AC 2011-1067: THE USE OF HISTORICAL PRECEDENT IN TEACHING STRUCTURAL ANALYSIS TO ARCHITECTURE STUDENTS.

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THE USE OF HISTORICAL PRECEDENT IN TEACHING STRUCTURES TO ARCHITECTS

Abstract

Structures are a vital but oft overlooked facet of the architecture curriculum. Structural and historical analyses of innovation in structural engineering and the evolution of structural form provide a useful pedagogical tool. Such analyses facilitate student understanding of fundamental structural principles and foster a greater appreciation for the design potential associated with structural optimization.

Introduction

The teaching of structures is often viewed as marginal in the overall architecture curriculum. A search of JAE archives produces very few articles devoted to the subject. My senior colleagues anecdotally report that they have seen the number and level of complexity of required structures courses decline over the course of their teaching careers. I regularly survey the students on the first day of their first structures course and less than 30% say they would take the course if it were not required. Historical analysis represents a rich opportunity to engage students in the subject material of the traditional structures course, as it is a mode of pedagogy that is familiar to them and it has the potential to foster a deeper understanding of the role of structure in architecture.

Our graduates will practice in a world of hyper-specialization and an ever more technologically complex environment. We must find an appropriate way to prepare them for both the status quo and the technical challenges yet to come. However, we must also acknowledge that students in general and architecture students in particular, are not always interested in or qualified for, advanced technical courses at the university level. There are those who would assume that a lack of fundamental mathematical knowledge is this generation's problem, but it seems that it was ever so. Speaking in 1958 at a meeting of the ACSA, Mario Salvadori bemoaned that

> "you don't know anyone who would boast in public of not understanding Shakespeare's HAMLET, but you find thousands of people who boast about not understanding mathematics at all"[1]

A lack of understanding of fundamental structural ideas can stymie the creativity of architectural design. But an aversion to mathematics does not preclude an understanding of, and an intuition for, how structures work. Plesums argued "knowledge of mathematical methods, however, does not assure a feeling for structural behavior."[2] Severud stated that it is more important for architects to have a sense of the basic fundamentals of how structures work and that the figures can be left to the engineers.[3] I further argue that it is this very intuitive understanding of structural form and its possibilities that newly-trained engineers lack, making it all the more vital that architects can argue persuasively and competently for innovative structural solutions in their design work.

Although they receive a rigorous technical education, engineers are not formally trained to understand the goals and ideals of the architect. Salvadori observed that while there is an enthusiasm to work together the two groups simply do not share a common vocabulary.[4] Obviously there are notable exceptions to this argument, and engineering and architectural professionals doubtless learn a great deal about each other's professions over the course of a career. There is however, a clear disconnect between the two groups in their training. Engineering students are not exposed to the history of their disciple and indeed are relatively rarely exposed to real structures either in the classroom or on site visits. A traditional engineering education focuses on technical skill building and on learning to solve specific, bounded, and isolated problems in a series of early courses whereas synthesis of those skills to solve a complex design problem usually comes late in the undergraduate student career. The engineering teaching paradigm divides complex problems into many pieces which students are then taught to solve independently, all the while anticipating, as Katehi describes in the prominent report "Educating the Engineer of 2020", that eventually they will "be able to develop a solution by combining them."[5] However,

> "Eventually […] the effort involved in learning about the small pieces is so overwhelming that we can longer synthesize the original problem–the parts become more important than the whole."[6]

Engineering educators have long argued that this approach needs to change, but despite efforts such as first year design courses[7] and calls for increased use of problem based learning[8] the situation remains largely unchanged.

In a separate study, I have found engineering students to be largely unfamiliar with the practice of engineering. In an informal survey, I asked a group of 102 engineering (a mix of civil, environmental and biomedical engineering) students at the start of their sophomore year to name an engineer whose work they admired. Not a single student was willing to venture an answer. When I further asked them to *name any* engineer, the group collectively offered up: Nikola Tesla and a handful of names of College of Engineering Faculty. In a more controlled environment, when carrying out initial evaluation for a cross-disciplinary architecture/engineering seminar, 24 third and fourth year structural engineering and architecture students answered a survey about their cross-professional perceptions. In general architecture students were more familiar with the people and objects of *both* the architecture and structural engineering disciplines. All students were asked to name three engineers and three architects whose work they found interesting. In a group of eleven, only four engineering students even attempted the question. The four "engineers" they named were Leonardo daVinci, Thomas Edison, Michelangelo, and (questionably) Benjamin Franklin. Architecture students answered the same question with a mix of prominent historical and contemporary structural engineers. The students were asked to identify three buildings or structures they found aesthetically or architecturally interesting and three they found structurally interesting. Architecture students (as expected) answered this question competently. Engineering students when they answered these questions at all often cited buildings on the SU campus and the same three case studies they had encountered in previous courses. The same study found architecture students to have a more applied knowledge of structural engineering than did their engineering counterparts, for example engineers were more likely to know the formula for a parabola but architects were more likely to know that it was the correct shape for a uniformly loaded arch to be in compression.[9]

In the role of project manager and creative director the architect needs to extract the best technical help possible from their team. To this end, a solid grasp of the fundamentals of structural engineering is vital. An intuitive understanding of structural engineering grounded in real world examples is vital to inculcate structural innovation in architecture student's future work. Using historical precedent is an extraordinarily powerful way to do this. It provides a framework for how structural innovation has happened in the past and a presents a rubric for how bowing to the physical forces at play and activating the capacity of the material in question can lead to efficiency and elegance of form. It is particularly important to use historical precedents that represent the very best and most innovative examples of structural form and material use. The case studies that are most illustrative of structural art emerged as engineers strove to find new forms for new industrialized materials and to span ever wider and build ever taller. These examples can best activate the relationship between structure and form and generate student enthusiasm and appreciation for the role of structure in their design work.

