ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/283231819

Graphic Statics and Interactive Optimization for Engineering Education

Conference Paper · April 2015

DOI: 10.1061/9780784479117.223

CITATIONS
2

READS
750

3 authors, including:

Caitlin T. Mueller
Massachusetts Institute of Technology

47 PUBLICATIONS **228** CITATIONS

SEE PROFILE

John Ochsendorf
Massachusetts Institute of Technology

94 PUBLICATIONS **1,527** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project 3D Sampling View project

Project Smart retrofit for Resilient Historical Cities View project

All content following this page was uploaded by Caitlin T. Mueller on 13 April 2017.

The user has requested enhancement of the downloaded file.

Graphic Statics and Interactive Optimization for Engineering Education

Caitlin Mueller, Corentin Fivet, John Ochsendorf
Structural Design Lab, Massachusetts Institute of Technology, Cambridge MA, 02139.

ABSTRACT

Although conventional structural analysis software is widely used by practicing engineers, its pedagogical value for students is limited, especially in design applications. Nevertheless, there is an established value in students exploring engineering problems through computational means.

This paper presents alternative computational techniques and tools that are effective improvements upon structural analysis software in the university classroom. The first set focuses on graphic statics. The second involves interactive evolutionary optimization. The paper provides feedback about their effective implementation in classrooms and demonstrates how the new tools can continue to be used by students beyond the classroom, to expand explorative opportunities for conceptual structural design in practice.

INTRODUCTION

Structural Engineers' Current Software and Education

Since the advent of finite element analysis, structural engineering and building technology educators have sought ways to integrate computational tools and commercial structural analysis software into classroom learning. It has been argued that mastering such programs is not only a practical skill for future work in practice, but can also transmit and instill a level of structural intuition unattainable by conventional analog methods. This benefit has even been explored beyond the education of structural engineers: for example, in 1994, Black and Duff wrote an essay arguing for the use of finite element analysis software in the structural education of architecture students based on their experiences at UC Berkeley.

However, many of the limitations of finite element analysis, both in universities and in industry, are also widely documented. The well-worn mantra *garbage in, garbage out* reminds engineers that the quality of the results from structural analysis software depends on the operator and the validity of his or her assumptions and inputs. Best practice today requires verification of software results with simplified hand calculations. In some cases, misplaced trust in seemingly precise computational output can indicate a lack of structural intuition, the opposite of the intended effect in education.

Beyond these well-known issues, there are further limitations with finite element analysis in engineering education, at least if used alone. Complicated and cumbersome interfaces are frustrating for beginners to navigate, and the results are often difficult to interpret. More importantly, the focus on analysis provides little insight into what design changes should be made to improve performance or simply to ensure stability. Finally, the linear process required by such software does not favor a critical outlook and a creative mind. This criticism is well expressed in a quote from EPFL's Aurelio Muttoni (2005):

> *"Structural analysis and calculation have become increasingly precise and detailed. Proportioning pushed to its limits has allowed structures to be even more daring and efficient, but unfortunately all this has had a negative effect on structural design, leading to a slow and inexorable deterioration of the creative element involved."*

The goal of this paper is to expand on these limitations and offer possible solutions, through the use of software and computational techniques focused not only on analysis but on design.

Design Skills for Structural Engineers

Despite the recent focus on structural analysis software, the primary and most fulfilling role of the structural engineer is not to analyze and size members, but to give form to structures. To empower engineers to reach this level, their education must include more than calculations and analysis. An emphasis on open-ended, creative design thinking, evidenced through skills like brainstorming for many good solutions, is crucial. Furthermore, critical thinking and ethics are necessary to push engineering students past conventional solutions towards innovation that improves design performance and quality. Finally, a stronger connection with architecture, the sister discipline to structural engineering that too often remains disconnected in the university, is imperative. These arguments are not new (although they bear repeating), and in fact echo the thoughts of the greatest structural engineers of the last century. A few examples are given below:

> *"Engineering is not science. Science studies particular events to find general laws. Engineering design makes use of these laws to solve particular problems. In this it is more closely related to art or craft; as in art, its problems are underdefined, there are many solutions, good, bad or indifferent. This is a creative activity, involving imagination, intuition and deliberate choice."* – Ove Arup (1986).

