5.2. A helmet fabricated using this technique, (left) and comparing force-displacement curves of different structures before and after soap coating (right).

Figure 6.1.

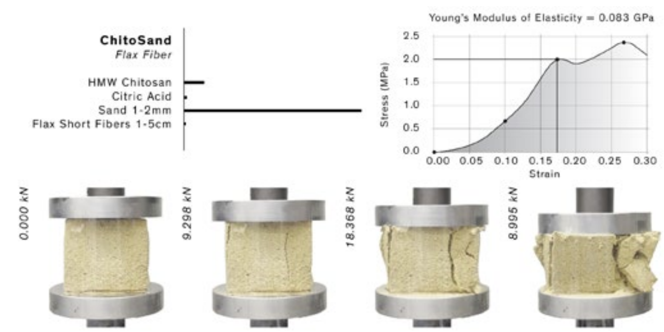


Figure 6.2.

Figure 6.3.

6 Terrene/ *Biomaterial Systems and Shellular Structures for Augmented Earthen Construction*

In collaboration with Liam Lasting, Abigail Weinstein, Shivani Chawla, Laia Mogas-Soldevila, Masoud Akbarzadeh

Contribution: In this project the author worked on the design, structural analysis, fabrication and material study.

The construction industry is shifting towards sustainable practices and renewable materials. This research focuses on developing a tension-compression anticlastic shellular structure using sand as a primarily compressive material. To enhance the sand's mechanical properties, the mixture includes flax fibers for tensile strength, citric acid as a natural plasticizer, and chitosan as a natural adhesive, creating a biodegradable material system that supports a circular economy.

Figure 6.1. Interior view of the Terrene structure.

Figure 6.2. ChtioSand cube with flax fiber compression testing data.

Figure 6.3. Detailed process photos: application of burlap sleeve to pneumatic formwork, anchoring of PLA frames to burlap, ChitoSand administered to burlap exterior.

Figure 7.1.

7 Self-healing shellular structures with complex morphology

In collaboration with Hsain, Zakaria, Adhokshid Prasanna, Zhimin Jiang, Masoud Akbarzadeh, and James H. Pikul

Contribution: In this project the author worked on the design, structural analysis, and fabrication.

This research presents a framework for effective room temperature electrochemical healing based on a model that links geometric, mechanical, and electrochemical parameters to the recovery of tensile strength in repaired metals. This framework enables full recovery of tensile strength in a nickel alloy and two "unweldable" aluminum alloys, over 100% recovery of toughness in an aluminum alloy, and full recovery of tensile strength in a 3D-printed difficult-to-weld funicular shellular structure. In this technique, the structure is soaked in a solution of liquid ions in which the ions settle in the fracture and heal the structure. [11]

