AC 2012-4324: TOPOLOGY OPTIMIZATION: THE USE OF CUTTING EDGE NUMERICAL METHODS IN TEACHING STRUCTURES TO ARCHITECTS.

Dr. Sinead C. Mac Namara, Syracuse University
Prof. James K. Guest, Johns Hopkins University

Jamie Guest is an Assistant Professor of civil engineering at Johns Hopkins University. His research and teaching interests focus on topology optimization and structural engineering. He received his M.S.E. and Ph.D. from Princeton University and B.S.E. from University of Pennsylvania, all in civil engineering.

The Use of Cutting Edge Topology Optimization Methods in Teaching Structures to Architects

1. Introduction

This paper describes an example of design education in architectural structures at Syracuse University. This study examines a design assignment using topology optimization algorithms (proprietary software provided by a researcher in the field of numerical methods in engineering) undertaken by Masters of Architecture students in their first semester of structures education. This paper presents the results of the assignment and the student evaluation data for the course as whole and this assignment as part of an overall effort to understand the value of structural engineering in the architectural design process.

2. Background

2.1 Teaching Structures to Architects

The teaching of structures is often viewed as marginal in the overall architecture curriculum. The first author's 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. When surveyed on the first day of their first structures course, less than 30% of the architecture students of Syracuse University say they would take the course if it were not required. 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.

A search of architecture education and engineering education literature archives produces very few articles devoted to the subject of teaching structures to architects. However, in the scant sources that do exist there is general agreement that while there is enthusiasm on the part of architects to work with structural engineers the two groups lack a common vocabulary.[1] There is also consensus that a conceptual intuition for how structures work is of more importance for architecture students than complex mathematical capacity. [2,3] Many writing on this topic agree that the traditional mode of teaching engineers is often imported from civil engineering without much modification to teach structures to and that this approach is unsuitable for architects.[4,5] Specifically, it argued by a number of researchers that fostering the ability to select and configure structural systems as opposed to the more fine-grained mathematical skills that an engineering student would have to acquire are the most important aspect of teaching structures to architects.[6,7,8]

Education researchers in this area have also argued persuasively that the most successful teaching of structures (and technical material more generally) to architecture students happens in the context of design assignments. In discussing the lager problem of disconnection between lectures and studio, Gelernter posits that the oft observed problem of students being unable to apply principles learned in lecture in the studio is much more complex than students merely lacking interest or attention in the lecture material (including structures). Rather, the problem is the underlying assumptions that students must master a set of principles in its entirety before trying to apply them. There is a much more symbiotic relationship between knowledge acquisition and application, he argues, and architecture students are much more receptive to knowledge acquisition when it comes in the context of trying to solve a design problem.[9] Many others support this view and offer examples of technical instruction in the form of design assignments.[10,11,12,13]

At Syracuse University there is only one structural engineer on the faculty (the first author) and so teaching a structures based studio to all students is not a practical option. However using the principles supported in the literature that a) the most important aspect of structures education for an architect is the development of structural intuition and b) that the optimal way to teach technical material to architects is in the context of a design assignment, the assignment described in this paper was designed. The assignment is intended to improve conceptual intuition about structures by exposing students to a structural form finding method that finds the optimal form to resist a given set of loads.

Traditional engineering education is largely concerned with teaching the normative case and students rarely engage with contemporary practice or new innovative technologies. Architecture education, by contrast consciously studies contemporary practice and students are very aware of new technologies and methods that are in vogue. As such, architecture is a very good testing ground for the computational design tool of topology optimization, which is currently undergoing growth across many engineering disciplines.

2.2 Topology Optimzation

Topology optimization is a free-form approach to optimizing the distribution of material across a design domain. Unlike structural sizing optimization, which optimizes member selection for each component of predefined structural system, topology optimization allows material to be placed or removed from any location in space, meaning structural connectivity and shape are simultaneously optimized (Figure 1). Design updates are driven by formal computational analysis and in many instances solutions can be mathematically proven to be optimal.

