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Form & Force: teaching form-finding and fabrication of complex geometry through the design and construction of a structural sculpture

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Abstract

This paper presents the newly introduced elective course "Form & Force" offered to master's students at the Faculty of Architecture at KU Leuven. The course introduces the concept of structural form-finding to students, with a focus on the relation between form and structural behaviour and on control of complex geometry. Besides theoretical classes and practical exercises, the course culminates in a hands-on project where students design and construct a structural sculpture themselves. This paper briefly outlines the theoretical contents of the classes, provides an in-depth view on the collaborative design process of the structural sculpture, and discusses the learning outcomes based on student feedback.

Keywords: Architectural Education, Form-Finding, Structural Design, Collaborative Learning, Interdisciplinary Approach.

1. Introduction

This section discusses the aims of the newly introduced course "Form & Force" against the background of the Bachelor program at the architecture faculty of KU Leuven.

1.1. Background

Architecture can be regarded as an interdisciplinary field, but educational programs for architects are traditionally characterised by disciplinary boundaries with a separate organisation of courses [1], [2]. In the Bachelor of Architecture program at KU Leuven, architecture students take three courses on structures and structural design. They learn about equilibrium, internal forces and stresses, and how to calculate these. Additionally, they explore various structural concepts: section-active, vector-active and form-active structures [3] and how structures are often hybrid forms of these main concepts. In these courses, various form-active structural typologies are explained and illustrated with examples; however, the program does not delve deeply into these topics. The bachelor program's studios primarily focus on the design of buildings. Structural design, spatial structures, and complex geometry are not often discussed in-depth in the design studios.

The course presented here is intended to provide the students with insights and skills that are complementary to the content already provided in the bachelor program. However, as it is part of a Master program taught in English, many students have completed their bachelor program elsewhere and thus have a different background.

1.2. Course aim

Apart from introducing students to form-finding methods and the use of form-finding as a design tool, the main aims of the course are to increase students' understanding of structural design and to make students aware of the interplay between form and structural behaviour. These latter aims are not limited to form-found structures: they are intended to help students integrate their understanding of structures and its detailing more actively in future design projects. This way we aimed to enrich the students' tacit knowledge, enabling them to design while understanding and acting upon technical and practical constraints or boundary conditions that might be unfamiliar to them at first.

Further aims are to help students develop an understanding of digital fabrication (including material and fabrication constraints), to increase their fluency in the use of digital design tools and to strengthen their experience in developing details.

An important goal of the course is to let students experience an actual design and construction process. We aim to let students experience the dynamics of professional architectural practices by structuring part of the course as a collaborative multidisciplinary process. Furthermore, by designing, detailing and constructing a structure themselves, the architecture students get hands-on experience with materials and fabrication logic.

2. Course contents

This section discusses the contents and organisation of the course.

2.1. Course structure

The course consists of eleven classes of three hours each and has a course load of 4 ECTS. The first five classes start with lectures on topics such as structural design, form-finding, geometry, and digital fabrication (see Section 2.2). During some of these classes, students work on individual exercises as well (see Section 2.3). The last six classes are organised as a group project to design, prototype and fabricate a structural sculpture (see Sections 2.4 and Section 3).

2.2. Theoretical classes

In the theoretical classes, topics such as equilibrium, statics and internal forces are refreshed, after which three-dimensional truss systems or networks of tension and compression are discussed. By showing the stress-volume number of various truss systems, topologically optimised trusses and variations on trusses with equal topology, students learn that not all networks of tension and compression are equally efficient.

The concept of form-finding is introduced as a design process (both physical and digital), that leads to the form of a structure in static equilibrium under given loads and boundary conditions. Starting from tension-only elements such as cables, examples of catenary shapes, cable nets and membranes are given, accompanied by examples of historical and contemporary projects. Once the concept of pure tension was explained, the structural behaviour of pure compression structures is discussed and illustrated using examples of built projects. Simultaneous with the theoretical background of tension and compression-only structures, physical methods of form-finding are introduced by the analogies of hanging chain models for compression-only structures or soap films for membrane structures. Additionally, various methods of form-finding such as the force density method by Schek [4], particle spring systems [5], the dynamic relaxation method as introduced by Barnes [6] and Combinatorial Equilibrium modelling [7] are introduced on a conceptual level.

