Proceedings of the IASS Annual Symposium 2020/21 and
the 7th International Conference on Spatial Structures
Inspiring the Next Generation
23 – 27 August 2021, Guilford, UK
S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds.)

Visualizing Structures: Integrative Methodology for Teaching Structural Principles to Architecture Students

Maged S. GUERGUIS*, Kristin K. PITTS

*The University of Tennessee, Knoxville, College of Architecture and Design
1715 Volunteer Blvd, Knoxville, TN 37996
maged.guerguis@utk.edu

Abstract

Traditionally, technology courses such as structures are typically taught to architecture students in silos. That is, they tend to be lecture-based, theoretical, and separated from the core architectural design studios. Translation of the abstract structural principles into design concepts is usually challenging, resulting in either compromise of design intent or implausible structural solutions. Therefore, there is a necessity for a pedagogical overhaul to address these challenges in academic and, ultimately, contemporary design practices. To address these challenges, the work presented in this paper proposes a comprehensive four-module active-learning approach, which includes: 1. manual calculations; 2. computational structural analysis and form-finding simulations; 3. physical models fabrication and load testing; and 4. design studio integration. As a proposal for an integrated technology and architecture design curricula, this paper describes the strategy, approach, assessment, and value of a more comprehensive and congruous curriculum that better prepares the next generation of architects.

Keywords: Education, Pedagogy, Teaching Methods, Structural Education, Architectural Education, Structures for Architects, Structural Concepts, Physical Models, Form Finding, Structural Simulation.

1. Introduction

In the traditional approach to teaching structural systems to architecture students, introductory technical and structure courses are taught. Students are required to demonstrate a knowledge of basic structural principles and systems, evaluate their performance, select and apply the appropriate structural systems (2020 Conditions for Accreditation [1]). In the United States, it is required that the teaching methodology and curricula implemented fulfil the educational requirements outlined by the National Architecture Accreditation Board (NAAB). To fulfil these requirements, curricula are often borrowed from structural engineering courses that primarily involve manual calculations based on algebra, calculus, and trigonometry. External professionals such as structural engineers are often invited to teach structures, and while highly qualified, the pedagogical approach can be incompatible as architecture students are mainly visual learners and often can’t be fully engaged in the courses (MacNamara [2]). This has mostly resulted in creating silos within the curricula as the theoretical and lecture-based content derived from engineering courses is not easily interpreted into the ambitious complex design concepts presented in design studios. As a result, this incongruity is reflected in irrational structural solutions or compromise of design intent.

In recent years, more emphasis has been placed upon the provision of “active learning” techniques through model making practices to complement the traditional pedagogical model and engage students on a deeper level (Prince [3], Khodadadi [4]). A revived interest in structural design and interdisciplinary research has resulted in increasing awareness to address the incongruities experienced in the teaching of structures to architecture students. Recent studies proposed incorporating physical models to teach structures in architecture schools (Vrontissi et al. [5], Soto-Rubio [6]). The pedagogical model proposed in this paper seeks to contribute to this effort by proposing a holistic approach in which more comprehensive methodologies are employed to teach structure concepts in a way that is geared towards the architectural discipline.

This novel approach to teaching structural principles is augmented with a set of comprehensive active-learning methodologies that facilitate a more successful integration with the design culture of the architecture, which better relates to the needs of architecture students. The study presents examples of integrated manual calculations, computational structural analysis, form-finding simulations, physical models fabrication, load testing, and design studio integration. The goal is to create a complete learning curriculum that enables the synthesis of structural concepts with studio-based design. These methodologies were offered to both undergraduate and graduate architecture students.

2. Integrative Approach for Teaching Structural Concepts

Architectural design studies and methods of learning focus on collaborative and problem-solving strategies and initiatives that are designed to support the creation of building designs, spatial environments, and program organization. Technology courses, including structures, are intended to provide the technological frameworks and knowledge to successfully realize architectural concepts. To make this synthesis and collaboration more practical, it is necessary for structures courses to assume a multidimensional integrated approach that incorporates lecturing with active learning and workshops that more closely reflect the design-driven studio culture and learning environment.

2.1. Principles of Mechanics: Analysis of Forces with Vector Algebra

To introduce the students to fundamentals of mechanics, the following exercise was designed to identify the magnitude and direction of the resultant of four forces using vector algebra in Grasshopper® (GH), a visual programming language and environment that runs within Rhinoceros® by Robert McNeel & Associates. To find the magnitude and direction of the resultant of the four forces provided, endpoints of all curves were established, and vectors created with assigned directions. The sum of these vectors was digitally calculated to identify the magnitude of the resultant force (Fig. 1). The students experimented with three additional forces scenarios with varying directions and magnitudes to visualize the impact on the point of application, direction and magnitude of resultant force. This exercise served as an introduction to visual scripting workshop series and worked in tandem with in-class lectures to demonstrate the mechanical principles of composition and resolution of forces using computational vector algebra.