> "*There is no method that enables us automatically to discover the most adequate structural type to fit a specific problem, as it is faced by the designer. The achievement of the final solution is largely a matter of habit, intuition, imagination, common sense and personal attitude. Only the accumulation of experience can shorten the necessary labour or trial and error involved in the selection of one among the different possible alternatives.*" – Eduardo Torroja (1958).

> *"A structural engineer who is preoccupied with mathematics is like a tennis player who watches the scoreboard and not the ball."* – Waclaw Zalewski (Allen 2006).

> *"Creativity is necessary not just for issues around form, but also for purely technical aspects: processes, materials and static systems. This creativity is the difference between people who are happy to calculate and real engineers."* – Jürg Conzett (2008).

The Structural Engineer's Role in Conceptual Design

Global form-making and design thinking skills are most critical for engineers when large-scale, impactful decisions are made, in early-stage, conceptual design. Too often relegated to architects alone, this design phase offers opportunities for large cost and materials savings and greatly improved quality through decisions informed and supported by engineers. However, as discussed above, this requires a shift in mentality from pure validation and analysis toward design and synthesis. Early involvement of engineers also requires close and deep collaboration with architects for an integration of many important goals. Both of these requirements are ill-supported by existing structural analysis software tools, which are most appropriate for later-stage, autonomous engineering tasks.

This paper proposes a new class of computational tools, distinct from conventional structural analysis software, aimed specifically at collaborative, conceptual structural design. Arguments are given for use in practice as well as specifically in engineering education, where design thinking skills are sorely needed. Two key features will be specifically addressed: graphical methods and interactive design optimization. Together, these two ideas offer a new way forward for fluid, interactive, intuitive, and creative design software for structural engineering students and practitioners.

GRAPHICAL METHODS FOR BETTER INTUITION

The first set of techniques focuses on graphic statics (Allen 2009), a graphical method to analyze and explore equilibrium of axial-force structures.

The following sections trace the original and latest developments of graphic statics and highlight its strong connections with engineering education.

An Obsolete Tool for Structural Analysis

Developed in the 1870's, graphic statics was a very powerful alternative to the more conventional numerical approach of resolving structural equilibrium. The approach relates a form diagram of a structure to a reciprocal graphical representation of its internal forces, the force diagram. This geometrical, graphical simplicity gives the method its power.

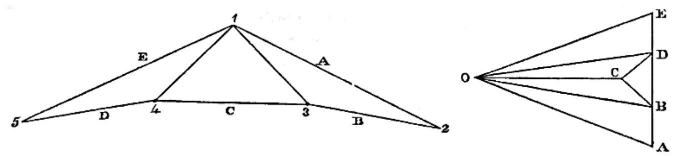

Figure 1. Form diagram (left) and force diagram (right), from Rankine (1858), page 143.

Graphic statics was very popular for solving analytical problems such as finding the stresses inside a reticulated structure, computing the deflection of a simple truss or a beam, and checking the stability of masonry structures. However, this remained true only until the invention of affordable electronic calculators in the mid-20th century. It then became easier and faster for engineers to solve these analytical problems with numerical methods, and later on, to employ computerized finite element methods.

A Proven Tool for Structural Design and Form-Finding

Curiously enough, none of the books on graphic statics published during this 'first golden age' address issues related to the shaping of structures. They only dealt with the computation of the inner stresses or the deflection of an existing structure. The first book that presents graphic statics as a tool of choice for design was the pioneering *Shaping Structures*, published in 1997 by Waclaw Zalewski and Edward Allen, who both taught structures in Civil Engineering as well as Architecture at MIT. More recently, their subsequent volume, *Form and Forces* (2009), expands on this viewpoint with a wealth of examples.

However, using graphic statics as a powerful design aid was not an alien concept to past great engineers such as Robert Maillart (Zastavni 2008, Fivet 2012) and Maurice Koechlin (Fivet 2016). Also, engineers at SOM have lately described how graphic statics is still relevant for tasks such as identifying optimal cable layouts (Beghini 2013).

