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THINNESS: Pedagogical Form Finding Explorations in Eco-Ethical Shell Structures

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Abstract

Drawing from an academic experience focused on introducing beginning design students to physical form-finding processes, the authors present their pedagogical approach, observations, studio outcomes, and recommendations. By adopting a geometry-based approach that integrates formal, structural, ecological, and ethical interests, this paper describes the methodology and rationale behind students' efforts in creating diverse catenary arches. After observing the behavior of hanging chains supported from their ends, the analysis focused on the optimal forms these arches took when subjected to their weight in a uniform gravitational field. During the course, students crafted scaled models of expressive structures to show the interplay of form, force, and masses. They analyzed complex doubly curved hanging chain networks, cutting cotton canvas strips for a stiff fabric shell with added resin. They then designed a thin, self-supporting pavilion integrating skin, support, and form.

Keywords: Form-finding Pedagogy, Geometry-based Approach, Catenary, Funicular Shell Structures, Eco-Ethical Construction.

> *"The lesson in the airplane is not primarily in the forms it has created...the lesson of the airplane lies in the logic which governed the enunciation of the problem and which led to its successful realization."*
> Le Corbusier

1. Introduction

In response to the urgent need to minimize the environmental impact of the construction industry and adapt to urban population growth, it is crucial to revamp the educational approach for future designers in constructing new buildings. A sensible approach is to design long-lasting structures with fewer materials, relying on geometry instead of material mass to achieve strength.

By leveraging the intelligence embedded in tools, materials, and contextual factors, this paper explains a form-finding-inspired pedagogy for first-year architecture students at California College of the Arts (CCA) (Figure 1). This teaching method directed an introductory design studio in exploring the necessity, formation process, and fabrication aspects of funicular shell structures (compression only). The proposed pedagogy aimed to help early-stage design students consider the form of their proposed building as a medium for addressing technical, functional, structural, and environmental considerations, seamlessly incorporating them into the building's aesthetic and tectonic qualities.

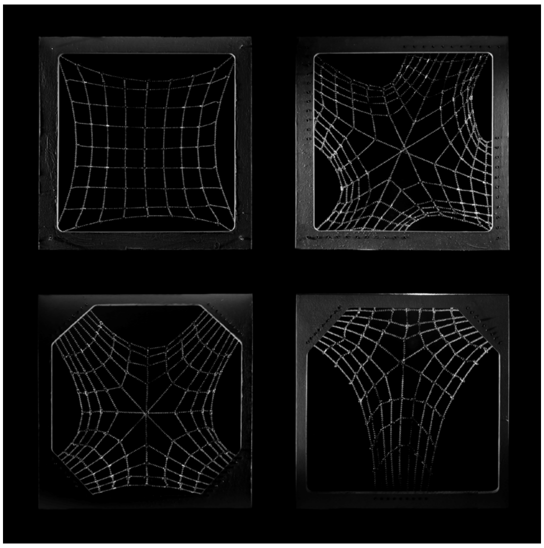

Figure 1: Exploring experimental and iterative structural form-finding in response to design constraints

2. Overview: Exploring Form-Finding in Freshman Architectural Curriculum

This paper reflects on a teaching experience in a three-credit elective course offered to freshman students during the spring semester of 2023. Over the 13-week semester, students met twice a week for various activities including lectures, tutorials, workshops, discussions, and reviews. The course involved 16 students with little to no prior background in using CAD software. Beyond theoretical discussions, students were guided step-by-step in three-dimensional drawing using Rhinoceros software, while also learning the basics of parametric thinking through Grasshopper. The course facilitated familiarity with both analog and digital fabrication tools, offering students a unique learning experience.

Alongside understanding the relevance of form-finding in architecture and its historical context, methods, and pioneers, students gained insight into different forces and their impact on structural systems in both classical and modern buildings. A brief overview of available materials before the Industrial Revolution provided students with an understanding of masonry structures and the critical role of their geometry in determining final strength. Additionally, students studied the use of hanging chains to improve architects' and engineers' understanding of the structural behavior of various arches.