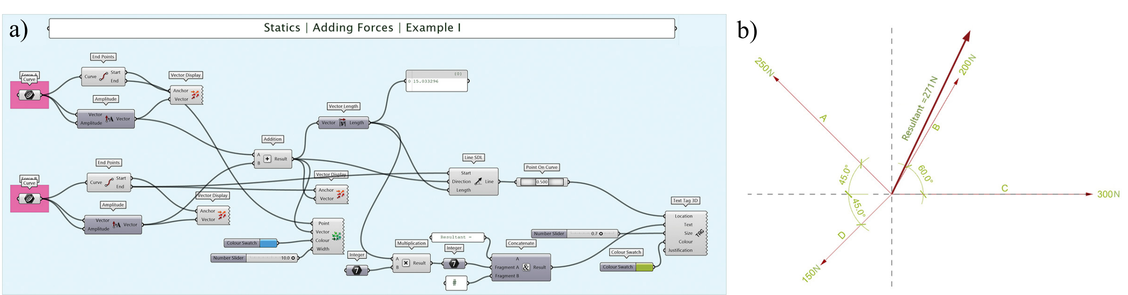


Figure 1: Computational analysis of forces with vector algebra: a) Grasshopper visual script of forces analysis, b) visualization of forces vectors and the resultant [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, spring 2018]

2.2. Manual Calculations, Computational Analysis, and Equilibrium of Beam

To introduce the three equations of equilibrium for beams, the students performed manual calculations to determine the reaction forces of the beam loads. These hands-on calculations were critical as they established understanding of the basic principles of mechanics before performing more complex analysis using digital tools.

Subsequently, the students were given a workshop to computationally solve the same exercise using Karamba, a parametric structural engineering tool developed for Grasshopper (Preisinger & Heimrath, Moritz [7]). Once mastered, the parametric beam model was used to solve for reactions values and generate shear and moment diagrams. With all other parameters remaining constant, the students were able to experiment and visualize the beam behavior under varying load scenarios, materials, and different cross sections (Fig. 2). This provided the students with firsthand observation of the impact of these parameters on the overall performance of the beam while observing bending failure under each scenario.

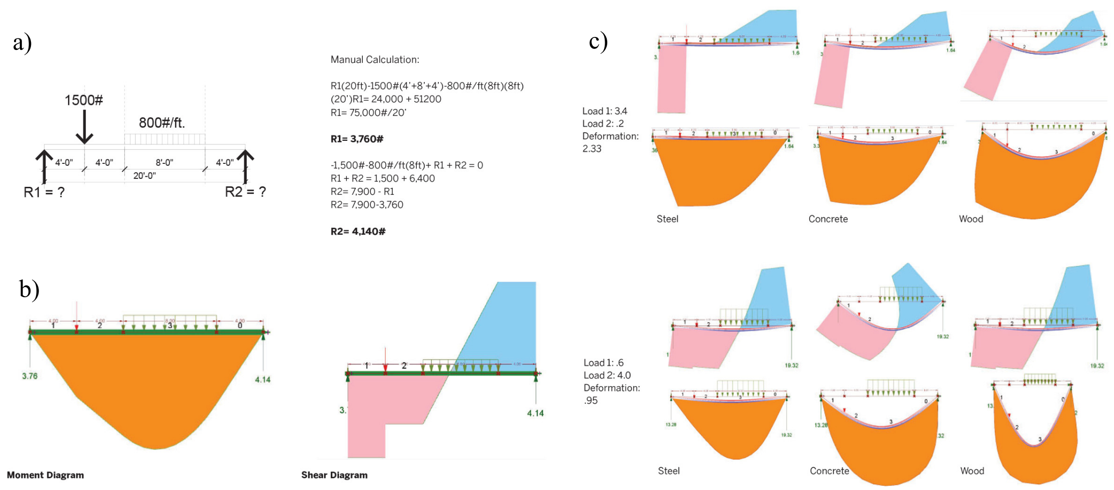


Figure 2: a) manual calculations of a beam with concentrated and uniformly distributed loads, b) parametric structural model of the same exercise with shear and moment diagrams, c) experimentation with the effects of different load cases, cross sections, and materials on the beam deformation [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, spring 2018]

2.4. Beam Cross Sections Physical Models and Load Testing

To physically demonstrate the findings from the previous exercise, a hands-on activity was deigned to allow the students to investigate beam performance in relation to its cross section. The objective is to design and construct three beam models using varying cross section profiles that spanned 300 mm using modeling clay. Physical load testing was conducted to determine their ability to resist the greatest load and compare their performance using the beam's strength to weight ratio (Fig. 3). Testing results confirmed that wide flange section profiles perform the best since most of the material is concentrated in the flanges, at the greatest possible distance from the neutral axis. This activity allowed the students to observe the beam behavior and introduced them to the first physical load testing procedure in the course.

