

# Teaching structures to architecture students through hands-on activities

Niloufar Emami<sup>1</sup>, Peter von Buelow<sup>2</sup>

<sup>1,2</sup>Taubman College of Architecture and Urban Planning, University of Michigan, USA

<sup>1</sup>nemami@umich.edu

<sup>2</sup>pvbuelow@umich.edu

## Abstract

Henry Kamphoefner's opening for Mario Salvadori's talk reveals a key historical shift in considering structures in the education of architects. He points to the Beaux-Arts school of thought and its emphasis on buildings as pictures and rendered drawings, and highlights that as students they were told by their teachers to ignore the structure, that Engineers were a dime a dozen, that almost everyone can tell them how to make it stand up. This highlights the main reason that even some of the very best architects don't understand structures, emphasizing that there has not been too much emphasis on structural knowledge in the architectural schools. This calls for a different approach in teaching structures to Architectural students than engineering students. Soft knowledge is oriented to architectonic sense, thus hard knowledge through soft methods should be facilitated. There is a gap that must be filled between the theory of structures and the art of teaching it to Architectural students. This paper first reviews some different methods in teaching structures to Architectural students. Next, it will report on the "Arch 324: *Structures II*" course being taught by Professor von Buelow at the University of Michigan. And finally, it will compare the undertaken methods in the aforementioned course with the array of methods reviewed earlier to identify the strengths and the ways in which it can further improve.

**Keyword:** Education, Teaching structure, Architecture students, Hands-on activities

## 1. Introduction

Salvadori (1958) considered a good knowledge of mathematics as a prerequisite to the learning of structures, and then other technical subject areas such as mechanics, the strength of materials and structures. He also highlights that the "importance of scale related to absolute gravity pull of the earth must be put in the mind of the student. Otherwise, he will stumble and dream impossible structures 10,000 feet in span" (Salvadori 1958:6). Severud (1961) expresses that there are certain fundamentals that architects should get as the basis for thinking, and then the figures can be handled by engineers (Severud 1961). He also points out that an education in structures should be addressed by a direct approach to "build a structure and destroy it and then see what happens: this is by far the best means of recognizing what goes on" (Severud 1961:18). Michael Chiuini (2008) highlights the objectives of structures courses as having an intuitive understanding of the behavior of building systems, and the quantitative analysis skills (Chiuini 2008). Considering the formal Architectural education in the USA, MacNamara (2012) points out that the NAAB (National Architectural Accrediting Board) accredited Bachelor of Architecture programs are required to have two structural courses, one focusing on analysis and another on design calculations (MacNamara 2012). However, as Vassigh (2005) points out, architecture faculty and students struggle with a traditional engineering-based approach to structures instruction (Vassigh 2005). Michael Chiuini (2008) lists three main issues with structures courses in architecture schools: first, students' struggle in understanding statics and applying mathematical procedures to problems; second, the inadequate time to teach complex structures to students; and third, a perceived separation between design disciplines and structures (Chiuini 2008). Some of the issues above need to be addressed at an administrative level in the educational systems, such as the decision about the minimum required credit hours for structural courses throughout the students' education. This will directly affect the issues about inadequate time in the teaching process. This paper, however, focuses on various methods to teach structural courses to architects, within the already defined credit hours, towards making it more fruitful. Some educators have also suggested integrating structural education with design studio courses, to reinforce the concepts learned by the students, and to fill the gap between design discipline and structure. This subject is beyond the scope of this research, and the goal of this paper is to identify teaching methods that help architectural students better understand statics and structural analysis, towards establishing a basis for understanding structures throughout their future career.

## 2. Review of different methods in teaching structures in Architectural schools

There are several methods to reinforce intuitive understanding and integrate quantitative analysis skills in teaching the structure courses to architects. Ilkovic (2014) lists two methodologies of teaching, namely PBL (Problem-based learning), and PPBL (problem and project based learning). In these methods, the teacher sets a problem in an assignment, which is solved by developing a project (Ilkovič et al. 2014). Reviewing the literature, there are major techniques that can be used in addition to lectures, to teach structures to Architectural students, including:

- a) Hands-on activities in a lab-based environment, making physical models and structural testing of models.
- b) Computer-based simulation through structural analysis and interactive programs.
- c) Web-based interactive structural education.
- d) Integrating Structures with design studio.

These techniques are further presented in the next sections along with related case studies.