Finally, digital fabrication strategies for the realisation of structures with complex geometry are introduced. This lecture includes geometric principles of single and double curvature, geometrical properties of grid patterns on surfaces, segmentation and cutting patterns for doubly curved surfaces and subtractive and additive manufacturing methods.

During the theoretical classes, students and teachers do not yet know what the structural sculpture will look like. The contents of the theoretical classes are therefore intended to form a broad basis of knowledge that students can use when starting to design.

2.3. Practical exercises and assignments

Through a series of assignments, students complete exercises on the topics introduced during the theoretical classes. Most assignments combine digital form-finding with the making of a physical model.

The assignments include an exercise on form-finding with the help of graphic statics based on subdivisions of a force polygon [8]. When studying catenary shapes and cable nets, Kangaroo3d [9] is used for form-finding exercises, as the instructors consider Kangaroo3d an intuitive tool that converges easily towards a solution. To show the relation between form and force diagrams in compression-only structures, RhinoVault [10] is used. Figure 1 shows examples of assignments submitted by students.

Figure 1: Examples of digital (top) and physical (bottom) student assignments

In the design studios, students are primarily encouraged to draw by hand and create physical models: digital drawing and modelling play a limited role in the educational program. In this course, the authors aim to make students aware of computational methods for advanced geometrical design and form-finding by working with Grasshopper [11].

2.4 Group project

At the end of the theoretical classes, students are asked to work on proposals for the concept and general shape of a structural sculpture. After comparing the initial ideas, groups of students are then formed to further elaborate the design proposals collaboratively. At the start of the second phase of the course, consensus on the general concept of the sculpture needs to be reached.

To structure the design process further from this point onwards and to establish workable boundary conditions and constraints to design with, groups of students are formed that focus on different aspects of the design, such as form-finding and digital modelling, materialisation, detailing, and lighting. Each of these groups (which we coin "expertise groups") is then asked to come up with proposals to develop the design further and to identify possible constraints.

Neither the expertise group nor the instructors know beforehand what the sculpture will look like. Every week each expertise group presents their work at the start of the class (and sometimes also at the end) as part of an iterative design process in which the different constraints from the expertise groups can be reconciliated and an interdisciplinary design thinking process [1], [2] can be established. The final sculpture design thus takes shape in incremental steps, by integrating input and findings from all expertise groups.

3. Structural sculpture

This section discusses the group project created by the sixteen students who participated in this elective course in the fall semester of 2023.

3.1. Brief

The following boundary conditions were provided: the sculpture should consist of compression and tension elements only, the sculpture should fit within a volume not exceeding three meters in each direction, and the sculpture would be hung from a single point. The choice of material and fabrication processes was left up to the students.