The Course

ARC 211, Structures I, is the first of a two-course sequence in structures required for all students in both the BArch and MArch programs at Syracuse University School of Architecture. The course introduces basic concepts of structural system behavior; gravity and lateral loads, analysis of major structural forms, and structural performance of materials. These topics examined to gain a physical understanding of major structural forms through the study of historical and contemporary examples of structural engineering. This course is intended as a first course in structures for architecture students. The course focuses on the tools required for analysis of structures; forces, vectors, stresses, moments, loads, reactions, connections, principles of static equilibrium, free body diagrams, shear force and bending moment diagrams, properties of area (centroid, moment of inertia), These concepts are learned through the analysis of trusses, beams, cantilevers, columns, cables and arches.

Historical precedents are used in two ways in the course: as lecture examples that introduce the fundamental principles of structural engineering and as individual case studies that the students carry out as course work at the end of the semester. Although almost any historical example might be instructive the precedents are generally chosen for their innovative nature. Examples of the very best of structural engineering, those structures that embody the principles of Efficiency, Economy and Elegance[10] make for the best teaching examples when the aim is to generate an appreciation for the role of structure in architecture and design.

A series of lectures introduce new topics in the structures curriculum through historical examples. The study of Thomas Telford's iron bridges introduces the mathematics of the cable and the arch and the importance of new forms for new materials. The Eiffel Tower is an object lesson in the importance and relevance of the dreaded bending moment diagram. The George Washington Bridge represents an opportunity to talk about safety and load probability calculations. Discussing Fazlur Kahn at SOM working on the first tube buildings with Bruce Graham (the Hancock Tower, the Sears Tower) serves as both an introduction to the most widely used forms for tall buildings but also into how the architect/engineer relationship can have a synergy that creates something entirely new that neither discipline would likely produce in isolation. The bridges of Robert Maillart are a favorite among architecture students and illustrate the nature of concrete, the evolution of structural form to match and to manipulate the forces resulting from the loads on the structure. Shells and plates are very difficult to understand mathematically, and are generally only covered in graduate level courses for engineers. But, Pier Luigi Nervi's ribbed domes, slabs, and barrel vaults are so structurally expressive with the ribs literally tracing the flow of the forces, that any student can gain an appreciation for the potential of such forms. The inverted hanging forms of Gaudi and Heinz Isler are similarly accessible in principle despite their complexity in detail. The students of ARC 211 all build their own shell models, and test them to failure, using the methodologies of Gaudi and Isler. Seeing the historical form finding methodologies of someone like Gaudi, who is familiar to them from their architectural history courses, and understanding how concerned with efficient load carrying he was (like the Gothic stonemasons before him) is an eye opening moment for architecture students who do not see structures as integral to their design agenda. Taking a 2 ft x 3 ft piece of canvas and some rockite, and making a shell only millimeters thick, and then finding that it can hold the weight of one of their tem members, is an object lesson in the power of the curve and the potential of appropriate structural form that students remember three years after they take the course. The work of Torroja and Candela provide insight into how a properly designed shell can in one simple move provide structure, enclosure and aperture.

Student Work

The students in the course also undertake a case study of their own at the end of the semester and it counts for 25% of the final grade. They are required to complete an original structural analysis of their chosen structure explaining the primary structural mechanism that supports it. They are further required to discuss both the functionality of the structure and the broader historical, political, economic and architectural context of the structure and how those topics are interrelated. This project has evolved with increasing student numbers to be a group project, and students may chose any structure (contemporary or historical) that they are interested in, just over half chose a historical precedent to study.

Considering these students have only one semester of structural engineering training the range and depth of the case studies they undertake is laudable. Figures 1-7 show images from student analyses of historical case studies. Although being asked to write in a structures course often surprises students, the idea of precedent study is familiar to them. Ultimately almost all students produce a reasonable mathematical analysis of their chosen structure, but more importantly all can demonstrate diagrammatically how the principal load carrying mechanism functions.

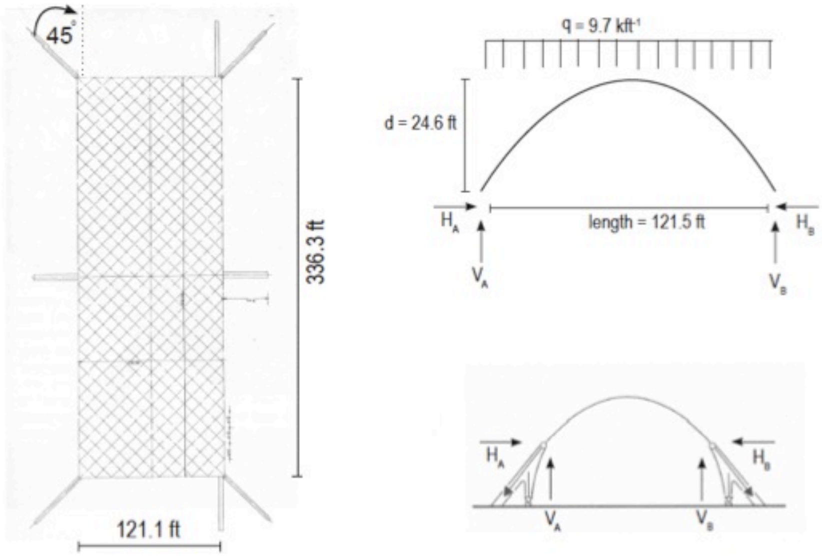

Figure 1
Student case study analysis of the Orvieto Hangar, designed by Pier Luigi Nervi, 1935.
Credit: Vijaya Diana Pieterson, Syracuse University School of Architecture.