### 2.1. Hands-on activities

Many educators expressed that theoretical lectures were to be complemented by other activities. Hands-on activities such as making physical models are one of them. The possibility of physical contact with the material, as well as immediate observation of the effects of loading, contributes to the development of students' structural intuition. They are also valuable since they have the potential as a conceptual design tool in structural studies. Using physical models in structural education can cover a wide range of activities. Vrontissi (2015) suggests several methods, namely *Metaphor*, which refers to examples from nature or common experience, *Analogy* which is to recall and relate, *In-scale precedent models*, *In-scale trial-and-error experimentation*, and *full-scale prototypes* (Vrontissi 2015). Another educator refers to Active Learning strategy as an overarching theory for teaching structures to architecture students (Khodadadi 2015). Pawel Ogielski et al. (2015) highlight that the shaping of structural intuition can be done through the direct observation of the structural behavior which is present in physical modeling. They used various materials and methods to make physical models of structural systems, including the Zometool system to make *Bar Structures*; wooden sticks, and thin wire ropes to make *Tensile Structures*; reverse modeling technique to form-find *Shell Structures* and soap films for inspiring the design of *Minimal Surfaces* (Ogielski et al. 2015). Estes and a colleague reported on defining a hands-on project for a whole class as to use the K'nex toys to build a 50-foot structure that will support a one-hundred-pound concrete panel. This project illustrates the importance of structures and relates how structure fits into the process of a large-scale structures course (Estes & Baltimore 2014). Reviewing the above survey, educators have been using an array of methods in making physical models, from analogy and small-scale models to full-scale prototypes towards reinforcing students' learning.

### 2.2. Computer-based simulation and virtual reality

Several tools have been developed that employ finite element analysis and numerical methods to provide structural performance feedback to the user. Some of this software is capable of providing real-time results including internal forces, reaction and sometimes required materials or costs. "Arcade" by Martini, "SAP2000," "Dr. Software" and "Force Effect" by Autodesk are a few (Mueller 2014). However, there are some limitations associated with these tools. One limitation associated with numerical tools is that architectural students need to spend a lot of time to learn how to work with the software, and since they usually do not know the logic behind computational calculations, they trust the outcome without being able to validate it with other means. Another limitation is that these software systems are mainly designed for engineers and not for architects. This opens the avenue for integrated numerical analysis modules for architectural modeling tools, such as Karamba, which is a plugin for the Rhino NURBS modeling tool (Preisinger 2014). All in all, it seems that using numerical tools can be a good strategy in advanced education of structures such as graduate courses, where students have acquired a basic knowledge of statistics and structures, and are prepared to further develop it. Virtual reality is another tool that can be used to train future architects and engineers by teaching them about structural concepts. The 3d Lab at the University of Michigan possesses a 10 foot by 10-foot CAVE (Computer Assisted Virtual Environment) (Navvab 2012). In this approach, one can place himself in a computer-generated world, and interact with

it. The students can also observe how a structure collapses from different perspectives. Observing this complexity at the educational level can benefit students. The College of Engineering at the University of Michigan has employed virtual reality to teach basic concepts of structures to engineering students by allowing interaction between the students and a computer model (Sherif El-Tawil 2015).

### **2.3. Web-based educational support and interactive education**

Another method for teaching in the digital age is through using online mediums such as web sites, to share educational materials, as well as innovative teaching tool programs. Vassigh (2005) refers to a project that aims to create an environment for teaching and learning structures for architectural students. This project is composed of three components namely “Interactive Structures Software (ISS)” which is a multimedia program, “Structures Learning Center” as the instructional support and finally “the student performance evaluation tools” (Vassigh 2005). In addition, Martin et al. (2015) refer to innovative teaching tool programs for teaching structural analysis to architects such as *Easy Statics* by Claudia Pedron and *eQUILIBRIUM* created by BLOCK Research Group (Pospíšil et al. 2015). *eQUILIBRIUM* is an interactive online tool that illustrates graphic statics techniques on example problems. Demi Fang and colleagues introduced a web platform named *NovoEd* that hosts a variety of online courses to teach *Mechanics of Solids* to students. To achieve one of the course’s learning goals, namely helping students to understand the fundamental principles of solid mechanics, online videos that encompass worked-out problems are part of the course’s pedagogical approach. (Fang & Adriaenssens 2015). It seems that with student’s wide access to the internet, online teaching materials provide a great platform for putting forward teaching concepts.