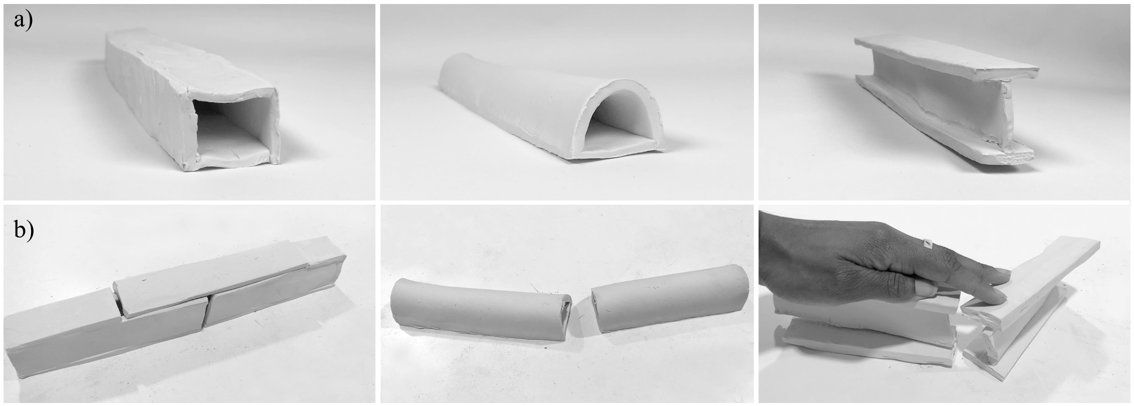


Figure 3: a) clay models of different beam cross sections, b) beam failure after load testing [Arch 557 Structural Principles in Architecture course developed and taught by Maged S. Guerguis, Fall 2019]

2.4. Vector-Active Systems: Trusses

Starting investigations of long-span structural systems, this exercise explored the analysis of planar trusses with the objective of designing and constructing multiple digital analytical truss models. The goal was to find the values of the reaction forces and internal axial forces of specific members, and to determine whether the members are in tension or compression. The students were able to evaluate the performance of various truss topologies in relation to mass, maximum displacement, and axial stress.

After mastering manual calculations of trusses using the method of joints, the method of sections, and graphic statics, the students were given a workshop to script computational structural analysis of the various planar truss configurations. They were asked to construct, analyze, and compare the following truss typologies: parallel-chord truss, Howe truss, bowstring truss, and crescent truss, while keeping all other parameters constant including span, cross-sections, and loads (Fig. 4).

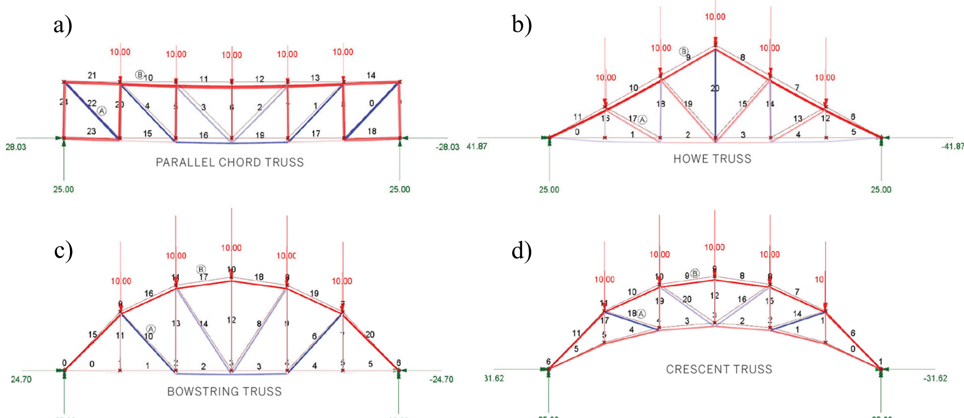


Figure 4: Computational analysis of different planar truss types: a) parallel chord truss, b) Howe truss; c) bowstring truss, d) crescent truss [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, spring 2019]

The students observed that the crescent truss performed the best as it had the least mass and registered the lowest maximum displacement value. The axial internal stresses of the specified members also had the lowest calculated values. The bowstring truss performed similarly in regard to the maximum displacement value but had more mass and indicated slightly higher axial stress values. The parallel cord and Howe trusses exhibited the least performance as it had the most mass and a higher displacement value with markedly higher axial internal stress values. By performing such a study, students were able to begin to create tangible associations with the impact of topology and members arrangements on truss strength and performance preparing them for their first structural design exercise.

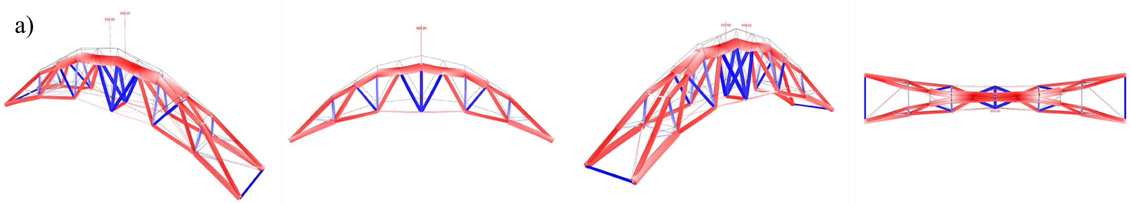
2.5 Introduction to Topology Optimization

In a continuation of exploring structural analysis methods and their integration with structural design principles, a lab project was developed to simulate the design process of architectural studio while maintaining a focus on the technical aspects inherent within the study of structural systems. Previous methodologies of structural analysis and computation of stresses and forces were to be expanded with the addition of topology optimization that would further inform design decisions.