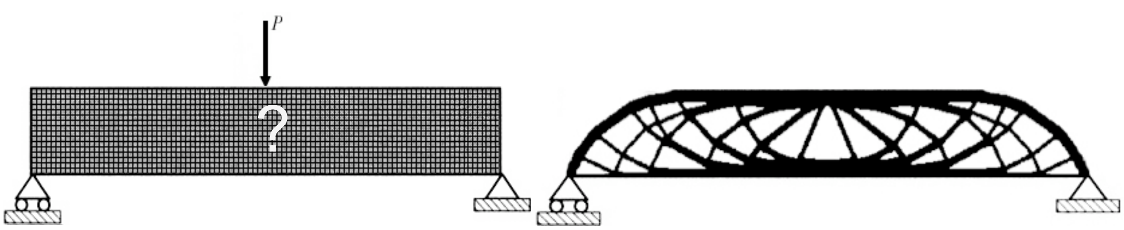

Figure 1: (a, left) Beam design domain geometry, loading, boundary conditions, and nondescript initial guess, and (b, right) topology optimized maximum stiffness design.

Topology optimization has primarily been used in the design of minimum weight/maximum stiffness structures, though it has been extended over the past decade to design devices and materials optimized for thermal, fluid flow, and optical properties, to name a few (see Bendsoe and Sigmund 2003 for review[14]). More recently, topology optimization is working its way in to the structural design practice, including recent building projects by Skidmore, Owings, and Merrill.[15,16] Topology optimization is also working its way into engineering education, typically at the graduate level. Most such courses focus on structural optimization, particularly sizing and shape optimization, with a component of topology optimization. In order to broaden its introduction into engineering and architecture curriculum, the second author developed a GUI-based topology optimization software capable of designing 2d continuum structures.[17] The first version of this program, which will be referred to as TopOpt below, was used at Johns Hopkins in undergraduate and graduate technical electives on structural optimization, and was distributed to civil engineering colleagues in Manhattan College and Virginia Tech. This paper focuses on the lead author's experiences using the software in architecture engineering at Syracuse University.

3. The Topology Optimization Assignment

The assignment described here was undertaken as a one credit seminar that ran alongside a three credit lecture course, Structures I, a required course for all MArch I (first professional degree) candidates at Syracuse University. The students are generally in their second semester of a seven-semester program and most have undergraduate degrees in areas other than architecture (or engineering).

The first part of the assignment required the students to propose a design problem defined only in terms of a rectangular 2D design space, the location of load, and the location and nature of boundary conditions. No presumption of form could be made, such as in Figure 1a. This proved to be the most challenging aspect of the assignment as many students turned in the first assignment (where they had to create a problem to test using the TopOpt tool) with a pre-determined idea of what the final form would look like.

The next part of the assignment was to begin to use the TopOpt tool to generate optimal forms. The inputs that the tool required were: (1) domain information including the maximum permissible dimensions of the design, location and magnitude of the applied loads, and the location and nature of the boundary conditions; (2) design specifications, including the target structural volume fraction (percentage of the design domain to be filled with material) and the minimum allowable structural member size (for influencing design complexity); and (3) design and analysis resolution measured as the number of pixels in the mesh. After the students input the dimensions and mesh resolution, the tool outputs the index numbers for each of the mesh elements at the corners of the design space. Most students used this information to make a grid in excel to then identify the index numbers of the mesh elements at the locations of the loads and boundary conditions. The students made multiple iterations of their designs before selecting the one with the most visual appeal, or best fit for the materials and program they had in mind. In some cases this involved adjusting loads positions and boundary conditions, or other design specifications such as member sizes. The result of this part of the assignment was a diagram of an optimized form. It is important to note that the TopOpt tool is effectively dimensionless and scale-less, and assumes linear elastic behavior. It optimizes the flow of forces through the domain, with relative thickness of members indicating the relative load carried (as confirmed later with FEM analysis). A formal structural analysis using material strengths, actual load magnitudes, etc. is then required to tune and size the design to satisfy design codes. The output of the TopOpt program should therefore be viewed as an idea generator for discovering new, optimal structural forms.

