Comprehensive and Creative Conclusions: Enhancing Structural Design Educational Opportunities in Labs for Architecture Students

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Abstract
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COMPREHENSIVE & CREATIVE CONCLUSIONS: Enhancing Structural Design Educational Opportunities in Labs for Architecture Students

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ABSTRACT
For decades, structural design has erroneously been taught to architecture students using a modified version of an engineering-based pedagogical model. Instead of imparting a broad range of information for how structural design considerations could be critically integrated into architectural design, these courses instead focus on a narrow range of curricular topics and analytical methods that negatively impact the preparedness of architectural students for practice.

To help address these deficiencies, the entire building technology course sequence at Iowa State University, has been dramatically reconfigured as a collaborative and integrative teaching environment that uses active learning environments and unique classroom activities to enhance student learning. Specifically this paper will present three different labs that occur during the final five-week course module of this structural design sequence. Each of the three exercises demonstrates particularly important, capstone-level, learning objectives.

The paper will describe the means, methods, challenges, and benefits of these specific assignments and how these represent other important improvements throughout the new sequence. Examples of student work will be shown, and an assessment of the efficacy of the assignments will be presented including reflections upon lessons learned and suggestions for future improvements.

INHERENT INEFFECTIVENESS
Effectively teaching structural design to architecture students is an important, but complicated process. At its most basic level, architectural education teaches ways to create accommodating and experiential spaces and forms, yet the extent of possible responsive solutions requires the coalescence of a multiplicity of diverse cultural, aesthetic, and technological considerations. Although design is a reiterative process that rarely has a single correct or obvious answer, there are aspects, like structural design, that do require quantifiable verification for viability. Therefore, designing requires an ability to experiment and evaluate different arrangements and assembly options using both qualitative and quantitative analytical means and objectives. Learning these different skills can be complex and confusing, especially because these skills are frequently taught quite differently.

Unfortunately, for the last fifty years, structural design has been predominantly taught to architecture students in a manner more in line with an engineering education. By continuing to base the course content and pedagogical approach primarily on calculation-based means of analytics and evaluations practiced by the engineers,
architecture students miss critical opportunities to learn about the larger design implications of structures. Ultimately this mismatch of learning/teaching preferences between engineering and architecture leads to diminished enthusiasm for learning and decreased retention levels for the subject matter (Felder, Silverman, 1988).

This discord between what is taught and what should be taught to architects isn’t just a problem of missed opportunities for enrichment, it affects professional preparedness if students are unwilling, or unable, to critically engage or evaluate aspects of structural designs. In fact, the lack of student preparedness to critically integrate building technologies is frequently listed atop the complaints from practitioners and recently graduated students alike in the National Council for Architectural Registration Boards (NCARB) annual Practice Analysis of Architecture reports (NCARB, 2012). Unfortunately, even though structures typically comprise between 15-40% of the overall cost of construction and represent the single biggest risk factor for professional liability, the National Architectural Accreditation Board (NAAB) provides very few requirements for structural education, granting this topic only one sentence in their most recent draft for requirements for an accredited architectural education (NAAB, 2013).

Although it is clear that at some level an alternative pedagogical approach is needed, there are often fundamental impediments to these changes and few mandatory requirements for initiating these changes.

**IMPEDIMENTS TO IMPLEMENTATION**

The challenges of teaching structural design are relatively unique in an architectural curriculum. In practice, structures is very design-oriented with a focus on problem solving, but the ability to solve these problems relies upon detailed knowledge of math, physics, material science, and construction methodologies that must first be understood before significant design options can be viably explored. In other words, there are two distinct, and often divergent, sets of skills need to be taught: design and technology. Historically, the common thinking has been that the technological knowledge needs to preclude design so frequently the classroom settings, teaching methods, and course content aren’t inclusive to both sets of needs—focusing on the traditional approaches to teaching engineering.