2.5.1. Bridge Design and Topology Optimization

For this lab assignment, students were asked to design and build bridges using spaghetti as their primary building material. An analytical truss design was to be created, analyzed, and simulated using GH and Karamba. The structural performance of each scheme was then evaluated using optimized cross sections algorithm based on each member's internal stress and maximum displacement values using an evolutionary solver. The highest performing truss topology with the least amount of material and optimal weight was chosen to create and fabricate a bridge physical model with a minimum one-meter span that would eventually undergo load testing to evaluate its performance (Fig. 5).

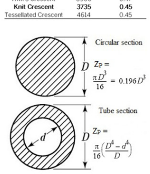
a)



b)

	Design	Outside Diameter (mm)	Wall Thickness (mm)	Area Moment of Inertia (mm^4)	Equivalent solid rod diameter (mm)	Integer Ratio	Spaghetti Count	Compression /Tension
Top Chord	48	139.7	12.7	1.03E+07	120.4	3	9	-
	47	139.7	12.7	1.03E+07	120.4	3	9	-
	46	152.4	12.7	1.37E+07	129.3	4	12	-
	45	323.9	12.7	1.51E+08	235.3	7	21	-
	44	355.6	12.7	2.01E+08	253.1	7	21	-
	43	355.6	12.7	2.01E+08	253.1	7	21	-
Bottom Chord	49	190.5	12.7	2.82E+07	154.8	4	12	-
	50	127	12.7	7.54E+06	111.3	3	9	-
	51	48.3	3.0	1.10E+05	38.7	1	3	-
Diagonals and Verticals	36	42.2	3.6	8.20E+04	36.0	1	3	+
	60	88.9	7.6	1.62E+06	75.8	2	6	+
	35	42.2	3.6	8.20E+04	36.0	1	3	-
	34	88.9	7.6	1.62E+06	75.8	2	6	+
	59	73	6.4	7.49E+05	62.5	2	6	+
	33	127	12.7	7.54E+06	111.3	3	9	-
	32	127	12.7	7.54E+06	111.3	3	9	+
	58	127	12.7	7.54E+06	111.3	3	9	+

Design	Optimized Mass (lbs)	Deflection (in.)
Competition Fan	4247	0.47
Isosceles Crescent	**3853**	**0.45**
Hwk 5 Crescent	3900	0.47
Knit Crescent	**3735**	**0.45**
Tessellated Crescent	4614	0.45



c)

Figure 5: Bridge analysis: a) cross section optimization of truss members based on the internal stresses and maximum allowable displacement, b) calculated spaghetti count based on the computational analysis of optimized cross sections, c) bridge model with optimized cross section. [Arch 557 Structural Principles in Architecture course developed and taught by Maged S. Guerguis, Fall 2019]

2.5.2. Bridge Fabrication

Prior to fabrication, the optimized design cross sections were translated into its spaghetti equivalents. The beam cross sections of a circular tube were the closest match to the more practical solid rod used in spaghetti construction. The next step was to convert different optimized cross section sizes and the area moment of inertia of each member in the computational model to determine the number of pieces of spaghetti to be bundled to create each truss member (Fig. 5b).

To construct the bridge, students first pre-bundled the pasta using colored rubber bands, red for members under compression and blue for members under tension. Each truss member diameter was determined by the radii measurement provided by the optimization analysis performed on the selected topology.

The bundles were then cut to size based on printed full-scale templates and the ends were secured with glue to create the individual members. The members were glued guided by the template to create each side of the bridge.

2.5.3. Physical Load Testing and Analysis

Using a digital load testing apparatus, fabricated in-house, each team's bridge was weighed then tested using a remotely controlled linear actuator monitored by a digital scale (Fig. 6). The maximum weight value that caused failure was recorded and the strength to weight ratio was calculated. By conducting physical load testing, students had the opportunity to observe firsthand how forces act on the bridge structure, identify the location of weak joints within the structure, evaluate the design performance, and compare the final results against their initial hypothesis informed by the computational structural analysis.

