Lines of Action: Investigating How Behaviors of Structural Systems Can Be an Informing Agent for Architectural Design

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Introduction

Students of architecture are required to take a series of courses that present concepts of statics, structural principles, and system analysis as part of an accredited curriculum. As the students participate within these courses, they often unfairly assume that the lessons taught of structures are peripheral or reactive to architectural design. This paper challenges this perception by introducing a pedagogical approach focused on investigating and embracing the performance of structural assemblies as an inspiration for architectural design within these supporting structures courses. A series of exercises that required students to design and fabricate physical models to be tested under various performance criteria challenged the students to consider ways in which structural behaviors and architectural design might inform one another. Along each of the phases for these projects, students were asked to consider the mode and method of failures as well as how the actions of constituent parts systematically contributed to the performance of its composite assembly.

Concerning Architectural Form and Structure

In many instances, students of an architectural curriculum formulate opinions of architectural form as enveloping shape generating procedures limited to the three-dimensional massing of an architectural act. Similarly, structural considerations are frequently perceived by students as consequential of form making processes and devalued within the creative design process. Often, these assumptions result in students over-emphasizing the appearance of an architectural act, as opposed to how it performs, offers spatial organization, and engages the site and its users.

In his book, D'Arcy Wentworth Thompson describes nature's form generation processes: "In short, the form of an object is a diagram of forces that are acting or have acted upon it."[1] Peter Pearce and Susan Pearce expand upon Thompson's writings as they argue for designers to consider the capacities of a body's structural disposition to respond to all influential intrinsic and extrinsic forces as governing principles towards the manifestation of form. "To minimize the arbitrariness of form in the built environment is to maximize its performance…One of the limitations of a visual effects approach to form is that it encourages a direction that is not particularly sensitive to performance-orientated solutions."[2]

Alexander Zannos offers the argument that form and structure should not be viewed as interchangeable terms, yet both are integral to the design process: "The term *form* is more suitable when applied to an entity taken as a whole, to the end product of the creative process, whereas the term *structure* should be used when the whole is to be analyzed by its components."[3] Zannos' definitions acknowledge that structural considerations and form generating procedures should not be seen as disassociated terms within the creative design process or when analyzing how an architectural act was created. By embracing these lessons, students can learn a great deal about how architecture and structure can inform one another by focusing on how the constituent elements within a composite entity speak to one another through performance-based design objectives throughout the design process.

Lessons though the Evidence of Performance Failure

Structural analysis and strength testing methods are honest and objective for how they reveal evidence pertaining to the behaviors of a system and properties of materials. Often these lessons are best delivered through discovering failures and vulnerabilities. In the case of studying structures, testing for failure is something that should be valued as it not only confirms or refutes whether initial assumptions are true, but also hints to address the questions: *why* or *why not*.

Engineer, inventor, and mathematician Robert Le Ricolais placed value on discovering how things performed with an investigative mindset as he states, “To discover the nature of things, the secret is to be curious."[4] Throughout his work, Le Ricolais was skeptical that initial assumptions and findings may be misleading as he gave preference to the use of physical models within his testing of concepts, asserting that we need to experience a physical “contact with things” to provide knowledge with truth and evidence. In interviews with graduate students at the University of Pennsylvania Le Ricolais commented, “Things themselves are lying and so are their images – therefore, experimental evidence is of critical importance in order to evolve beyond the arbitrariness.”[5] Further, Le Ricolais believed that the strength of the physical model within a project was as a “hierogram,” which he deemed as an abstracted model of a conceptual intention that acknowledged properties of materials, rather than as the literal representational “apparatus” device.[6]

In architectural school, students primarily are asked to complete a project or assignment and receive feedback as part of the final submission. The assumption is that the students will learn from the reviewers’ comments and integrate or expand upon this feedback in subsequent assignments. The projects described within this paper celebrate the intersection of structural behaviors and architectural form generation, while challenging the aforementioned model of teaching and learning by placing value on failure as an integral step required to complete each project. In this way, curiosity is promoted as the students are given opportunities to test the limits of their projects and discover strategies to recalibrate their design maneuvers.

