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BUILDING FREEFORM: A WORKSHOP EXPERIMENT FROM DESIGN TO FABRICATION

C. DOUTHE[1], M. BAGNÉRIS[2], L. DU PELOUX[1] AND R. MESNIL[1]

[1]Ecole des Ponts ParisTech, Laboratoire Navier
6&8 avenue Blaise Pascal, Cité Descartes, F-77455 MLV Cedex 2
cyril.douthe@enpc.fr

[2]ENSA Marseille

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Abstract. In the following of an already old tradition of design/build workshops in architecture, the works presented here illustrate an attempt of introducing design/build teaching experiments in structural engineering education. This one-week experiment was conducted yearly during the last nine years at the Ecole des Ponts ParisTech, France. The workshop, called "Building free-form", is organised by founding members of the thin[k]shell project, an academic initiative for mixing advanced research, teaching and practical realisations with industrial partners. This project will be first detailed, because it is essential to the framework and objectives of the workshop. Then the evolution throughout the years of the pedagogy and of the supporting objects (first textile structures, then elastic gridshells) will be detailed. Finally, last year experiment centred on the use of robotic fabrication and its impact on the whole design process will be presented. Main aspects of workshop programs, teaching material and financial issues will be given for each type of structures, as well as some feedback on the various editions.

1 THE THIN[K]SHELL PROJECT

In the following of an already old tradition of design/build workshops in architecture (see for example the experiments of M. Vrontissi [1] in Volos Greece, those of J. Ramon in Talca Chile [2], M. Kawaguchi in Tokyo-Japan [3]), we present here feedback on an attempt of introducing design/build teaching experiments in structural engineering education at the Ecole des Ponts. We focus on a one-week workshop called "Building freeform", hold yearly during the last nine years.

This workshop is a typical illustration of initiatives hold in the framework of the thin[k]shell project at the Ecole des Ponts. Or, to be more accurate, the educational principles of the thin[k]shell project are a direct emanation of the experience gained in the teaching of the "building freeform" workshop. The spectrum of the project is however wider and extends to expeditions in the field of structural engineering beyond education. It promotes an integrated vision of research, education and fabrication which embraces the whole design process from the very first sketches to the construction of full scale buildings, from material/assembly testing to the development of original numerical tools. The team (about 15 persons) gathered around the development of the first prototypes of elastic gridshells in composite materials [4].

Nowadays, it combines expertise in the field of architecture, material science, structural engineering, historical buildings, architectural geometry and numerical fabrication.

The thin[k]shell project was initiated by members of the laboratoire Navier, but is now developing with fruitful collaborations with partner laboratories (the Geometry and Curvature group of LAMA, the IMAGINE group from Laboratoire d'Informatique Gaspard Monge (LIGM), or the laboratoire Géométrie et Structures pour l'Architecture (GSA) from the School of Architecture Paris-Malaquais) and many industrial partners.

This integrated vision of research, education and fabrication is promoted throughout the courses taught by the members of the project at the Ecole des Ponts (especially the "Structural design" and "Advanced structural design" courses, the "Design by Data" postgraduate program, and the workshops "Crossing my bridge", "Fold me a shelter" or "Building an arch", see figure 1) and in other higher education programs in the schools of Architecture of Grenoble, Paris-Malaquais, Marne-la-vallée.

Figure 1: Design built workshop at Ecole des Ponts: crossing my bridge (left) and fold me a shelter (right), photo by courtesy C.Douthe (left) and A. Lebee (right)

About eight PhD candidates are currently concerned by the design of structures and provide regularly small scale projects related to their research to master students for exploration, experimentation or numerical development. This is beneficial to the candidates who can hence test ideas, process, tools or methodologies before they might be introduced in a larger scale workshop or prototype (this, of course, helps also improving the academic productivity of the team and academic publications). This is also beneficial to the master students who get initiated with up-to-date research, digital fabrication processes or metrological advances and who may then apply for PhD funding.