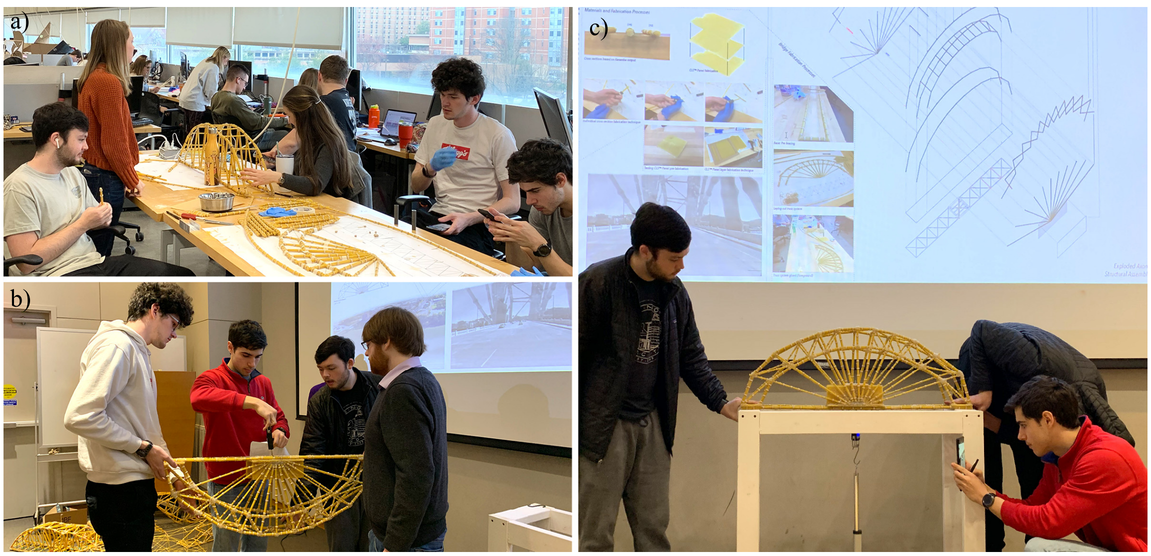


Figure 6: Topological optimized bridge analysis: a) Students teams building bridges physical models based on the computational topology optimization results, b) calibrating bridge model weight, c) Physical load testing of the optimized bridge model [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, Spring 2020]

2.6. Space Frames: Introduction to computational form-finding

The students were introduced to computational form-finding using Kangaroo physics engine plugin for Grasshopper (Piker 2013 [8]). For this exercise, the goal was to create a shell mesh simulating the behavior of a hanging chain model where all the forces are in an equilibrium of pure tension. The loads directions were then reversed to create tension-dominating form. In Grasshopper, surface-based Space Truss definition was scripted to create a space truss based on the resultant mesh of the form-finding simulation. The students generated a permutation of an infinite number of possible space frame configuration by manipulating the locations and the number of supports. They then created an analytical model in Karamba with different load cases to the joints locations. Using this workflow students were able to experiment with different space truss configurations, observe the stability of the generated design, and calculate the reactions at the supports. Afterward, the students were asked to find the value of Internal Axial forces for two truss members out of approximately 600 members and to determine whether each member is in tension or compression. Finally, a high fidelity mesh was generated and 3d printed as a scale model prototype (Fig. 7).

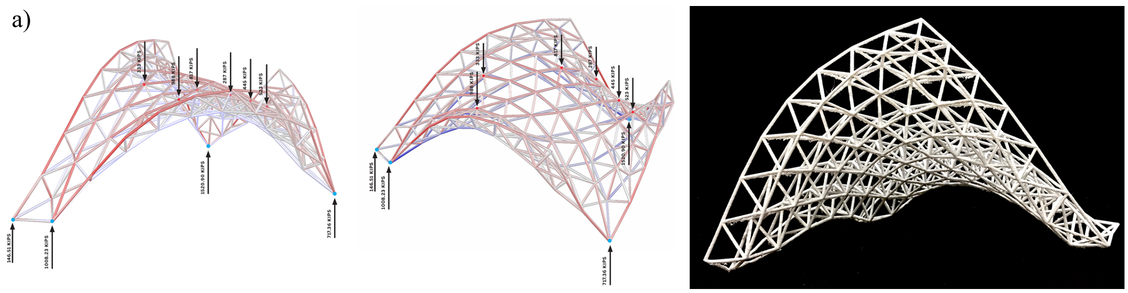


Figure 7: Space frame analysis: a) computational form-finding simulation and Karmaba3D computational structural analysis of the space frame, b) 3d-printed scale model of the space frame [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, Spring 2018]

2.7. Form-Active Systems: Computational and Physical Form-finding Simulations

Additional methods of form-finding were studied through both digital and physical models. A series of workshops on physics simulation, optimization, and form-finding was provided to the students for developing structural forms through advanced computational scripts. Traditional lectures were supplemented with videos and workshops introducing new digital tools for computational structural analysis that enabled the students to explore and create lightweight structures.

2.7.1. Tensile Structures simulation and analysis

Tensile structures were introduced through a series of exercises to simulate the design and the form-finding process to recreate Frei Otto's tensile structures as a precedent study (Otto *et al,* [9]). The students simulated the tensile forms and computed the forces flow and the principle stress lines. A physical model of fabric membrane was constructed referencing the computational model (Fig. 8).

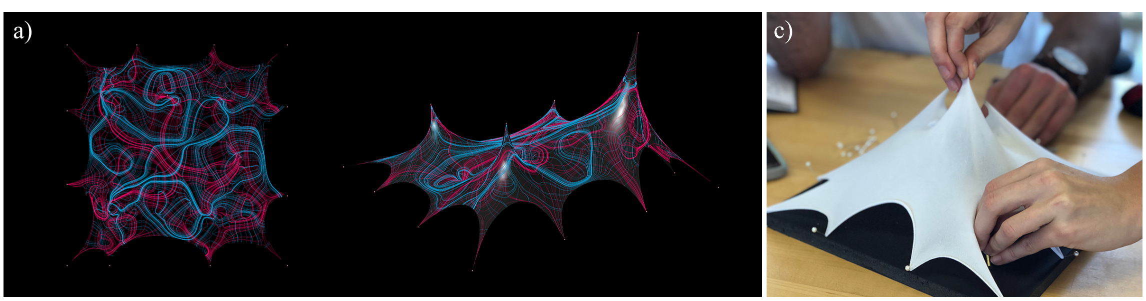


Figure 8: Tensile structure: a) computational form finding and principle stresses b) scale model [Arch 363 Design Implementation III course developed and taught by Maged S. Guerguis, Spring 2018]

3. Research-Driven Structural Design Projects

In the second half of the graduate level course, the focus shifts to a more research-driven style designed to incorporate and demonstrate the students' understanding of fundamental structural concepts, form-finding techniques, and structural analysis. The project works to align the architectural design process with structural technologies as it is designed to mimic the design-based studio culture and learning environment of architecture education.