Project 1a: Hollow Column/Stick Tower

Design and Fabrication Phases

As part of the introductory structures and statics course, the first physical project that was presented provided an opportunity for the students to build upon their understanding of the structural principles that were concurrently being taught in class. The project was dually titled “Hollow Column/Stick Tower” to urge students to consider the project at a variety of scales, instead of assuming their designs of a structural system were representative of a singular architectural typology. Presenting the project in this way encouraged the students to concentrate on the performance of their designs of a structural assembly, as opposed to potentially inheriting associations for form generation and organizational strategies based on preconceived notions of architecture and structure. Delivered over a series of sequential phases, the project was intended for students to predict, test, acknowledge, and reconsider how loads are transferred between constituent members of an organized system and determine whether these forces, deduced graphically as linear vectors, acted in compression or tension within their assembly designs.

Working in teams of three, the students were asked to design and fabricate a thirty-inch tall vertical structure, using repetitive or modified pattern formation strategies, to successfully support an externally applied gravitational load of seven pounds. Material restrictions were limited to only 1/8” diameter dowel rods, glue, and quilting thread. Further, all dowels were specified to be circular in cross section, requiring the students to give thoughtful consideration for how adjoining members might be detailed with the thread and/or glue as either rigid or soft joints to optimally transfer the forces in tension or compression among the members of the design. In this way, the thread assumed an expanded role beyond a diagonal tensile chord in many of the designs as several student teams opted to lash the dowel connections to increase the structural integrity and capacity of the system at these junctures.

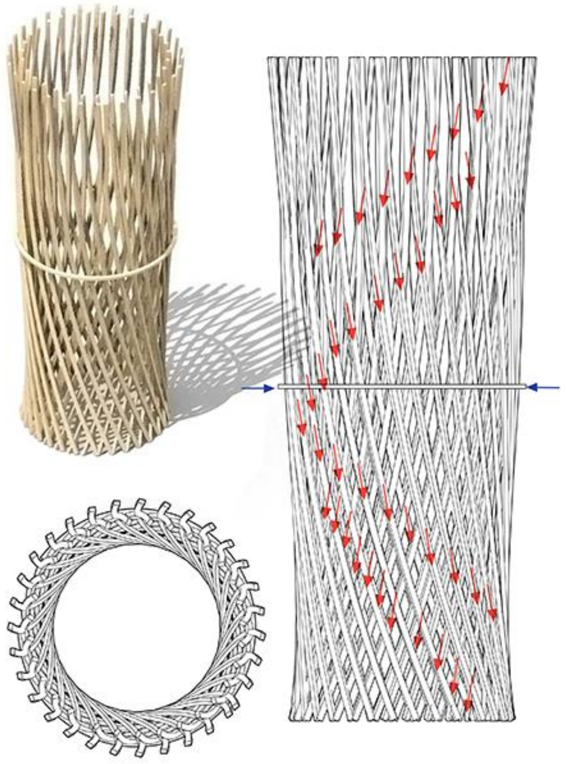

Fig. 1. One of student team’s initial options for consideration indicating ability of structural assembly to flex upon its acceptance of applied load. Student work by Eric Peters, Caitlin Liskey, and Andrea Wesson.

Each student team was tasked with developing an authentic assessment criteria for the design of the structural assembly, beyond its ability to meet the established structural performance requirement, to assist them in their design decisions throughout this preliminary phase. Student responses included emphasis on weight-to-load capacity efficiency, asymmetrical organization of patterns, capability of the structure to accept eccentric loading, and the ability of the structure to absorb the applied load and reactively respond by changing its original configuration. Prior to fabricating a model for testing, each of the student teams presented three diverse design options for review and consideration that included predictions for how the externally applied gravitational load would be transferred as compression or tension forces through the structural assembly’s members and joints [fig 1]. As many students struggled designating the correct path of travel for the forces within their structural assembly, this process provided an opportunity for the teams to present and discuss their initial assumptions and reflect on strategies to best meet the structural performance and assessment criteria requirements prior to committing to a final solution.