This class had a specific goal: to clarify the concept of form-finding, emphasize its importance for architecture students, and demonstrate how a range of analog and digital tools can assist them in finding suitable forms. The series of class design activities aimed to distinguish between free forms that are mathematically defined (Fund [8]) and forms that emerge under specific applied constraints, including loads.

showcasing the buildings of various designers, including Antoni Gaudí (1852-1926), Eduardo Torroja (1899–1961), Pier Luigi Nervi (1891–1979), Sergio Musmeci (1926–1981), Anton Tedesko (1904–1994), Félix Candela (1910–1997), Heinz Isler (1926–2009), and Frei Otto (1925–2015), helped students understand that the form of these buildings wasn't necessarily predetermined or solely based on the designers' formal aspirations represented in abstract drawings. Instead, these forms often emerged from a combination of factors such as available materials, workforce, site conditions, building program, and budget.

Through reviewing the work of Frei Otto and Heinz Isler in the class, students learned how form emerged and evolved despite the parameters set during the formation process, such as boundary conditions, load distributions, or material choices (Boller & D'Acunto [3]). In this way, the class aimed to expand the concept of form-finding to include self-formation and self-organization systems in both natural and human-made environments.

3. Diving into Design: Class Activities for Exploring Catenary Form

3.1. First Assignments: Gravitational Harmony, Exploring Balanced Shapes of Catenary Curves

As a hands-on class, students engaged in various design activities to experience form-finding approaches. In their first assignment, students were asked to bring a cord, chain, or rope to class. Before suspending the chain or cord between two push pins, students were encouraged to visualize and sketch the anticipated form of this suspended chain/cord under the influence of gravitational force. After hanging and observing, students noted the resulting curve, which differed from a typical circular arc. Then, they were asked to find comparable arc shapes in both natural phenomena and manmade objects, while looking for suitable terminology to describe its form. To name such a curve, students found the term "catenary," rooted in the Latin word "catēna," which refers to "chain." (Catenary [4]). Students' exploration of catenary arches in architecture led them to study Tāq Kasrā (Built: ca. 3rd-6th century AD), the largest free-standing vault constructed until modern times (Taq Kasra [15]), along with several other historical examples. This exploration revealed a longstanding scientific debate concerning the geometry of a catenary curve, tracing back to Galilei's book (1638) and the contributions of Robert Hooke in the 1670s, as he explored the application of mathematical properties of the catenary in the construction of St Paul's Cathedral (Heyman [12]).

To conclude the first assignment, students were tasked with exploring the various shapes that a free-hanging chain can take when suspended from two fixed endpoints. They observed a range of forms emerging, influenced by the horizontal and vertical distance between these points. Students were directed to study drawings by John Ruskin (1819–1900) focusing on the "Study of Catenary Curves under Tension." These drawings involved tracing a pencil line to show the geometry of five hanging chains, with one end anchored at the center of a semicircle perpendicular to the ground, while the other ends touched the semicircle border (Ruskin [14]). Inspired by this drawing, students created their own 12” X 12” catenary-based compositional drawings, tracing any number of hanging chains they desired, while experimenting with different line types, colors, or thicknesses (Figure 2).

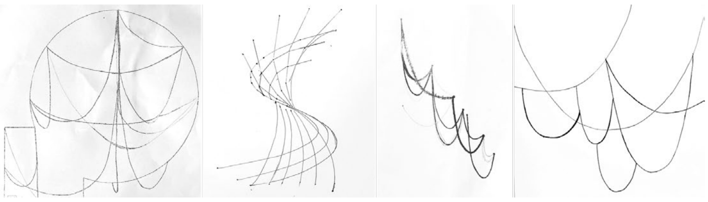

Figure 2: Creating catenary curve compositions by tracing hanging chains/ropes with a pencil

3.2. Second Assignments: Expanding Catenary Curves in Space

In their next design activity, students observed that the shape of the hanging chain under its weight varied from shapes produced when adding concentrated loads. Altering the location and magnitude of these loads adjusted the chain's shape. Introducing non-uniformly distributed loads and positioning each fixed point at a different level resulted in asymmetrical shapes. After suspending the chain from both ends, students captured sequential photos to represent how the shape of the chain changed with the relocation of its endpoints or the addition of loads. Ultimately, students used Photoshop to modify their photos' transparency and overlay them, creating photo-montage images illustrating the different catenary curves of the chain (Figure 3).