Once a structural form had been chosen, the students undertook a Finite Element Analysis of the design under real load conditions and estimated structural member size. The students used SAP2000 with dummy (weightless) linear elements along the lines of the optimized design from TopOpt, with appropriate boundary conditions and loads. They used the FEM program to get the axial force, shear force, and bending moment diagrams for their structure. With this information the students estimated the appropriate size of the members in their chosen material. At this point in the semester they had enough knowledge of tension, compression, bending, buckling, material strength, material elasticity, and section properties to do this. Note this assignment was intended to undertake investigations of form and produce a novel form with reasonable estimates of the member size. As such, loads were conservative estimates rather than factored live loads from the building code and deflection was not considered.

For the final segment of the assignment the students produced a poster detailing their design process and showing renders (in 3D where appropriate) of their final design, to scale, with the calculations they had performed. Some images from these final posters are shown in the next section. It was made explicit in the problem statement that the vignettes or renders were as important as any other part of the assignment. The role of the structures instructor in a school of architecture is often one of persuasion, it is as important (and as difficult) to convince students of the importance of structures in their design education, as it is to teach the material itself. This part of the assignment was intended to show the students how a capacity to size members (even approximately), allows for a richer and more finely detailed representation of their design work.

4. Student Work

Students were encouraged to pick their own program and scale for this assignment. They chose structures from the scale of furniture up to the scale of elevated highway support structures. Examples of the students' TopOpt results, associated FEM analyses and final renderings are shown in Figures 2-6.