3.1 Advanced Research Topics

Students were divided into groups and given the opportunity to select and research one of the following major structural systems currently involved in an ongoing research in the instructor's lab including, thin shell, grid shell, tensile and funicular vault. The project created a tangible opportunity to utilize digital and physical form-finding processes, apply their knowledge of computational and simulation tools. Students then researched their selected structural system to familiarize themselves with its principles, history, and current publications in primary literature.

3.1.1 Design Process

The project was divided into four stages: research and concept design, form-finding, analysis, and fabrication. Students were to conduct in depth research to deepen their understanding of the systems and review precedents to assist in design decisions. The next phase addressed the fabrication of the design proposals and students were asked to evaluate, test, and utilize materials of their choice. This process included the students learning to translate digital models into a format that could be fabricated.

3.2 Structural Design Research Project Case Study: Unreinforced Funicular Vault

A research project on funicular vaults inspired by early work of Guastavino vaulting was conducted. Force density methods of form finding were developed using Rhino Vault plugin by Block Research Group (ETH) to create an unreinforced 3d printed structure. The structure was made stable through a compression-dominant form in equilibrium. The students purposed to create a prototype scale model using Thrust Network Analysis (TNA), and three-dimensional graphic static analysis (Block *et al,* [11], Akbarzadeh *et al,* [12]) (Fig. 9).

To investigate different forms for their final design, the students used physical test models to find various forms as the first process to inform the design. A hanging model using cheesecloth was constructed in similar fashion to the hanging chain models. Then, using physics-based simulation tools in Kangaroo, the form was generated and structurally analyzed to observe forces behavior, and identify potential structural deficiencies. The final form was subdivided into panels using NGon plugin (Vestartas P. [12]). Each panel was extruded to create the mesh to 3d print the physical prototype. After printing, the students assembled the vaulted structure (Fig.9).

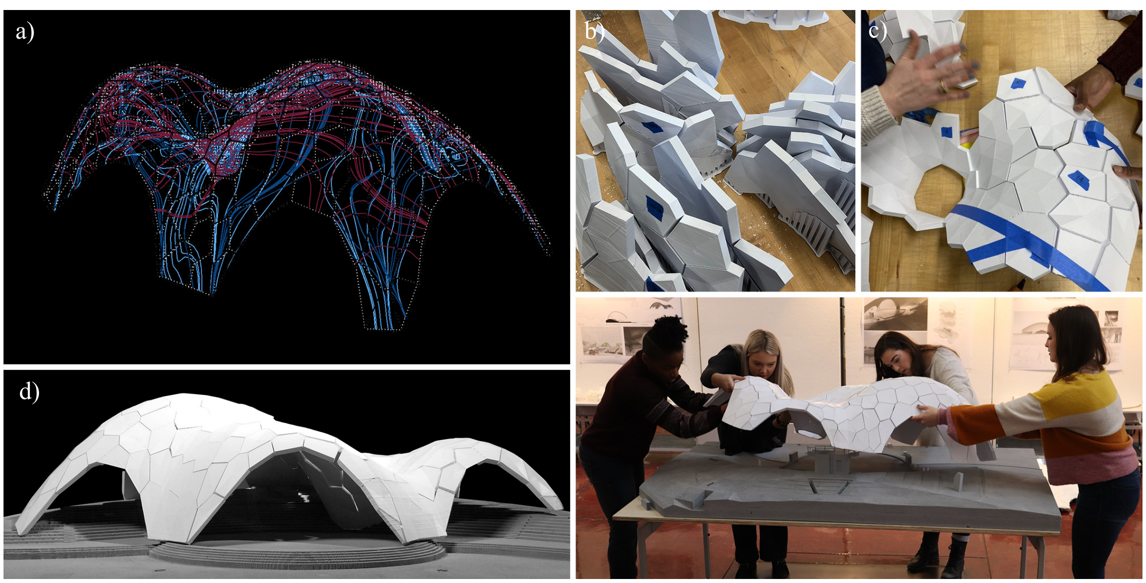


Figure 9: computational form-finding of unreinforced funicular vault: a) principle stresses b) 3d printed panels, c) physical model assembly, d) final model [Arch 557 Structural Principles in Architecture course developed and taught by Maged S. Guerguis, Fall 2019]

4 Breaking the Silos: Structures and Design Studio Implementation

A newly developed series of design studios titled *Extraordinary Methods in Architecture* that incorporate structural principle from the technology course was offered at undergraduate and graduate levels. The smaller number of students allowed for in-depth application of structural principles in design studio projects proposals. The studios were divided into three different phases: extraordinary methods (research), historical archive (precedents studies), and application (projective design).

