How Structures Move: Three Projects in Deployable Structures

Dr. Sudarshan Krishnan, University of Illinois, Urbana-Champaign

Sudarshan Krishnan specializes in the area of lightweight structures. His current research focuses on the structural design and behavior of cable-strut systems and transformable structures. His accompanying interests include the study of elastic and geometric structural stability. He teaches courses on the planning, analysis and design of structural systems. He has also developed a new course on deployable structures and transformable architecture. As an architect and structural designer, he has worked on a range of projects that included houses, hospitals, recreation centers, institutional buildings, and conservation of historic buildings/monuments. Professor Sudarshan serves on the Working Group-6: Tensile and Membrane Structures of the International Association of Shell and Spatial Structures (IASS), the American Society of Civil Engineers' (ASCE) Aerospace Division's Space Engineering and Construction Technical Committee, and the ASCE/ACI-421 Technical Committee on the Design of Reinforced Concrete Slabs. He is the Program Chair of the Architectural Engineering Division of the American Society of Engineering Education (ASEE). He is also a member of the Structural Stability Research Council (SSRC). From 2004-2007, Professor Sudarshan served on the faculty of the School of Architecture and ENSAV-Versailles Study Abroad Program in France. He has been a recipient of the "Excellence in Teaching Award" and has been consistently listed on the "UIUC List of Teachers Ranked as Excellent/Outstanding by their Students" for architecture and civil engineering courses.

Ms. Yaxin Li, University of Illinois, Urbana-Champaign

Ms. Yaxin Li is currently a Ph.D. student (Building Structures) in the School of Architecture, University of Illinois at Urbana-Champaign (UIUC). Her Ph.D. research focuses on the geometric and structural design of deployable structures. She obtained her M.Arch degree from UIUC and B.Arch from Xiamen University in China.

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Abstract

This paper describes three projects from a graduate structures course in the architectural curriculum at the University of Illinois, Urbana-Champaign. The senior author has been teaching "deployable structures" as part of required courses, as independent study and as an exclusive course when possible. Constructing transformable designs has been exciting and challenging to architecture students who typically design structures to be static. Students have been able to implement the principles and advantages of transformability, namely ─ deployability, lightness, ease of transportation, ease of erection and material reuse, in their design projects either in portions of their buildings or as the main structural system. This paper starts with a brief discussion of the importance of courses dedicated to deployable structures in architecture and architectural engineering curricula. The three projects are described to provide a sense of the knowledge and skills required by students to be successful in the endeavor. Both "research" and "learning by making" were central to the projects assigned. With American universities intrinsically serving as experimental grounds for rethinking design curricula, the possibilities of teaching a course on transformable architecture in the context of disciplinary diversity has never been as ripe.

Key Words: deployable, transformability, architectural curriculum, learning by making.

Introduction

In 1832, the French socio-economic theorist Prosper Enfantin lamented that architecture as a theory of construction was an incomplete art because it lacked the notion of mobility and movement [1]. Some modern-day foldable structures respond and adapt to changing needs and conditions. This has made them multifunctional and with enhanced performance. They include retractable roofs, movable theaters, rapidly-deployable emergency shelters and kinetic facades, among others. Much remains to be discovered and understood in this field. While the need is clear, courses specifically dedicated to transformable architecture and deployable structures are seldom offered in architecture and architectural engineering curricula. Architectural programs typically offer courses that are essential to a students' body of knowledge and those which support design studios. Building structures are designed to have long life-spans and structural designers are trained to design static structures. There is, however, an advantage in introducing measured instability in structures. The result is a whole new world of transformable structures whose attributes are likely to serve human needs better. They also represent dynamism and delight that architecture constantly seeks. It is in this spirit that the senior author has been teaching "deployable structures" as part of required courses, as independent study and occasionally as a full course. Students have been able to implement transformability in their design projects either in portions of their buildings or as the main structural system. The content on deployable structures was covered in three courses: ARCH 502 *Structural Planning*, ARCH 597 *Independent Study*, and ARCH 595 DS *Deployable Structures*. In ARCH 502, deployable structures was taught as a series of project-based exercises while ARCH 597 and ARCH 595 DS were designed as exclusive courses to include a variety of transformable design projects. The courses were taken by architecture students. This paper will focus on three deployable structures projects assigned as part of ARCH 502.

