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Philippe Block, Giulia Boller, Catherine DeWolf,
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Discipline and Play, Spatial Form Finding for Students Studying Structural Engineering

Edmond SALIKLIS*

*Professor of Architectural Engineering
Department of Architectural Engineering
California Polytechnic State University
San Luis Obispo, CA 9347
esalikli@calpoly.edu

Abstract

In the realm of three-dimensional form creation, the engineer, architect, and sculptor each wield their unique skills and knowledge, drawing inspiration from historical precedents. However, it is within the realm of structural engineering that the greatest constraints and the least unbridled freedoms lie. The structural engineer shoulders the weight of codes and regulations, necessarily ensuring life safety and compliance. Yet, it is precisely within these constraints that the engineer's ability to create groundbreaking designs emerges. A polytechnic training, coupled with aesthetic sensitivity is the domain of the new structural engineer of the 21st century.

Today, the structural engineering profession finds itself at a critical juncture, in need of a revival and a reaffirmation of its role as a form finder. In the late 20th century, too much creative control has been ceded to the architect, and in the early 21st century, the spectre of design by Artificial Intelligence looms large. A “Call to Action” is proposed here, which reinvents a venerable form finding tradition guided by the engineer’s unique skill set. Regrettably, engineers have often succumbed to a formulaic and robotic mindset, eroding the vitality of our profession. It is imperative to reimagine and reinvent 19th-century geometric analysis and design tools for the 21st century.

With this in mind, a new geometric form finding technique that empowers engineers to rapidly create spatial structures, has been recently created and field tested with a variety of college students. At its core, this methodology involves the sequential stabilization of points in 3d space, focusing on restraining unstable spherical and circular paths or "mechanisms" experienced by unconstrained structural elements. Through a surprisingly simple and approachable parametric and digital design palette, an infinite array of designs can be swiftly generated, exploring boundless possibilities while simultaneously achieving unconditional stability and minimalism through static determinacy.

Keywords: conceptual design, form finding, student exercises, spatial structures, geometric structural analysis, global stability

1. Introduction

Many of us teach a wide variety of students, and it is tempting to teach the same way to varied groups of learners. The question of “rigor” or “engineering light” for architecture and construction management students is an acute one, as many professors tend to simply teach in the manner that they themselves were taught, which was typically more “rigor” and less “play”. The Architectural Engineering Department at California Polytechnic (Cal Poly) teaches structural engineering principles to architecture students, to construction management students as well as to our own engineering students. It is tempting for our department to either use the same pedagogy for all three groups, or to “lighten” the engineering rigor for the non-engineering students. Many of us do this because of inertia, but also because we lack tested methods of trying something different. Over the past few years, the author has taken a previously established teaching method, namely sequentially stabilizing a series of nodes in three-dimensional space and reinvented it for the world of parametric modeling [1]. The purpose of this paper is to lay out the methodology of the new method, so that other teachers and researchers can use it, but also to inspire the readers to develop their own *new ways* of presenting “tried and true”, yet also perhaps “tired and true” existing methods. The method is truly a form-finding method, one that empowers the students to explore new and intricate spatial structures, in a way that echoes some of the giants of our profession from the 1950s and 1960s.

This new method considers the stability of an arrangement of points in 3d space, but it does so using spatial truss members only, i.e. only pin-ended struts are used, loaded only at the nodes. This is the most challenging way of presenting the topic to students, there are no cantilever members fixed against rotation at their base for instance. Furthermore, this method seeks to create statically determinate, not indeterminate structures. The reason is that this is most pedagogically interesting, to study the minimum number of struts needed is useful. Of course, real structures can always add more elements, but if the student does not know the minimum number of struts needed, they are not able to judiciously understand how the additional elements making up an indeterminate structure would influence the behavior of the structure. Finally, students were asked to study the load flow in their structures, but only using geometric tools, not statics and not the finite element method [2].