4.1 Design Studio Case Study I: Extraordinary Methods in Architecture I - Morphologies of Non-Orthogonal Net Zero Skyscrapers

In a third-year undergraduate architectural design studio, students focused on the design of high-density structures within an urban context. The studio's premise was to address the issue of contemporary public space through the development of non-orthogonal skyscrapers with novel twisting, helical designs achieved through structural design rather than ornamental details. Using differential geometry students researched and experimented with morphologies of spiral minimal surfaces within structural and architectural applications (Fig. 10).

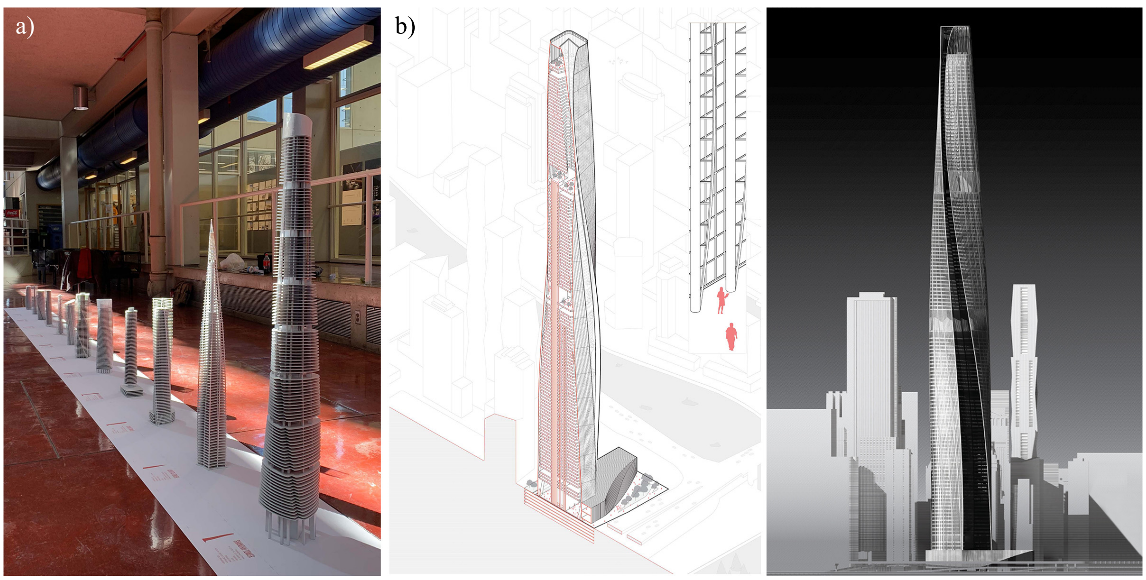


Figure 10: Examples of students' design studio work: a) Precedents analysis of twisted skyscrapers structural models scale 1:500, b) design proposal for a mixed-use tower featuring an optimized steel framing and belt trusses at sky lobbies [Arch 372 Studio developed and taught by Maged S. Guerguis, Spring 2019]

4.2 Design Studio Case Study II: Extraordinary Methods in Architecture II - Morphologies of Boolean Operations in Contemporary Design Practices.

A second newly developed design research studio aims to develop and analyze the effect of geometrical form-editing techniques on the architectural design processes, in particular, the geometrical Boolean operations. Structure principles and technologies are integrated into the studio where the implications building technologies on the politics of a space is examined. Both digital and physical modeling techniques developed in the structures course were used to create design proposals of a music hall program with long span structures (Fig. 11).

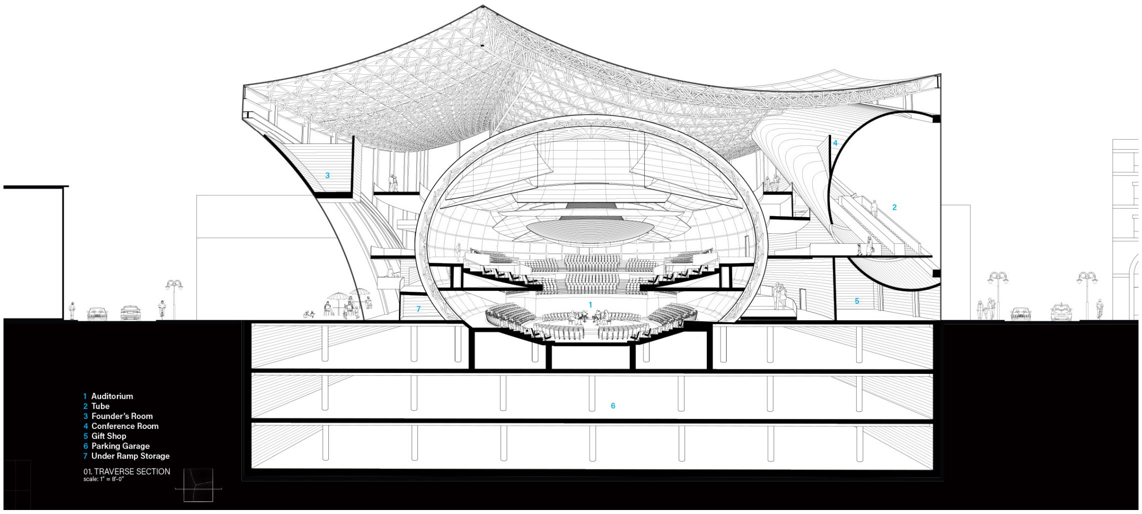


Figure 11: Examples of students' design studio work: a) design proposal for a music hall featuring a long span space frame [ARCH 372 Studio developed and taught by Maged S. Guerguis, Spring 2018]