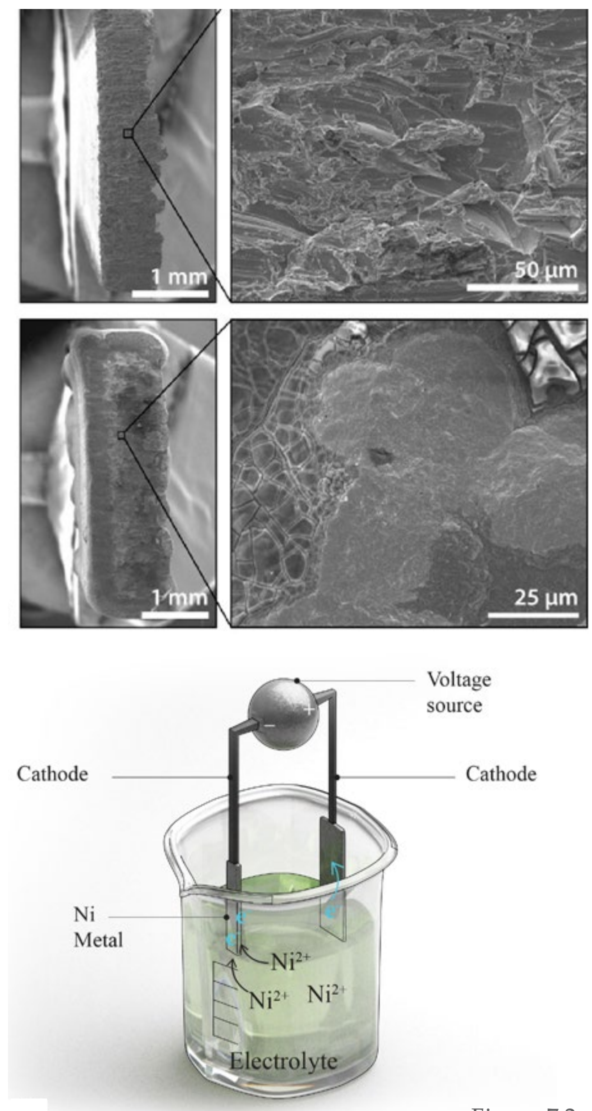
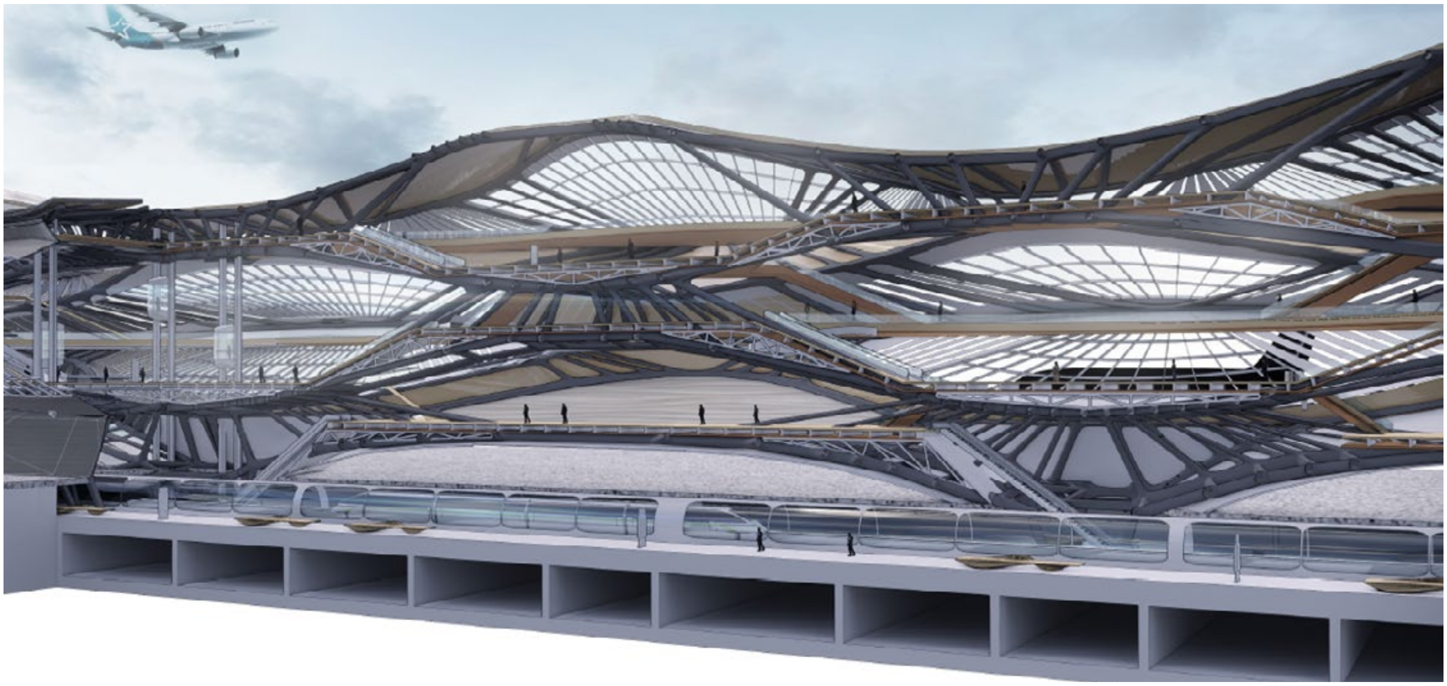


Figure 7.2.