Course structure

ARCH 502 *Structural Planning* was a required 4 credit hour graduate course that surveyed a range of building structural systems made of conventional structural materials. It was an appropriate course to introduce deployable structures along with the state-of-the-art structural systems and current practices in structural engineering. As the goal was to provide a survey of types of deployable structures, the project-based exercises assigned were based on existing references. With a class of 74 students, teams of four and five were formed. A set of three exercises comprised 10% of the overall course grade. The assignments were spread through the semester. The geometric design principles were discussed during the lecture sessions. Students were required to research and read seminal papers and patents that provided fundamental knowledge about deployable systems [2, 3]. The projects ranged from simple to complex, and required both intuitive and mathematical thinking. "Learning by making" was central to evaluating successful designs. Students made decisions as a team, and through cooperation and coordination, they completed the geometric designs, AutoCAD drawings and the table-top models as part of each project. They worked over a reasonable duration of time in order to complete the deliverables. The well-equipped woodshop and fabrication lab at the University of Illinois facilitated the model-making process.

The major goals of the projects were:

1. To enable students understand the geometric principles of deployability.
2. To acquaint students with a range of potential two-dimensional and spatial deployable systems.
3. To develop physical and/or digital models of different systems using the foldability criteria and constraints.

A description of three sample projects, to wit, (1) deployable ring; (2) deployable grid; and (3) deployable dome, is presented herein. The nature of the projects also allowed students to engage in digital three-dimensional modeling and fabrication, as precision and careful detailing were key to reliable deployability. Through these exercises, knowledge of transformable geometries and mechanical movements were developed. These projects did not require any expertise in advanced mathematics, mechanics and structural engineering.

Project 1. Deployable ring

Ring structures were constructed using angulated members [3] whose geometry is determined from the number of polygon sides n and subtended angle φ of the angulated members. Figure 1 is a plan view showing the basic building block and deployment geometry of an eight-sided ring. To determine the member dimensions, the geometry in the fully expanded state is considered. The central angle α of the polygon equals $2\pi/n$. Using this, the kink angle of each angulated member can be calculated as $\varphi = \psi = \pi - \alpha$. Note that every angulated member has identical geometry. Each pair of angulated scissor members are end connected using hinges to form the predetermined regular polygon. Students use HDF for the members and polystyrene rods for connections that allow free rotation, see Figure 2. More sophisticated models may be made using metal for members and screws and bolts for the connections.