### **2.4. Integrating structure in Design Studio**

Chiuini (2008) proposes to make structural systems as part of the intuitive design vocabulary of the architecture students, by bringing it to the realm of design either by making it an integral part of the studio problem statement or by teaching structures courses around a building design project. He teaches a “structures project”, in which students are asked to configure a system in the context of a basic architectural brief, and then the primary element of the system is analyzed, members are sized, and connections are designed. The main materials are steel and wood or steel and concrete (Chiuini 2008). As noted earlier, this can be an encouraging method to teach structures to architectural students, once students are familiar with the basic concepts of statics and structural analysis. In another attempt, Professor Karl Daubman and Professor von Buelow from the Taubman College of Architecture and Urban Planning at the University of Michigan combined structures into a design studio course, which explored wood properties by reconstructing a bridge designed by Da Vinci.

## **3. Methods of Teaching Structures in the Taubman College of Architecture and Urban Planning**

Many educators and researchers confirmed that quantitative scientific methods might be effectively integrated with qualitative and conceptual methods, to transfer hard knowledge through soft methods. Structures I and II courses at the Taubman College of Architecture and Urban Planning are being taught by employing such technique. Every week, there are two lectures that are taught by the professor, and one recitation session taught by a graduate student instructor (GSI) (actually 5 recitation sections in parallel). During the recitation sessions, small scaled lab projects are conducted by the GSI so that the students can better understand a structural concept or the behavior of a structural system. There is also some regular time spent on solving sample quantitative homework problems during the recitation sessions (Fig. 1 left). Most, if not all, of the teaching materials, such as recorded lectures and recitations, recitation notes, homework problems, exam samples and study questions are accessible for all of the students through a web site (Fig. 1 middle). The homework that the students need to work and submit each week is of the same problem but with different given values for each student (e.g. structural dimensions and loads). Therefore, no two students will be solving the exact same problem. This ensures that the students work their own, individual homework problems, while at the same time they can collaborate on the methods and process of solving the problem with their classmates. In addition, students are given a second and even a third chance to submit correct values for the questions. Their best attempt at the solution from the three tries is then taken for the grade. This encourages a “try again” attitude in solving the problems. As a course project, students form groups and design a tower. In this process they analyze the structure, make a balsa-wood model of it, and

finally test it structurally by loading it to failure. Within a certain weight limit, the tower that combines high load capacity and greater height is ranked the best among the towers (Fig. 1 right). The following section focuses on the experimental projects undertaken in the recitation sessions, and how they relate to reinforcing students' understanding of statics and structural systems.



Fig. 1: (left) a GSI teaching a recitation session; (middle) a page from the website that makes all of the teaching resources accessible for the students; (right) The towers are made using 4 oz. of balsa wood and loaded to failure

### 3.1. Buckling in Columns

Demonstrating structural failure due to lack of stability is the focus of this lab experiment. The students are required to observe a slender column under load, and to calculate the effect of its slenderness on column capacity. The goals of this experiment are to first, observe the buckling behavior of the columns through physical modeling; second, to find the slenderness ratios for the weak and strong axes; and third to calculate the critical buckling load for both of these axes. For this lab experiment, a 6" (15.24 cm) long basswood stick with a cross section of 1/16" (1.5mm) by 1/4" (6.3 mm) is provided. The students are asked to first calculate the weak and the strong slenderness ratios, and thus the critical buckling load. Then, they are asked to approximate the actual critical buckling load using their finger. Finally, they are asked to repeat the procedure for shorter lengths of wood including 3" (7.6 cm) and 1" (2.5 cm) sticks (Fig. 2). The learning outcome of this lab experiment is threefold: first, students experience buckling behavior in slender elements including columns; second, they observed the effect of cross-section on the direction of buckling; and third, they observed the effect of the length of the element on the critical buckling load.

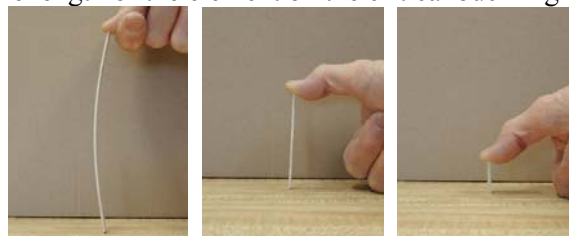


Fig. 2: Buckling in columns: 6 inch, 3 inch and 1 inch

### 3.2. Deflection in Cantilever Beams

This lab experiment uses observation and calculation to help students understand how a cantilever member deflects under load. The students are required to place a basswood stick on one support. Then they load it in the mid-span as well as at the free end, and observe the effect of load placement on the deflection. The goal of this lab experiment is to first, demonstrate the bending behavior of a cantilever beam through physical experiment; second, to use the diagram method to find the deflection; and third, to calculate deflection through equations and verify the results with the experiment. For this experiment, a 1/16" by 1/2" basswood stick is placed flatwise on a 2x4 support, and the free end is loaded. Then the deflection is measured against graph paper. The procedure is repeated for a load at the half point, as well as with two loads, one in the middle and one at the free end (Fig. 3). The measured deflections are recorded, and then the diagram method is used to calculate the deflection. Afterward, the deflection of the first case with the load at the free end is calculated by using equations. Finally, the values retrieved from the experiment, the diagram method and the equations are compared with each other. The learning outcome of this lab experiment is threefold: first, students observe how moving the same load across the length of a beam can affect the amount of deflection; second, they experience verifying analytical methods with experimental results. Finally, by sharing the measured values in the class, they notice the difference between the measured values of deflection for each group. This led to a class discussion around how material properties may be