Each team then revised their design, or developed a hybrid option, and constructed their final “Hollow Column/Stick Tower” with a high level of craftsmanship and precision. The resulting assemblies exhibited a variety of thoughtful strategies for how the load would transfer as vector forces among and throughout the assemblies. The student team of Lauren Afendis, Conner Million, and Jake White developed and fabricated a design that utilized a five-inch tall tripartite modular unit. The module was stacked upon other replicated units to create six horizontal tiers, each rotated 10-degrees clockwise in the x-y axis from the contiguous module below. While this addressed their team’s assessment criteria of using a single modular unit in an altered configuration, it did result in interrupting the continuity of the lines of action at each tier. Thus, the overall configuration of their design suggested a prolonged path of travel for the load through the assembly and to the ground. Further, the team discovered that the connection points along the horizontal bands at the extremities of the stacked modules became critical junctures that required additional lashings, beyond what was initially anticipated, to provide the necessary structural integrity for the composite assembly and ensure the structure's ability to withstand the applied force. Alternatively, the benefit of their design approach was that the team utilized shorter lengths of dowels to prevent buckling failure as the load was successfully absorbed by the tiers, in sequential manner, and then transferred to each successive lower tier along the horizontal banding of each module [fig 2].

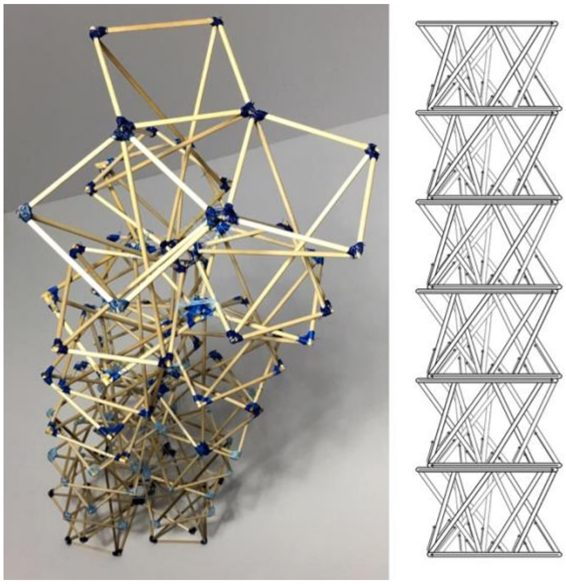

Fig. 2. "Hollow Column/Stick Tower" final design by students Lauren Afendis, Conner Million, and Jake White using a stacked, modular strategy to accept and transfer the anticipated load.

Testing towards Failure

Prior to testing, each of the team's physical models were weighed to compare the efficiency of the use of materials for the project among the class, in the event that this was a factor in the team's assessment criteria. Students were also asked to predict the point of greatest concern for ultimate failure and inscribe this point on their diagrammatic drawings for their design. It should be noted, that all of the team projects successfully met the minimum loading criteria for this initial charge without incurring any noteworthy damage.

The testing phase of the project was then continued to allow the students an opportunity to physically test their structural assemblies to a state of structural casualty and reveal the prominent points of failure within their designs. Each of the projects were placed beneath a Kuka robotic arm, which applied an incremental compressive force to the respective structures. The goal of this process was to damage the structural body, but not induce catastrophic failure, for each of the student team's structural assembly.

Project 1b: Prosthesis Design

Upon competition of the critical compressive testing exercise, the teams were then each given the opportunity to accept the edifice in its newly-established damaged condition and design a prosthesis that would allow their structural assembly to again be capable of supporting an externally applied gravitational force of seven pounds. The prosthesis was to be envisioned as a secondary device to be grafted to the impaired structure and constructed of dissimilar materials from the original "Hollow Column/Stick Tower." The task of this exercise was not to repair the original structural assembly to its previous condition. Instead, the students were asked to physically examine the current vulnerabilities and failures of the injured assembly in its new configuration and upon their analysis, create a device that acknowledged and responded to these deficiencies to extend the life of the original assembly as a structural element.