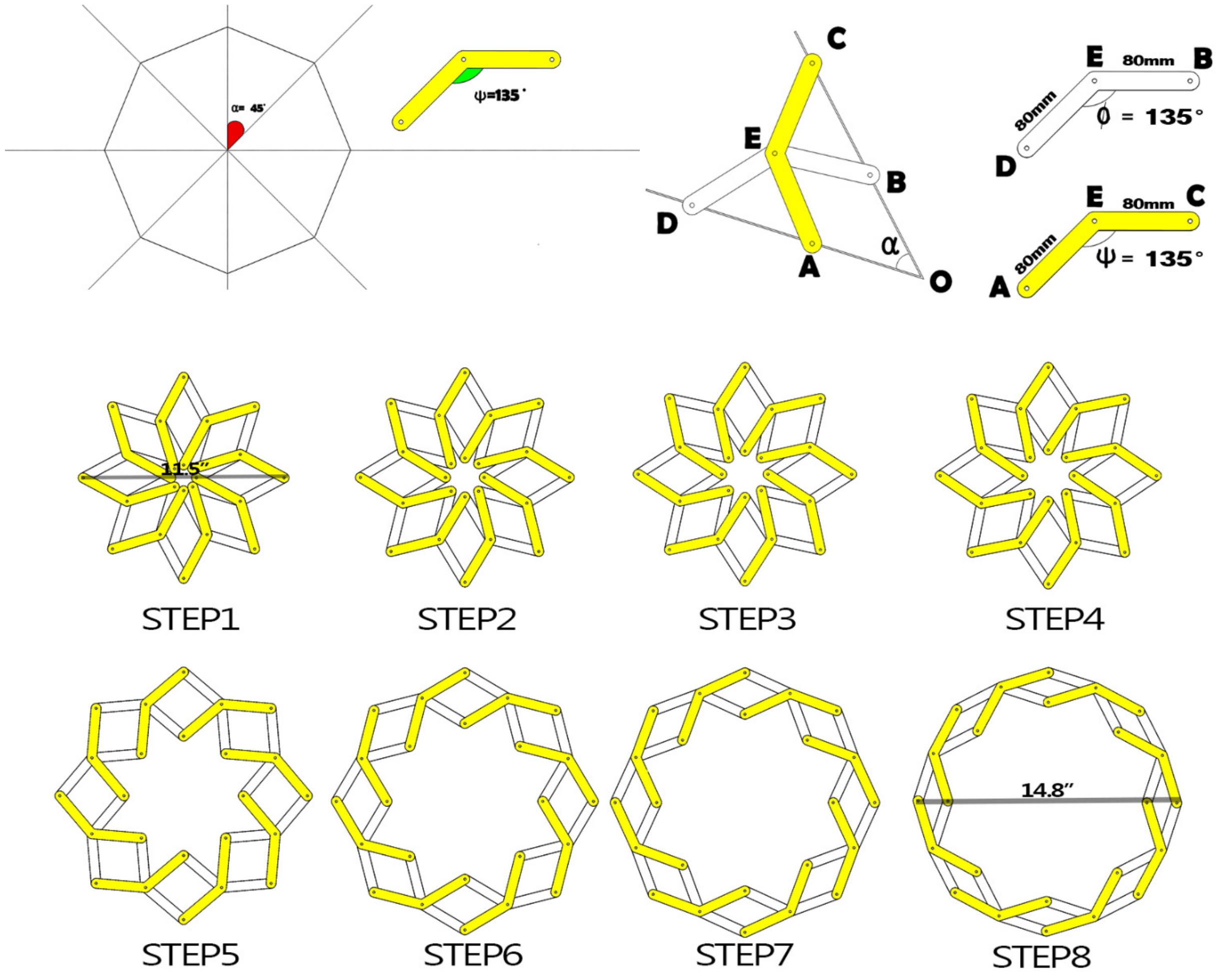
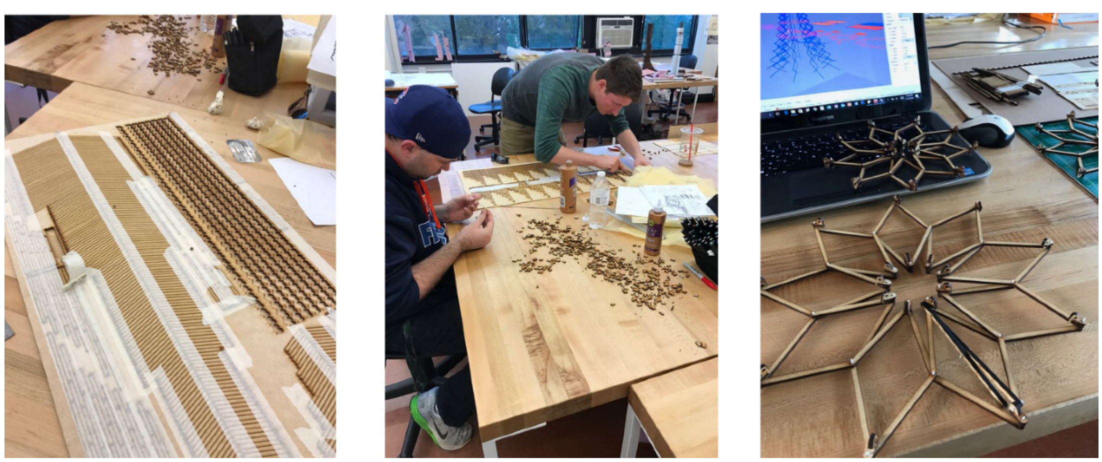