Benefits for Engineering Education

The benefits of graphic statics as a tool for design during engineering education are many and are better explained when compared with numerical methods:

> *"I believe that graphical statics should play an important role in* [engineering education], *since its procedures give a direct understanding — much better than that afforded by analytical methods — of force systems and their composition, decomposition, and equilibrium."* – Pier Luigi Nervi (1956).

Moreover, graphic statics offers the advantage of clarity, in contrast to black-box methods. Inputs, outputs and intermediate computations are all part of the same drawing. Track of the entire design process is kept in the diagrams. Also, it is easy for the designer to highlight geometric shortcuts that simplify the description or the resolution of the structural problem. Graphic statics has the potential to develop deep intuition in students about the internal flow of forces and its fundamental relationship to geometry. Finally, graphic statics provide an ideal common ground for engineers and architects since it mixes statics with aesthetics in a fully visual synthesis.

Computer-aided graphic statics

The computerization of graphic statics does not withdraw these benefits. It actually brings speed, repeatability and memory which are the qualities that graphic statics lacked in order to compete with other numerical tools. For that reason software implementations have emerged in the past years (Greenwold 2003, Van Mele 2011) (Figure 2). They take the form of interactive applets involving predefined diagrams whose nodes can be moved and whose geometry can thus be modified. They constitute an unrivalled way for students to grasp how the geometry of a truss behaves together with its internal stresses (Van Mele 2012). Students, however, cannot interactively build new custom diagrams unless they have the required software skills to tweak it.

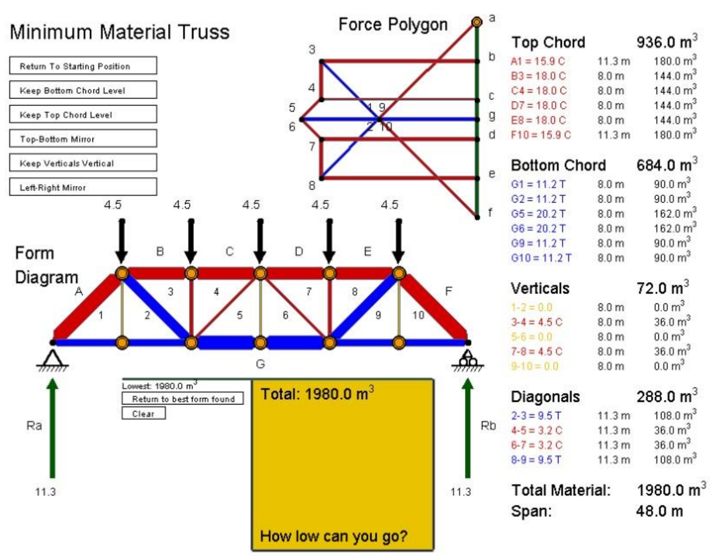

Figure 2. Screenshot of the "Active Statics" applet (Greenwold 2003).

Yet, more and more students (especially within the architecture curriculum) develop parametric programming skills as they now become involved with interactive tridimensional modelling. As a result, they are able to build custom parametric graphic statics diagrams, to explore alternative geometries using them and finally, and to optimize them very quickly within the same interface. The last section of this paper illustrates student explorations within Rhino and Grasshopper software.

One further progression of graphic statics in engineering education is currently being actively researched by the authors (Fivet 2013). On the one hand, it aims at simplifying the construction of parametric diagrams by defining two interdependent canvases (instead of one as in any CAD software) and by allowing the user to construct diagrams by combining primitive structural equilibriums. In other words, diagrams are not built one after the other or line by line. They are built through successive manual operations that transform the form and the force diagrams simultaneously without jeopardizing their static equilibrium (Figures 3 and 4).

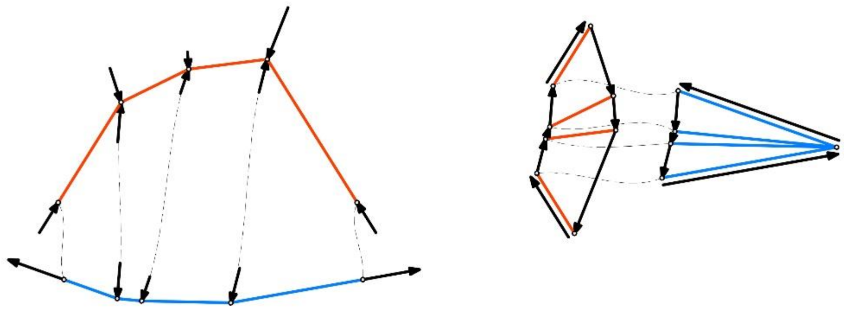

Figure 3. Before combination: two independent simply-connected networks in static equilibrium. (Form diagram on the left and Force Diagram on the right)