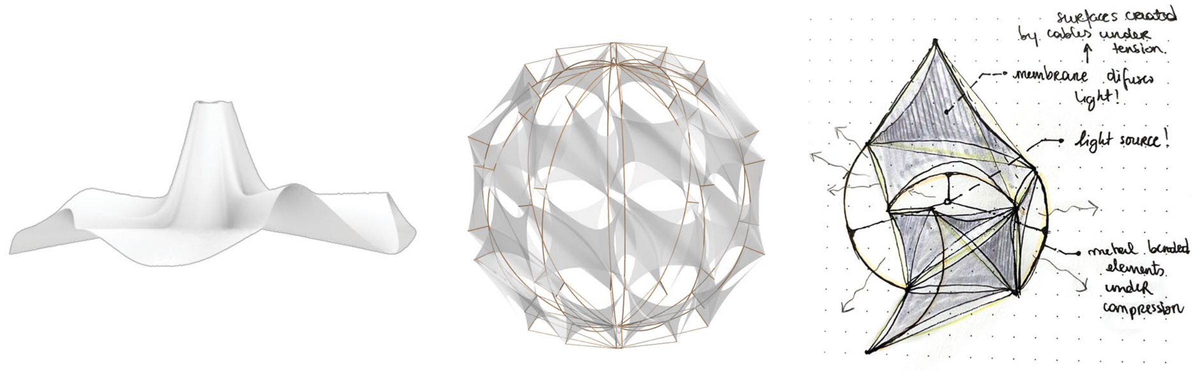


Figure 2: Design ideas proposed by students

3.2. Concept development

Figure 2 shows some of the submitted ideas for the final structural sculpture. The submitted ideas formed the starting point for a discussion to find a common ground for the design that the students could work on; a lot of common interesting topics could be identified between all submission. In a round table discussion, the decision was made to design a structural system that consists of compression struts and membranes. The exact form of the sculpture would be determined in the subsequent design and decision-making process.

3.3. Expertise and focus groups

This section describes the roles of the expertise groups in the fall semester of 2023.

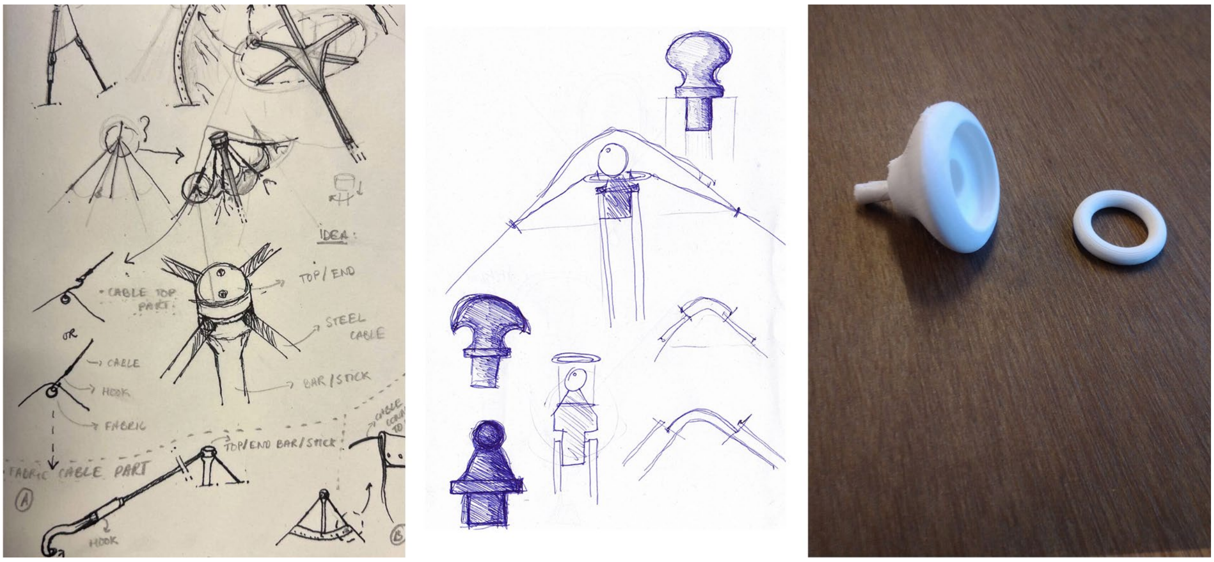


Figure 3: Sketches and ideas for connecting the membrane to a compression rod

3.3.1. Detailing

The detailing group investigated detailing for membrane structures and how compression rods can be connected to a membrane. Figure 3 shows some drawings of the investigation.

3.3.2. Form-finding and digital modelling

The form-finding and digital modelling group came up with various ideas for membranes and compression struts. Figure 4 shows designs that were digitally generated with the help of Kangaroo3d. Based on the input from the detailing and the lighting group, the students opted for a sculpture that consists of compressed rods enclosed by a tensioned membrane, with openings that create an interesting light play and make it possible to see the internal compression rods. The complexity of the detailing and the time needed to manufacture these designs were taken into account when choosing the final proposal.