different from their theoretical values, how one member of wood or steel may be different from another member, and how people have different levels of precision in measuring physical phenomena.

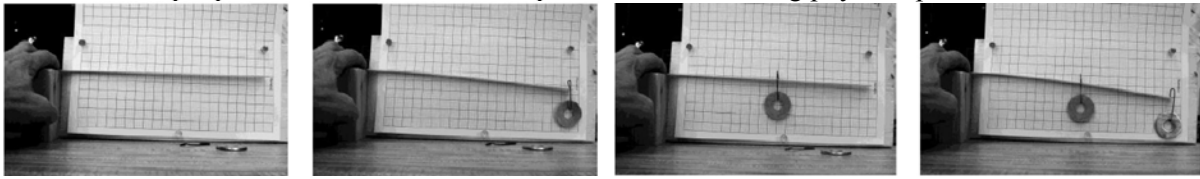


Fig. 3: Deflection in cantilever beams

### 3.3. Steel Beams

This project uses observation to help students understand how unbraced compression edges and lateral torsional buckling reduce the ultimate load capacity of steel beams. The students use a U-shape folded paper supported on two wooden blocks, along with a wooden block and some washers for loading, to observe the effects of loading a beam that is supported on two ends. The goal of this project is to first observe the behavior of the unbraced edges of a section in compression, versus tension; and second, to measure the capacity loss due to lateral torsional buckling. For this experiment, students position the U-shaped section on the supports with the free edges on the upper side of the span. Then they place the wooden block in the middle of the span and place the washers on top of it to determine the number of the washers that the section will support before failure (Fig. 4). They closely observe the failure mode. Next, they repeat the procedure with the section inverted, meaning that the U-shaped beam is placed on the supports with its free edges downward, and they record the number of washers it takes before failure. Finally, they compare the load level carried by each orientation of the paper beam and describe the behavior of both under load. The learning outcome of this experiment is that the students observed the different load capacities of the two beams, as well as their failure due to lateral buckling.

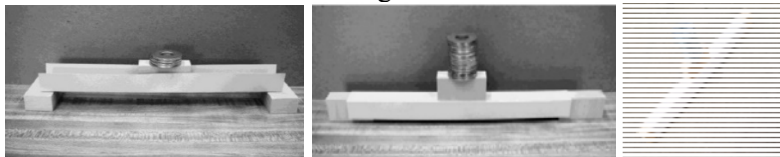


Fig. 4: Unsupported edges in steel beams

### 3.4. Flitched beams

This project relies on observation to develop a qualitative sense of the effect of the combined material behavior of a flitched beam. Students are provided with one basswood plate and two pieces of styrene, as well as a wooden block for support and some washers as loads. The goals of this project are to first, observe the behavior of the unbraced plate alone; second, to observe the behavior of the styrene beam sections alone; and finally, to observe the behavior of the combined materials in the flitched section. The students were asked to place the basswood plate on one support acting as a cantilever, and to load it with three washers at the free end. They then observe the deflection at the free end. In the next stage, they are required to bond the two styrene beams together with some rubber bands, and load it in a similar fashion with the same number of washers. Finally, they are asked to make a flitched section by placing the basswood plate in the middle and the styrene on the outside, and hold the composite together with rubber bands. They then load it at the free end with the three washers, and increase the load until it fails (Fig. 5). The learning outcome of this project is to observe the efficiency of flitched beams in terms of having a higher capacity with smaller deformation. The composite is actually stronger than the sum of its parts.



Fig. 5: Performance advantage of flitched beams

### 3.5. Continuous beams

This project uses observation to understand the behavior of continuous beams over multiple supports. Students are provided with a 24" stick and four wooden blocks. The goal of this project is to observe the behavior of continuous beams under different loadings, to estimate positions of contra-flexure and effective lengths, and to determine locations of the positive and negative moment based on curvatures.