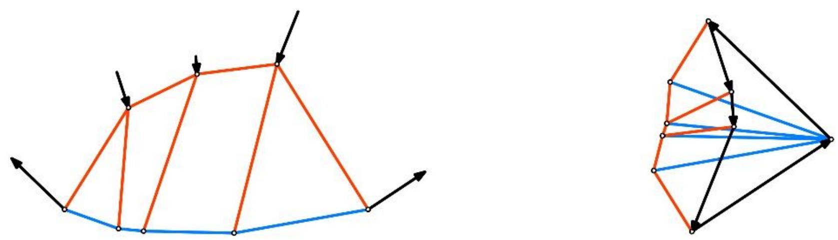

Figure 4. After combination: a reticulated network in static equilibrium. (Form diagram on the left and Force Diagram on the right)

On the other hand, the proposed method defines the diagrams within a fully geometrical constraint-based environment. Using this feature, one can apply a constraint onto a diagram (for instance a boundary condition in the form diagram or maximum stresses in the force diagram) and instantaneously visualize the impact of it onto each variable of the model, the corresponding solution space being represented by graphical regions inside which points of the diagrams can move (Figure 5).

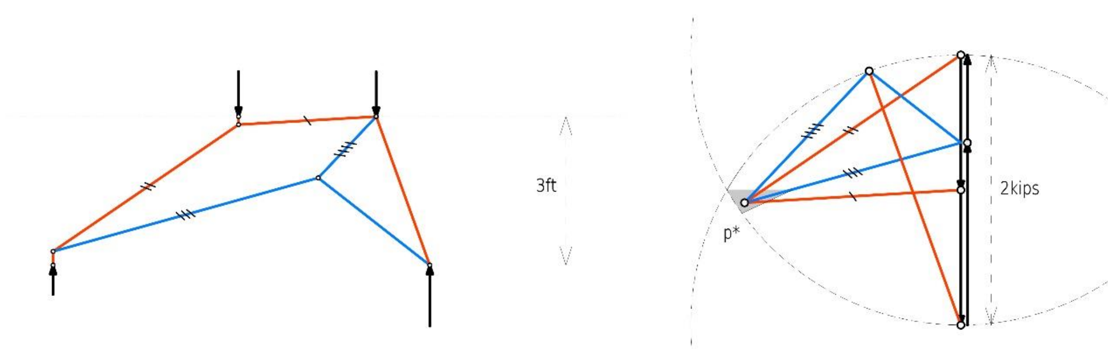

Figure 5. The grey triangle in the force diagram (right) is the entire set of positions that the point p* can hold in order for the strut-and-tie network to be smaller than 3 feet and for the bars to be of magnitude lower than 2 kips-force.

Although, for now, only some of these concepts have been tried out with students, it can readily be seen how they would improve their understanding of structural behaviors and how it would fasten design explorations of effective structures.

OPTIMIZATION FOR DESIGN EXPLORATION

The second set of techniques involves interactive optimization and design space exploration, an approach that combines the goal-seeking nature of traditional optimization, such as structural weight minimization, with qualitative input and judgment from human designers. The method therefore guides users toward high-performing solutions without forcing them to a single answer, and provides the opportunity to incorporate important but hard-to-formulate design criteria, such as constructability and aesthetics. Like graphic statics, interactive optimization shifts the focus of computation from analysis to design, and in the classroom, helps to build critical structural intuition in students.

Critique of Standard Structural Optimization

Standard, non-interactive optimization seeks to compute the best performing design according to mathematically formulated constraints and objectives, which can relate to a variety of standard structural engineering goals. Compared to a guess-and-check approach, this more systematic method offers a much more efficient and powerful means for engineers to find the best solutions for design problems. However, in its standard form, optimization is often inappropriate for the conceptual design of structures, both in practice and in the classroom. The primary reason for this is the focus on a single, optimal solution. Real-world engineering design problems are often difficult to formulate fully in a clean, mathematical way, especially when other disciplines with qualitative goals like architecture are involved. Therefore, the single answer provided by optimization is approximate at best, and likely doesn't solve the full, unformuate-able problem at hand.