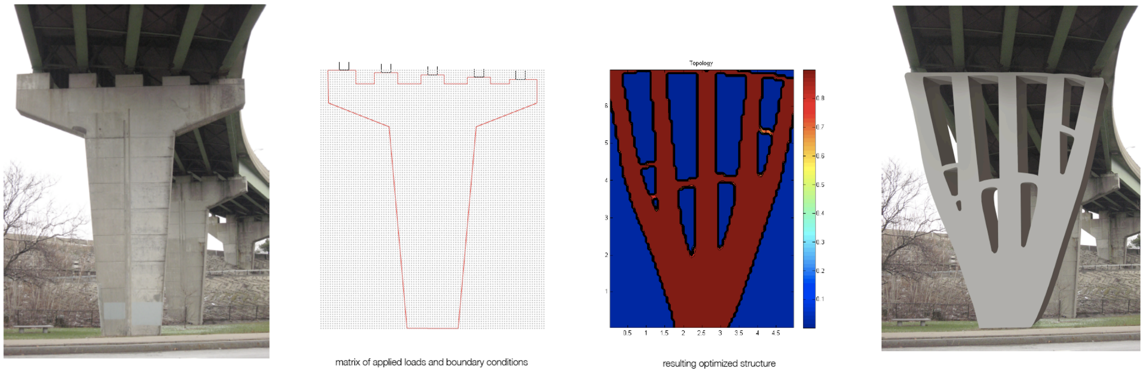

Figure 2: Topology Optimization Student Work

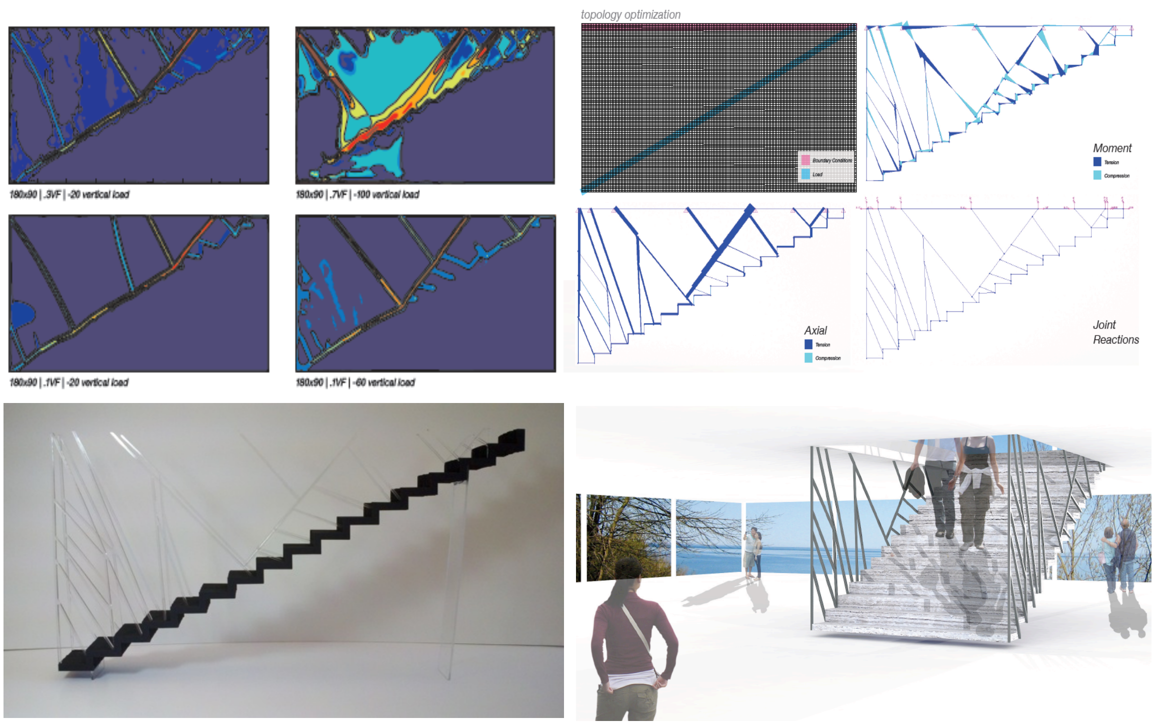

Figure 3: Topology Optimization Student Work

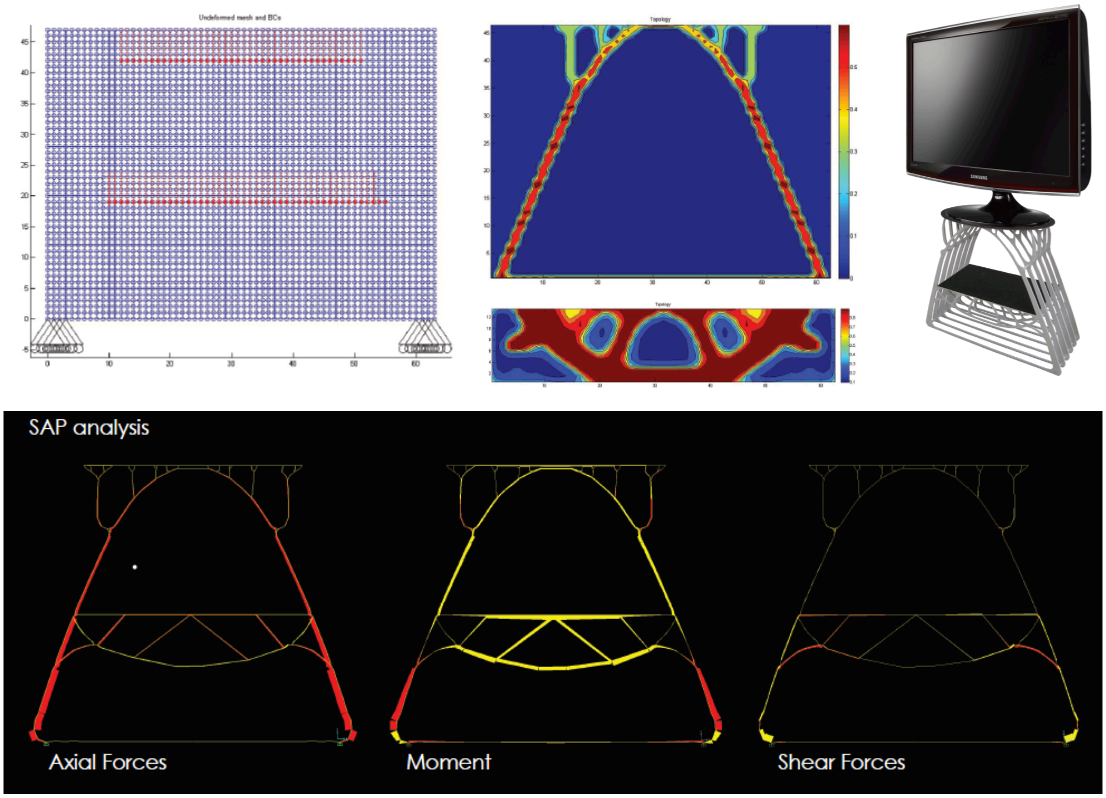

Figure 4: Topology Optimization Student Work