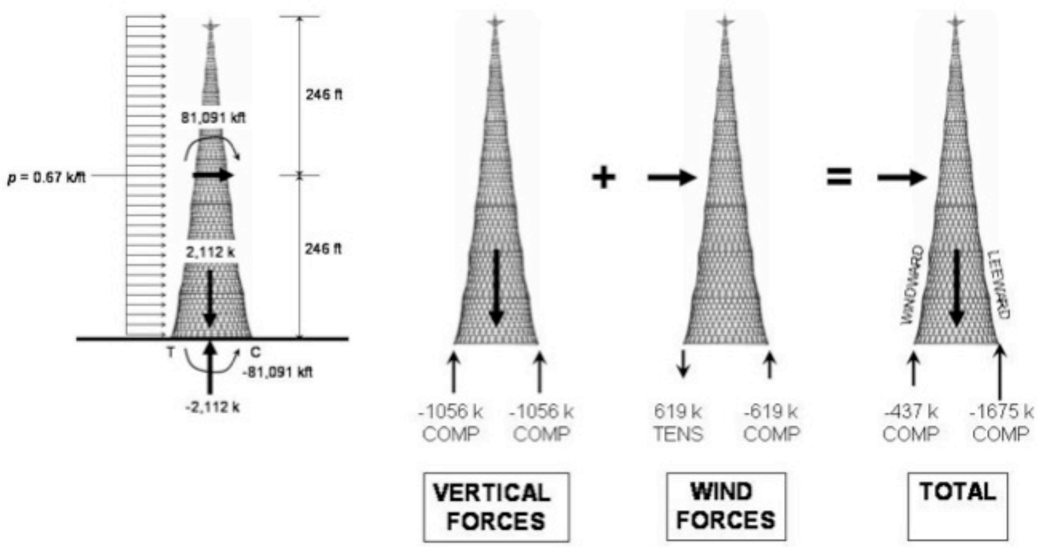

Figure 2
Student case study analysis of the Shabolovka Tower, designed by Vladmir Shukov, 1922.
Credit: Vasiliy Lakoba, Syracuse University School of Architecture.

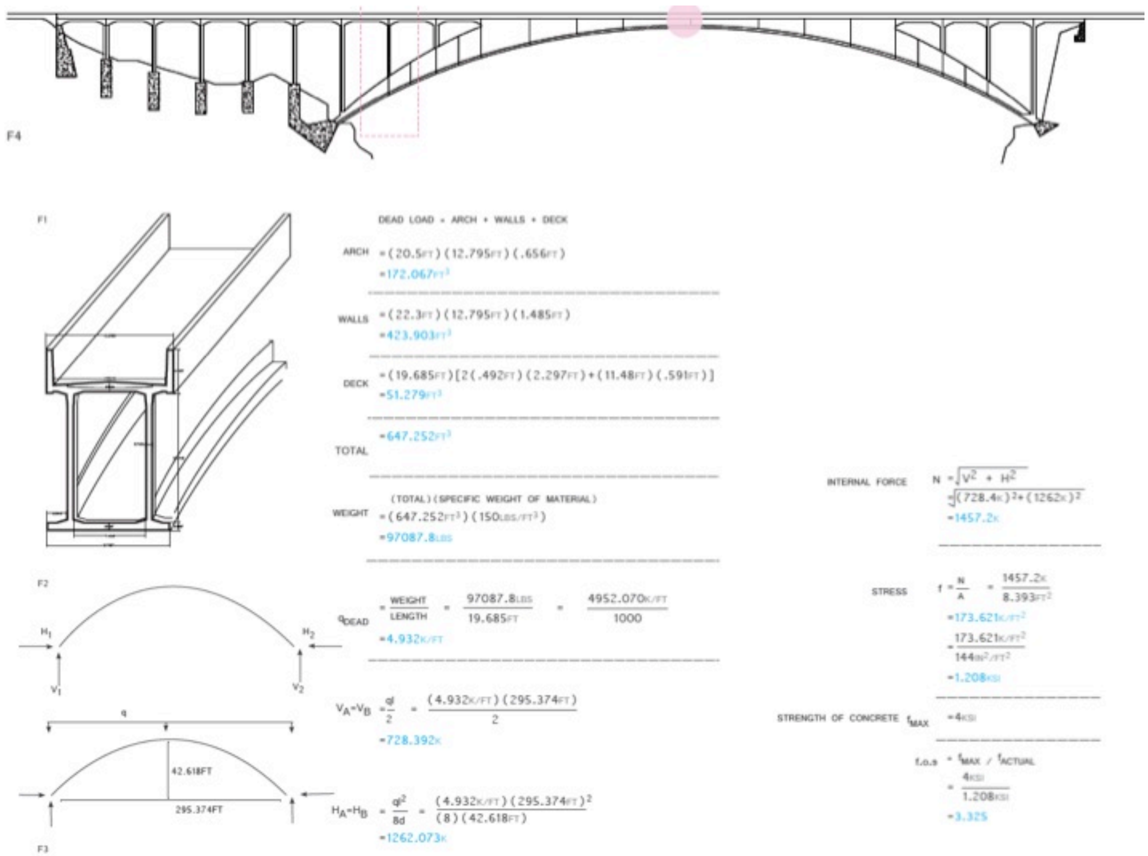

Figure 3
Student case study analysis of the Salginatobel Bridge designed by Robert Maillart, 1930.
Credit: Timothy Gale, Syracuse University School of Architecture.