Figure 7.1. The self-healing process of a shellular funicular structure fabricated using metal 3d printing.

Figure 7.2. Illustration of an electrochemical cell for nickel electrodeposition (bottom), and SEM image of a cross-section of half-dog bone Ni 200 sample before and after healing (top).



Teaching

1 Next Generation Airport Terminals

Design Non-conventional Architec
tural Structures

Research/ Design studio
Instructors: Masoud Akbarzadeh, Mostafa Akbari
Spring 2019
Master of Science in Design, 2nd year students
University of Pennsylvania, Weitzman School of Design

Indeed, architects should play a signicant role in designing and rethinking the future of infrastructures. In response, this studio aims to research the formal and organizational conguration of the next generation of infrastructures specically airports. The studio is divided to 5 main modules; workshop on parametric 3D Graphic Statics, Structural module developement, Material computation, programmatic studies of future terminals, developing massing and sectional strategies based on stractural module.

After exploring different spatial qualities using 3D graphic statics, students design a structurally informed architecture, incorporating circulation and different spaces in the system. In this process they use a geometry-based form finding technique to design the structure and fabricate large models, exploring different details and materials.

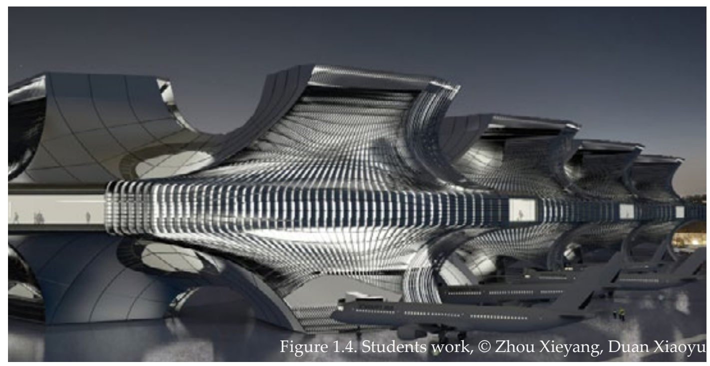


Figure 1.4. Students work, © Zhou Xieyang, Duan Xiaoyu

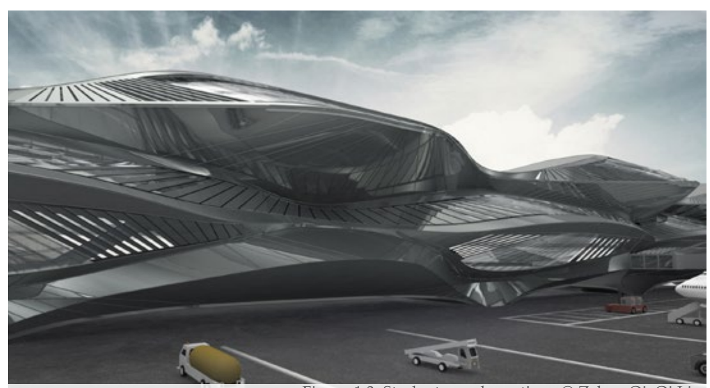


Figure 1.3. Students work, section, © Zehua Qi, Qi Liu.

Figure 1.6. Students work, physical model, Zehua Qi, Qi Liu.

Figures. Students’ design in the studio, Spring 2019.