Interactive Evolutionary Optimization

To address this problem, this paper argues for a hybrid approach that acknowledges that full problem formulation is often impossible. One promising method that achieves this is interactive evolutionary optimization. In structural design, this method can combine quantitative structural goals, formulated in the conventional way, with qualitative goals, not formulated but incorporated by a human designer (Mueller and Ochsendorf 2015).

This approach uses an evolutionary model that generates populations of design alternatives over multiple generations, and a combination of quantitative performance and user-indicated preferences are used to select the parent designs that produce the subsequent offspring. This results in a plurality of high-performing design alternatives that also meet unformulated but important design goals.

This approach has been implemented by the authors in an interactive, web-based design tool called structureFIT (Mueller 2014), used primarily in design education for structural engineers and architects (Figure 6). Research has shown that both populations find the tool intuitive and enjoyable to use, and are able to discover a wide variety of design possibilities that perform well structurally (Arnaud 2013). Because of the repetitive nature of the evolutionary exploration approach, students gain significantly more intuition than from finite element analysis alone; studying many varying solutions to a design problem reveals global behaviors and patterns that add significant clarity and insight. Examples of resulting designs are shown in Figure 7.

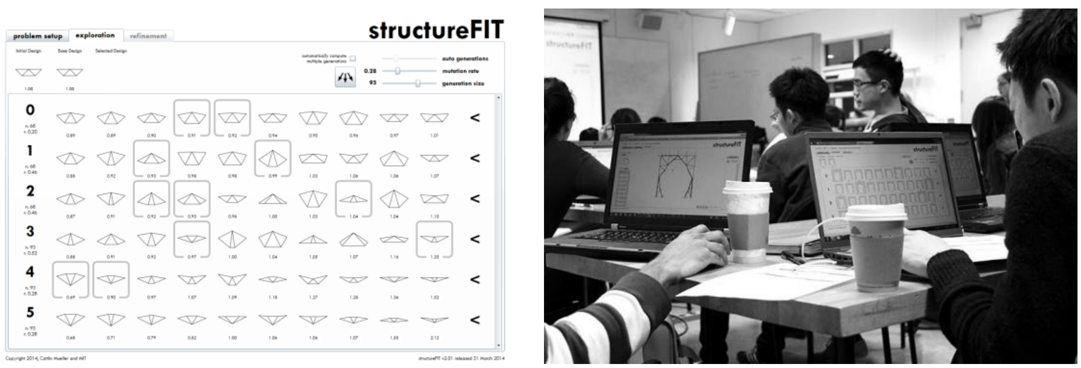

Figure 6. Screenshot of structureFIT (left) and photo of masters students using the tool in a structural design class (right).