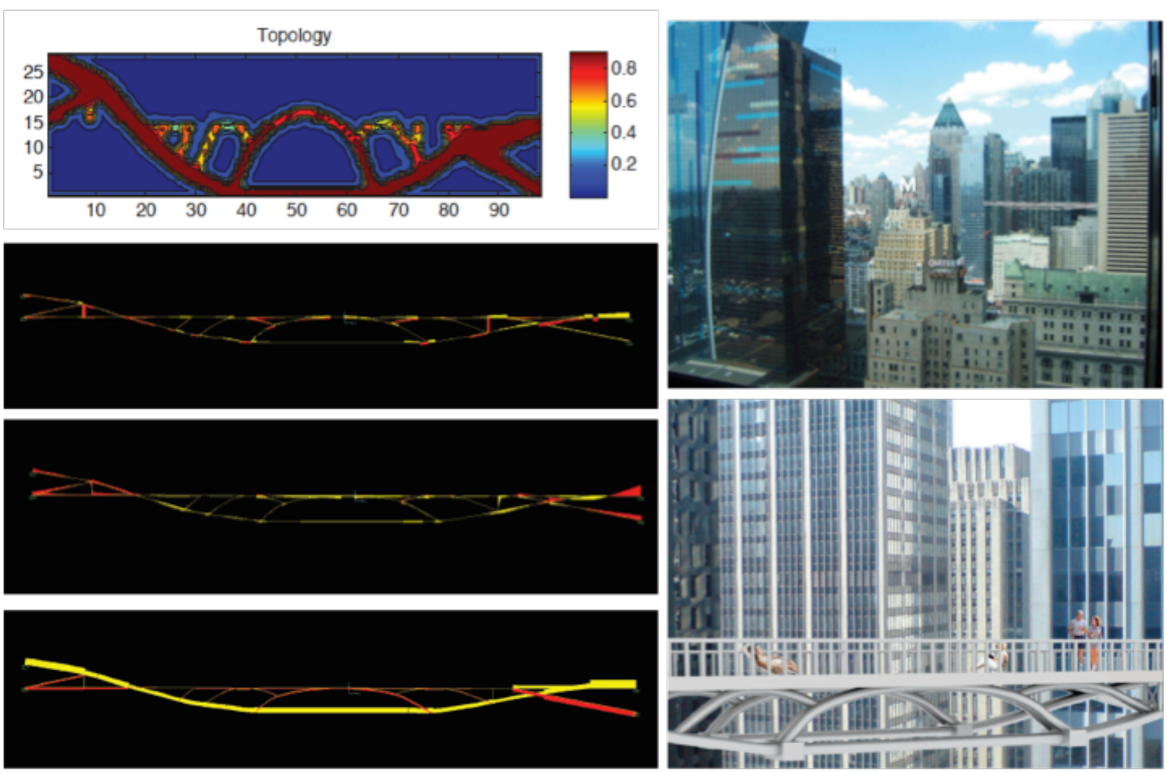

Figure 5: Topology Optimization Student Work

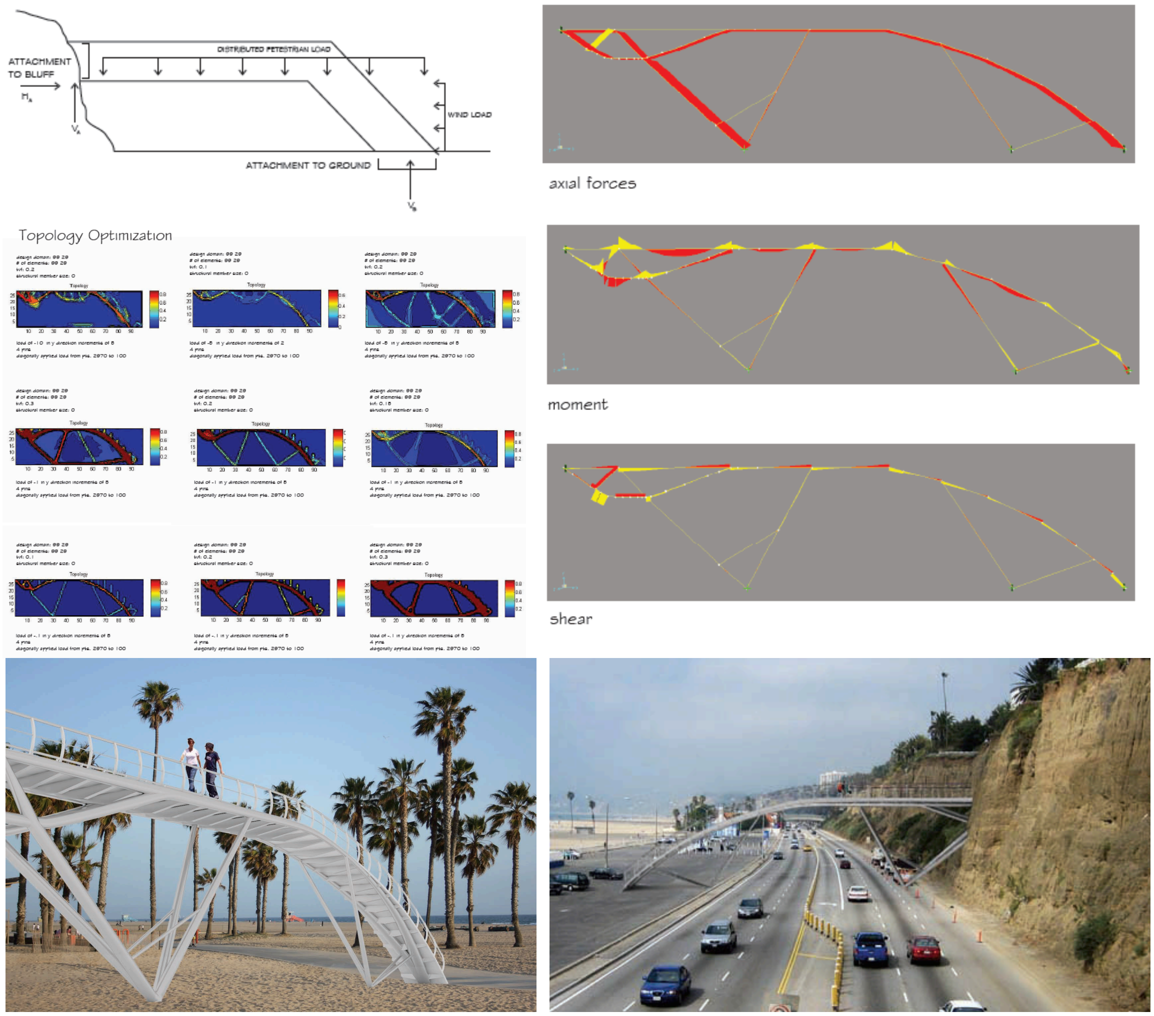

Figure 6: Topology Optimization Student Work

5. Student Response

In order to investigate student impressions of the topology optimization assignment a survey was sent to the approximately 30 MArch students who have completed the Structures I course in the past two years. The response rate was over 30%, which makes for a small study size but a reasonable percentage of the available population.