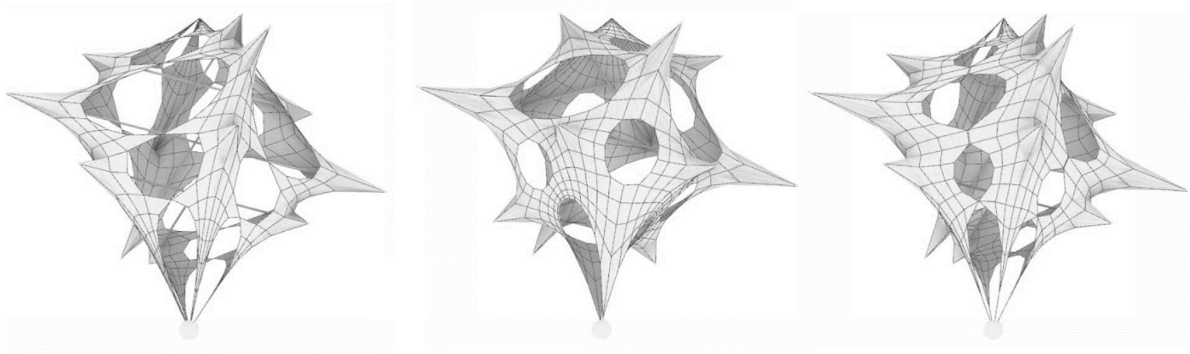


Figure 4: Design proposals created by the form-finding and digital modelling group

3.3.3. Lighting

The lighting group aimed to create an interesting play of light that would strengthen the visual presence of the structure. They investigated various lighting ideas applicable to sculptures. Together with the form-finding and materialisation expertise group, the choice was made to have an enclosed light-coloured membrane structure in which light sources are placed. This way the structure appears opaque when not illuminated from the inside, but the inner compression rods could be observed when illuminated. The holes in the membrane helped simplify the installation of the wiring.

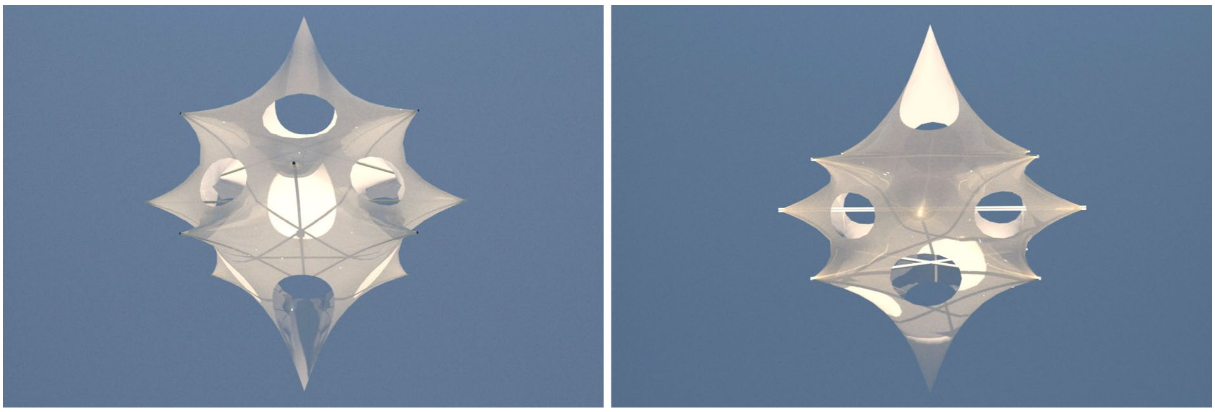


Figure 5: Reference images (left) and visualizations of the proposal created by the lighting group (right)

3.3.4. Materialisation

Knowing that a membrane structure would be created, the materialisation expertise group bought several samples of fabric to test various aspects. The stretchiness of the membrane was an important factor, as the membrane should be stiff enough to limit deformation under tension, yet flexible enough to smoothly deform as a result of fabrication inaccuracies, while also being easy to sew. Apart from a variety of fabrics, various sewing patterns were tested and evaluated on appearance, strength and sewing speed.