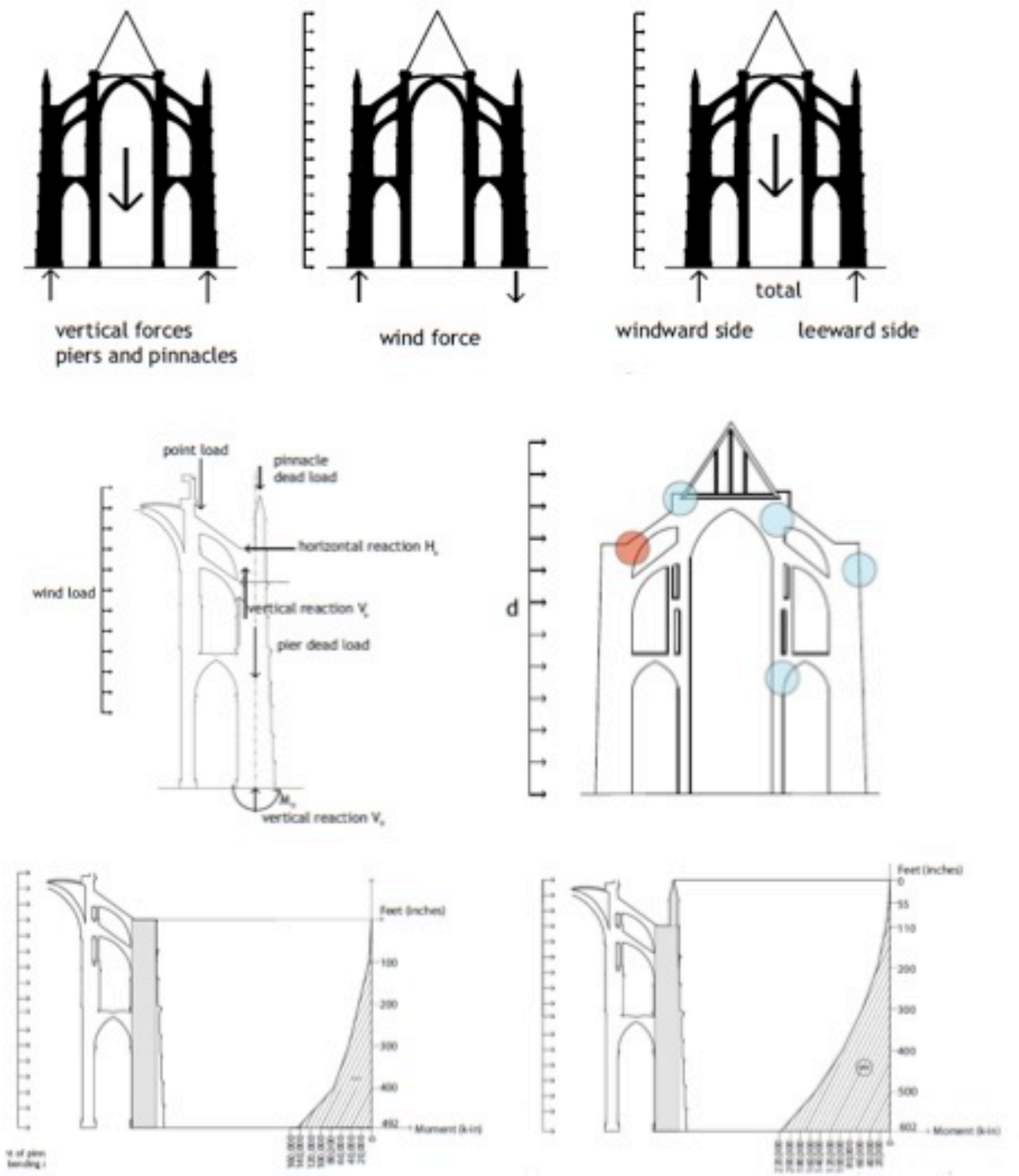

Figure 4
Student case study analysis of the Amiens Cathedral, designed by Robert de Luzarches Thomas de Cormont and Renaud de Cormont,1228-1260.
Credit: Hilary Barlow and Laya Pattana, Syracuse University School of Architecture