This pedagogical method typically favors the sensing/active or factually based learners (like many engineers), as opposed to the intuitive/reflective learning preferences most typically self-identified as architecture students (source). The course information is typically taught deductively (going from fundamentals to application), even though the opposite approach, induction, is the predominant method used in the plurality of a project-based design curricula of architecture. Further problems occur when courses are lecture-based, passive learning environments, with little opportunity for alternative activities (Felder and Silverman, 1988).
At a curricular level, structural design courses may run counter to the larger educational culture of architecture if the various structures courses don’t require escalating levels of expertise between courses (e.g., traditional courses sometimes focus simply on analyzing different materials each semester). When fundamental skills are developed across multiple years in the courses, it becomes more in line with the larger learning objectives for the program and the evolving skills of the students.

These observations point to two major categories of constraints that architectural programs face in trying to amend their structural sequence: Curricular/administrative limitations (such as course credits, classroom settings, staffing, etc.) and pedagogical intentions (reconciling required and desired learning objectives, teaching practices, expertise/experience of instructors, etc.). As this paper will demonstrate by examining the revised building technology sequence at Iowa State University, when both constraints are amended in concert, a slew of educational benefits can occur.

**EXPERIMENTS IN INTEGRATION**
The goal of the reconfiguration process was to create a better, more integrated, undergraduate technology sequence that created better opportunities for innovative teaching and effective learning opportunities (Whitehead, 2014). To facilitate these changes, the initial major modifications were necessarily administrative.

All three building technology courses (materials/assembly, environmental forces, and structural design) were combined together into a single course sequence spanning across five semesters. Each semester is equally divided into three equal modules of five weeks (one module per topic). The credit hour total for each class was increased but the overall amount of credits within the entire curricula for all tech courses (when combined) remained unchanged. At least three different instructors (each with practice experience) teach the courses so each instructor can teach “across topics” and include integrated design assignments as part of their module (Nelson, Whitehead, 2014).

All aspects of the courses were updated accordingly and reconfigured, including the classroom settings. The courses use a “lecture-lab” system in which the first portion of the class is a lecture that presents the information that students need to solve a set of design “problems” during the lab portion of the class that immediately follows. The combination of the two classroom settings provides an opportunity to have both active and passive learning portions of the class and a diversity of activities and representations of learning to occur (a significant improvement upon the traditional either/or choice for classroom settings).

Research about effective engineering educational influenced our choice to include problem-based and project-based learning opportunities in our labs (Mills, Treagust, 2003). However, scholarship on the matter published in the *Journal for Engineering Education* over the last 20 years has been consistently rare (Feisel, Rosa, 2005) so much new ground needed to be established.
The structural module, titled Structural Technology in Practice (STP) incorporates a series of purposefully selected, structural-centric, design exercises into the labs (alongside the occasional traditional calculation-based assignments). During these multi-hour active-learning labs, which are intentionally more akin to a design studio, students are taught to develop different strategies for creating and assessing their work—a process simply known as “think, make, break, + evaluate” (Figure 1) (Whitehead, 2013). Interestingly, some of the scholarship about effective engineering education frequently referenced the architectural studio model as influential (Kuhn, 2000).

Assessment is typically based upon the lab reports for the “project” that the student teams create. These lab reports feature technical diagrams, drawings, models, calculations (when required), written justifications work, and a summary of “lessons learned” about the topic. This broadens the options for learning styles and promotes a multimodal means of representations—both demonstrated strategies for increasing the learning capacity, retention and enthusiasm (Tolentino, 2009). Ultimately, because this project-based learning approach is pervasive throughout their studio education, the structural courses become more in line with their overall educational experience and not a curricular anomaly.

Because the course spans across five semesters (beginning during the student’s first semester in the professional program and concluding during their comprehensive studio semester), a larger pedagogical narrative can be established for each course individually and for the entire sequence collectively. Across the sequence students complete forty different labs, allowing a diversity of lab activities to occur in correspondence with the subject matter (e.g., some labs require frequent calculations while other explore detailing). This is one of the most important benefits to the reorganization process because it allows instructors to maintain contact with students each semester, helps monitor students development, helps to improve student retention, and allows the courses to develop a natural trajectory of escalating complexity and difficulty.