For the compression rods, bamboo sticks were proposed because of their sustainability, appearance and availability (one of the students had a source of freshly grown bamboo at his disposal). A detail was designed to join two bamboo sticks with a steel threaded rods with nuts (see Figure 6). These nuts would allow to adjust the length of the compression rod, which could be used to add tension to the membrane. Because of the holes in the fabric, the threaded rods would be accessible to adjust their lengths. However, after testing the bamboo sticks on compression, they failed due to buckling and the bamboo sticks splintered where the threaded rods were inserted. Because of this failure, the design continued with thicker wooden rods.

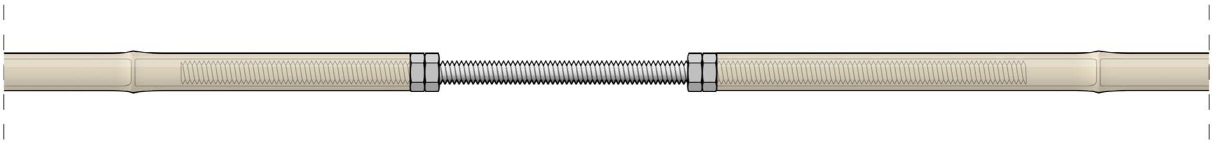


Figure 6: Detail of bamboo rods with an inserted threaded rod

3.4. Prototyping a membrane structure

To gain experience with membrane structures and their behaviour, a prototype of a roughly conical membrane structure was created. Besides learning how to fabricate such a structure, this helped the different expertise groups evaluate the viability of their proposed solutions for cutting patterns, lighting, detailing and materialisation. Figure 7 shows the fabrication and final shape of the mock-up. A round wooden base with a vertical post (consisting of a cross of two plates) was used to fix the membrane on.

By building the mock-up, the materialisation group could measure the time needed to sew a certain length of seams. Additionally, the difficulty of sewing the tip of the conical shape (due to limited space) became clear.

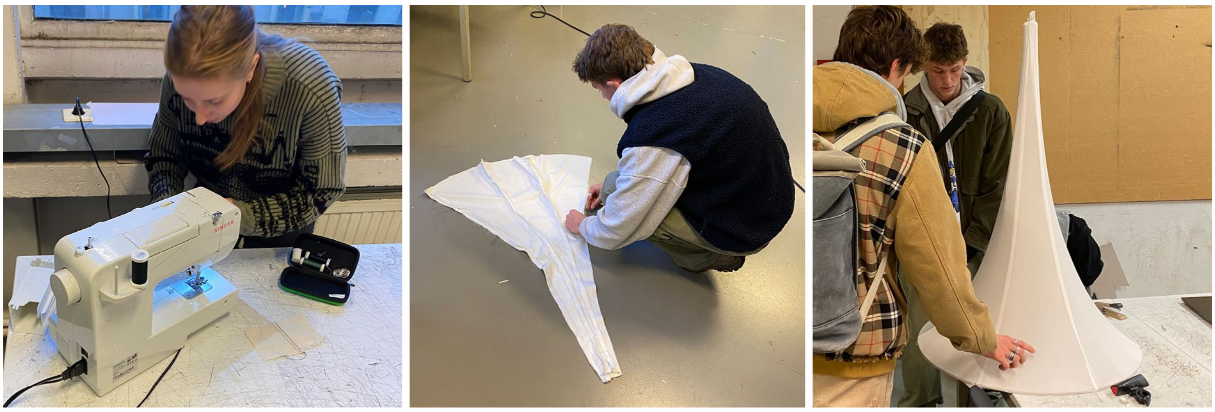


Figure 7: Fabrication of a membrane structure mock-up (left, centre) and the final shape of the mock-up (right)

3.5. Manufacturing and construction of the structural sculpture

Once a design was agreed upon that satisfied all constraints and concerns from the different expertise groups, preparation of the fabrication started.

The form-finding and digital modelling expertise group proceeded with finding an appropriate cutting pattern for the doubly curved membrane. A subdivision of the membrane into smaller patches would allow to approximate the intended doubly curved geometry more closely. However, the total length of the seams should be limited due to the available time. Once the students decided on the cutting pattern (Fig. 8, left), all patches were flattened digitally (Fig. 8, centre) and printed on pieces of paper. The textile patches were cut out manually, after which the different patches were sewn together using ordinary sewing machines.