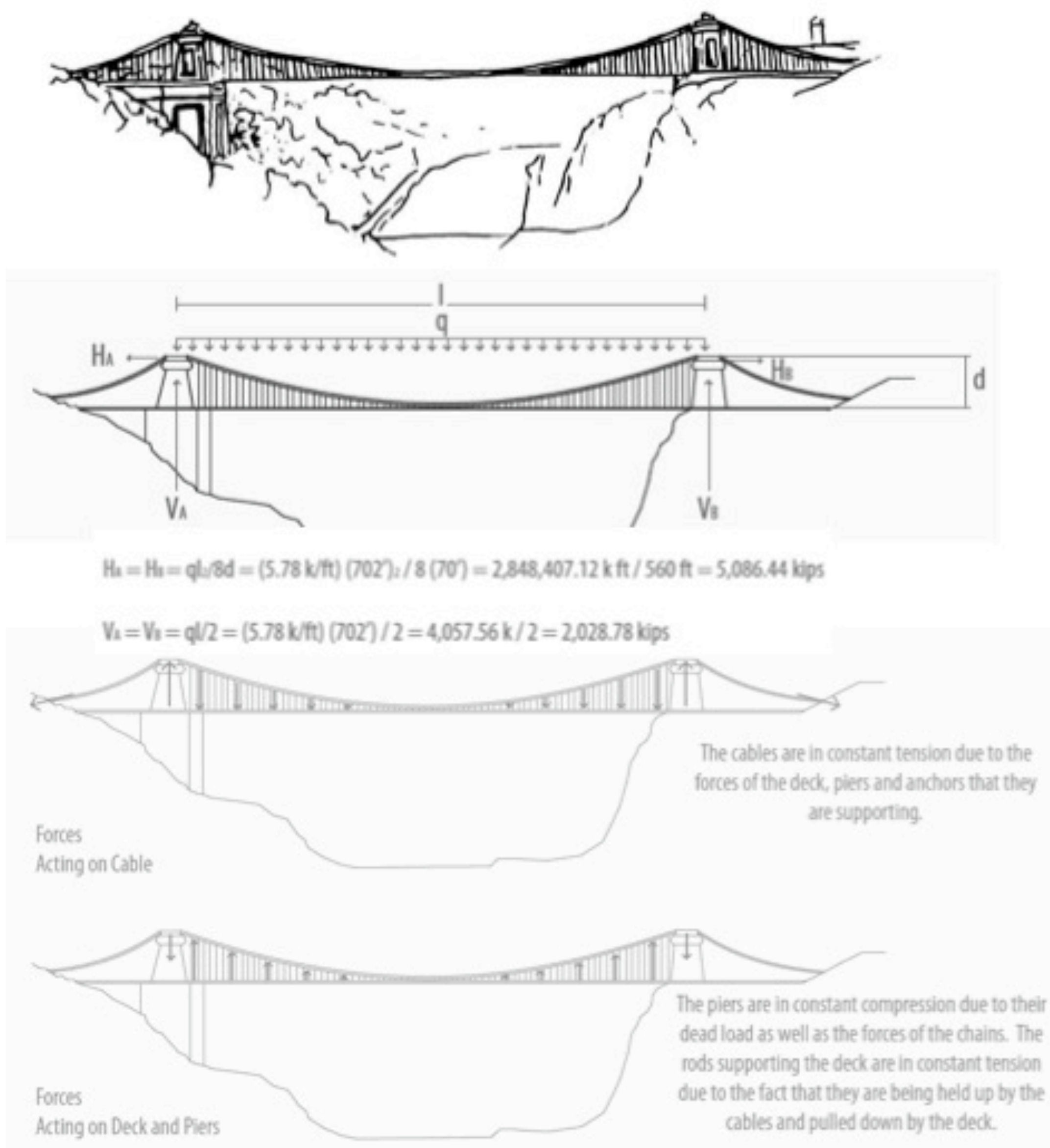

Figure 5

Student case study analysis of the Cliften Bridge designed by I.K. Brunel, 1864.

Credit: Nicole Perez and Kara Thompson, Syracuse University School of Architecture.

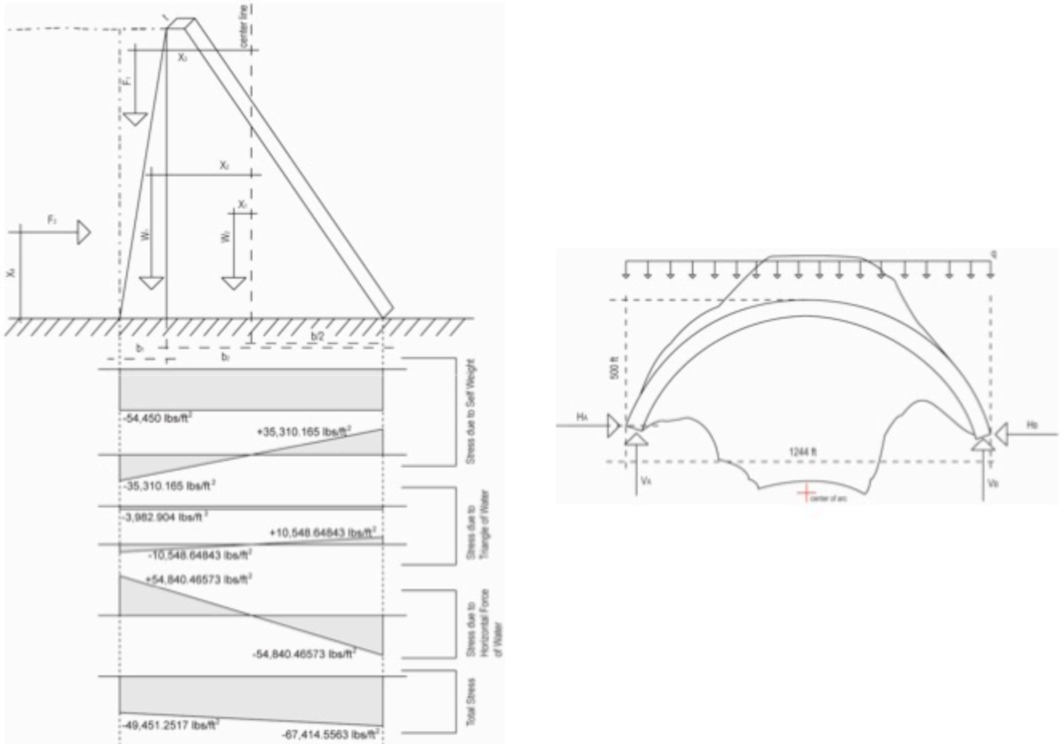

Figure 6
Student case study analysis of the Hoover Dam designed by the U.S. Bureau of Reclamation, 1936.
Credit: Alexander Tafrov, Syracuse University School of Architecture.