This paper will focus on the three lab projects completed in the fifth, and final semester of structural program. The three projects are all intentionally quite different
from each other in terms of learning objectives and activities. They are capstone projects, so students are asked to demonstrate expertise and application of previous knowledge while exploring/engaging in the advanced realm of long span structures. As the paper will demonstrate, establishing diversity in the final lab exercises is highly beneficial because it allows students the opportunity to demonstrate the broad range of structural/architectural knowledge that they have accrued across the entire sequence and covers a broader range of learning objectives, and it teaches them a range of problem solving skills.

A LONG EDUCATIONAL SPAN
Ultimately the goals for the final course in the structures sequence reflected a more comprehensive view about the types of knowledge and skills that architecture students should possess upon completion of their structures education, including integrative thinking between design and technology. The course goals were also informed by other curricular goals such as the ability to research, document, and effectively communicate.

The structural content of the final course is, expectedly, advanced. In previous semesters, the course had followed Engel’s general classification of structural typologies: form-active, vector-active, section-active, surface-active, and height active systems, but this semester focused on long span structures, in part because long span systems can typically be created using most of these different structural strategies (Engel, 2007). As a result, any new work would require students to call upon their previous knowledge about structural behavior and materiality.

Long span systems offer additional advantages as capstone exercises because in practice, they are evaluated by considering a range of other traditionally “non-structural” factors such as cost, fabrication, assembly, detailing at connections, and spatial composition. Because of the integrated nature of their technology sequence established by combining the three courses together, these types of considerations were easily be adopted into the expected learning outcomes.

Many types of long span systems are indeterminate and/or can’t readily be calculated by students, and so mathematic evaluation of long span systems was never desired as an objective. Instead the course focused on a more practical system of evaluation and sizing based on rules of thumb and precedents. Various long span structures were discussed and designed, so students could compare different systems to each other and comment upon the various design aspects of each typology.

Because long span systems are typically very expressive, or at least, quite formally dominant, many assessments of their structural work necessarily needed to also include a certain degree or architectural design and aesthetic judgment—a circumstance that was a great benefit to course. Two of the exercises required students teams to design a long span structure for a given scenario, while the third exercise asked students to specifically evaluate the design intentions of a long span structures from an architectural and structural perspective. Basically, by selecting
long span systems for the course, the labs could simultaneously consider advanced design and technology considerations concurrently.

The first assignment, an ambitious multi-week comprehensive research project, outlined and initiated many of these course goals and gave students immediate exposure to a broad range of successful and celebrated long span projects.

MOVING FORWARD BY LOOKING BACK
At the start of their final module, as a way of introducing the multiplicity of options for long span structures and demonstrating the expectations for the course’s activities, students were given a list of 75 different long span structures projects from all around the world, all built within the last 100 years, primarily designed by renowned architects and engineers, representing a broad range of structural typologies in material, assembly, and program. Students were asked to immediately form teams (up to 3 people), collectively review the list of projects, and make their selection. The handout summarized the overall exercise objectives in this manner:

“The purpose of this research assignment is to allow you to demonstrate the breadth and depth of knowledge you have gained about structural systems throughout the course, and to apply these lessons towards your analysis of a long-span system. You will research, analyze, understand, and communicate comprehensive considerations of design, construction, structural performance, and environmental factors related to the long span projects. You will collaborate as a research team to produce written, graphic, and three-dimensional analyses of an existing building and defend these findings in a verbal presentation to structural engineers and architects.”

This work takes place continuously across five weeks of the module (running concurrently with the other labs discussed herein) and included two intermediate deadlines for abstracts, paper outlines, and a mock-up of the overall presentation. This gives the instructor and teaching assistants opportunities to productively direct the research and to answer technical questions that arise. Ultimately the teams were required to write an original 2000 word essay, produce two original drawings that demonstrate the scope and performance of the building’s structural system, and construct a sectional model that accurately demonstrates critical information about the structural system’s components, scale, connections, and interactions with other key building systems.