Student response to the assignment was overwhelmingly positive. The full results are shown in Figure 7. Over 90% of respondents agree that the assignment was interesting, if difficult (60% agreement). Over 80% of students agree that the experience was useful in improving their structural knowledge. Most encouragingly, over 90% of respondents agree that the TopOpt tool engendered increased appreciation for the creative potential of structural knowledge. This is the primary aim of the assignment, so it is gratifying that most of the students found design inspiration in a technical assignment. This finding is reinforced by the number of students who agree after the assignment that they are now interested in learning about or using other structural optimization software (80%) or other form finding software (90%). Further, the vast majority of respondents would consider using the TopOpt in future design work.

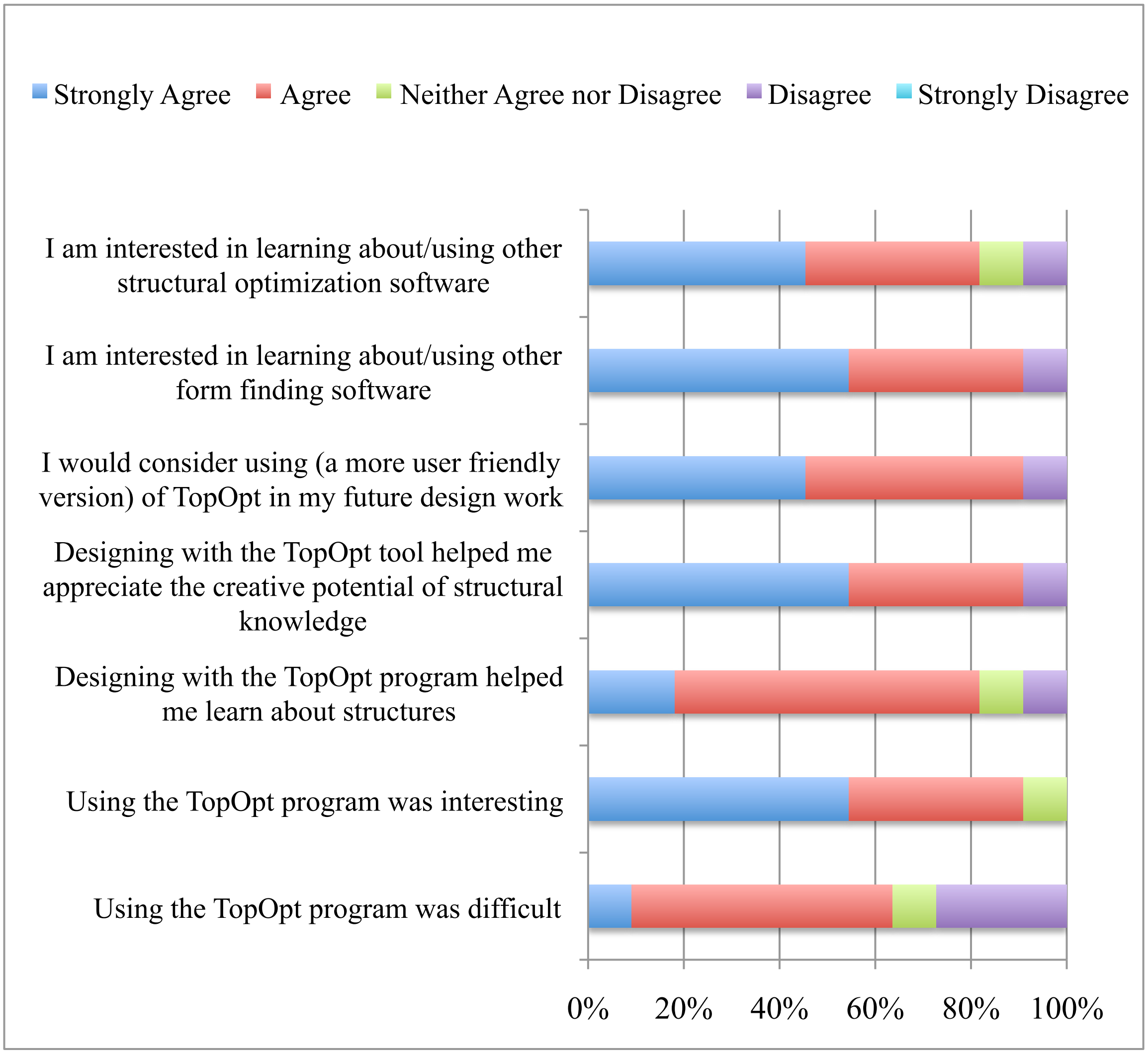

Figure 7: Student Responses to using Topology Optimization to do form finding as part of a structural design assignment.

In addition to the questions shown on the chart the students were offered the opportunity to offer any comments they might have on the educational usefulness of the topology optimization tool. The results from this open ended question reflected the students' initial assumption that they could predetermine form, and their pleasant surprise that the program threw up forms that were more interesting than those they might have arrived at alone. They also expressed considerable enthusiasm for using the tool again.

"it can be a tool used while designing, to give and spark further rationale to the

optimization of form"

"I found the iteration process ….was very interesting in that you push the program towards some idea of form that you have, but at the same time the program tends to resist and restrict to some degree that I think brings you to much more responsive and interesting conclusions."

"Having to resolve to point loads, though frustrating, provided less predictable results. These were, perhaps, more exciting and useful than what I might've ended up with otherwise. I really like TopOpt and hope to make use of it in the future. But I hope Prof. Guest doesn't perfect it too much and make us pay lots of money to use it."

"it seems like a very useful way to combine design with structural efficiency. It would be curious to see how it would integrate with a 3D modeling program so that the structure is optimized on all axes. Could be very useful in a studio."

Since the tool was introduced in the structures course, two students have sought a consultation on using TopOpt in their studio work, and a group of students in charge of the graduate student exhibition used TopOpt to design the form of a cantilever frame from which to hang some of the exhibition boards.

6.0 Conclusions and Further Work