2. The legacy of form finding and the pedagogy of Myron Goldsmith

We begin by looking at the recent past, not with a nostalgic longing, but with a curiosity of how the master teacher Myron Goldsmith nurtured and guided his students in the creation of novel spatial structures. Myron Goldsmith's pedagogy at the Illinois Institute of Technology (IIT) in the 1960s was characterized by a commitment to innovation, interdisciplinary collaboration, and a hands-on approach to learning. Goldsmith played a pivotal role in shaping the design ideas of the graduate program pedagogy and he fostered an environment that encouraged experimentation and exploration [3].

One of the key aspects of Goldsmith's pedagogy was his emphasis on the integration of architecture and engineering. He believed that architects should have a deep understanding of structural principles and engineering concepts to create buildings that were not only aesthetically pleasing but also functional and efficient. This interdisciplinary approach was reflected in the curriculum at IIT, where students were encouraged to collaborate across disciplines and engage in practical, hands-on projects. It was also a primary design ethos at Skidmore Owing & Merrill (SOM) where Myron worked from 1955 to 1983.

Goldsmith also believed in the importance of pushing the boundaries of architectural design through experimentation with boldly expressed structural systems. Myron Goldsmith's pedagogy at IIT in the 1960s was characterized by its commitment to innovative, structurally rational systems, always with, practical applications. His approach to teaching architecture helped shape a generation of architects and engineers and left a lasting impact on the author’s own pedagogy. It is this pedagogy of Goldsmith, with particular emphasis given to his students’ long span structures, that is the focus of this paper.

Expressing structure in architecture involves making the underlying structural elements of a building visible and integral to its overall design aesthetic. Rather than concealing structural components behind finishes or decorative elements, architects who express structure aim to highlight and celebrate them, using them as a means of artistic expression. This approach often results in buildings with a strong sense of honesty, where the structure becomes a defining feature of the architecture itself.

During the 1960s, a group of newly disciplined, yet playful architects and engineers emerged in Stuttgart Germany, led by figures like Frei Otto, Jörg Schlaich. While Otto and Schlaich have been deservedly well-studied by academics, a lesser known pedagogue named Curt Siegel [4] has also influenced the author greatly. These designers pioneered new approaches to structural design that emphasized lightness, efficiency, and elegance. Their work exemplified the idea of expressing structure in architecture, as they sought to create buildings where the structural system was not only functional but also visually striking. It is telling that Goldsmith and Schlaich were personal and lifelong friends.

One notable example of expressing structure in architecture from this period is Frei Otto’s German Pavilion for the Montreal Expo of 1967. That Pavilion’s innovative tensile roof structure, consisting of a series of steel cables and translucent membranes, was not only an engineering marvel but also a visually stunning feature that became an iconic symbol of the World Expo. Otto skillfully expressed the primary structural system, turning it into the architecture itself. This approach not only enhances the aesthetic appeal of the building but also fosters a deeper appreciation for the artistry and ingenuity of structural engineering. Finally, it remains a didactic tool for generations of future designers in its extensive impact, most clearly in the 1972 Munich Olympic structures.

Expressing structure in architecture is about more than just functionality—it's about creating buildings that tell a story, where the structural elements become part of the narrative and contribute to the overall experience of the space.

In the 1980s, significant shifts occurred in both architecture and structural engineering pedagogy, influenced by different philosophical and practical considerations. This era saw a resurgence of ornamentation and historical references in architecture, often associated with the postmodern movement. Meanwhile, structural engineering education was undergoing a transformation with the widespread adoption of matrix methods and computational tools. While these developments brought advancements in their respective fields, they also led to a philosophical and practical educational divide that diverged from the integrated approach advocated by Myron Goldsmith.

Postmodern architecture embraced ornamentation, historical pastiche, and eclectic references, departing from the perceived uniformity of modernism. However, this focus on ornamentation sometimes led to superficial or disconnected decorative elements, divorcing buildings from their underlying structural logic. In some instances, architecture became more about surface appearance and historical references than about functional efficiency or structural expression. The same might be true in some of today’s architecture schools with their fascination for the skin of a building.