This assignment was clearly different in scope and complexity from other assignments they’ve completed in the sequence up to this point, primarily because there is no explicit “design” component of the lab for the students to create. In this project, the design intentions of others become part of the overall evaluative an analytical process—interestingly, students were much more honest and critical of issues related to design integration then they had been previously in evaluating their own work. The process of researching and analyzing precedents is commonly used throughout the architectural criteria in seminars and studio so the application of these skills to a technology class was relatively seamless, albeit a bit unexpected as
evidenced by certain course evaluation comments (e.g., “Is this a history class or structures?”).

Ultimately, teams present their work to practicing architects and engineers during their final class period and answer questions about their conclusions (Figure 2). An overall assessment of the quality of the work is difficult to quantify in traditional terms (as it is a non-traditional structures assignment), but feedback from visiting professionals, other instructors, and even the students themselves has been overwhelmingly positive. In general, the most surprising aspect of the student work noted by reviewers relates to the insightful conclusions that many groups find through the analysis of the construction process—especially when there have been complications in constructing the buildings. As an example, one group analyzed Saarinen’s Kresge Auditorium at MIT and found that the geometry of the building was not only inefficient as a structural shell but also incredibly difficult to construct—their drawings and model focused on these problems (Figure 3).

Not all projects are successful, or even correctly analyzed by certain teams. At times this is a reflection of overall effort and insight, but there are certain projects that seemingly defy a logical analysis of all components from a purely structural perspective (e.g., some of the work of Santiago Calatrava) or other projects that are simply too complex to accurately understand (e.g., other projects by Calatrava!).

Overall, by presenting this project during the first class and requiring students to continually work on it during the remainder of the module helps reinforce the connections between technological considerations and design intentions. However, because practice requires more than analysis, the other two projects are more design-oriented with varying levels of required technical resolution.

EVALUATING PROCESS AND PERFORMANCE
After a week of lectures outlining general design guidelines for one-way and two-way long span trusses systems and their components, student teams were given two days to design and construct a lightweight truss system using only 1/8" diameter wooden sticks and hot glue. These platform trusses could use ANY configuration and scale of components and supports as long as it was at least 2’-6” wide with a 4’ clear span between supports and maintained a 10” clearance underneath the middle of the truss after being uniformly loaded with 50 pounds of weight (bags of ice or sand). In lectures, students were taught that actual long span trusses typically offer a high level of structural efficiency in terms of weight to bearing capacity so there was a class-wide competition for the team that could design the lightest compliant structure.

Due to the compressed time frame for design and construction, students were clearly directed towards making certain decisions about the truss configuration (one-way or two way system), the system of support (soda cans were allowed as columns), and the relative size, spacing, and placement of the truss components as it related to the type and number of hot glue connections (under testing, hot glue accurately responds like a typical pin joint found in most truss connections if the teams construct the joint accurately).

The intention of the assignment parameters was to cause the trusses to fail under testing, primarily because certain failures help students develop cognitive anchors when they are able to visualize certain structural behaviors that are frequently hidden or abstract (Barsalou, 2008). Specifically, the heavily loaded long spans test the limits of the joints and components, cause great stress at the connections to the columns, and present options for many different types of failures. When the trusses deflected, bowed, cracked or warped under loading, it was much easier for the student groups to identify the liabilities of their design and to comment upon these failures in their lab reports. Creating, observing, and ultimately analyzing these failures enhances embodied cognition, which is an important learning method for intuitive learners (Han, Black, 2011).

There are typically three different design approaches proposed. First, some groups try to shape the truss profile in response to the anticipated moment diagram by using an arched truss. This was a common strategy employed for section-active systems in earlier courses, but it is not as directly effective in vector-active systems unless the configuration of the other diagonal components is accurately placed and sized (a lesson many quickly learned).