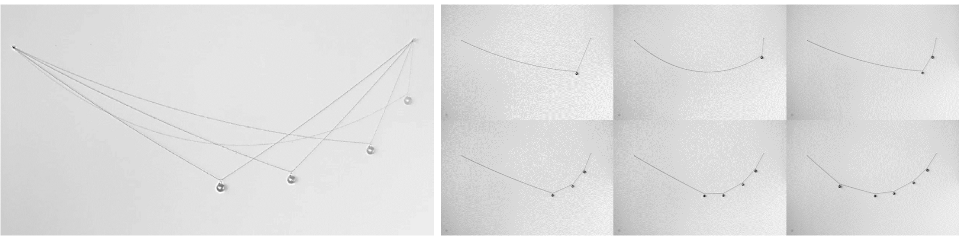

Figure 3: Exploring catenary curves through adjusting location, distribution, and magnitude of various loads

As students studied how the geometry of a "single" catenary curve can be manipulated by various factors like endpoint positioning, level, and load characteristics such as location, distribution, and magnitude, students explored the potential of combining and intersecting "multiple" catenary curves. This exploration informed the design of a sculptural chandelier proposed for the San Francisco City Hall Rotunda, intended to celebrate the elegance of catenary curves in a city renowned for its bridges built with similar geometry. Inspired by the Gabriel chandelier by Ronan and Erwan Bouroullec, students examined how gravity interacts with materials and forms to shape the aesthetic expression of their proposed designs intended to suspend from the central dome above the Rotunda's Grand Staircase (Figure 4).

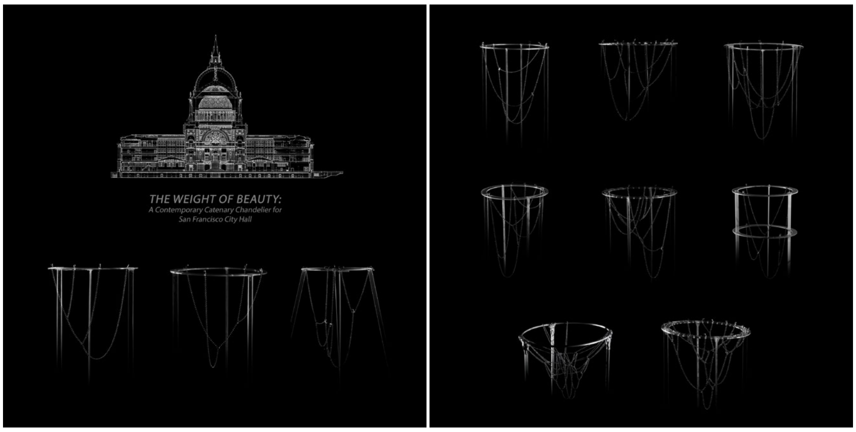

Figure 4: Proposed catenary-based chandeliers for San Francisco City Hall Rotunda

3.3. Third Assignments: Exploring Equilibrium Forms, Hanging Chain Models

Reflecting on the enduring question "What is the ideal shape for an arch?" in architectural history and Hooke's statement "As hangs the flexible line, so but inverted will stand the rigid arch" (Huerta [11]), students came to understand that an optimal arch follows a reversed catenary curve. Moreover, by hanging and then reversing a chain, they could predict the structural behavior of an arch. Understanding how optimally efficient two-dimensional arches can be made from catenary curves, students found it exciting to design vault-like forms out of multiple intersected catenary arches (Figure 5).