Concurrently, advancements in computational power revolutionized structural engineering. Matrix methods and computer-aided design enabled engineers to analyze complex structural systems with unprecedented accuracy and efficiency. This shift empowered engineers to analyze structures of greater complexity and sophistication. However, there was a risk that the emphasis on computational tools could lead to a detachment between design intent and structural logic. Engineering students found themselves to be analysts, not form-finders. Engineering faculty became enamored with ever more sophisticated analytical tools, but perhaps unwittingly, they embraced technical rigor over architectural aesthetics, further compromising the integration of structure and form.

Philosophically, these trends created a tension between the education of the architecture student and that of the structural engineering student. In fact, students of structure became relegated to Civil Engineering departments in Colleges of Engineering around the world, and architecture students embraced the artistic freedom afforded to them by Colleges of Art and Design, thus furthering the distance between the two groups, a direct antithesis to Goldsmith’s integrative approach.

Given his integrated approach to architecture and engineering, Myron Goldsmith would likely have viewed these developments critically. He believed in a holistic design process where structure and form were inseparable aspects. Goldsmith's pedagogy emphasized understanding both the aesthetic and technical dimensions of architecture, promoting a synthesis of design and engineering. Today in 2024, *by embracing innovative form finding without sacrificing structural integrity, and leveraging computational tools to enhance architectural expression, designers could strive to reconcile the divide between architecture and engineering* in a manner aligned with Goldsmith's vision.

Yet another historical example of this hybrid approach to structural architecture is found in the work of Iannis Xenakis, a highly influential figure who straddled the worlds of architecture and structural engineering. He cannot be strictly categorized as part of either the architectural or the engineering tradition alone. Instead, Xenakis's work and contributions spanned both disciplines, making him a unique figure whose ideas and innovations continue to influence architects and engineers to this day.

Xenakis studied Civil Engineering, but he was fascinated with mathematics, music, and engineering. He worked closely with the renowned architect Le Corbusier, where he applied his mathematical and engineering knowledge to architectural projects, particularly in the design of the innovative structural system used to create the Philips Pavilion for the Brussels World's Fair of 1958. Xenakis's work on the Philips Pavilion transcends traditional disciplinary boundaries, making him a figure who defies easy categorization. Instead, he represents a synthesis of architectural and engineering principles, demonstrating how creativity, mathematics, and technology can intersect to create truly groundbreaking and interdisciplinary works of art and design.

Thus, we propose a "call to action", namely a return to form finding that is driven by structural intuition, not by fanciful randomness. In particular, this paper will focus on how a newly developed method for sequentially stabilizing points in three-dimensional space leads to striking and surprising spatial forms, forms which are not strictly "modern", but they certainly resonate with some of the IIT students' long span studies [3]. Figure 1a and 1b shows several examples IIT graduate student work.