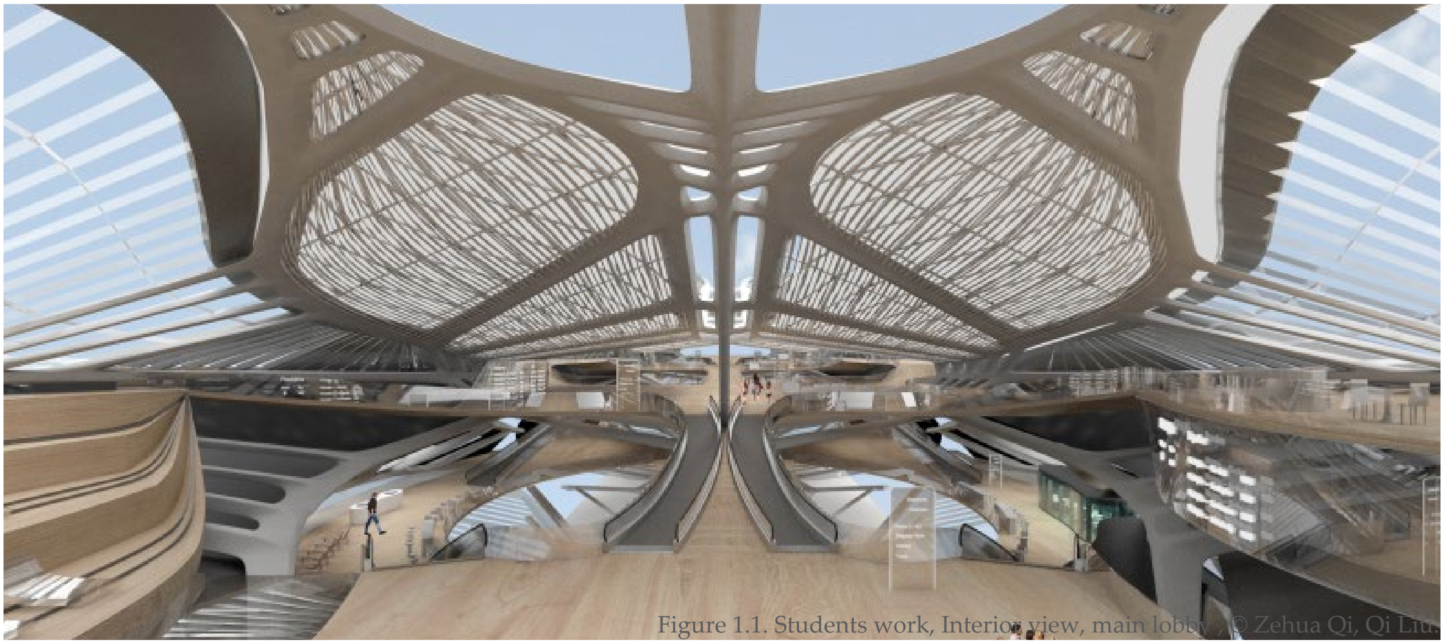


Figure 1.1. Students work, Interior view, main lobby, © Zehua Qi, Qi Liu.

Figure 1.2. Students work, physical model, © Yuchen Liu, Ye Huang.