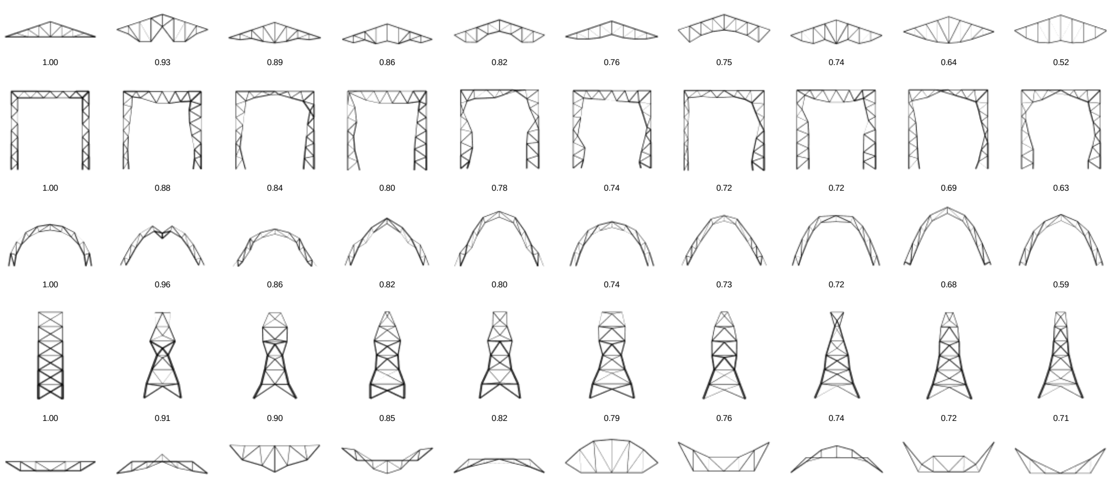

Figure 7. Resulting designs found using structureFIT (performance improves from left to right, numerical scores indicate required material).

Integrated Optimization Tools

While the stand-alone, web-based structureFIT tool has advantages of being free and easily accessible, tools that integrate with existing architectural modeling and structural analysis software are also attractive to students. Graphical programming and scripting environments such as Grasshopper (for McNeel's Rhinoceros) and Dynamo (for Autodesk's Revit) allow custom optimization and exploration functionality to overlay robust geometry and analysis libraries. For example, using Galapagos, an evolutionary optimization plugin, combined with Karamba, a finite element analysis tool, in Grasshopper, students can efficiently and easily explore high-performing solutions to parametric design problems. By changing parameter bounds and the objective function, a range of possible solutions can be explored. Beyond this, the authors are currently working on expanding the full interactive evolutionary functionality of structureFIT to these platforms.

CLASSROOM EXPERIENCE

Although MIT has a long tradition in the teaching of graphic statics to students in architecture (Zalewski 1997), the use of design-oriented graphical methods in the curriculum of civil engineers is relatively recent. The classroom exercise we describe here is part of the one-year CEE masters degree program in High-Performance Structures. Groups of 4-5 students were asked to design a roof to cover a 70' by 100' courtyard on the MIT campus surrounded by 4-story facades. Students had to define their own performance goals, and it was generally assumed to be an optimized function of cost, volume of material, embodied carbon, feasibility, usable floor space, and aesthetics.

Moreover, students were asked to make explicit use of graphical methods in order to find and express the global structural behavior in a very synthetic way. Numerical methods would then be used later on to check specific requirements (buckling, dynamic behavior, etc.). During early working sessions, the use of graphic statics was very helpful to quickly assess first design assumptions or to improve the initial geometry of certain elements (number, orientation, length, connections) with regards to the overall behavior of the structure.

Because performance has to be reached, students employed various tools to optimize the geometry. The following figures illustrate the design process of one team of students as well as their proposal. Figure 8 describes their initial iterations towards the structural typology chosen. Iterations concerned the use of the space and the global stability of the roof.

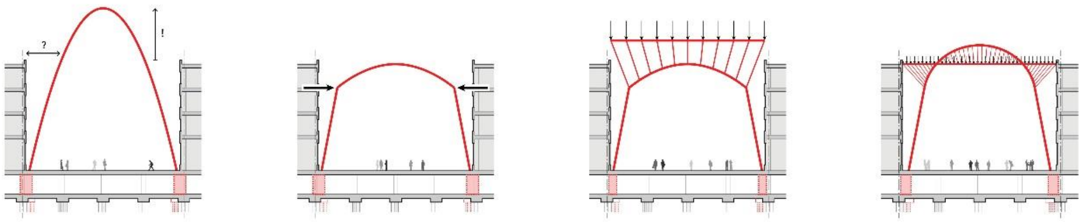

Figure 8. Initial iterations towards the final typology.

This typology and its force diagram have then been introduced in the parametric software Grasshopper for Rhino using a little bit of scripting in Python. The design exploration and optimization then continued through the variation of design parameters such as the height of the arch (given by the position of the pole in the force diagram, Figure 9) and the quantity of radial struts (Figure 10). The overall estimated weight of each iteration was used as the objective function. The weight, assumed as a linear function of the volume, was simply computed as the sum of the length of each member in the form diagram times its corresponding length in the force diagram, which is proportional to required cross-sectional area for stress-governed elements. As the spatial implications of the parameters could be directly grasped and discussed, the final solution chosen was not the "optimal" solution according to the weight-based objective function, but was neverthless high performing. Figure 11 renders the final, high-performance structure.

