IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Design-oriented approach to teach structures in architecture based on graphic statics

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Abstract

During the last decade, a few academic institutions have reintroduced in the academic curriculum Graphic Statics, a method for structural design developed during the XIXth century, to teach structures to students in architecture. A question that is currently receiving a great attention is how to teach Graphic Statics in a way that allows the students taking advantage of its potential in the development of structural concepts that enrich architectural design. This paper presents a design-oriented teaching approach based on Graphic Statics, which has been recently tested in a design project of a mater course at the ETH Zurich.

Keywords: Structural design, Graphic Statics, Strut-and-Tie models.

1. Introduction

The conventional approach to teach structures to architecture students focuses on dimensioning structural elements using mathematical calculations. Due to this, the students often get the idea that designing the structure of a project consists in fulfilling a series of complex technical requirements, instead of seeing it as a creative task that can improve their designs. This educational approach makes that in professional world structural considerations are only considered at a late phase of the design project. This limits the design potential, makes difficult the communication between architects and engineers, and reduces greatly the chance of optimizing the use of material resources.

The greatest masters of structural engineering such as Robert Maillart, Antoni Gaudí and Pier Luigi Nervi among others emphasized the importance of creativity in structural design. A common factor of their work is the importance of designing structures tracking the flow of internal forces within them. For this purpose, these creative engineers used powerful tools such as Graphic Statics and physical experimental form-finding models. Graphic Statics, which was developed in the XIXth century and which is grounded on the lower bound theorem of the theory of plasticity, allows the visualization and calculation of the internal forces within structural elements by means of two reciprocal diagrams: the form diagram and the force diagram. This greatly helps in the understanding of the relationship between the form of a structure and the internal forces within it and, therefore, it has a great potential for designing structures. During the last decade, well-known academic institutions such as ETH Zurich, EPFL Lausanne, MIT, UCLouvain and Accademia di Architettura di Mendrisio among others, have integrated this method in the academic curriculum to teach structures to students in architecture. The main approach to teach Graphic Statics has focused on the analysis and form-finding of known structural typologies. A question that is receiving a great attention is how to teach Graphic Statics in a way that allows the students taking advantage of its potential in the development of structural concepts that enrich architectural design. This paper presents a design-oriented teaching approach based on Graphic Statics, which was tested in the design project of the master course “Structural Design V” in the academic year 2017-18 at the ETH Zurich.

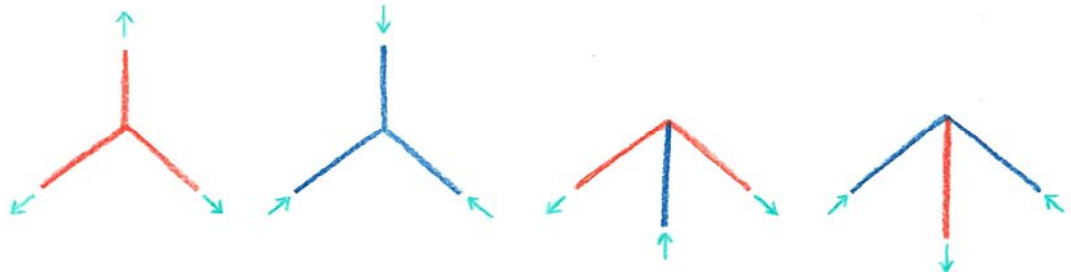

Figure 1: Nodes with three forces.

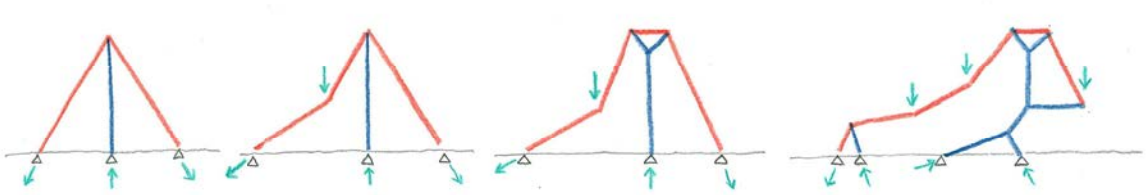

Figure 2: Example of the design process in two-dimensions.