5.0 Discussion and Conclusion

With the successful newly developed curriculum and course strategies described in this paper we illustrated that conceptual understanding of structural systems can be achieved through integrative active learning approaches. The students were able to integrate concepts of high level of structural complexity developed in the technology courses directly into their design studios projects. Additionally, this paper showed new directions for the use of computational structural analysis and digital and physical form finding for the students to visualize, simulate, and observe structural assemblies behaviour and different material performance. Furthermore, the students had the opportunity to be trained on advanced digital fabrication techniques such CNC milling, 3d-printing and robotic fabrication, combined with advanced design-to-fabrication methods for the production of structural model prototypes with optimal structural performance.

A deep understanding of structural fundamentals is necessary to enforce and enrich any design concept. The newly designed structure course provides the students with all the principles, tools, and techniques to be able to realize their design ideas developed in the studio. The students first master manual calculations of various principles of mechanics and then utilize advanced parametric structural analysis tools within the same software they use for design. Additionally, the students learn how to model complex structure systems and apply cutting-edge structural analysis tools to run preliminary form finding simulation and structural analysis of these systems. This allows them to break free from the limitations of manual calculations and ultimately achieve their initial design intent.

The paper showed the successful, first results of the newly developed structures and studio courses that are breaking the silo between these two fundamental courses in architecture education. Two projects from the ARCH 372 studio course were recognized by Council on Tall Buildings and Urban Habitat (CTBUH) as Semi-Finalists at the International Student Tall Building Design Competition, which can be considered as a first validation of this new approach. Moreover, the newly developed courses were awarded the 2019 National Innovation Award as part of technology courses overhaul at the college of architecture from the American Institute of Architects (AIA).

The authors consider this research as a first step toward a novel, fully integrated approach to a more comprehensive and congruent curriculum driven by active learning methodologies and has the potential to transform the current pedagogical practices in preparing the next generation of world-class architects.

Acknowledgements

The authors would like to thank Marshall Prado, James Solly, Marcio Soto Rubio, and William F. Baker for invaluable input while developing this curriculum; Clemens Preisinger for providing educational licenses of Karamba for the computational structural analysis and Philippe Block for RhinoVAULT.

The authors would also like to thank The University of Tennessee, Knoxville office of Teaching & Learning Innovation for supporting the developing of the courses with the Online & Hybrid Teaching Support Award.

References

[1] 2020 Conditions for Accreditation. (2020). The National Architectural Accrediting Board.

[2] MacNamara, S. (2012). Bringing Engineering into the Studio : Design Assignments for Teaching Structures to Architects. *American Society of Engineering Education.*

[3] M. Prince, "Does Active Learning Works? A Review of the Research," *Journal of Engineering Education*, vol. 93, no. 3, pp. 223-231, 2004.

[4] Khodadadi, A. 2015. Active Learning Approach in Teaching Structural Concepts to Architecture Students. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015*. Amsterdam.

[5] M. Vrontissi, J. J. Castellón, P. D'Acunto, J. Schwartz and L. E. Monzo “"Constructing equilibrium": A methodological approach to teach structural design in architecture”, *IV International Conference on Structural Engineering Education. Structural Engineering Education Without Borders* At: Madrid, Spain 2018.

[6] M. Soto Rubio “The Use of Physical Models to Teach Structures in Architecture School: A Pedagogical Approach” in the Interfaces: architecture, engineering, science: *Proceedings of the IASS Annual Symposium 2017,* At: Hamburg, Germany.

[7] Preisinger, C. & Heimrath, M. (2014). Karamba—A Toolkit for Parametric Structural Design. Structural Engineering International. 24. 10.2749/101686614X13830790993483.

[8] Piker, D. (2013). Kangaroo: Form Finding with Computational Physics. Architectural Design. 83. 10.1002/ad.1569.

[9] Otto F., Bodo, R., 1996. “Finding Form: Towards an Architecture of the Minimal”, Edition Axel Menges; Auflage: 3. Edition, ISBN-10: 3930698668, ISBN-13: 978-3930698660

[10] Block, P. and Lachauer, L. and Rippmann, M. Validating Thrust Network Analysis using 3D-printed, Structural Models, IASS Symposium, Shanghai, 2010. (2015).

[11] Akbarzadeh, M., Mele, T., Block, P. (2016). Three-dimensional graphic statics: Initial explorations with polyhedral form and force diagrams. International Journal of Space Structures. 31. 10.1177/0266351116660802.

[12] Vestartas, P. (2018). NGon Plugin- Mesh NGon Methods for Grasshopper.