The second, and most common approach was to build a flat truss platform with differently sized and configured components—either big/wide or small/frequent. Some teams grouped and glued many sticks together in order to create large cross-sectional components for the truss. Their thought was that large verticals and diagonals could hold more weight (again, like the section-active components) and therefore could be spaced further apart. These components certainly were stout enough for the loads, but the hot glue connections frequently weren’t sufficient for the extent of consolidated forces at the connections under testing. This allowed for
two important discussions about truss design: the nature of forces within the components (axial forces only, not bending so overall massive cross-sectional area isn’t necessary) and the importance of carefully designing connections in trusses.

Other groups that used smaller more frequent components typically created more of a space frame truss platform, and these were generally quite successful (unless the components were too small) with two important exceptions. First, frequently these space frame trusses didn’t make any modifications to the components at the point of connections to the vertical supports so these areas would show obvious levels of stress and deformation (which they correctly identify as punching shear). Second, because the components are small, many of the truss components under loading start to bow out (or buckle). This buckling is a very beneficial teaching moment because it helps students visualize how the different types of axial stresses within their trusses affect the component sizes; specifically the way that compression members need to be sized like columns to resist buckling and not loading (Figure 4).

![Figure 4: Images from the truss lab showing the variety of designs and performances of projects.](image)

The third types of solutions were more unconventional hybrid trusses. Frequently, these projects lack a particular consistent order or hierarchy to the arrangement of components and seem to be motivated more out of a creative spirit of architectural invention than a logical perspective of structural behavior. These always fail under loading, often immediately and dramatically, usually as a result some sort of inherent inconsistency in the arrangement of components that leads to a strange flow of forces. These solutions reveal a key potential liability in the project—when architecture
students are asked to design something, many rely upon the ingrained practice of breaking the rules in search of originality. While this can lead to some interesting approaches to the problem, it rarely works as well structurally. When design and technology don’t correspond, it is difficult to present options for how the structure could have worked without simply suggest that it use a conventional arrangement. As a class we discuss how this becomes a key issue in practice between architects and engineers.

Ultimately, the lab was successfully completed by most teams. The average weight of the structures was around 2.5 pounds, and most held 40 pounds (a respectable 1:16 weight to load ratio using only wood sticks and glue). The best structures have exceeded a 1:20 ratio but ultimately fail due to the limits of the wood sticks. As a result of the lab, the class learned lessons about consistency in design, redundancy in components, and rules of thumb/design guidelines for trusses. Ultimately they realize that trusses are lightweight and efficient, but are complicated to design and engineer correctly.

SELECTION, DEVELOPMENT, AND EXPANDED CONSIDERATIONS
Over the next three weeks, additional information was presented about other long span systems: structural shells, folded plates, geodesics, pneumatics, and lamella structures. Pros and cons of the different systems and key aspects of their behaviors were practically discussed, and this information became the basis for their final design lab of the module.

Student teams (up to 6 people) were given a handout for a hypothetical building with particular requirements for area (80’ x 250’ column-free space) and clearance (40’ height for the middle 25% of the area). Teams were asked to select a long span structural system for the project, develop the design in drawings and details (of a connection), and produce a testable scale model. These systems are advanced, their behaviors are unique, and their construction challenges are profound, so these labs required students to focus less on the intuitive form-making or calculation-based analysis covered in previous modules.

However, in order to substantially differentiate these learning goals from other long span labs, the handout included an important set of exercises that emphasized certain evaluative and comparative standards. The students were taught that each different long span system comes with particular consequences/liabilities inherently associated with their implementation and performance, and these were summarized as “four points of emphasis” that each design needed to address:

1. **Structural Performance: Pros/cons, allowable spans, deflection concerns, shape/strength relationship relative to materiality**
2. **Generation of the Structural Form: Is there a structurally responsive form? How can one test this? Correspondence between macro and micro aspects of the form.**
3. Constructability: Does the structural performance and form dictate a particular means of construction? Does constructability limit or deter the selection of certain materials? Are there CAD/CAM possibilities & off-site construction opportunities?

4. Sustainability & Efficiency: Are these building types relatively efficient because they can enclose a great deal of space with less material? What are the consequences/ecological profiles of the materials used? How does the constructability of the system affect its level of sustainability?