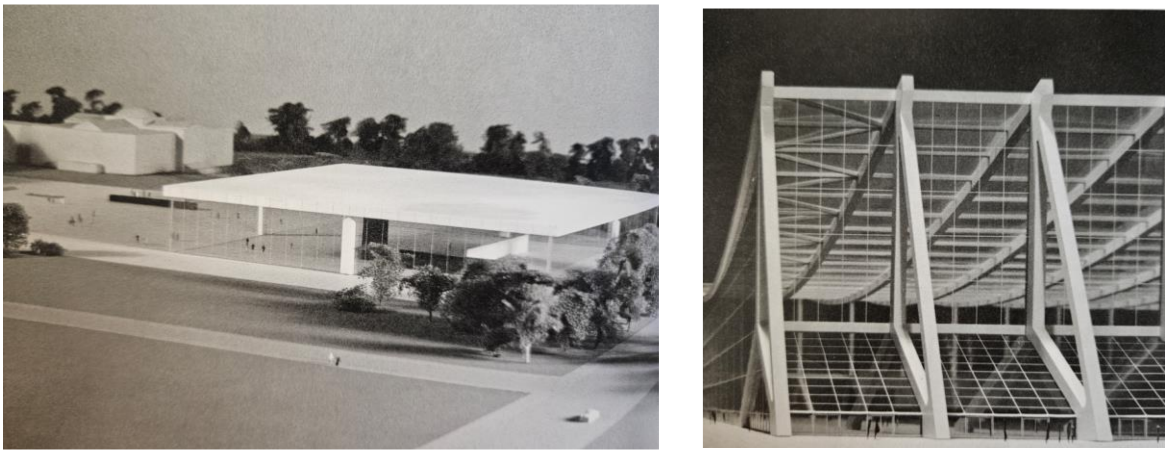


Fig.1a Graduate student work by Watanabe and 1b by Doyle

3. The basic premise of stabilizing points in space

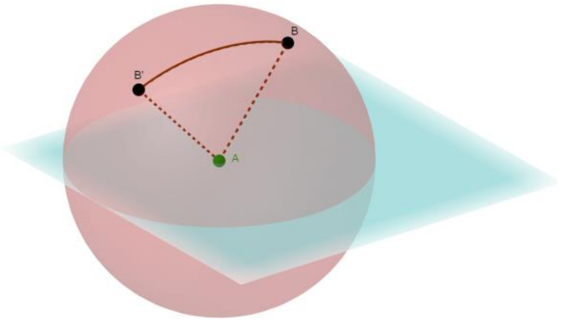
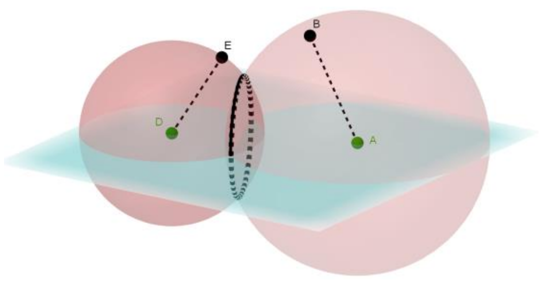


Fig.2 Starting point is a spherical mechanism

Recall that the premise of the method starts with pin-ended struts. Consider a single strut AB as shown in Figure 2, which is pinned at its base, here shown as Point A. It is unstable, with Point B swinging along a spherical path to B' at the unrestrained end of the strut. This is a degree of freedom which must be "locked down" or prevented, with subsequent judiciously placed members.

Consider now a second strut DE, pinned at its own base Point D. If the placement of Points A and D are such that there is an intersection between the two spheres as shown in Figure 3a, a circular mechanism or degree of freedom remains for the node at the apex of the two struts as shown in Figure 3b.



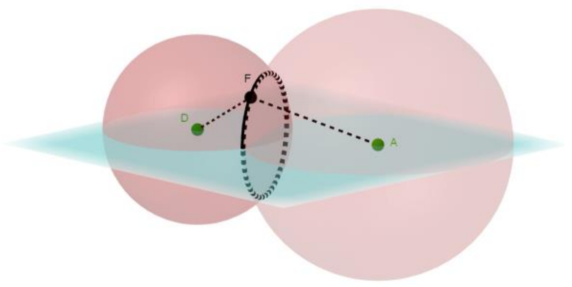


Fig.3a Intersection of two spheres is a circular mechanism 3b. This is a False Crown

Notice that the lengths of strut AF and of strut DF are controlled by the designer. These are the radii of the spheres surrounding base Point A and base Point D respectively. Yet a two-member structural form is not stable, as the circular degree of freedom or mechanism still exists at the False Crown, and it must be locked down.

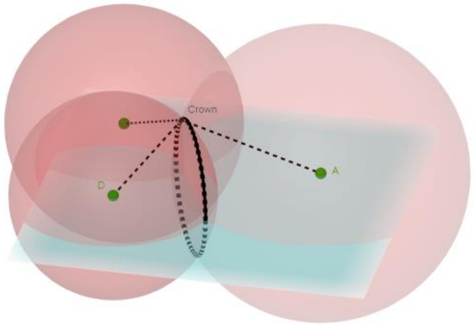


Fig.4 Intersection of three spheres or intersection of one sphere and one circle is a stable point

However, the intersection of three spheres as in Figure 4, or the intersection of one sphere and one circle, is a unique “Crown”. Actually, there are two such stable Crowns, one above the ground plane and one below. We choose to focus on the Crown above the base and we use that to create an unconditionally stable tripod.