The concepts with the highest potential get then further developed and come out with full scale realizations associating clients and/or industrial partners. The 3 days' temporary pavilion of the Solidays festival 2011 (see figure 2 left) was led by a group of 8 final year students (a two-semesters adventure with "officially" a half day per week dedicated to the project) and the design office T/E/S/S [4]. The temporary cathedral of Créteil had to hold for two years and therefore required deeper investigation and was thus designed by T/E/S/S and the laboratoire Navier [5]. Last realization is an exploration of the possibilities offered by developable surfaces for the construction of freeform without formwork or scaffolding (see figure 2 right).

Figure 2: Full scale prototype: Solidays forum 2011 (left) and Metal Euplectela Folie (right), photo by courtesy LdPeloux (left) and C. Douthe (right)

2 THE “BUILDING FREEFORM” WORKSHOP: PAST RECORDS

2.1 Pedagogical objectives

The “Building freeform” workshop was thus initiated by a group of academics working in the field of structural design and pretty much influenced by the thoughts of the structural morphology group of the International Association of Shell and Spatial Structures, especially by R. Motro [6]. In this founder paper, R. Motro explains that structural design is at the frontier of: form (geometry), forces (static), structure (topology and relations between elements), material (mechanical behaviour) and technology (fabrication process). The general idea of the workshop was thus to get the students initiated with the constant compromise that exists in structural design between those five fields and how much it has become necessary to embrace those five fields to succeed in the design of contemporary freeform architecture.

Indeed, this branch of architecture which denotes fascinating doubly curved structures and envelop, seems to be within easy reach thanks to contemporary digital fabrication tools. However, they remain enigmatic and hard to comprehend by the designers, who are often extremely dependent on a technological process in comparison with “classic” buildings where they can really explore various design alternatives. The workshop organization has evolved throughout the years, but it always started with an overview of the possibilities offered by doubly curved structures, both from technological and conceptual perspectives. The major part of the week being then devoted to the design and fabrication of medium to full scale pavilions, with various typologies: tensile structures, then elastic gridshells and finally rigid gridshells.

2.2 The tensile structure years

During the first years, the workshop focused hence on the construction of a tensile pavilion with a 10 m² to 30 m² covered surface (see figure 3). Tensile structures were chosen for their didactic aspect because they are very hierarchic structures that allow to address every steps of the design process and every fields of structural design, as well as their interactions:

1. Definition of a form in equilibrium under self-stress (form-force interaction),
2. Definition of the supporting members (force-structure interaction),

3. Dimensioning of members (introduction of material parameters),
4. Definition of the cutting pattern (form-material-technology interaction),
5. Design of details (forces-material-technology interaction),
6. Mounting of the structure (structure-technology interaction).

Especially, tensile structures offer the possibility to address all these issues at real scale, to work with the real materials, with realistic details (although knocked up) and with structures larger than human. The physical experiment is thus not biased by any scaling and students encounter all problems linked with structural design from design to fabrication, including control of geometry, management of tolerances and the necessity of tuning.

Practically, the week was organized as shown in table 1. After some introductory conferences, the students start working in groups of three and to prepare pavilion proposals based on physical models and drawings on scale. They defend then their proposal and make critics on the other proposals in order to choose collegially the prize-winners that will be built at full scale. This collective evaluation of proposals was very effective and forced them to stand back to assess the feasibility of the structures that they will all have to build together, based on what they have just learnt about the design of free-form structures. By orienting some questions and explaining clearly the learning objectives of the workshop, democracy always brought an acceptable solution, except once where authority was necessary to rebut a proposal which would have directed all the design effort toward a post design instead of toward tensile architecture… Then, in the second part of the week, the students work all together on one or two structures and experience the necessity for tasks separation, coordination and interoperability of tools or procedures, which is really key in free-form architecture.