The students are asked to place the stick over three supports, and load only one span and then both spans respectively with their fingers (Fig. 6 left). They need to hold the beam down on the reaction if it lifts up. Next, they are asked to observe each case and draw the elastic curve, label the positive and negative curvature as well as the points of contra-flexure. They are asked to repeat the same experiment for a continuous beam placed over four supports (Fig. 6 middle), and to load two sequential spans first, and two end spans second. The same observations and recordings are repeated (Fig. 6 right).



Fig. 6: A continuous beam over three supports (left), over four supports (middle), recording of the deflected shape by the students(right)

The learning outcomes of this project are twofold: first, they observe how different spans of a continuous beam are affected by loadings on their neighboring spans; and second, they notice how the effective length of a beam in a specific span is affected by loadings.

### 3.6. Combined Stress

This project uses observation of a physical trial to see the effect of flexure combined with tension or compression. Students are provided with a wooden stick, two wooden blocks for supports and washers for loading. The goals of this experience were to observe the behavior of tension plus flexure; then to observe the behavior of compression plus flexure; and finally, to estimate the addition of combined stress profiles. Students are provided with a 12" wood stick with a cross section of 1/16" by 1/2". Then four washers are put in the mid-span which causes the beam to deflect. The flexure of the beam is calculated through equations. Next, an additional axial tension force (approximately 10 pounds) is applied to the stick which pulls on it and causes the deflection to be reduced. This additional axial stress is calculated along with a sketch showing the addition of the stress profiles of flexure plus tension. In the next stage, the aforementioned process is repeated, but instead of an axial tension force, an axial compression force is applied to the beam. The change in deflection is noted, and the combined axial stress is calculated (Fig. 7). The learning outcome of this project is seeing how loads (flexure and compression) may work together to increase the deflection, or work against each other (flexure and tension) to decrease the deflection.

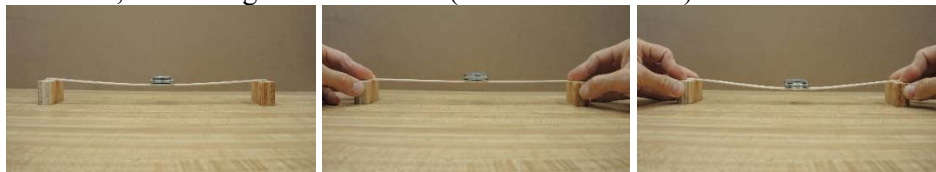


Fig. 7: Combined stresses in beams: flexure only (left), flexure + tension (middle), flexure + compression (right)

## 4. Results and Discussion

There are different approaches in teaching structures to architectural students. The overarching approaches are categorized as hands-on activities, computer-based methods, web-based educational platforms and integrating structures into the design studios. Reviewing the structures course in the Taubman College of Architecture, it mainly employs the first three strategies in educating architects summarized in Table 1. Reviewing the table, reveals that there is a strong emphasis on conducting hands-on activities in this course, through making, analyzing and loading the "tower project", as well as mini projects and experiments conducted in the lectures and recitation courses. These activities increase the intuitive understanding of the structural behavior of systems and help student remember the concepts.

Table 1: Different methods in teaching Structures to Architectural Students

|   |  | Structures I and II in TCAUP  |
|---|--|---|
| Hands-on activities                       | Metaphor and analogy                             | Yes, through lab-based recitation sessions  |
|   | In-scale precedent models                        | No  |
|   | In-scale trial-and-error experimentation/ models | Yes, through term project of making a tower out of balsa and testing it                                 |
|   | Full-scale prototypes                            | No  |
| Computer-based methods                    | Computational Simulation                         | Yes, students are encouraged to work with Dr. Software to test their tower models                       |
| Web-based educational platform            |  | Yes, online weekly problems are shared through the website, as well as the recorded lectures and notes. |
| Integrating structures with design studio |  | No  |

Teaching and learning are a multi-faceted activity that need to be addressed through various approaches. Different strategies complement one another. However, teaching hard knowledge through soft methods helps architects to intuitively comprehend the subject matter. In this regard, hands-on activities in which students use trial and error with some materials to understand the concept, can greatly complement the lectures. Hands-on activities such as small lab experiments, making scaled models, loading them and observing their failure, all contribute to the strategy above. Putting students in groups helps them to exchange ideas and ultimately better absorb the theory. Class discussions around the hands-on activities can further help them to analyze the process and the outcome, and to guide them to pay attention to the points which they might have missed. One important point is that analogy combined with the hands-on activities can be a great strategy to help them remember the concept throughout their future studies and later on throughout their career. Analogy links the structural concept to a real-world, every-day phenomenon. All in all, hands-on activities are an effective strategy to be employed in teaching structural courses to architectural students.

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