2. Proposal

The proposed approach had three main objectives:

- Motivating the students to design both architecture and structure simultaneously.
- Allowing the students to fully control the relationship between form and internal forces during the design process.
- Encouraging the design of structures beyond known structural typologies.

In the design task, the students were asked to design a children playground located at the shore of river Limmat in Zurich. This program was chosen since it has no other technical requirements than those related to the structure, and, therefore, the students have a greater design freedom. In addition, such program has a rather small scale that allows the students controlling their design and exploring solutions beyond the limitations of large-scale building projects.

Graphic Statics creates a powerful visual link between the form of a structure and the internal forces within it that opens a new possibility: designing forms by designing the forces within them. Based on this idea, the proposed approach consists in starting the architectural design process by creatively sketching flows of internal forces in equilibrium using Graphic Statics. A flow of forces in equilibrium is a network of forces in compression (blue) and/or tension (red) that meet at nodes, where the sum of the forces acting at them equals zero and, therefore, they are in static equilibrium. The students were encouraged to see these sketches not only as diagrams representing the internal forces in the structure, but also as the main lines shaping the form, functions and spaces of the building they are designing. In this manner, architecture and structure are designed simultaneously. Since mastering equilibrium requires practice and the students had no previous experience with Graphic Statics, the students were encouraged to:

1. start sketching flows of forces composed of nodes with only three forces acting at them.
   This is due to two main reasons: first, such nodes are two-dimensional and, therefore, easy to visualize and comprehend; second, only four different nodes meet such condition, which facilitates the combination of such nodes for the creation of a force flow. As figure 1 shows, these four node types emerge from bifurcating a tension force into two tension forces, bifurcating a compression force into two compression forces, redirecting a tension force thanks to the action of a compression force and redirecting a compression force thanks to the action of a tension force. By combining such nodes, it is possible to create two-dimensional and three-dimensional flows of forces in an easy manner.

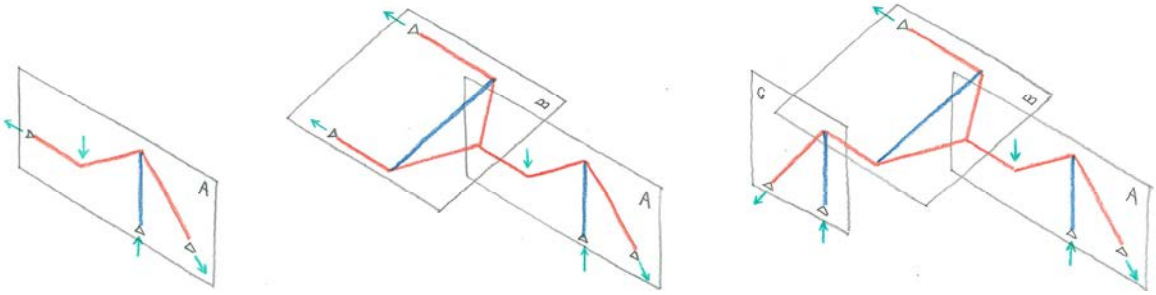

Figure 3: Example of the design process in three-dimensions.

2. start from a sketch composed of only one node in equilibrium and add nodes progressively to the sketch (fig.2). This allows controlling the design process and checking the equilibrium of the node and the magnitude of the internal forces by means of Graphic Statics.

3. begin sketching 2D force flows and later 3D ones. Three-dimensional sketches can be constructed in several ways such as creating compositions of nodes that lie in different planes (fig.3) or by first defining a series of force flows lying in two or more different planes and later connecting such flows by means of an additional force flows lying in an intersecting plane.