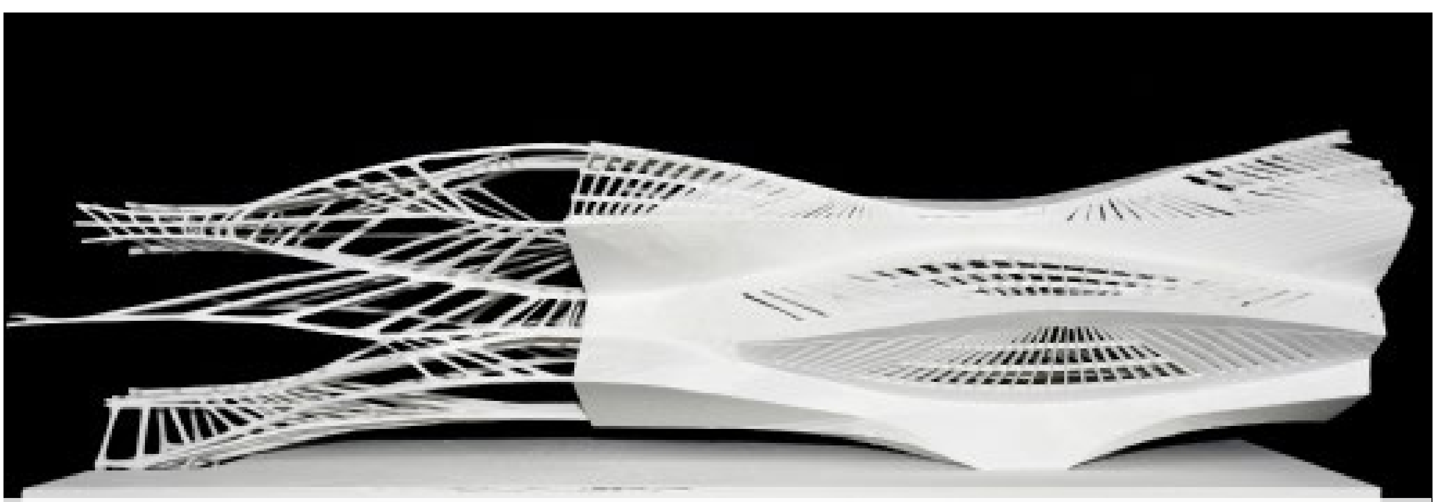
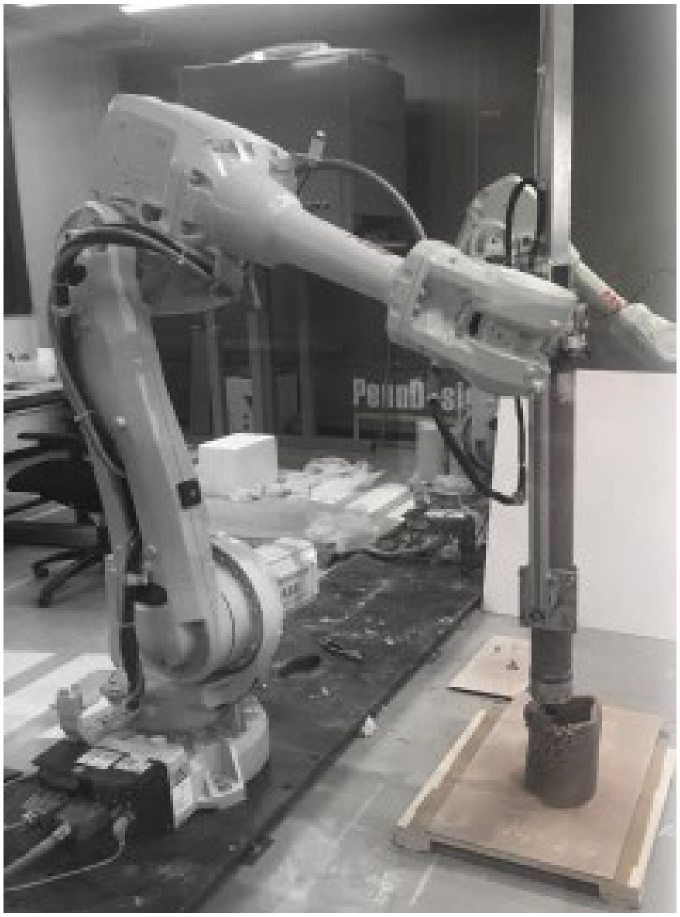
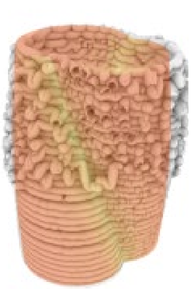
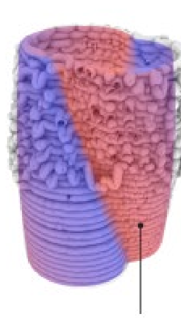


Figure 1.5. students work, Physical Model, © Zihua Qi, Qi Liu.