CONCLUSION

As a complement to classical analysis software, educators should seek tools that are oriented towards the early form-finding of structural solutions. This paper presented two possible alternatives. The first builds on graphic statics and the second proposes design explorations by comparison of partially optimized solutions. The paper has highlighted their respective benefits for curricula in civil engineering. An example of implementation in the classroom finally illustrated how the two approaches may be combined into a fruitful design process that remains equally relevant for everyday professional practices.

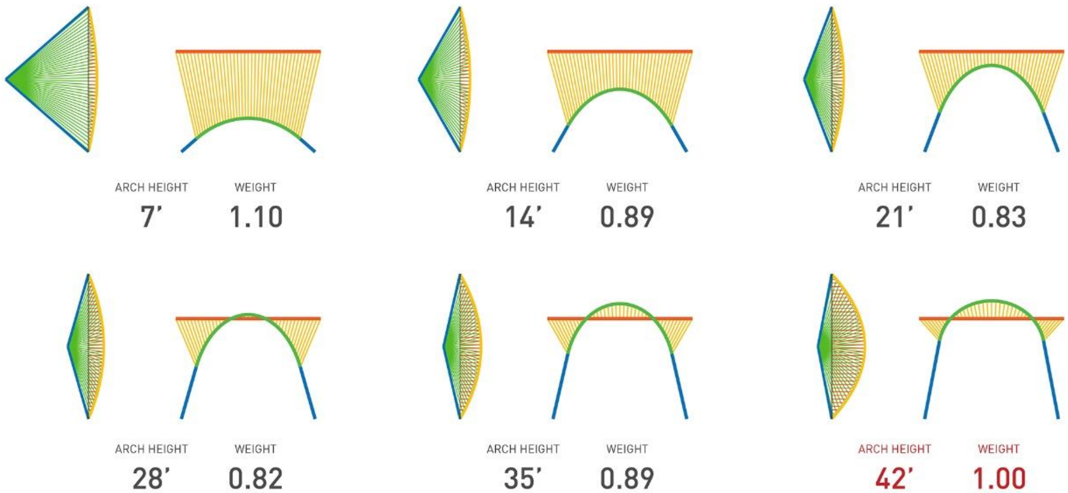

Figure 9. Design exploration with variation of the height of the arch.