While doing the sketches, the students were asked to construct physical models of the force flows. Such models had to show the physical behavior of the structure and its stiffness. The models helped visualizing the space and motivated the students to think about how such flows should be materialized into a real structure. The production of sketches and models was not linear, instead the students were encouraged to include in the sketches the modifications done in the models and vice versa in order to understand the implications of such modifications.

3. Selected student projects

3.1. “hanging under the bridge”

The playground is based on the idea of crossing the Limmat river in a playful way (fig.4). It also proposed extending a near public bath by creating a new platform to rest and jump into the river. The initial sketches helped exploring possible forms to achieve this goal. These sketches also allowed the students to understand the need of compression elements at both extremes to elevate the bridge and separate it from the river bed. In order to avoid creating such supports, the proposal used as support an existing elevated bridge. By building physical models, the students materialized the proposal as a lightweight structure composed by a network of tensile cables and platforms subjected to compression forces.

3.2. “star catcher”

The concept of the playground is to create a space for jumping (fig.5). The initial tension-compression sketches explored different ways to support the jumping bed. Finally, this was hanged in order to emphasize its separation with the ground. By rotating the main section around the central vertical axis and connecting these different sections the three-dimensional shape was created. Using graphic statics it was possible to find out the internal forces in this complex structure. By building the physical model, the students materialized the compression forces as timber struts and the tensile element as elastic bands. In this manner, the movement created by the action of jumping was propagated to the entire structure.

4. Conclusion

The presented approach to teach structures in architecture based on Graphic Statics proposes a new starting point for architectural design that integrates the structure from the very first line sketched. Its key features are:

- Reversing conventional approach placing structure at the beginning of the design process.
- Architecture and structure are designed simultaneously.
- Highly abstract start with open-ended design process.
- Bottom-up approach that pushes the exploration beyond known structural typologies
- No need of computational methods, just a red and blue pencil.