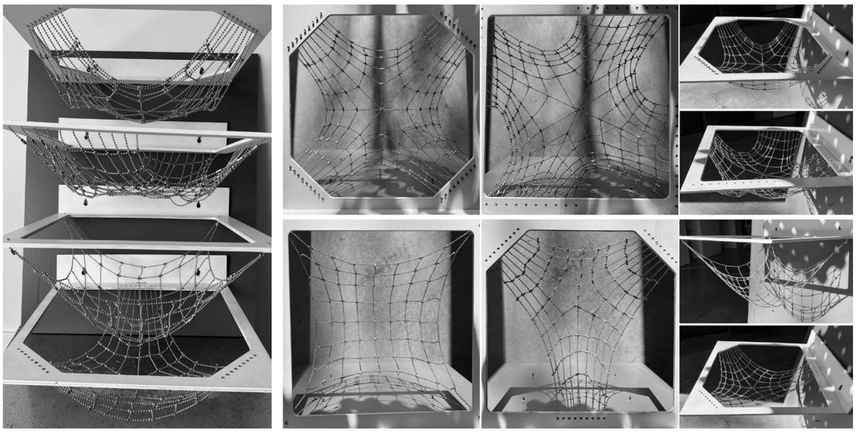

Figure 5: Crafting uniformly loaded hanging nets from ball chains with multiple catenary curves

Pairs of students teamed up to create 3D hanging models in pure tension, capable of withstanding pure compression forces in an inverted form. With the ability to draw in three dimensions using Rhino and understanding the basics of the Kangaroo Plugin in Grasshopper, students tried to find a way to create a net from ball chains to resemble a suspended vault. Starting with an 18" X 21" L-shaped base, each team quickly built a study model using paper clips under a rectangle-shaped opening in the base. The goal was to make 3D quad grid patterns from intersecting chain-like ribs using paper clips, approximating the overall shape of their vault (Figure 6). Factors such as the quantity, length, weight, and connection of paper clips impacted the final form. Soldering or gluing the paper clips could enhance the vaults' rough shapes. These paper clip models provided immediate insights for refining models with ball-chain pieces in the next phase.

Figure 6: Using paper clips for rapid assembly of low-fidelity catenary vaults under tension

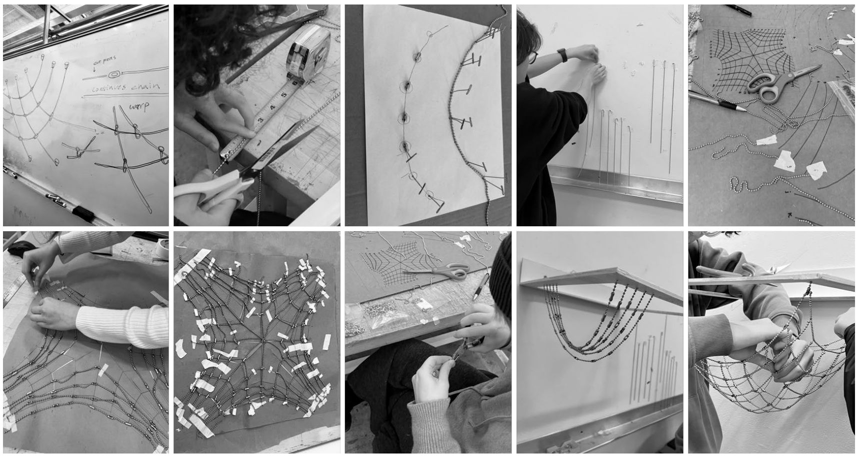

Figure 7: Process of measuring, cutting, organizing, hanging, and adjusting chain lengths

By integrating digital and physical tools to realize the proposed hanging vault designs, students explore the best strategies for iteratively measuring, cutting, and adjusting chain pieces to achieve progressively accurate assemblies (Figure 7). The grid geometry of each hanging vault featured numerous nodes where two or more rib parts intersected. Recognizing the critical importance of precise control over these node locations, students prioritized measuring the length of chain segments and determining the position of each node. To find out the exact cutting length for each chain segment before making any cuts, they needed to convert the 3D chain ribs into planar ones. This method ensured the desired uniformity in the final model. In addition to ensuring enough control over the length of cut segments, students used adjustable chain-connecting accessories like Chain Loop links, Splicing links, and Screw-Mount links. These accessories enabled them to modify the node locations and gradually adjust the length of their connected pieces. Students continued the process of fine-tuning each chain node's position and the length of its connected pieces until achieving a satisfactory result.