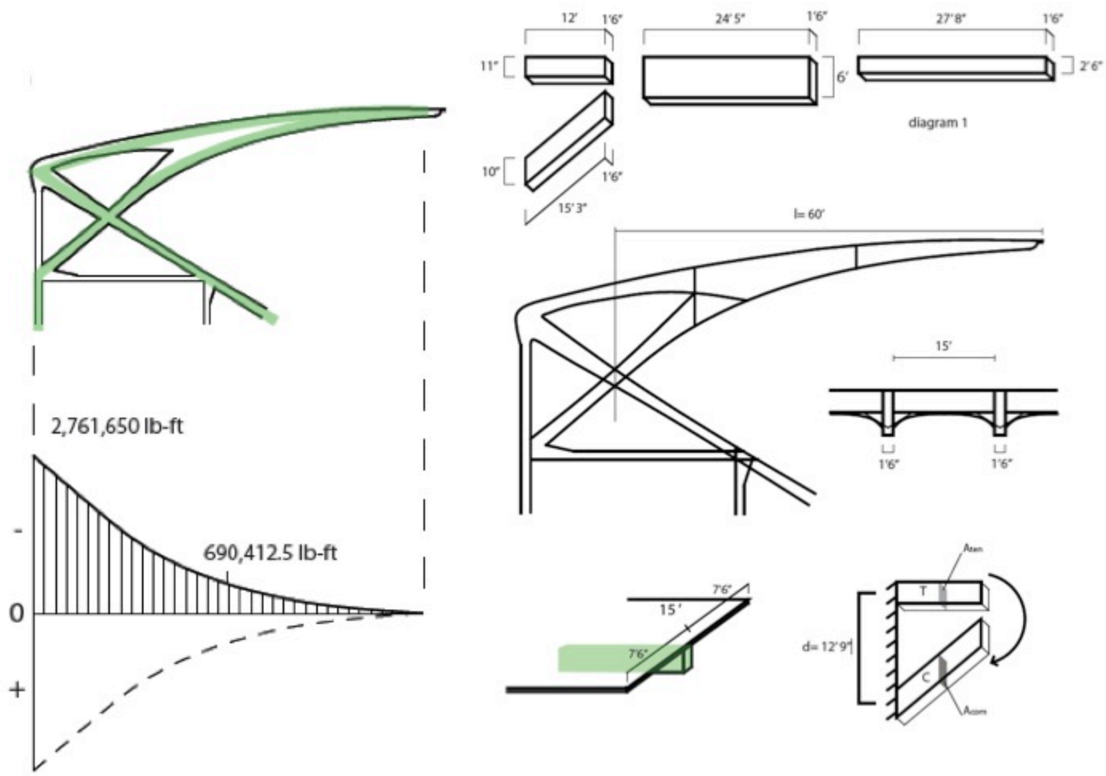

Figure 7

Student case study analysis of the Florence Stadium designed by Pier Luigi Nervi, 1931.

Credit: Karen Kentile, Syracuse University School of Architecture.

Student Response

The response of students to the historical component of the structures course has been overwhelmingly positive. In four years of teaching the introductory structures course this way at Syracuse University School of Architecture the students have shown considerable enthusiasm both for the historical examples used in the lectures but also for further historical research. When given the opportunity to choose any structure they wished for the final project in the course half of the students chose from pre-1970 structures. Their willingness to attack complex source material and extract the fundamental structural behavior of a building or bridge has been impressive. The School of Architecture's working drawing collection has seen heavy use and some were even brave enough to cross the quad to the science library where such gems as the engineers report on the construction of the Golden Gate Bridge were checked out for the first time in decades. Students who have taken the current version of the course also continue to display an appreciation for the role of structure in design after their required courses have ended. Between 25% and 30% of the graduating class request a structural consult on their thesis design project, this was not so before the course was taught as described here.

In order to gather more formal student response data a survey was sent to approximately 350 students who have taken the course over the last three years (those from four years ago having graduated). The response rate was 127 students within three days. The group had a mix of bachelors and masters students and a ratio of men to women that was similar to that of the total population who had taken the course. The size and make-up of the response group lends considerable weight to the validity of the responses.

Student reactions to the historical examples used in ARC211 to introduce fundamental structural principles in the survey show broad based support for this approach (Figure 8). A concern when using analysis of real structures with novice structures students is that it may be unnecessarily complex and cloud the students understanding of the underlying principle. On average, students did not share this concern and over 75% of students disagreed that abstract textbook examples would be easier to digest. Of the remaining 25% the majority were neutral on the subject. Far from being put off by the historical examples, students seemed to think it was the obvious way to approach learning structures with over 90% of students in agreement or strong agreement with that statement. This revelation is perhaps not surprising to those in architecture education where history surveys are an absolute pre-requisite, but to engineering educators it is almost revolutionary. The most encouraging results from the survey were that students felt the study of historical precedent had value both in learning the new concepts *and* in appreciating how those concepts were useful and relevant in their own work. Approximately 90% of survey respondents either agreed or strongly agreed that historical case studies made it easier to understand the course material and facilitated a deeper appreciation of the role of structural engineering in architecture. Furthermore, 60% agreed or strongly agreed that this approach made them more confident in applying their new knowledge in the studio. Thus, the value of the historical precedent in activating student engagement in both structures and the application to their design work is clear.