Fig. 1 Deployment sequence of a 8-sided ring made of angulated units

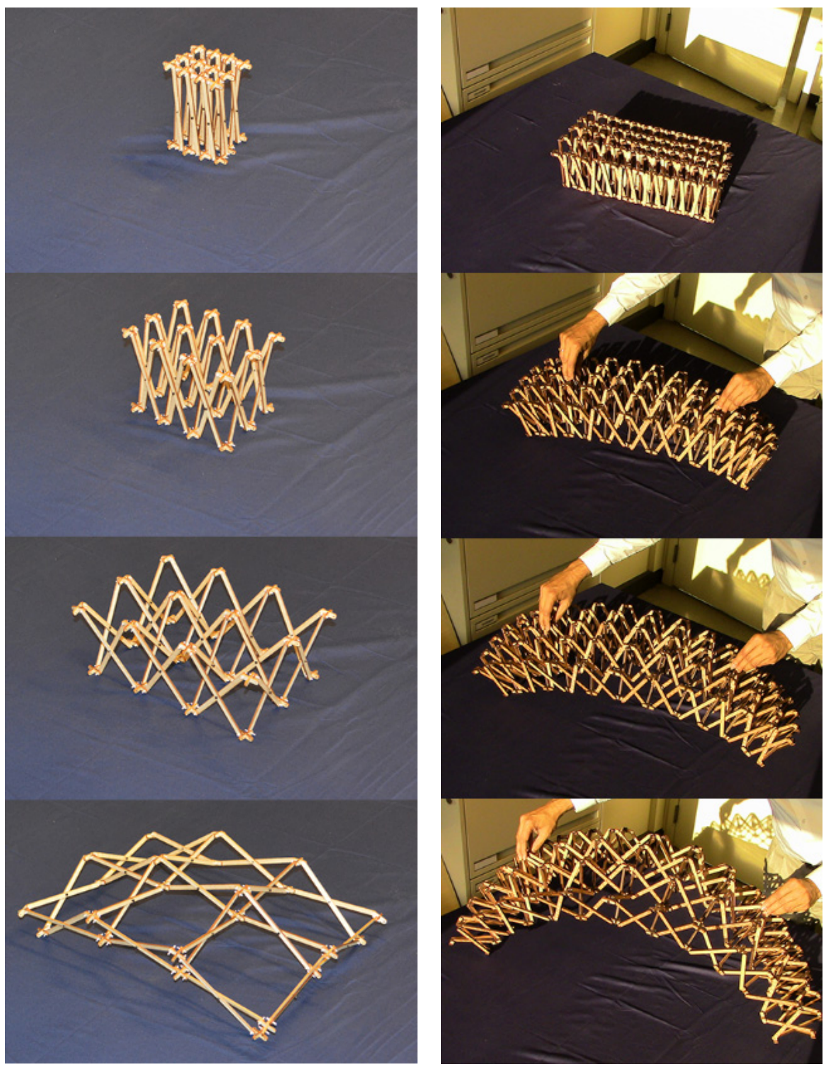


(a) (b) (c)

Fig. 2 (a) Laser-cut pieces; (b) Students making connection details; (c) Deployable ring structure

Project 2. Deployable grid

Scissor units using straight members are used to construct frames and grids. The motion of scissor units whose members are hinge-connected at their mid-lengths, is translational. However, when the same units are connected at an eccentricity, the resulting motion is curvilinear, see Figure 3. The latter are referred to as "polar scissor units." The greater the eccentricity of the connecting hinges, greater is the curvature of the deployed form. Knowing about these fundamental principles and by using members of different geometries and eccentricities, students develop an intuitive understanding of forms and motion. Thereafter, the geometric conditions are applied to ensure full deployment and maximum packaging [4]. Due to the modularity of the structures, it was prudent and efficient for students' to first start with a single module to ensure that the unit deploys and packages as needed. Then, multiple modules were added to check the compatibility between the individual modules. With the lessons learned and confidence gained, full models were constructed.



(a) (b)

Fig. 3 Deployment sequence of grid structures made using polar scissor units.

Project 3. Deployable domes

The term "dome" is used to describe the overall shape and should not be confused with the conventional sense of dome as surface structures under compression. Students were tasked to design deployable domes using three-dimensional scissor units. To achieve the overall form, different methods may be used for partitioning a spherical surface, namely, geodesic grid made of triangulated pentagons and hexagons, lamella grid based on the rhombic pattern [4], or a grid based on meridians and parallels [5]. Either polar or angulated scissor units may be used to construct the dome. For this project, the student groups used polar units, see Figure 4. There were useful lessons learned while constructing the final model. It was not possible to build a completely closed sphere as the scissor units will not converge to the two poles of the sphere. Also, a hemispherical grid with polar units does not maintain a spherical trajectory during deployment or retraction. Lastly, because of geometric incompatibility between units during circumferential motion, the members and joints develop stresses [6].