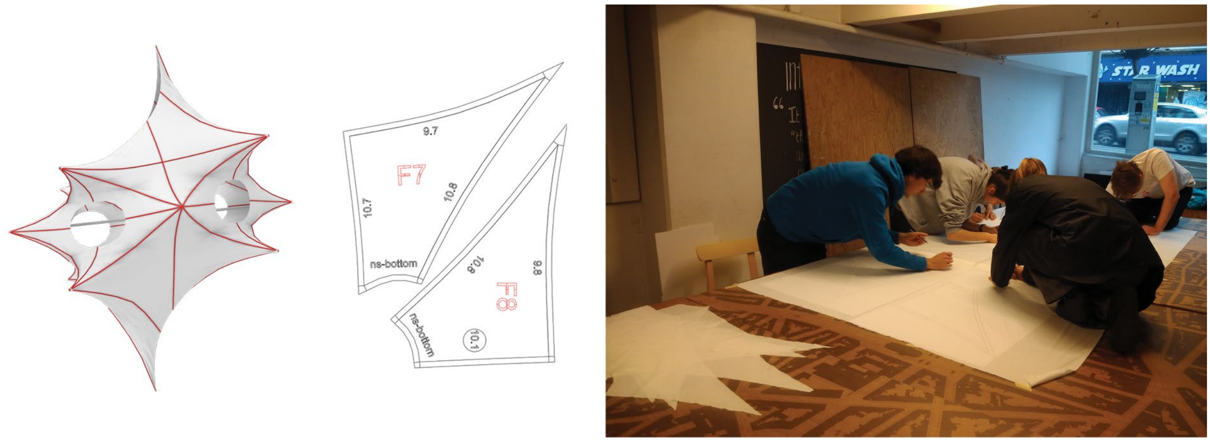
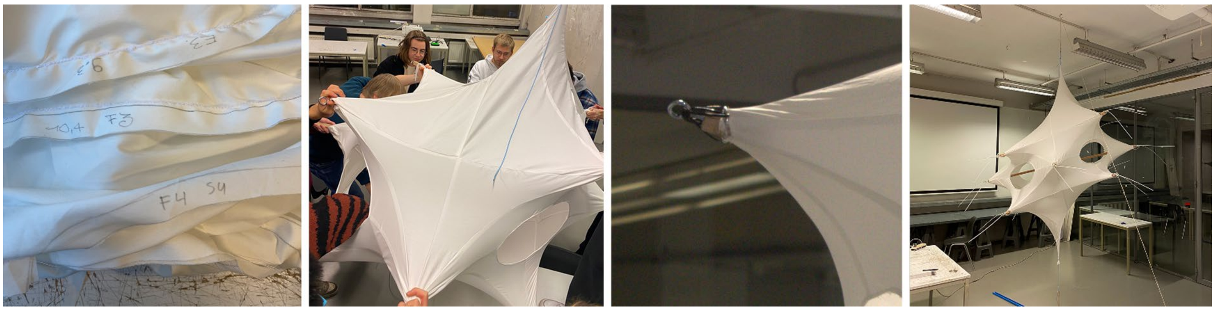


Figure 8: Marked seams on the 3d model (left), 2d drawings of unrolled fabric patches (centre), tracing and cutting process (right)

The students devised a numbering system to identify the seams that should be sewn together (Fig. 9a) in two sessions of about three hours each. Once the membrane was finished, it was first tensioned by pulling the spikes of the sculpture apart manually (Fig. 9b).

When estimating the forces necessary to pull the fabric into a smooth shape, it became clear that the bamboo sticks would fail due to buckling under compression force. Therefore a last minute change was necessary, using wooden rods instead. As these wooden rods could not be extended using the detail devised for the bamboo rods, a detail was devised using plastic cable ties that connect an eye screw at the rod's end to a metal ring sewn in the membrane (Fig. 9c). Figure 9d shows the first time the entire sculpture was assembled as a test.