Figure 3: “El paraiso de la siesta”: Lycra model and final structure (photo by courtesy C. Douthe)

The workshop started with 15 students in 2009 and ended with 32 in 2015, all final year students (one third from architecture school, the rest from the Civil Engineering department). Supports included experimental facilities, one full time academic per 10 students and about 1000 € consumable: the PVC textile was kindly offered by Serge Ferrari textile. The form-finding and cutting pattern were done with dedicated codes, for Sketch-up and Autocad respectively, provided by the teaching staff.

Table 1: Typical organisation of the one-week workshop during the first years

Monday	8h30–10h30: *Overview of double curved structures* (conf. by C. Douthe). 11h00–12h: *Form-finding* (conf. by C. Douthe).	14h–16h: Design of textile structures, technology, details and standards… (conf. by M. Bagnéris) 16h - 18h: *Presentation of the project and team work by group of 3 students.*
Tuesday	8h30 – 10h: Design of doubly curved shapes (conf. by M. Bagnéris). 10h30 – 12h: *Team work by group of 3 students.*	13h30 – 18h : *team work by group of 3 students:* *Proposal outlines for the pavilion competition (lycra models and drawing on scale 1/20)*
Wed.	8h30 – 10h30: Collective evaluation of proposals by students and staff. Collegial choice of prize-winners. 10h30 – 12h: *Team work by group of 10 students: organisation and separation of tasks (geometry, details, dimensioning, construction process)*	13h30 – 18h30: *Experiments and fabrication of prototype details, Definition of the cutting pattern and full scale printing of laise, setting up of anchorage, etc.*
Thursday	8h30 – 12h: *Finalisation of shop drawing: Definition of the cutting pattern and full scale printing of laise*	13h30 – 18h: *Fabrication*
Friday	8h30 – 12h: *Assembly*	13h – 14h: *Tuning of the structure* 14h-15h: *Collective evaluation of the built object and feedback on the workshop* 15h – 17h: *Tidying, gathering of production (photo, sketches, prototypes, shop drawing, reports of team work)*

2.3 Extension to elastic gridshells

Considering the success of the tensile structures formula, the authors attempted to apply it to the realization of an elastic gridshell, a structural typology closely linked with their research expertise [4-5]. The goal was to investigate ways of direct transmission from laboratory to the next generation of engineers. For financial reasons, the experimentations started at reduced scale: first 2x2 m grids made of 5 mm circular GFRP profiles, then 4x4m made of 20 mm bamboo stems and finally a 6x8 m grid made of 10 mm circular GFRP profiles (thanks to the offer of *Solution Composites* for the composite materials). The themes addressed were very close to those of the textile pavilion:

1. Form-finding, mapping of the grid on the desired surface,
2. Definition of supports (free edge, opening, anchorage…),
3. Sizing of members and structural analysis,
4. Construction process.

However, concerning detailing, especially grid connections, the main choices had to be made before the workshop, so that the consumables could be supplied on time. In comparison with the tensile pavilion, an essential part of structural design could not be investigated by the students. This is why the size of the prototype was progressively increased, trying to find a size at which one will shift from mock-up to realistic detailing, with little success (the small size of the grid members did not allow for knocked up details and most of the time pluming pipe connectors were used) until 2016. It is worth mentioning here the "SheltAir pavilion" built by G. Quinn *et al* in Berlin 2018 where very convincing details with similar circular composite profiles were designed and will certainly inspire future editions of the workshops.

Figure 4: 2015 edition with mock-up like grid (left) and 2016 edition with its full scale wooden grid (right) (photo by courtesy C. Douthe left and S. Lenne right)

2016 represents indeed a turning year in the workshop organization and pedagogy. Guided by this desire of working at real scale, with real material like for the tensile pavilion, we took the chance to work with two sponsors: Würth France who supplied all the hardware and the *Association Filière bois Haut Languedoc Sud Massif Central* who provided the premium quality wood for the structure. Thanks to this financial support, it was possible to get over the gridshell size limit and to build a representative structure (50 m² on the ground), with realistic cross-sections (12x48mm), realistic details and a realistic construction process. This size change was not harmless to the pedagogy of the workshop:

- materials and consumable still had to be supplied in advanced,
- industrial sponsors had expectations on the quality of the results,
- working at such scale implies additional workload for fabrication and assembling.