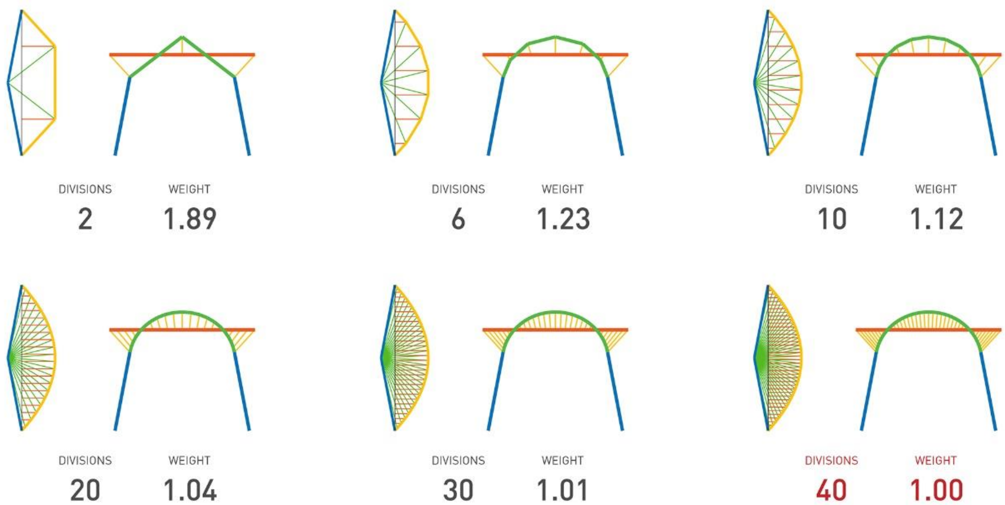

Figure 10. Design exploration with variation of the quantity of radial struts

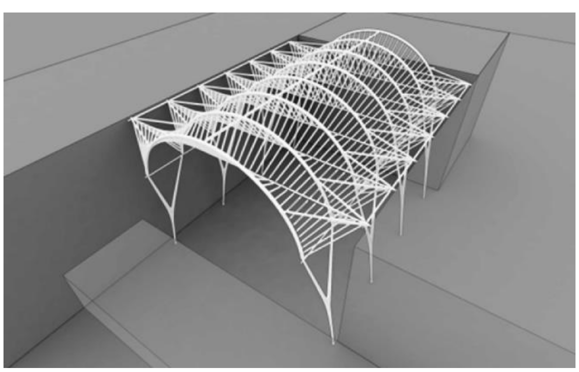

Figure 11. Rendering of the final structure

ACKNOWLEDGMENTS

The authors would like to acknowledge MIT students of 4.462 (Spring 2013) and students in the High-Performance Structures program (2013 – 2015). More specifically, they thank Stephanie Borchers, Juney Lee, Isabelle Su, Mingze Sun and Abram Wasef for agreeing to share the images displayed in this paper.

REFERENCES

Allen E. (2006). “The Essence of Building Technology”. *Proceedings of the 2006 Building Technology Educator’s Symposium*, D.J. Oakley and R.E.Smith Eds., University of Maryland.

Allen E., Zalewski W. (2009). *Form and Forces: Designing Efficient, Expressive Structures*. John Wiley & Sons.

Arnaud, V. (2013). *Quantifying architects' and engineers' use of structural design software* (Masters thesis, Massachusetts Institute of Technology).

Arup O. (1986), *Ove Arup & Partners*, 1946-1986, London, Academy Editions.

Beghini A., Beghini L., Schultz J., Carrion J., Baker W. (2013). “Rankine’s Theorem for the design of cable structures”. *Struct. Multidisc. Optim.*, Springer-Verlag Berlin Heidelberg

Black G., Duff S. (1994). “A Model for Teaching Structures: Finite Element Analysis in Architectural Education”, *Journal of Architectural Education*, vol.48, no.1 (38-55).

Conzett J., Solt J. (2008). “Soigner le savoir-faire”. *Tracés*, volume 134.

Fivet C., Zastavni D. (2012). “The Salginatobel Bridge design process by Robert Maillart (1929)”. *Journal of the International Association for shell and spatial structures*, issue 53, pages 39-48.

Fivet C., Zastavni D. (2013). “Constraint-Based Graphic Statics: New paradigms of computer-aided structural equilibrium design”, *Journal of the International Association for shell and spatial structures*, vol.54, issue 178, pages 271-280.

Fivet C., Ochsendorf J. (2016). “Maurice Koechlin’s innovative graphical methods for the form-finding of the Eiffel tower (1884-1889).” To be published.

Greenwold S., Allen E., (2003). *Active Statics.* http://acg.media.mit.edu/people/simong/statics/data/.

Mueller, C. (2014). *structureFIT*. www.caitlinmueller.com/structurefit.

Mueller, C., Ochsendorf, J. (2015). “Combining Structural Performance and Designer Preferences in Evolutionary Design Space Exploration”, *Automation in Construction*, under review.

Muttoni, A. (2005). *L'art des structures, une introduction au fonctionnement des structures en architecture*. Presses polytechniques et universitaires romandes.

Nervi, P.L. (1956). *Structures Aesthetics & Technology in Building*, McGraw – Hill, New York.

Rankine WJM (1858). *A manual of applied mechanics*, C. Griffin and Co., London.

Torroja, E. (1958). *Philosophy of Structures*, FW Dodge Corp., New York.

Van Mele T., Block Ph. (2011). *eQUILIBRIUM*. http://block.arch.ethz.ch.

Van Mele T., Rippmann M., Lachauer L., Block Ph. (2012). "Geometry-based Understanding of Structures". *Journal of the International Association of Shell and Spatial Structures*, volume 53, issue 4, pages 285-295.

Zalewski W., Allen E. (1997). *Shaping Structures: Statics*. John Wiley & Sons.

Zastavni D. (2008). "The structural design of Maillart's Chiasso Shed (1924): A graphic procedure". *Structural Engineering International*, volume 18, number 3, pages 247-252.

View publication stats