Architecture education values experimentation and exposure to the newest and most innovative methods for design. Any tool that encourages interest in structures on the part of architecture students is valuable, as is any tool that helps them to understand structures. This experiment proved successful at doing both these things. It is particularly useful as it takes a whole-structure form finding approach, which is especially attractive to architecture students. All the available literature on teaching structures to architects emphasizes the importance of structural intuition over complex mathematics. This project allowed the students to play with structural form in a way that would otherwise be impossible without extensive mathematical and engineering training.

Although graduate students undertook this project, there is no reason to believe that undergraduate students could not use the tool as easily. MArch students at Syracuse have often come to architecture for the first time at graduate level and have no more training (relevant to this particular project) than the undergraduates at this stage.

When one thinks of the builders of the Gothic Cathedrals where the engineer and the architect were essentially one, it is clear that architecture has always been concerned with pushing technical boundaries. There is a wonderful tradition of speculative architectural work that imagines technical advances yet to come and presents challenges to the science and engineering communities to catch up. Increasingly, the first author sees architecture students eager to engage with the newest technologies and yet ever less mathematically ready to take the kind of engineering and math courses it would require to fully understand them. The value of TopOpt is that it allows access to boundary pushing technical ideas at a very early stage in an architect's education. The first author also sees architecture students doing a lot of faux-science and (erroneously) calling it parametric design. It is incumbent on architecture educators to model ways to engage with the software and the tools of more technical disciplines in a controlled way that will yield legitimate, verifiable and usable results. This project represents a first step.

Further work is necessary to scale this assignment up to a larger class size. Improvements to the user-interface and robustness of the tool, which are currently underway, will facilitate this move. Testing this tool with different student populations such as structural and mechanical engineers will likely yield interesting results for educators. Similarly if the tool is to be used in architecture education it would be very useful if there was integration with architecture software such as BIM or Rhino (or at least the potential for such integration with file portability).

7.0 Acknowledgements

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