Therefore, we decided to reorganize the week and to tell the students a story: the school, owner of the yard, wanted a small pavilion for demonstrating the lab know-how on elastic gridshells, the academic staff had conducted concept design studies and they, the students, had now been selected for conducting the developed and technical designs as well as the fabrication of the pavilion. After the introductory conferences, the results of the preliminary studies that had been conducted during the summer were presented and a notebook with preliminary sketches of all the details was given them. The competition phase of previous editions of the workshop was hence skipped, depriving them of the trial and error experimental way of learning and the associated self-criticism and step back. However, doing so, they were allowed to go deeper into the design and their understanding of the structure and all aspects linked with construction methods. On Tuesday, the 30 students were thus separated into five sub-groups (each supervised by an academic) which had all the charge of some aspect of the final design and had to experiment fabrication to be able then to systematize it:

- form and structure (definition of the final form and structural analysis)
- bracing (distribution over the structure and design of the tensioning system),
- foundation (design of anchorage, including slab characterization and setting-up),
- wooden grid (material characterization, framing, connection verification),
- covering (design and fabrication of covering casket system in PEHD)

Then on Wednesday, a general coordination meeting was organized before producing shop drawings and launching fabrication. Thursday was dedicated to the assembling of the grid, then Friday to the forming, bracing and covering.

To face the production requirements, it was also decided to introduce into the workshop some initiation to digital fabrication: robotized milling for the grid (cutting at length and opening of slotted holes), 3-axes milling cutter for the covering, laser cutter for the tensioning system of the bracing. The goal was not to learn them to master those tools but to understand how they can be used for the standard production of unique pieces and how to calibrate the necessary tolerances and to verify the accuracy of the produced pieces. However, due to the unforeseen high humidity of wood, the pieces got stacked in the conveyer of the milling robot and part of the fabrication at to be done last minute with hand tools: a good introduction to the necessity of redundancy in systems!

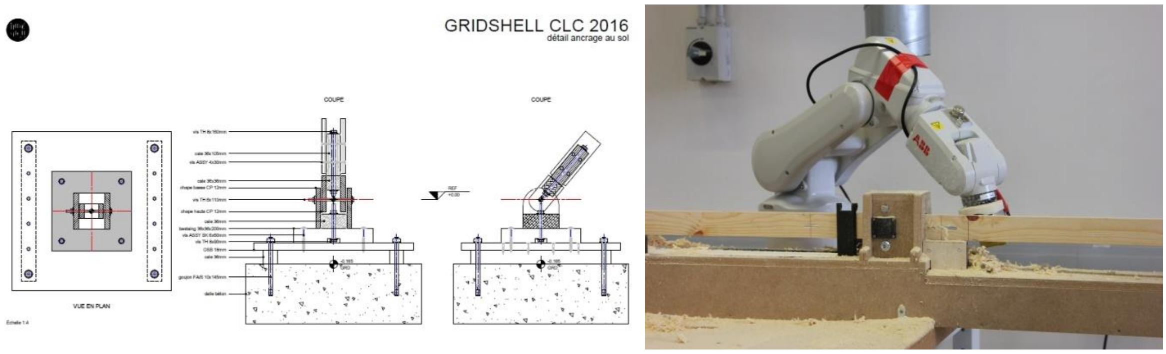

Figure 5: Example of preliminary sketch given to the students (left), robotized milling of members (right) (photo by courtesy L. du Peloux (left) & C. Douthe (right))

The 2016 edition was a real success, enthusiastic for all: students, organizers, industrial partners and administration of the school and laboratory who had gained a full scale prototype illustrating the most recent works on elastic gridshells covered with planar quads [7]. The students enjoyed being part of a large team work, even if the initial design was not their own. Preparation time was however about four times higher (around 6 months in cumulative) and therefore required the mobilization of additional persons for the supervision. This turn out to be very federative for the thin[k]shell group, also very time-consuming.