New struts can be built off the stable elevated Crown. The process repeats itself, either playfully, or in a disciplined manner, but the “rules” established before must be respected. This means that a subsequential node in space has a spherical mechanism that must be locked down via the intersection of three spheres, one of which was centered on the first crown, Crown1. Figure 5a shows the beginning of an additional strut. Figure 5b shows how three new struts (or spheres) are needed to stabilize the new additional node in space.

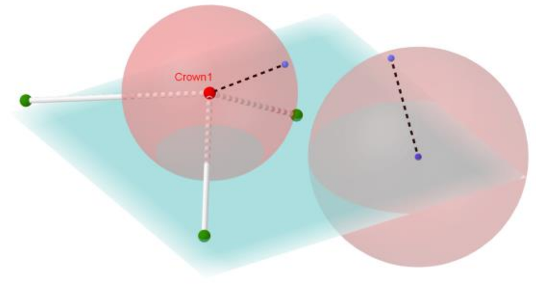


Fig.5a Adding a new point

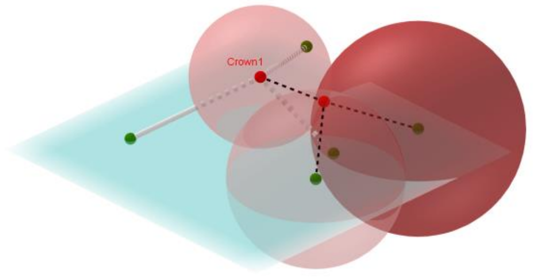


Fig.5b Stabilizing a new point

The process can be playful at first, discipline can come later. This workflow allows students to have fun and to freely explore fantastic forms, without the need for any artificial intelligence programs or any sophisticated coding skills. Here are some images capturing our workflow at Cal Poly. Figure 6 shows a technique for locating four nodes in space. The four nodes are not yet stable, the form itself is slowly emerging.

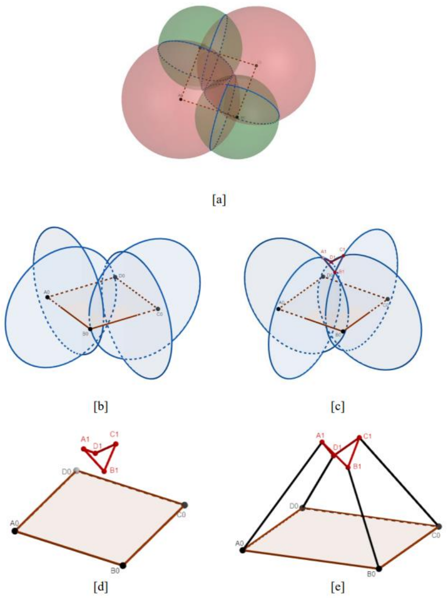


Fig.6 Locating four points in space, still unstable structure

Figure 7 is a series of snapshots of playful iterations on the ever evolving spatial structure. Students use sliders to manipulate the radii of the spheres and instant visualization guides their progress.