3.4. Fourth Assignments: Inverting Tension to Compression, Freezing Hanging Membrane Forms

Students successfully completed their wireframe-like vaulted forms from the network of linear chain ribs. While these forms functioned solely in tension and couldn't withstand compression, students found that employing the "Hanging Cloth Reversed" method enabled them to transform their vault forms into structures operating purely under compression. This method provided a constructive understanding of creating complex forms with minimal material, resulting in robust, efficient, and visually appealing shell structures. The vault forms were segmented into 3D strips, which were then flattened to produce 2D cutting patterns for crafting the shell. Using the geometry of their hanging chain vaults as a reference, students cut 2D strips from cotton canvas, assembled them with glue, and suspended them to form fabric shells (Figure 8). Additional strips were incorporated along the edges to strengthen the fabric shell and enhance its stiffness. Each student team constructed table-like stands out of cardboard to serve as formworks (Figure 9). Once these stands were completed, the fabric shells were hung upside down under their weight. Following the suspension of the shells, necessary alterations and modifications were made to eliminate any wrinkles (Figure 10).

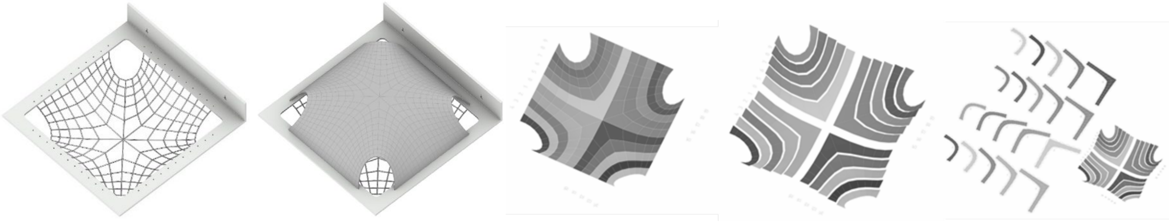

Figure 8: Using the previous hung chain model as a reference for designing, cutting, and adhering fabric strips

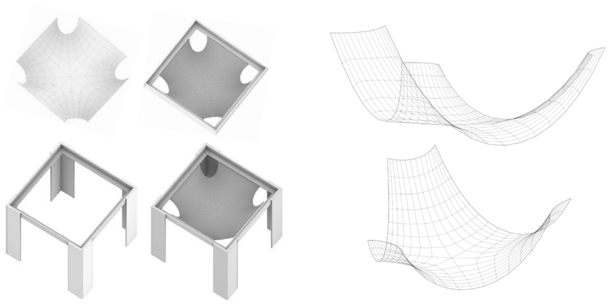

Figure 9: Fabricating a table-like stand for suspending and solidifying the cloth shell models

Coating the soft fabric shells with resin, like West System Epoxy Resin 105 and 207 Hardener, solidified them. Additional layers of resin were applied to the edges to reinforce them. After the shells had solidified, they were removed from their formwork and flipped over. This resin application process transformed the shells into robust funicular structures capable of operating in pure compression and supporting weight with minimal stress on the overall structure. In this assignment, the initial plan was to solidify the fabric shells using liquid plaster or cement. However, due to the school shop staff's concerns about maintaining a tidy environment for all users, Epoxy Resin was used as an alternative.