The survey respondents were also given an opportunity to add any open-ended comments they might have on the use of historical examples in the course. A number of students responded that it was the "reality" of these historical case studies that made them useful pedagogical tools:

> "I enjoyed the use of historical examples because I always find it helpful to look at something real rather than something imagined or just a diagram in a textbook. I think people can visualize it more easily that way."
>
> "Historical examples kept me interested in what we were learning in class. It helps to see real life applications to the concepts."
>
> "Memorization is not my strong point. Having a story to attach to the topic we were learning really helped me to remember it"

However, they also demonstrated more nuanced interpretations of the role of the historical precedents, such as the capacity to illuminate the evolution of structural form, which in turn made structural forms easier to understand.

> "I thought using historical examples was a great way to learn about structure and its evolution."

> "I believe that using historical examples of structural systems is very helpful to the learning process; it is important to understand not just modern structural systems, but where they came from and how they evolved into what they are today. Using recognizable historical structures also helps to give context to the examples being used, possibly making the material easier to understand/relate to real-life"

Further, they appreciated the study of individual engineers and engineer/architects and their approach to problem solving and how that might have relevance to their own design work.

> "I especially liked learning about the structural engineers and how they used simple ideas to manage design problems. It got me thinking that even in our studio projects we could potentially fix certain design problems by simply changing the shape."

The responses to the case study assignment were similarly encouraging (Figure 9). The majority of students agree or strongly agree that the case study where they had to perform an independent original analysis of a structure of their choice, improved their knowledge in both architecture and engineering and made for a better appreciation of the role of structure in architecture. Although confidence levels were reported as relatively high both before and after – there is evidence that for some students at least carrying out the case study improved confidence in their ability to analyze a real structure.

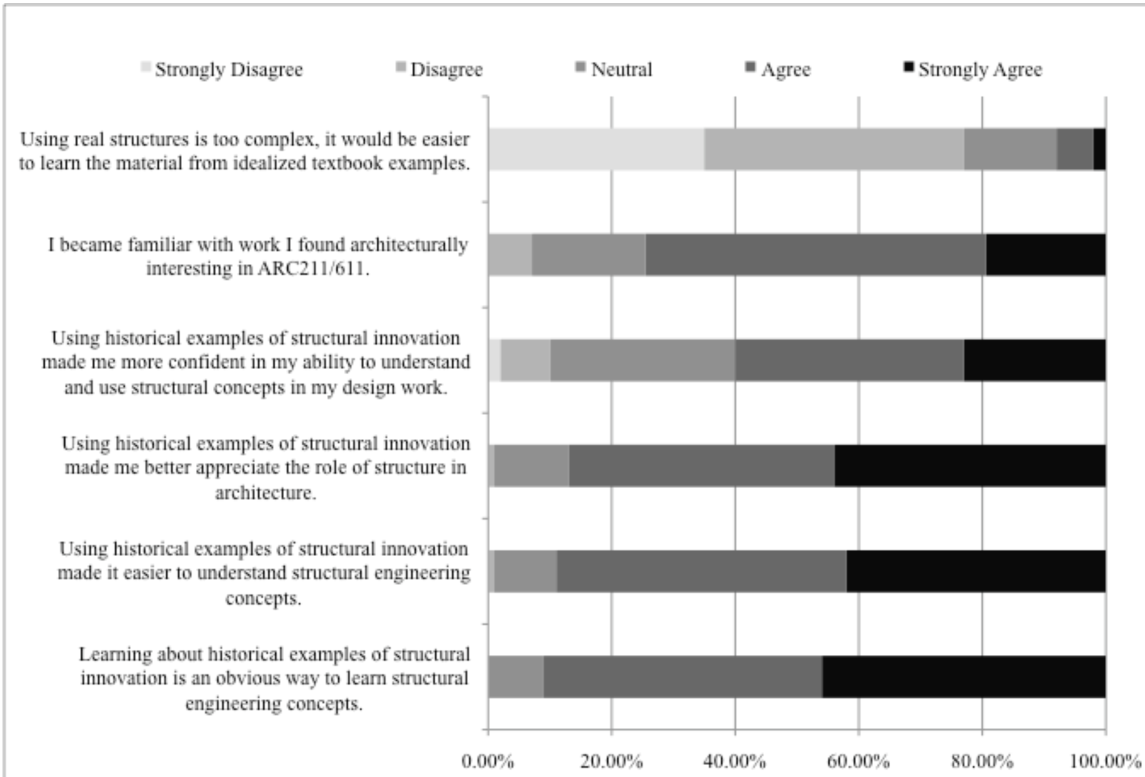

Figure 8
Student responses to use historical precedents in ARC211, Structures I.
Credit: Sinéad Mac Namara.