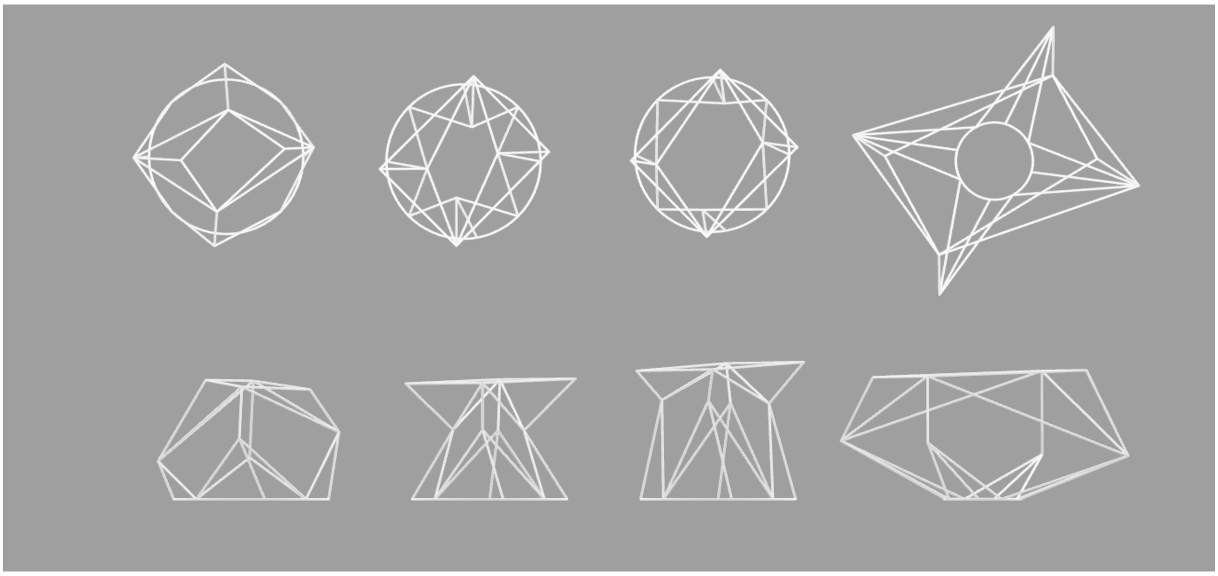


Fig.7 Playfully exploring spatial configurations

The form finding of spatial structures can present some insights into the design thinking of past brilliant designers like Enrico Richino Castiglioni (1914-2000) or Ann Griswold Tyng (1920-2011). This new design methodology of spatial structures is rapid, rigorous, surprising, and infinitely variable, something that Tyng and Castiglioni would immediately recognize as both structurally rational and meticulously crafted. Figure 8b and 8c is in fact a re-creation of Anne Tyng's unbuilt City Tower design for Philadelphia which is shown in Figure 8a [5]. This new design approach has been successfully applied in various studio environments and seminars, allowing for the creation of efficient, economical, and elegant forms.

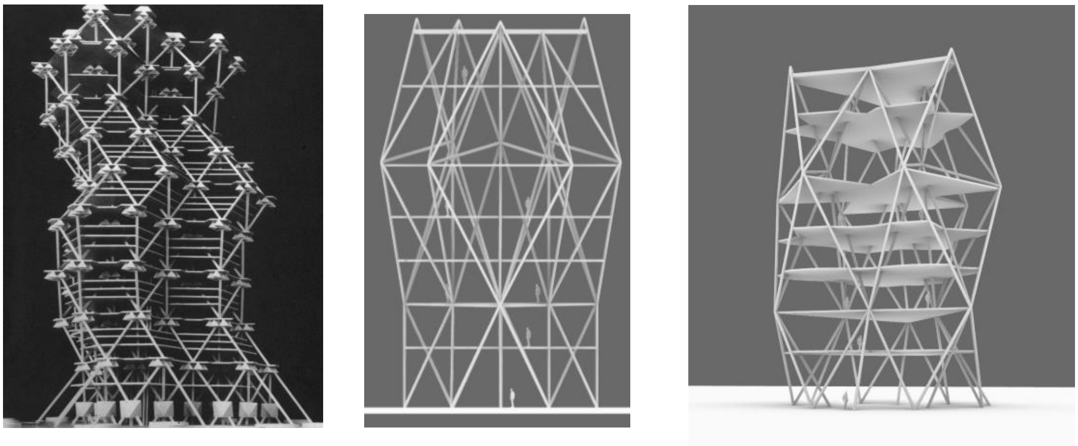


Fig. 8a Tyng's City Tower 8b reinvention of City Tower elevation by Cal Poly Grad student Jay Skaff 8c City Tower isometric

One of the surprises from this form finding process is that the structures are not only unconditionally stable, and minimal insofar as there are no redundant elements in a statically determinate spatial truss, yet they are often elegant, complex and truly interesting. In fact, the author finds echoes from the spatial exercises of Myron Goldsmith at the Illinois Institute of Technology in the 1960s at the Master's of Architecture program. Yet these 21st century forms were found by undergraduate students, many of whom have never created a three dimensional design before, and they did so after only a few tutorials. Figure 9 is a collage of some of the many forms generated using the new Cal Poly technique.