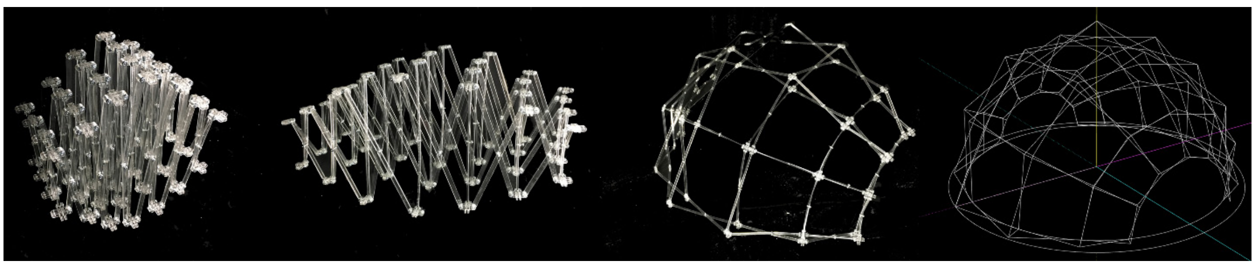


Fig. 4 Deployment sequence of a dome based on meridians and parallels

Assessment

In Project-1, students worked individually as comparatively lesser effort was involved to make the rings. They developed deployable rings for different number of polygonal sides and included a calculation procedure to substantiate their model. The product was graded based on the mathematical proof, AutoCAD drawings and physical model. This was a good exercise for students to experiment with the materials available for making models and to get familiar with laser-cutting and fabrication tools. Some students exceeded the expectations by creating multi-layered circular and elliptical rings.

In Project-2, students submitted a single deliverable as a team. "Curvature" was a requirement for the grid structure. The product was thus graded based on whether the designs incorporated curvature, the complexity of the model, the stiffness of the structure, attention to connection details, and the overall quality of work. Students were also expected to make a poster showing the deployment stages of their models.

The assessment of Project-3 hinged on its design complexity, quality of connections and overall form, AutoCAD drawings with dimensions, and a kit-of-parts with the number of pieces of every different member, their dimensions and hole locations. The reliability of deployment was an important factor. This depended on both accurate geometry and precision and quality of connections. As with the earlier projects, the teams had to produce a poster showing the deployment sequence of the model from the stowed to the deployed state.

While instructions to approach the projects were provided at the start of each assignment, adequate feedback was provided after the fact. This helped students improve their subsequent projects.

Feedback

As with most institutions, students at the University of Illinois complete a formal course evaluation at the end of the semester. The projects on deployable structures comprised 10% of the course content. In hindsight, the author should have customized the course evaluations to include specific questions about the deployable structures' projects. A survey of five questions was conducted after the fact. A statistical analysis is unwarranted due to small sampling. The students' feedback do provide insights on what made the first offering successful and how the author could conduct future projects effectively. Response to the questions are paraphrased here for brevity.

(1) *What were three important things you learned through your study of deployable structures?*

- I learned how to make these interesting physical models from knowing nothing about it.
- The experience taught me how to collaborate, grasp skills and learn effective methods to realize "unknown or new concepts."
- The projects provided a concrete recognition of relationships between different types of loads, load transfer paths, material selection, fabrication and built form.
- It taught me how to apply deployability principles in my own architectural design projects.
- I usually design the form first and then think about the structure for my studio projects. However, in deployable structures, I had to think of the structural geometry first or the structure would not work.
- I could translate the basic techniques of deployability and transformation of small scale models to larger architectural components and spaces.
- The geometry of structure is related to the path of deployment. A small change in the shape of the units or the connection point can considerably change the final deployed configuration.

(2) *In what ways did the projects change your thinking about structures?*

- I found structures were no longer just a "dead thing" but can be transformed in a rational and methodical way.
- What I learned can be used for design of everyday objects, such as furniture, toys, etc. This raised my interest to grasp the concepts and learn as much.
- I understood that structures can be used to not only transfer loads but also to transmit motion and velocity.
- A fundamental but deeper understanding of deployable structures would help students with further research interests to find eclectic opportunities in the professional field which is shifting away from static, stationary architecture to an architecture that responds and reacts.
- Understanding the concepts of deployability helped me realize that design and structure could be combined together in a program/space/object for better performance, functionality and efficiency.
- I have started to think of structures as active systems that may be designed to take different loads in different configurations.
- Deployable structures not only have the potential to create kinetic forms but also redefine the meaning of dynamic architecture.
- I never expected to learn about deployable structures in a structures course. However, I

was pleasantly surprised by the outcome as well as process of creating them. To me, three aspects surfaced in terms of importance: trial and error, reasoning, and potential applications.

(3) *What types of systems or topics do you wish were included as part of the deployable structures' projects?*

- If possible, the projects can have some content that relate to energy efficiency applications in buildings.
- Maybe add some readings or guest lectures about bionic deployable structures.
- I think it is important to understand mathematical methods of design and how to modify them for specific cases.
- Kinetic architecture, environmental envelopes, retractable roofs and similar systems where deployability is used could be some extended introductory topics for students to explore.
- It would be very interesting to analyze other types of structures that have a three-dimensional transformation in geometry other than just an expansion or contraction.