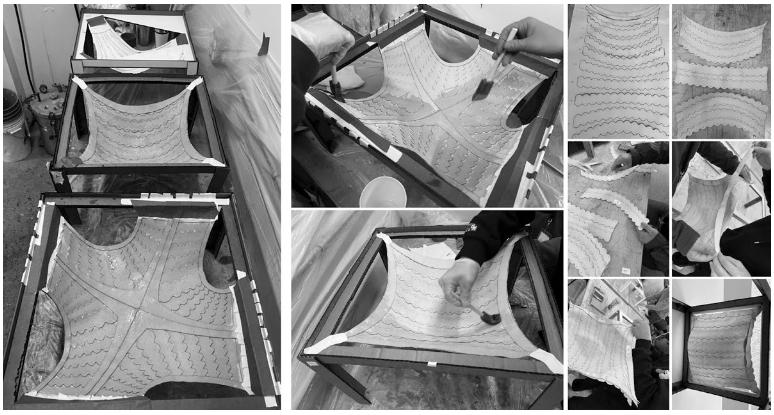

Figure 10: The process of crafting and solidifying hanging cloth shell models before inversion

3.5. Fifth Assignments: Funicular Pavilion: Blending Form and Function

By combining various design aspects such as stability, functionality, and aesthetic appeal, the final class assignment tasked students with applying the principles of funicular structure to design a visually compelling and structurally efficient Pavilion on a designated site (Figure 11). By integrating skin, support, and form, this pavilion was intended to serve as a permanent lightweight structure for diverse events including concerts, plays, festivals, and weddings. Here, students aimed not only to explore compression-only forms but also to design with them.

During this phase, the proposed designs were further developed digitally, with Kangaroo in Grasshopper serving as the primary tools for form-finding (Figure 12 & 13). In this assignment, students learned how their proposed designs could contribute to sustainability in architecture by minimizing material usage and reinforcement. They found that achieving this was possible by designing structures capable of minimizing or eliminating bending and shear forces.

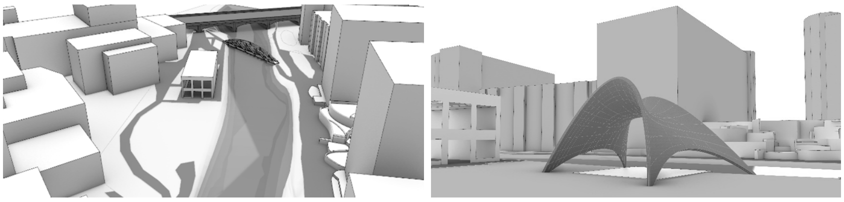

Figure 11: Designing freestanding pavilions on the proposed site

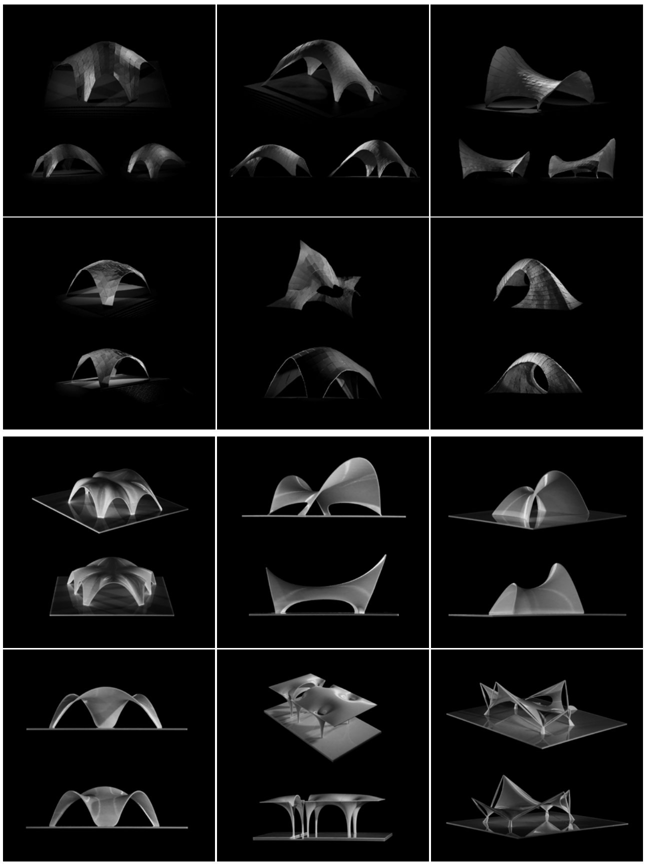

Figure 12: Exploring digital form-finding for funicular pavilion structures in static equilibrium

Figure 13: Constructing 3d vaulted structures from 2d warp-weft patterns

4. Form-Finding, Understanding the Interplay of Form and Force

One of the primary goals of this class was to offer students the chance to intuitively understand and methodically explore the direct correlation between forms and forces in architecture. Rather than relying solely on mathematical equations and abstract formulas to understand the impact of forces (Güzelci et al. [10]), students gained insights into structural performance by observing changes in geometry and material behavior through the process of form-finding (Figure 14).