The critical loading applied to the "Hollow Column/Stick Tower" by the student team of Antonio Medina, Brooke Salyer, and Roberto Fayad inflicted buckling and shear damage to their structure. This resulted in their structural framework being severed along all dowel members near the midpoint of the entire assembly, thus causing their physical model to fold over into two parts. The thread that was originally used to transfer tension between the joints of the assembly remained connected to each broken side of the project and therefore, acted to hinge the two pieces

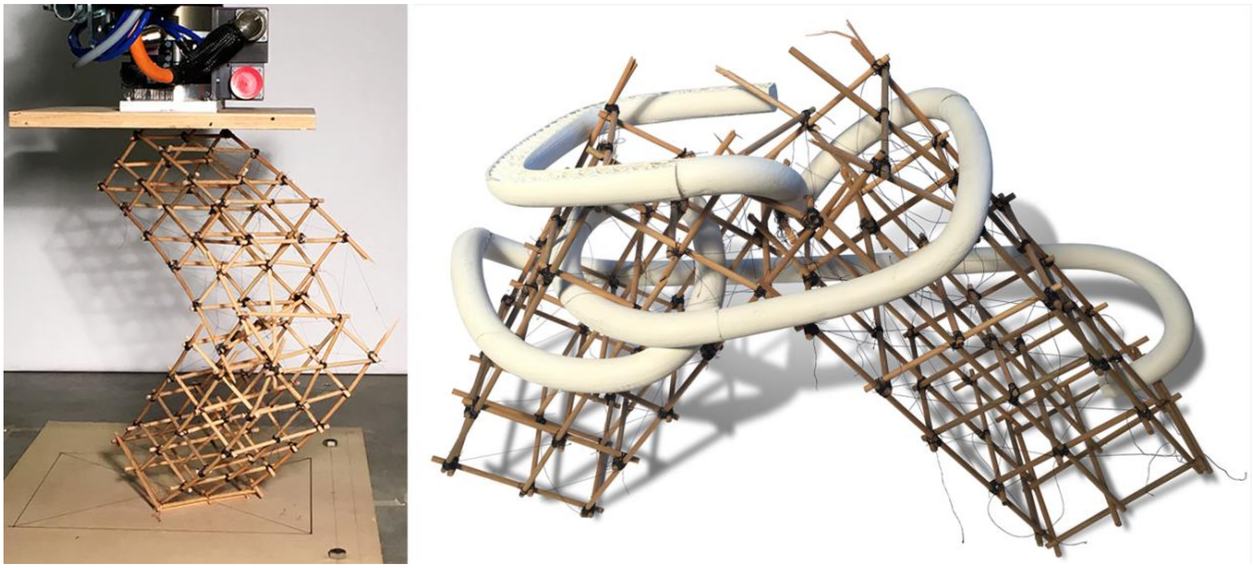

Fig. 3. Critical testing and prosthesis design and fabrication by students Antonio Medina, Brooke Salyer, and Roberto Fayad.

together. The project team evaluated their injured model and identified the greatest limitation, in its current state, was its tendency to spread apart at the base when a force was applied to the top of the broken structure. To address this concern, the team built a digital model of their project's new configuration to assist their design for a prosthesis device. Fabricated and assembled in sections using 3d printing technology, the prosthesis intertwined through the broken pieces to create rigid bracing through the composition as a means to oppose the lateral movement within the framework and ultimately allow the structure to accept the gravitational load successfully [fig 3].

Project 2: Equilibrium Scenarios Among Two Entities

The second project was presented as a collection of three separate studies, or scenarios, that targeted students working in teams of three to explore concepts of equilibrium, including mass and weight distribution, overturning moment, and the discovery of the neutral axes among disparate entities. At the outset of each scenario, the student teams were tasked with fabricating an unstable body, incapable of standing on its own accord, with stipulated rules provided to generate its formal language and configuration. As a response to the created unbalanced conditions of their physical model, each team was then asked to design and fabricate a secondary support system that was independent of their original assembly, using specified guidelines and constraints to bring the original object into balance. The two entities working in harmony to achieve balance was to be realized in a different manner for each scenario. Teams were required to consider strategies for how the secondary system might engage the unstable body and how the forces were transferred within the unification of each assembly to achieve a state of equilibrium among their comprehensive designs. All student teams presented their strategies and discoveries, specifically related to their successes and failures to meet the project's objectives, graphically and orally at intervals within each scenario of the project.