(4) *What could the Instructor do to make the projects effective?*

- Strengthening the connection between what we learn from these projects to actual situation and applications will be helpful for our future practice and further exploration.
- May be we can build one detailed learning model of façade structure with connection detail as a final project.
- Include a session about understanding connection designs and how members could be connected to make a model to successfully deploy.
- A combination of built large and small scale case-studies could help students understand the intensity of deployability being used in architecture in recent years and different ways they could be addressing their designs using deployability in future.
- Maybe ask students to think about the possible application of their projects to have a better understanding of size, materials, stability, control methods, etc.
- Provide a longer time frame to analyze structures and the types of nuances and iterations to produce stronger and more consistent results in the end.

(5) In retrospect, what do you wish you had done more or better in the projects?

- With more time on research, I may have found other ways to make deployable structures or create something new.
- Knowing computer programs like Grasshopper would have helped to explore more forms, deployment methods, and motion simulation.
- I wish we could have done some prototyping for the connections before constructing the final model.
- I wish we spent more time to derive the geometrical relationships to be applied to complicated deployable dome forms and validate them by making large physical models.
- Good team work could have brought better results with the 3D exercise as the technicality, coordination, and planning increase with complexity.
- I wish we could have realized the advantage of matching the scale of the model and the connections design early on the design process to create an efficiently deployable model.
- Our final project's model was heavy and the joints did not provide sufficient friction leading to instability. I wish we had tried multiple iterations and methods of construction.

The author also conducted an informal survey to gauge interest of students for an exclusive course dedicated to deployable structures. Of the 70 students from ARCH 502 who participated in the survey, 49 indicated strong interest in enrolling for the course. This prompted the author to develop a course ARCH 595 Deployable Structures which was limited to a maximum of 10 students. Details of this course are not within the scope of this paper.

The future and challenges

The projects have been quite successful in generating, sustaining interest and raising curiosity in the subject of transformable architecture. A precise calculation of geometry led to structures which had least stowed volume and maximum expansion. Errors in mathematics led to partially deployable models or immobile structures. It should be noted that the projects were limited to geometric design. Mechanical and structural design would be more appropriate to ARCH 595. This would require good command of mechanical principles, structural analysis and design [7]. Students wanting to accomplish complete designs on their own would require prerequisite courses in mechanical and structural design. Alternatively, an interdisciplinary group of students may alleviate the pressure and also lead to new design ideas. Such collaborations would be learning opportunities for students about areas alien to their own. Students should be willing to communicate and compromise. Far more important is the eagerness to learn and sustain frustration, especially when building precision models. With the opening of interdisciplinary design centers in many universities, the prospect of learning about transformable designs in the context of disciplinary diversity has never been as ripe.

Conclusions

Based on the first offering of projects on deployable structures, the following conclusions were made:

(1) Constructing transformable designs has been exciting and challenging to architecture students who typically design structures to be static. Students recognized the importance and need for architecture that reacts to external condition and stimuli. Students not only learned about novel kinetic structures but some also found the series of projects to be a useful inclusion in their design portfolios, unique from their design studio projects. Yet others found these projects positively influencing their studio projects.

(2) Students recognized how precision in geometry is essential for proper movement of parts and thereby foldability. “Learning by making” was key to understanding and enjoying deployable structures. In retrospect, the course can be made stand-alone for undergraduate architecture students (juniors or seniors) and be limited to geometric design aspects. At the graduate level, the course could include mechanical design of connections, and structural analysis and design.

(3) In order to avoid a myopic view, a course on deployable structures would interface better when taught in parallel with a studio design course. The studio design project and the course content can be designed to be synergistic as application-oriented efforts would bring out newer and novel ideas to advance the field. The projects may be divided into categories, namely, iconic structures, humanitarian architecture, rapid-assembly structures such as disaster-relief shelters, outer-space habitats, among others.

(4) With American universities intrinsically serving as experimental grounds for rethinking design curriculum, the possibilities of teaching a course on transformable designs in the context of disciplinary diversity is ripe [8].

Acknowledgments

Model credits. Figure 1: Seo Ho Lee; Figure 2: Vincent Lee and Kevin Smith, Figure 3(a): Ivana Rakshit, Krystn Rilloraza, Zenan Shen, Miya Teng, Yuqiao Zhang; Figure 3(b): Paul Kitchen, Amanda Ko, David O'Donoghue, Lindsey Stinson, Austin Zehr; Figure 4: Zebao Chen, Lei Gu, Alvin Hamilton, Yuan Liao.

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