3 THE 2017 EDITION

3.1 Scientific context and relation with industrial partners

Strengthened by the 2016 experience, we decided to pursue the idea that the workshop could be a way to link closely research and education: while the students learn about structural design, they can also take part in the thoughts of the laboratory on the possibilities offered by digital fabrication to the design of curved envelops. Indeed, in the last three years, considerable effort has been made by the members of the thin[k]shell group to re-appropriate geometry and to integrate the most recent developments of the new born field called “architectural geometry” into practical tools for designers. The close collaboration with Prof. L. Hauswirth from the UPEM helped a lot and has still extremely promising prospects, including the organization of workshops for the mathematic students around applications to structural engineering. In parallel to these theoretical developments, the Ecole des Ponts ParisTech invested in two robotic cells for building a Co-Innovation Lab around digital fabrication applied to civil engineering. And hence came naturally the idea that the workshop should illustrate the knowledge of the members on advanced discrete geometry, structural design and robotic fabrication.

The 2017 pavilion is thus based on an original structural system, called shell-nexorade hybrid, which derives from a surface initially meshed by planar quads which is transformed so that members are only connected by pairs [8] (see figure 6). The pavilion hence tackles main fabrication constraints of free form architecture: covering with quadrilateral panels, straight members, simple T-joints for connection. To achieve this, an intricate game of eccentricities between members (beam-beam and beam-panel) is necessary and realised by the machining by collaborative 6-axes robots of the extremities and the top surfaces of the members.

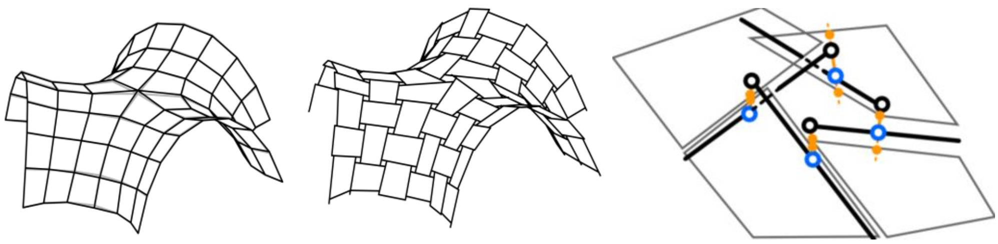

Figure 6: Initial PQ-mesh (left), structure obtained by translation of the edges: the opposite edges of the quads remain co-planar (middle), zoom on resulting eccentricities between members (right)

Industrial partners are really key to the project and were associated upstream of the design. As a matter in fact, the authors believe that successful realisations of freeform structures require a collaboration of all actors of the construction process: owner, designer and contractor, from the beginning. All roles are here endorsed by the academic staff of the week, especially that of the contractor which relies on a tailor made production process, but precisely this is where industrial partners were indispensable:

- Simonin SAS, supplied the wood and served as consultant for wood machining,
- HAL Robotics, developed the software linking geometry to machine control command,
- ABB, set the robotic cell, helped calibrating the robots, guarantying process accuracy,
- Würth France, supplied hardware and served as consultant for connection design.

All partners attended the workshop and could explain their contribution to the pavilion design and more generally their role into the design process of complex structures. For example, for connections, a screw that goes beyond Eurocode 5 was used because it allows to transmit normal forces along the grain of the wooden member. It was hence an opportunity to introduce in the teaching the procedure of European Technical Agreement and the method for bringing innovation in structural engineering practice.