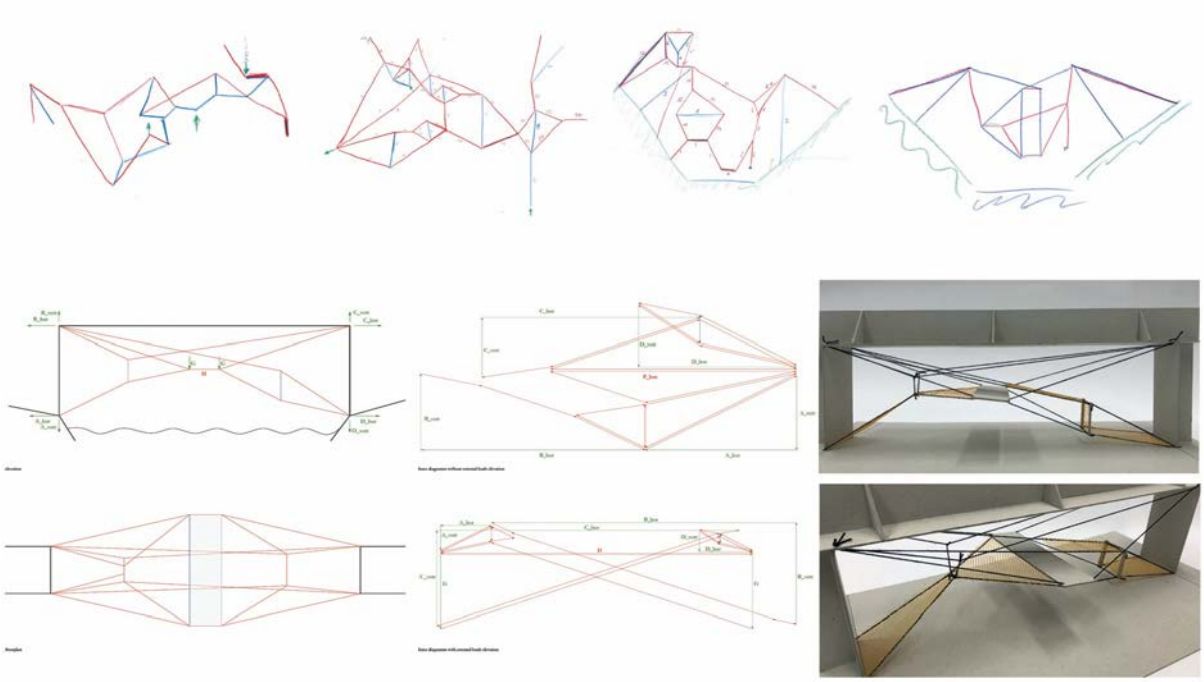

Figure 4: "hanging under the bridge" by Sebastian Kannewischer, Ivo Raffi, Lukas Steiner and Chenfan Zhu.

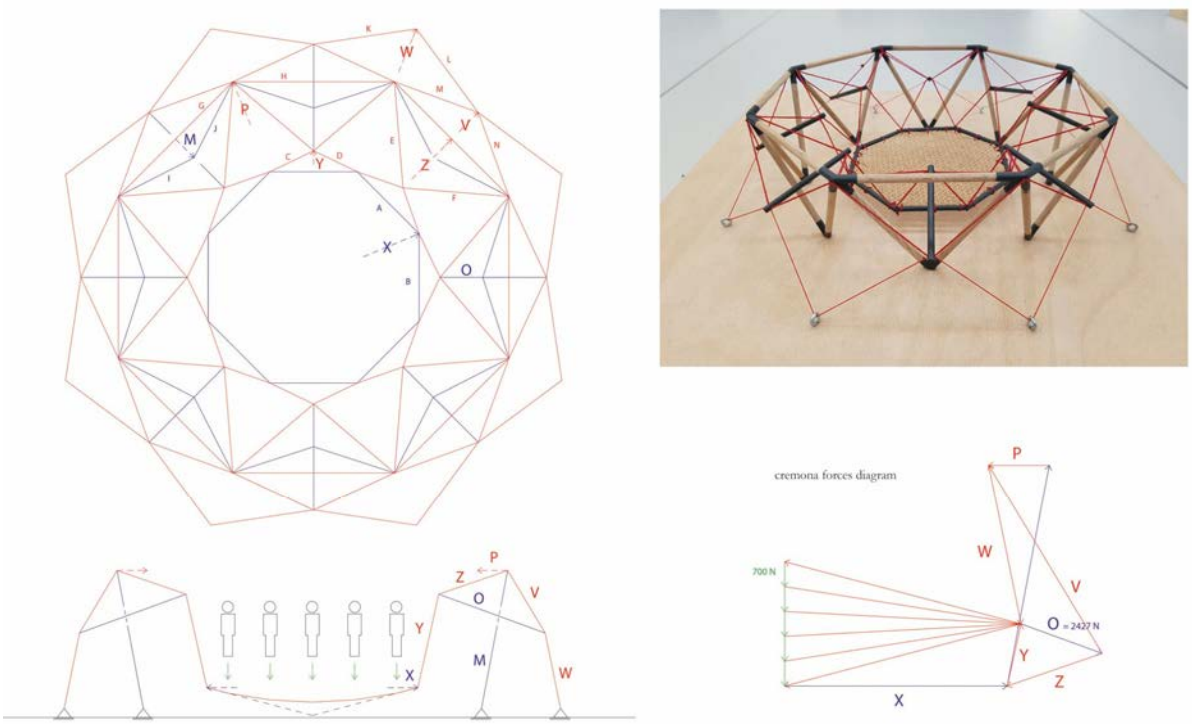

Figure 5: "star catcher" by Julien Tacca, Valenting Locher, Nick Böwing and Noemie Vetterli.

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