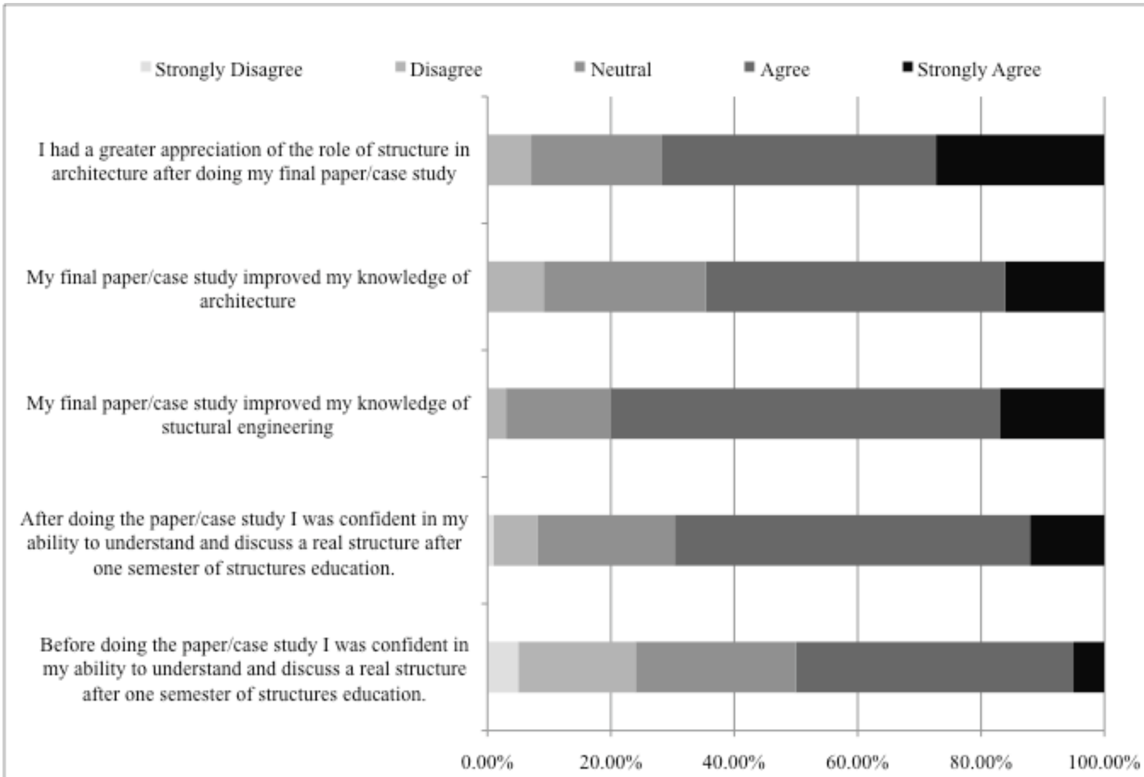

Figure 9
Student responses to structural case-studies in ARC211, Structures I.
Credit: Sinéad Mac Namara.

Conclusions

There is little discussion of the role of structures in architecture education in the relevant literature. The enthusiasm, and indeed background knowledge required, for students to undertake complex mathematics is not high. And yet, contemporary architecture students will graduate into an ever more technologically complex environment in their practice of the discipline. As such, it is vital to give students both an appreciation for the role of structure in design, and the critical skills required to analyze structures. We must equip them for the further study of the subject that will be necessary for those who wish to pursue innovations in the technological aspects of their practice. Historical precedents of structural innovation are an extremely useful tool for both teaching fundamental structural principles and in activating the relationship between history, structure, and design. The quality of the student work produced at the end of one semester augers very well for the success of this approach. The vast majority of students can produce an independent structural analysis of a real structure, identifying the primary load carrying mechanism, the loads on it, and the forces and stresses that result. The student response data is overwhelmingly positive in support of this claim, and the student engagement in the course is very high for a required course of this nature.

Acknowledgements

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References

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[1] Salvadori, Mario. "Teaching Structures to Architects." *Journal of Architecture Education* 13, no. 1 (1958): 5-8.
[2] Plesums, Guntis. "On Teaching Structure Systems." *Journal of Architecture Education* 27, no. 4 (1974): 68-77.
[3] Severud, Fred. "Structures: The Feel of Things" *Journal of Architecture Education* 16, no. 2(1961): 18-22.
[4] Salvadori, Mario. "Teaching Structures to Architects." *Journal of Architecture Education* 13, no. 1 (1958): 5-8.
[5] Katehi, L. 2005. The Global Engineer. In *Educating the Engineer of 2020: Adapting Engineering Education to the New Century,* ed. Committee on the Engineer of 2020 151-155, National Academy of Engineering.
[6] Ibid.
[7] Dally, J. W., and G.M. Zhand. A Freshman Engineering Design Course. *Journal of Engineering Education* 83, no. 2 (1994): 83-9.
[8] Dym, C.L., A. Agogino, O. Eris, D. Frey, and L. Leifer. Engineering Design Thinking, Teaching, and Learning. *Journal of Engineering Education.* 94 no. 1 (2005):103-120.
[9] Mac Namara, Sinead, Clare Olsen, Scott Shablak and Carolina Harris, "Merging Engineering and Architectural Pedagogy – A Trans-disciplinary Opportunity?" In *Proceedings of the International Conference on Engineering Education ICEE-2010,* July 18-22, 2010. Gliwice, Poland: INEER International Network for Engineering Education and Research.
[10] Billington,David P.. *The Tower and the Bridge.* 1 ed. Princeton, NJ: Princeton University Press, 1985.