(a) (b) (c) (d)

Figure 9: Edge numbering system (a), manual tensioning of the fabric (b), corner detail (c) and result of the assembly test (d)

After having tested the assembly process and having verified that the resulting shape was as intended, the sculpture was installed in the main ground floor space at KU Leuven's architecture faculty campus in Brussels. Figure 10 shows the completed structure.

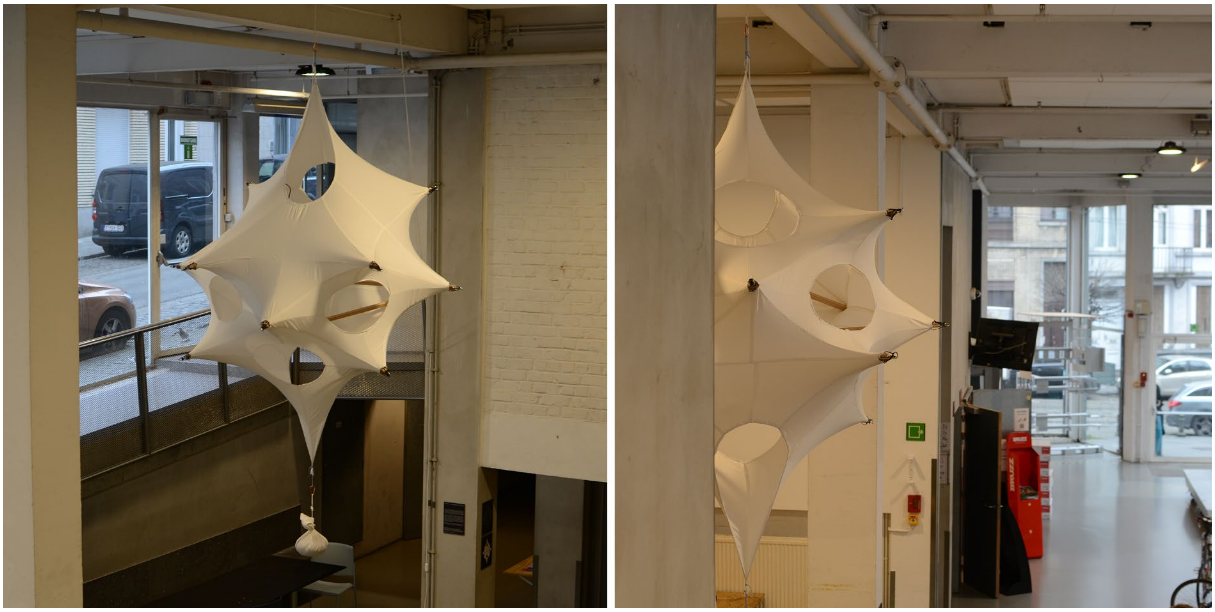


Figure 10: The structural sculpture made from fabric and wooden rods at its final location. The entire structure is prestressed at the ends of the wooden rods and by a mass attached to the bottom.

4. Learning outcome

This section discusses the learning outcome of the course by discussing individual student work, the group project and statements by students.

4.1. Individual exercises

The individual exercises comprised 2d graphic statics, physical models and digital simulations. The graphics statics exercise was linked to a physical model exercise. This exercise proved challenging: some students managed to create a physical model and a graphically derived solution that match, some created a valid graphic statics solution that was not matched by the physical model (due to inaccuracies or unsuitable materials), and some did not create a valid graphics solution. Furthermore, one student created a model that required more advanced knowledge of graphics statics than was provided in class. However, through the introduction, by trying and through the discussion of the results, we believe that students have at least become aware of the possibility to graphically predict form and forces.

The digital form-finding exercises were quite structured and almost all students managed to generate their own form-found geometry. This was helped by letting students work on part of the exercises during class, so that the teachers could assist with any problems that students encountered.

4.2. Group project

The group project resulted in a sculpture that fulfils the design brief and visually matches the digital model. Students thus experienced the whole workflow from conceptual design to realisation.

During the design process, the groups were not always proactively working on their tasks, but instead sometimes waited for decisions from other groups, who in turn were waiting for yet another group. Despite weekly meetings in which the groups presented their results to other groups, this led to a slight delay in the execution of the sculpture. From an educational perspective, we consider this a valuable learning experience.