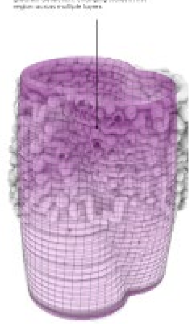




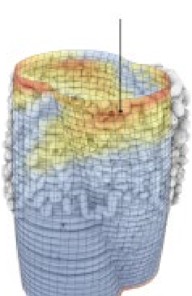
Curvature Overlay



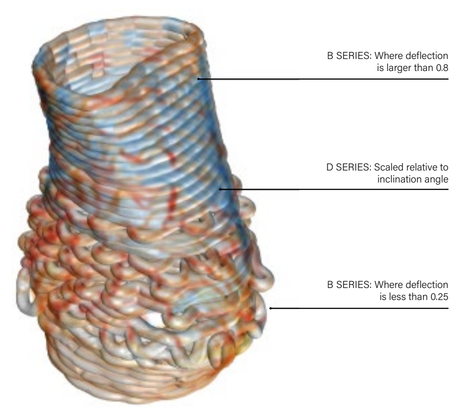
Inclination Overlay



Deflection Overlay



Stress Overlay



Local adaptation of the agent trajectory to principle stress

Teaching

2 Material Formations

Instructors: Robert Stuart-Smith, Mostafa Akbari
Spring 2019
March 2nd year students
University of Pennsylvania, Weitzman School of Design

Material Formations introduces principles of generative design into the discipline of architecture, providing opportunities for architects to synthesize multiple performance criteria within design that leverage organizational principles in order to negotiate relations between form, structure and material across a number of scales, with robotic production and material dynamics, also explores as active agents in design rationalization and expression.

In this course, stundets start by designing a simple shell structures and utilize computational tools to optimize the geometry structurally. Afterwards, they generate the tool path for clay printing using robotic arms and try to optimize they tool patch by evaluating the emergent behavior of the clay in different situations.

References

[1] Akbarzadeh, Masoud. “3D graphical statics using reciprocal polyhedral diagrams.” PhD diss., ETH Zurich, 2016. [link]

[2] Han, Seung Chul, Jeong Woo Lee, and Kiju Kang. “A new type of low density material: Shellular.” Advanced Materials 27, no. 37 2015. [link]

[3] Akbarzadeh, Masoud, Ali Tabatabaie Ghomi, Mohammad Bolhassani, Mostafa Akbari, Alireza Seyedahmadian, and Konstantinos Papalexiou, “Saltatur” , ACADIA , 2020. [link]

[4] Akbari, Mostafa, Masoud AKBARZADEH, and Mohammad BOLHASSANI. “From Polyhedral to Anticlastic Funicular Spatial Structures.” In Proceedings of IASS Symposium. 2019. [link]

[5] Akbari, Mostafa, Armin Mirabolghasemi, Hamid Akbarzadeh, and Masoud Akbarzadeh. “Geometry-based structural form-finding to design architected cellular solids.” In Symposium on Computational Fabrication, 2020. [link]

[6] Akbari, Mostafa, Armin Mirabolghasemi, Mohammad Bolhassani, Abdolhamid Akbarzadeh, and Masoud Akbarzadeh. “Strut-Based Cellular to Shellular Funicular Materials.” Advanced Functional Materials 32, no. 14, 2022. [link]

[7] Akbari, Mostafa, Y. Lu, and M. Akbarzadeh. “From design to the fabrication of shellular funicular structures.” Proceedings of the Association for Computer-Aided Design in Architecture (ACADIA) 2021. [link]

[8] Akbari, Mostafa, and Masoud Akbarzadeha. “Continuous Approximation of Shellular Funicular Structures”, In Proceedings of IASS Symposium 2022. [link]

[9] Akbari et al. “Bio-based composite spatial shell structures”, In Proceedings of IASS Symposium 2023. [link]

[10] Lasting, Liam, Mostafa Akbari, Weinsteina, Abigail, Chawla, Shivani, Mogas-Soldevila, Laia, Akbarzadeh, Masoud “Terrene 2.0 : Biomaterial Systems and Shellular Structures for Augmented Earthen Construction”, Materials and Design, 2023, under review. [link]

[11] Hsain, Zakaria, Mostafa Akbari, Adhokshid Prasanna, Zhimin Jiang, Masoud Akbarzadeh, and James H. Pikul. “Electrochemical Healing of Fractured Metals.” Advanced Materials 2023. [link]