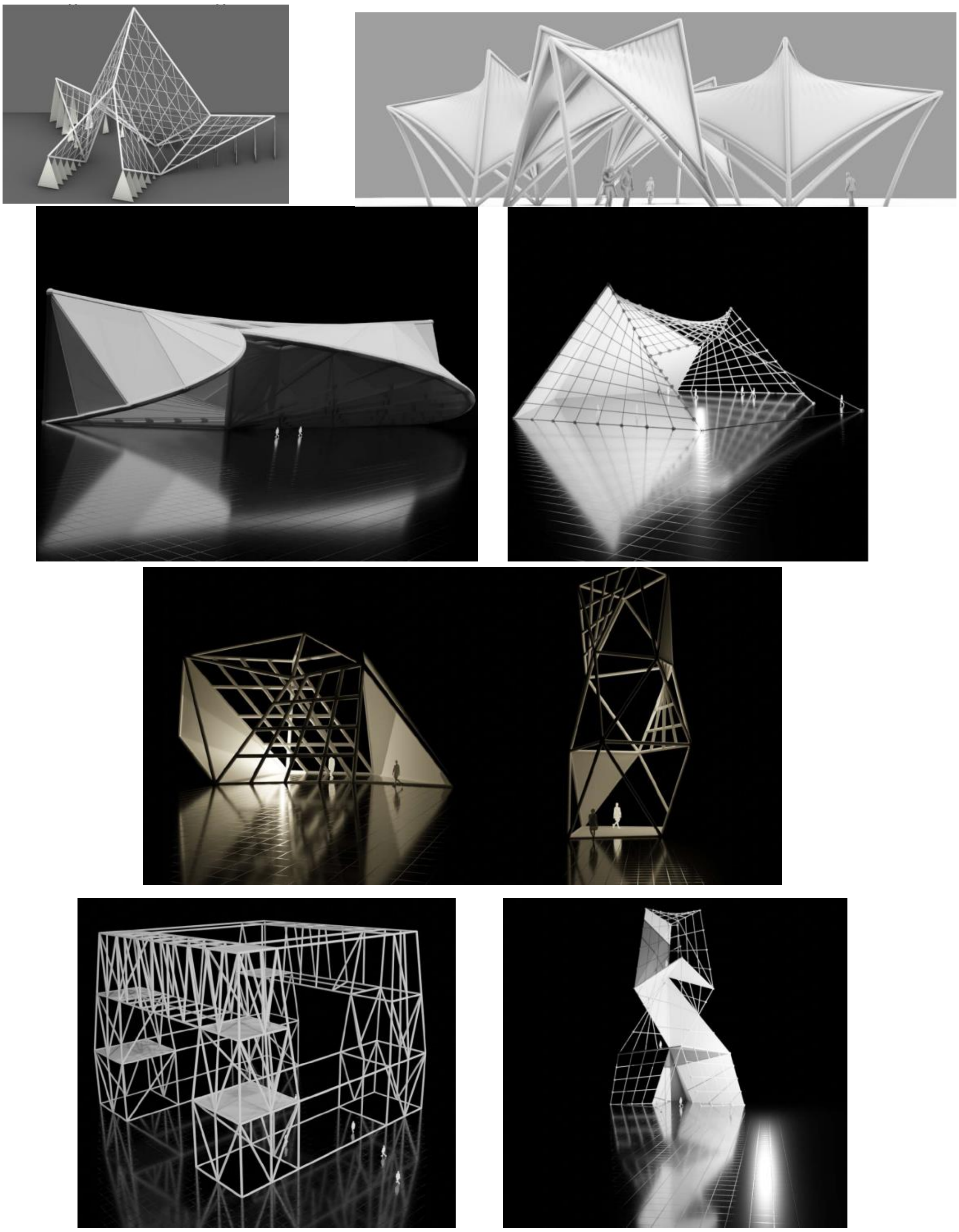


Fig. 9 Collage of undergraduate student works

4. The future can be a reinvention of Xenakis and Goldsmith's approach

In 2024, many choices exist for educators of structural design students, tools which were not available in a 20th century pedagogy are at our disposal today. The decision to use tools like Grasshopper, AI, and virtual constructions in architectural and engineering education requires discussion, trial and error and constructive critiques from the university community. For example, rendering with AI speeds up much student work, allowing them to focus not on renderings of skins, but on form finding and the channeling of load flow in their buildings. Academics must lead these discussions, and sadly today, many professional practices are far more forward thinking than university structural engineering departments. Several large opportunities (or threats!) exist today which we must grapple with, not simply avoid.

1. Grasshopper and Parametric Modeling: Grasshopper, a visual programming language for Rhinoceros 3D, and other parametric modeling tools offer powerful capabilities for exploring complex geometries, iterating design variations, and optimizing building performance. These tools can enhance students' understanding of computational design principles and enable them to create innovative and responsive architectural solutions. Integrating Grasshopper into the curriculum can empower students to explore parametric design strategies and develop computational design skills that are increasingly in demand in the industry. An enormous benefit of this path is that a full loop, from Rhino drawing, to Grasshopper parametricism, to finite element modeling via karamba3d [6] are all contained in a seamless environment.

2. Artificial Intelligence (AI): AI technologies have the potential to revolutionize various aspects of architectural and engineering practice, from generative design and optimization to building performance analysis and simulation. Incorporating AI tools and techniques into the curriculum can expose students to cutting-edge technologies and prepare them for future advancements in the field. AI can augment students' rendering capabilities. Perhaps it can evolve to facilitate the exploration of design alternatives. However, it's essential to approach the use of AI ethically and critically, considering issues such as bias, privacy, and equity. A perfect example of this is ChatGPT and Python. The two can work nearly magically together, but the effect is lost if the programmer solely relies on AI and has none of the requisite skills to judge, assess and change the Python scripts being suggested.