Although the points of emphasis helped establish a common set of assessment and comparative criteria, this was really a difficult lab for some groups because many of the evaluative criteria aren’t clearly spelled out in textbooks or other easily accessible sources. Additionally, not all systems were a good fit for the lab: folded plates can only span approximately 100’, geodesics may enclose too much volume if domes are used, pneumatics have environmental concerns in a cold climate, and the form of anticlastic shells can be very difficult to generate. Ultimately, a comprehensive understanding of the structural behavior of some systems was simply too difficult to fully comprehend in the brief amount of time spent on the lab.

Because each group focused on constructing a single structural system type, there was a concern that they may not get a chance to understand the pros/cons of their system compared to others. For that reason, we set up a system of evaluation where the teams were asked to go around and talk with four other groups, interview them about their structures, and summarize their findings and comparisons as part of their lab report. Creating opportunities for students to engage in two-way interactions was specifically created to help increase and expand their retention of the information (Dale, 1969).

Figure 5: Models of proposed designs showing the variety of proposals and designs.
Overall, there is a great deal of variety or work produced for this lab, not only in terms of the types of systems selected (folded plates, shells, and lamella structures are the most popular), but also in the amount of effort, resolution, and expertise displayed (Figure 5). Not surprisingly, the more successful student groups use the large number of team members to their advantage by assigning certain team members to specific tasks—including precedent based research and prototype testing similar to the previous lab exercises!

Watching student use the same methods explored in previous lab exercises is one of the most telling pieces of evidence that the diversity of approaches presented in this final course module is effective in helping students explore and solve difficult structural questions. Many of the written reports for this final lab easily stand out as the most comprehensive, clear, and technically correct work that most groups have produced throughout their entire structural sequence (Figure 6).

CONCLUSION AND SUMMARY OF EFFECTIVENESS
As the final course in their entire structural sequence, many of the goals and learning objectives established (design, communication, and technical aptitude) also reflect a broader set of comprehensive skills for their overall architectural education. As such, an overall assessment of the relative efficacy of the course, teaching methods, and exercises is more difficult to analyze in isolation. However, if one were to simply evaluate the course based on the level of technical aptitude displayed (and not consider subjective aspects of design integration), there is ample formative and summative evaluation evidence, including assignment grades and test scores, studio teacher observations, and student evaluations that points to the success of the program.
For most students, the work produced in the labs and final exams continues to improve in terms of accuracy and clarity throughout the sequence, and their final projects are frequently used as portfolio pieces—an achievement rarely seen in traditional structures education (one might assume). During this semester, the studio teachers have observed an increased level of demonstrable competency and knowledge for the integration of building technologies for most of these student’s design projects. Anecdotal feedback from students, in letters and evaluations, has also been primarily positive. Certain students, particularly in the first two classes of the sequence, don’t see the purpose of the teaching method but in later classes, particular the final course, students frequently comment upon the usefulness of the course.

Across all semesters, student comments frequently discuss how time consuming and difficult the courses is—a common complaint also for project-based learning courses in other disciplines (Mills and Tregast, 2003). This level of intensity was an intentional choice made to ensure the technology sequence was considered nearly on par with studio in terms of credits and effort. As with other project-based curricula, there are inherent challenges of teamwork and personal interactions that are hard to evaluate—in particular certain students habitual contribute either too much or too little.

Peer review of the program’s success has been overwhelmingly positive. The technology sequence was specifically praised by the National Architectural Accreditation Board (NAAB) during Iowa State’s recently successful visit of 2012. The structural portion of the course has been honored with a NCARB grant for the integration of practice into academy and a 2013 ACSA Creative Achievement Award.

Continued improvements in teaching methods and recalibrations of learning outcomes have been made yearly since the program first began in 2010. Each successive year brings additional opportunities for more formal assessments and comparisons of the effectiveness of the program. As a result of the relatively comprehensive nature of the labs described in this paper, future planned modifications to the program include additional exercises that better integrate all three building technologies together.

RESOURCES