Balance Amongst

Student teams began the first equilibrium scenario by constructing the unstable body as an aggregation of thirty 2” x 2” x 2” modular cubes, adhered together along the parallel faces of the units. The configuration of these units was directed to be asymmetric along the x-y-z axes and only three cubes were permitted to be in contact with the ground base plane, thus forming an equilateral tringle in plan view. As the assembly ascended, it was permitted to travel in multiple directions and pass beyond the confines of the implied triangle, although the entire assembly of units was to be arranged in a manner that it would overturn when at rest.

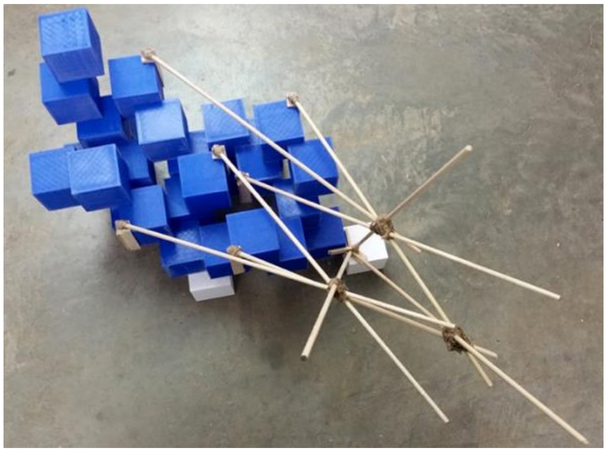

Fig. 4. "Balance Amongst" final solution by students Nick Conner, Eve Miller, and Hoff Campbell.

Upon presenting the leaning tendencies of their base models based on weight distribution, each team then strategized to design and fabricate a second system, using wood, glue, and thread, to offer support and counter the overturning moment of the modular assembly. Directions were given to the teams for this scenario that the secondary support system was not permitted to touch the ground plane or anywhere beneath the top surface of any of the three base cubes, although it was allowed to engage the cube assembly at multiple points. Further, the system was not permitted to be glued to the cubes and instead, was to be designed as a removable device to demonstrate that the modular unit model was unstable without the inclusion of the support system.

Students Nick Conner, Eve Miller, and Hoff Campbell utilized a tectonic frame that secured itself to their modular model at seven points before protruding from the unstable body in the inverse direction to counter the weight distribution of the original assembly. After several trials, the team discovered that binding the tectonic system together as a network offered the ability of the secondary structure to act as a system to best counter the overturning moment of the unstable body [fig. 4].

Balance Against

To create the form of the unstable base model for the second scenario, "Balance Against," the student teams were asked to translate their cube model from the previous submission as a homogenous form. The surface envelope of the homogenous form was to encapsulate the preceding modular unit assembly with a flowing path. The contoured boundary conditions of the form were to be smooth contours and were prohibited from exhibiting any sharp angles or creases. To achieve this, the teams worked in drawing format to initially define the boundary of the sinuous form and then cut sections in several axes to aid in fabricating the model [fig. 5].