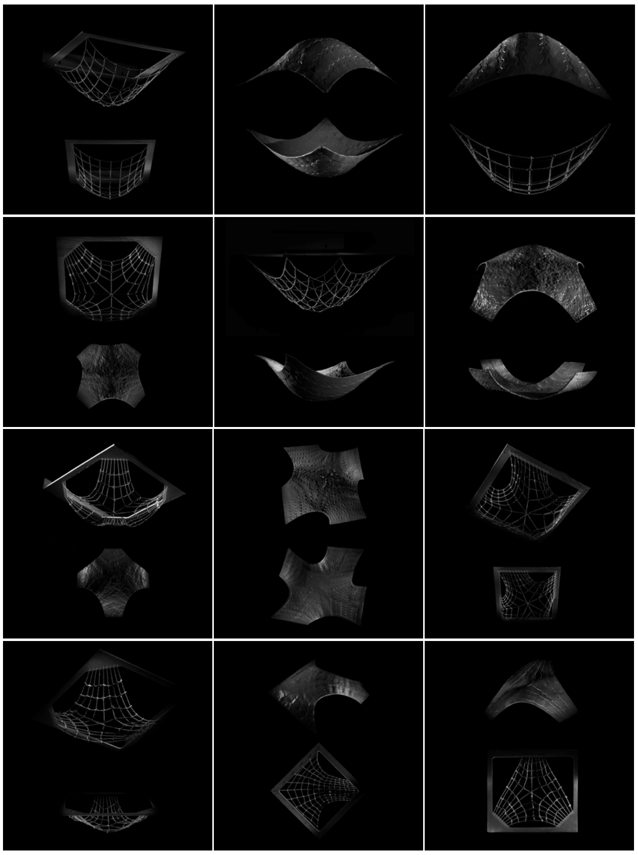

Figure 14: Using physical models to determine structure forms under specified loads & boundary conditions

Understanding the interplay between forms, forces, and load-bearing capacity could help beginning design students learn that structural design should be an integral aspect of any architectural design from the start, rather than merely focused on ensuring the building's stability, leading to an overly heavy structure (Block 2009). While this class encouraged freshman students to find the equilibrium form of catenary shells, the authors hope that these future designers will consider the entire structure of a building in equilibrium.

Describing Gaudi's hanging chain model as a "designing machine," Collins ([5]) highlights the significance of physical models as invaluable designing tools. In this course, the study models enabled students to visually feel forces (Dessi-Olive [7]) and engage with them interactively. Engaging directly with physical models in the form-finding process enabled students to understand the consequences of their design choices, whether they were altering the length and position of boundaries, adjusting the size of their shell grid, or modifying materials and connecting details. In this way, the form-finding process allows students not only to experiment with different parameters but also to establish a feedback loop to address both formal and structural concerns simultaneously. This is particularly important in an educational landscape where digitally driven thinking, drawing, and representation often dominate, resulting in less tactile and interactive feedback.

By going beyond conventional regular geometric shapes, the class provided the opportunity to design complex double-curved forms that required extensive knowledge of geometry and fabrication skills for drawing and prototyping. Student study models offered a helpful means of communicating challenges or suggestions with classmates and instructors, particularly when their drawing and 3D modeling skills were still developing.