Another learning experience was the unpredictability of materials: the bamboo rods that were envisioned to be used turned out not to be able to resist the forces that resulted from the proposed detail solutions. The inevitability of fabrication inaccuracies came to light during the manual cutting of the fabric and continued during the sewing process. While everyone was hoping for a smooth process and accurate execution, we consider these experiences to be valuable learning moments.

4.3. Student feedback

We asked all students to write an individual report on their contribution to the project and also asked them to write about their learning experience. This happened before grading, so we cannot exclude the possibility that students provided socially desirable answers. However, we find that these comments provide insights into which experiences students found most significant.

Multiple students commented on what they learned in relation to the design process: “learn how to work with forces”, “finding simple solutions for difficult problems”, “the meticulous decision-making process”, “the art of problem-solving”, “the iterative aspect of the design process” and “the initial idea serves as a starting point rather than a final destination”. These comments suggest that our aim for learning outcomes that extend well beyond form-finding were reached.

Regarding fabrication, students commented that the experience “has taught […] how complex its process is” and “helped […] understand the complexity of actually having to build something”, brought insight into the “transition from design to realisation” and highlighted “the complexity each detail brings”.

Finally, the way groups worked together was discussed by multiple students, showing that students are well aware of the importance of communication and of the difficulty of working together on projects with many open questions that can only be resolved progressively by collaboration.

4.4 Further observations

As teachers, we tried to limit our influence on important decisions, instead trying to nudge students to take decisions themselves. We deliberately did not create a backup design. However, when solutions turned out not to work out, at times we pushed for quick decisions, which turned out to frustrate some students. We also tried to stimulate all groups to work on their tasks proactively, but did not always succeed.

The end goal of the design and actual construction of a physical structural sculpture kept students engaged throughout the course. However, during both the design development and the fabrication process, there were moments where many students were needed and other moments where only a few students could work in parallel. This may have led to a perceived imbalance in contribution to the sculpture.

We believe that the division in expertise groups led all students to develop a sense of ownership over the project and consider this approach a generally successful strategy. It did however provide students the opportunity to steer away from topics they deemed difficult. Furthermore, within the groups, the work was at times very unevenly divided.

At one point late in the process, bamboo rods failed structurally when a student was testing how much force they could take. Another student commented that he had seen this coming, but had not raised the issue earlier. Others seemed unaware that the structural failure happened. This demonstrates that communication between the students and between students and teachers was not perfect.

Overall, we were surprised how many students had very little practical construction experience. This means we created an unintentional learning opportunity that we believe has benefited the students.

As a final remark, some students chose to follow this elective course but dropped out after a few weeks. We have only received feedback from students who completed the course, so unfortunately the reasons for these students dropping out are unclear.

5. Conclusion

This paper introduced the elective course "Form & Force" offered to master's students at the Faculty of Architecture at KU Leuven.

Results of the first time the course was taught (in the fall semester of 2023) show that many of the learning aims have been realised. This was reinforced by feedback written by students at the end of the semester.

First of all, students have been introduced to form-finding methods and experienced using form-finding as a design tool. Students' understanding of how to integrate structural design considerations in their design projects has improved, in particular where it comes to the interplay between form and structural behaviour. Additionally, students increased their familiarity with digital design tools and with digital fabrication. Furthermore, they gained hands-on experience fabricating an actual project, in the form of a sculptural structure. Finally, through a collaborative group project in which groups of students took different roles, students experienced both benefits and difficulties of such a collaborative process.

6. Discussion

As the aims of the course have largely been achieved, the course will be taught in a similar way in 2024. However, the time dedicated to designing and realizing the structural sculpture comes at a cost: not only does this limit the time available to focus on theory and exercises, the aim to construct a sculpture also means that time needs to be reserved to discuss digital fabrication. Within the curriculum, we feel that this time is well spent, but students only reach a basic level of familiarity with this topic. Similarly, more time would be needed for students to develop sufficient experience to apply graphic statics in a meaningful way in design projects.

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