3. Virtual Constructions and Digital Fabrication: Virtual constructions and digital fabrication technologies offer opportunities to simulate, visualize, and fabricate architectural prototypes and components with precision and efficiency. These tools can streamline the design-to-production workflow, enable rapid prototyping, and facilitate interdisciplinary collaboration. While virtual constructions can complement traditional physical model making, they should not entirely replace it. Hands-on learning experiences, such as physical modeling, provide valuable insights into material properties, construction techniques, and spatial qualities that may be lost in purely virtual environments. The best example of the efficacy of this technique is through rapidly evolving clash detection in newer versions of 3d modeling software.

Ultimately, the integration of Grasshopper, AI, virtual constructions, and digital fabrication into architectural and engineering education should be approached thoughtfully and strategically. These tools should be used to augment traditional pedagogical methods, enhance students' learning experiences, and foster critical thinking, creativity, and innovation. We have all seen how ChatGPT can augment one’s understanding of a topic, provided one has a background and some mastery of the topics being discussed. Balancing technological proficiency with a deep understanding of architectural principles, human-centered design, and ethical practice is essential for preparing students to meet the complex challenges of contemporary architecture and engineering practice. As Myron said, we need to “humanize technology” [7].

5. Conclusion

Modernism is a place where architecture students and structural engineering students can meet, Post Modernism is not. The nearly minimal aesthetic of Modernism lends itself to statically determinate spatial structure form finding. Both engineering and architecture students can participate in such exercises. Thin shell structures is another such meeting point, the random blobs and curves generated by pulling control points in Rhino is not such a meeting place. Structural Rationalism is not a style or a fad such as Post Modernism, it is deep wellspring of generative ideas that transcends current fashions or tastes which change frequently. By embracing innovative form-finding without sacrificing structural integrity, and leveraging computational tools to enhance architectural expression, designers could strive to reconcile the divide between architecture and engineering in a new manner.

Acknowledgements

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