3.2 Pedagogical objectives

Pedagogically, the principle remains the same: the academic staff (2 professors, 5 PhD students and 3 technicians) does the concept and development designs while the students are in charge of the technical design and fabrication/assembly of the pavilion. The week starts with one day conferences about double curved structures, digital fabrication and the concept design of the pavilion. On Tuesday and Wednesday, the students separate in sub-groups:

- geometry and structural analysis (interaction between form and forces)
- connection (experimental characterization of material and connection capacity, verification of each connection),
- construction process and geometric control (3d photogrammetric reconstruction, plumblines as well as triangulation with double decametres) design of anchorage plates, including concrete slab characterization and setting-up),
- robotized manufacturing applied to wood machining (analysis of the production process and fabrication of the last members and panels).

Each group is co-supervised by an academic and an external partner, which again allows for experience sharing between students, researchers and private industries. Thursday and Friday are then devoted to the assembly of the pavilion.

Contrary to the 2016 edition, no notebook with connection drawings is given to the students, because the 2017 workflow is fully integrated numerically into the 3d modelling environment of Rhinoceros/grasshopper. No shop drawings are produced or printed: the geometry being completely three dimensional, it is directly transformed into machine commands for the robots who mill the beams and bore inclined predrilling holes for screws (see figure 7). This disappearing of drawing is not obvious, and we insisted all the week on the necessity to introduce geometric control procedure and on the difficulty linked with the interoperability of all the numerical developments, which is another key issue for the successful realization of freeform architecture.

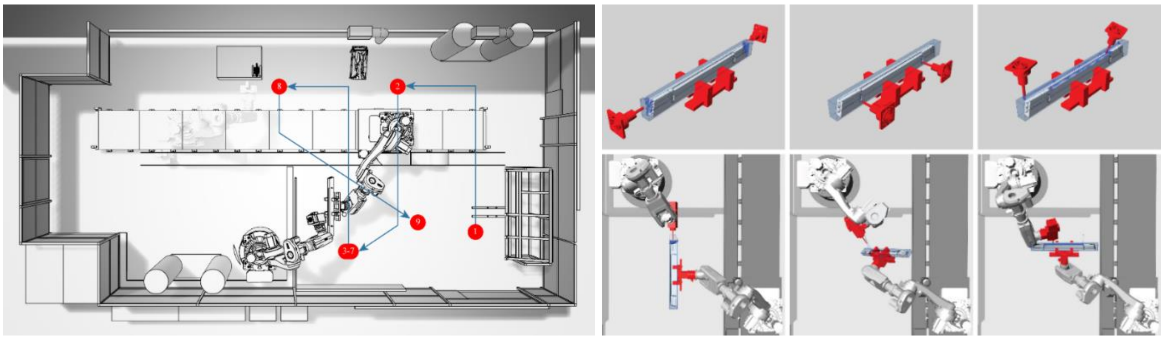

Figure 7: [right] Workflow in the robotic cell: fixed feeder (1), stationary circular saw (2), milling (3-7), fixed wood rooter (8). [left] First row: tool collision detection and second row: toolpath and robot simulation.

It must be noticed here that the ambition of building in one week a pavilion that should last for one year and illustrate actual research developments goes beyond a one-week workshop. Time spent for the pavilion was evaluated to approximately 18 months of a full time person, without counting the time of the 32 students during the week. This is a fantastic adventure that truly united the research group and helped progressing technically all the involved PhD students. Students were immersed in an enthusiastic framework and never complained being only a wheel of a complex organization. As a matter in fact, one month after the completion of the workshop, the school celebrated the 20 years of its settlement on the campus and the students of the workshop were the only ones who had the chance to present their work in pecha-kucha plenary session, which they have done brilliantly.

4 CONCLUSIONS

We presented here a feedback on a design/build workshop lead over the last nine years. This workshop is about structural design with application to doubly curved structures. It aims at experimenting the necessary compromise between form, forces, structure, material and technology in the design process. We insisted on the interest of working at full scale, with the real material (or at least realistic material) for the relevance of the work on detailing and construction process. We explored various situation scenarios to make the students familiar with the various phases from design to fabrication.

Figure 7: Photo of participants (staff, partners on side, students in the middle) in front of the 2017 pavilion.

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