4. Discussion

The various design activities in this class can be summarized as a process of seeking an emerging form under gravitational force within defined boundary conditions. While altering certain parameters may influence the final form to some extent, it could not completely dictate the resulting form (Cuvilliers [6]). The students observed that they could only manipulate the generative parameters of form without complete control over the form itself. The students' models illustrated how certain parameters could be adjusted, such as the primary grid size shape, orientation, and topology of the desired form, which encompassed factors like curvature, span, or sag. Additionally, factors such as the applied forces, including self-weight or prestress circumstances, the anticipated load-bearing capacity and stiffness (Adriaenssens et al. [1]), material properties of constitutive elements, and the boundary conditions, all played significant roles.

Altering these parameters until the emerging form matched the intended one was time-consuming and, at times, tedious. For instance, while making their vault chain models, students proceeded cautiously when adjusting chain lengths, as such alterations could mess up the balance of the entire network. Consequently, some students found themselves dedicating substantial time to readjusting all model nodes whenever certain sections lost tension.

A drawback of this academic experience in form-finding was the insufficient opportunities for students to introduce their design preferences and incorporate their design language into the final forms. This was particularly noticeable among some beginner designers, who typically rely on intuition to express themselves and aim to present designs closely resembling their imagined shapes. As achieving the best outcome often necessitated an iterative approach and considerable patience, the working process appeared to be relatively slow for students seeking quick results. Thankfully, the use of both physical and digital models enabled freshman students to obtain a comprehensive understanding and experience in form-finding. Using diverse approaches to form-finding allowed for a balance between speed, precision, hands-on experience, control, and the flexibility to engage with forms and forces.

5. Conclusion & Outlook

This paper discusses the authors' pedagogical principles, methods, and observations in introducing catenary geometry to freshman students while focusing on the interplay of forms, forces, and masses. Considering the important role gravity plays in shaping the aesthetic expression and structural integrity of catenary arches, this paper traces the journey from 2D lines to 3D forms through different form-finding processes (Figure 15). The paper explains various design activities that resulted in the creation of thin, self-supporting structures dependent on compression forces.

Drawing inspiration from numerous sources, including the hanging chain models of Antoni Gaudi, the hanging cloth shells of Hans Isler, the minimal surfaces of Frei Otto, and Graphic Statics and form finding optimization of Philippe Block, students incorporate computational approaches and digital fabrication techniques to develop three-dimensional shell structures. These structures prioritized the use of minimal materials while simultaneously enhancing longevity, recyclability, and ease of repairs.

Beyond employing form-finding methods for constructing thin funicular shells, the authors encourage their students and others to extend this approach by integrating diverse parameters, such as site conditions, spatial programs, economic feasibility, sustainability, cultural relevance, and aesthetic preferences. Inspired by Frei Otto's vision of the architect "as a midwife rather than God the creator" (Goldsmith [9]), there is hope that this course has empowered future architects to facilitate the continuous interaction of these parameters, thus aiding in the proper emergence of the building form.

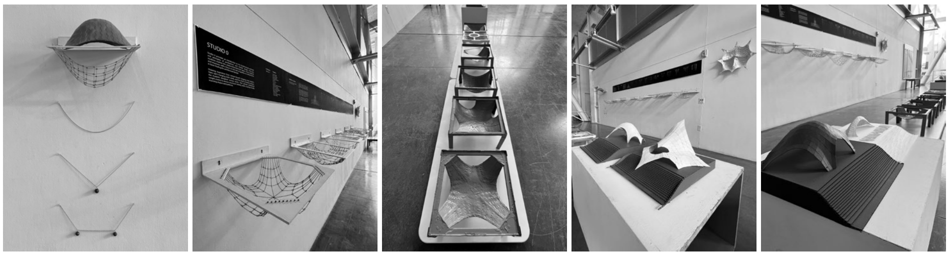

Figure 15: Showcasing various design activities during the final class review

Students; Canyon Allan, Maryiam Alwael, Ray- Jui Chang, Gino Deynaco , Corban Hamernick , Lois Kim, Tzu-yin Lin John Liu , Gabriela Johanna Mierkalne, Anhelina Rozum, Devan - Yunmiao Su, Rocio Urbano Guadalix, Xingmin Weng, David Yang, Sean Zhang, Gracie Zheng

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