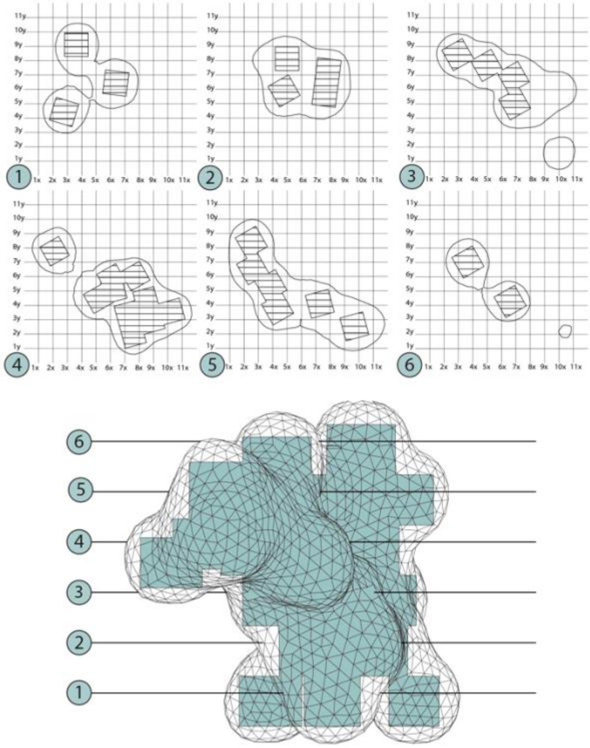

Fig. 5. "Balance Against" unstable body form generation study by students Sarah Fuller, Taylor Matthewson, and Simon Platt.

The secondary support system for this scenario utilized the same material guidelines of wood, glue, and thread from the "Balance Amongst" stage, yet the behavior and communicative constraints of the secondary system were amended for this scenario. Here, the support system was permitted to touch the ground plane at only one location within the implied equilateral triangle of its base condition to offer support to the unstable body. Students were also required to contact the homogenous form at multiple points, including one point along the apex of the base model, so not to create a wedge support for the unstable body. Further, the secondary system was not permitted to be adhered to the unbalanced homogenous form. To address these requirements, emphasis was therefore placed on the design of strategic connections for how the support system might successfully cling, grip, and or engage the smooth geometry of the base form and establish equilibrium among the interaction of both entities.

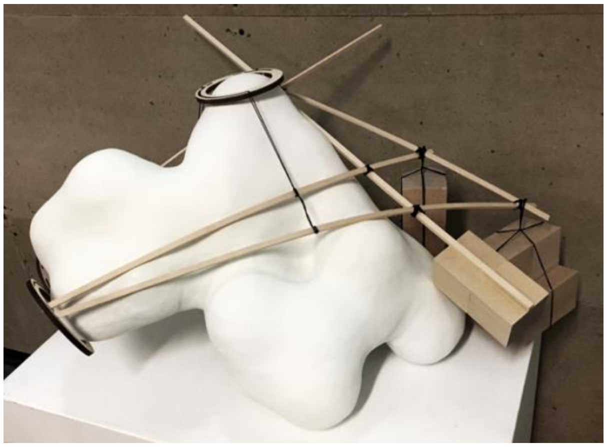

Fig. 6. "Balance Against" final solution by students Gage Workman, Gahyun Kim, and Jenny Cook.

To address the challenges of this scenario, the student team of Gage Workman, Gahyun Kim, and Jenny Cook began their design of the support system by first acknowledging the peak contours of their homogenous form to develop a series of standardized rings that would enable their counter-balanced system to successfully clutch the form through frictional resistance. Upon establishing these points of engagement, the team designed a network of linear elements that utilized the flowing surfaces of the homogenous body to influence the directional path and provide support for their network of linear elements. This network of wood and thread culminated in a calibrated counter-weight assembly, comprised of wooden blocks, that were tied to the system along the opposing axis of the unstable body's primary mass [fig 6].

Balance Within

The final scenario, entitled "Balance Within," required the student teams to translate their unstable body into a structural framework using strategies of triangulation, by means of rigid or tensile diagonal bracing members and designed connections constructed of wooden dowels and thread, to reinterpret the peaks and valleys of their homogenous form as a structural framework. Upon recreating their unbalanced body as a self-supporting structural system, the teams were requested to locate the centroid of their frame that would result in the edifice achieving a balanced state. After discovering the neutral axes within their design, the students were given the charge of applying a counterweight, in grams, to an internal area within their design of the unstable body to bring the composition into equilibrium and thus, stand on its own accord. This stage of the project distinguished itself from the previous scenarios in that it did not ask the students to develop a secondary support system to bring the unstable body into equilibrium. Instead, the students were required to compensate for the instability of their frame by locating the neutral axes, applying the counterweight, and compensating for any variations within their design by increasing the frequency of internal triangulation members at specific areas to calibrate their overall assembly.

After recreating the homogenous form from their previous exercise, the student team of Michaela Chrisman, Kristine Punzalan, and Michael Fleck applied a counterweight of 250g within their structural assembly near its presumed neutral axes, initially resulting in an over-compensation of weight distribution among the total assembly. As such, the team utilized dowel rods as internal members to redistribute the weight among their model and incorporated thread as diagonal tension members to disperse the load to the unbalanced portion of their physical assembly and ultimately, achieve the goal of this scenario [fig 7].

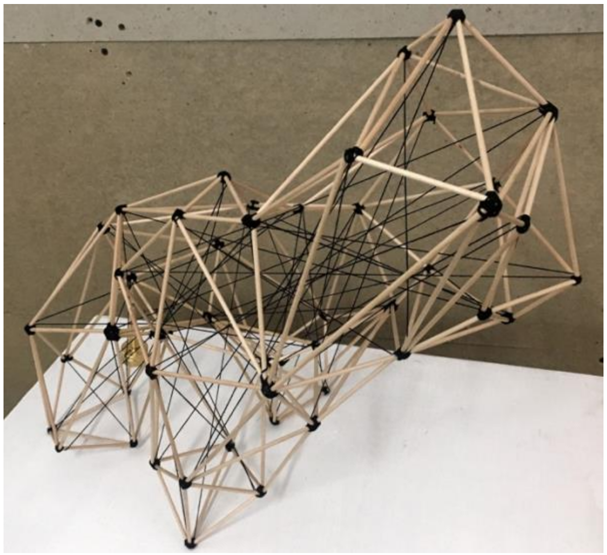

Fig. 7. "Balance Within" final solution by students Michaela Chrisman, Kristine Punzalan, and Michael Fleck.

Conclusions and Findings

These hands-on learning exercises provided the students an avenue to innovate, test, and reconsider their predictions for how systems behave and respond to applied external parameters. It is the author's observation, that by embracing failure as an integral part of the iterative design phase, students were discouraged from baseless form-finding exercises. Instead, the projects placed emphasis on the performance of dissimilar material systems in hopes of inviting students to integrate these lessons within their architectural studio projects. In future versions of the projects, students will be initially tasked with integrating case studies to better facilitate a design process that focuses on the interactions of forces and behavior of materials.

As commented by student Michaela Chrisman, who completed the series of balance projects: "All three phases of the project involved discovering how the systems worked together by first understanding how they failed. Each phase involved a process of trial-and-error testing to achieve a common goal, yet each exercise helped to inform the subsequent phase because of the knowledge that I gained throughout the process. The trials of the structures balance projects showed me how to use creative design strategies when thinking about fabricating new structural connections and how they work within a system."[7]

Notes:

1 D'Arcy Wentworth Thompson, *On Growth and Form*. (Cambridge: Cambridge University press, 1961), 11.

2 Peter Pearce and Susan Pearce, *Experiments in Form, A Foundational Course in Three-Dimensional Design.* (New York: Van Nostrand Reinhold Company, 1980), vii-viii.

3 Alexander Zannos, *Form and Structure in Architecture: The Role of Statical Function.* (New York: Van Nostrand Reinhold Company, 1986), 9-10.

4 Emma Nsugbe and Chris Williams, "Robert Le Ricolais — Visions and Paradox: AA Exhibition Gallery 11 January – 5 February 1999." in *AA Files*, no. 39 (1999), 55-60.

5 James Bryan, "Robert Le Ricolais: Things Themselves are Lying, and so are Their Images," in *Structures Implicit and Explicit,* ed. by James Bryan and Rolf Sauer. (Philadelphia: Falcon Press: Graduate School of Fine Arts, University of Pennsylvania, 1973), 197–199.

6 Maria Vrontissi, "The Physical Model in the Structural Studies of Robert Le Ricolais: Apparatus or Hierogram," in *Structures and Architecture: Beyond their Limits*, ed. by Paulo J. S. Cruz. (London: CRC Press, 2016), 1321

7 Michaela Chrisman, e-mail to author. January 10, 2019.