AA/ETH Pavilion

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Abstract

Lightweight structures are conventionally associated to membrane and pneumatic constructions. Aiming at rethinking this paradigm, a research collaboration between the EmTech Programme (AA School, London) and the DARCH Chair of Structural Design (ETH Zurich) has been recently activated to explore the potentials of the use of plywood in lightweight structural design. As a result of this collaboration, a temporary lightweight pavilion has been designed and built for the grand staircase of the ETH Science City Campus. The pavilion consists of three non-standard 18mm-thick panels of plywood (up to 11.0m by 2.5m) which have been individually bent around their transversal axis and connected together by a sequence of steel cables. Globally, this form-active structure has a maximum span of 8.5m and works as a system of self-stabilizing lightweight vaults. Moreover, the architectural qualities of its emerging spatial enclosure allows for the grand staircase to be activated as a new all-year meeting space for the students and faculty. A nonlinear static parametric digital model, based on the bending energy of the panels, has been calibrated with extensive physical tests and employed to explore different design solutions. The shape of the panels after the bending process emerged out of their initial non-deformed geometrical layout (geometrical parameter), the thickness and hierarchical organization of the wooden plies (material parameter) and the given load conditions (external constraint). By a systematic investigation into the defining parameters it has been possible to control the stiffness of the panels along their own longitudinal axis. This has allowed for their bending behaviour to be adjusted to achieve the required curvature. Employing panels of different lengths has made it possible to partially overlap adjacent elements and connect them together with a sequence of cables that stabilize the system and let the external forces to be evenly transferred within the structure.

Keywords: Lightweight, plywood, form-active, nonlinear static parametric model, bending energy.

1 Introduction

Traditionally, lightweight structures are directly associated with tensile structures like stressed membranes or pneumatic constructions. Such structures are characterized by a direct relationship between form and force resulting in an efficient use of material due to the optimal use of materials strengths. Because of this, one of the guiding principles in the design of lightweight structures is the avoidance of elements stressed by bending in favour of elements stressed purely axially by tension or compression [7]. The AA/ETH Pavilion has been designed by rethinking this principle in order to extend the notion of lightweight structural design.

The AA/ETH Pavilion is an experimental construction that has been designed and built out of a collaboration between the EmTech Programme (AA School, London) and the DARCH Chair of Structural Design (ETH Zurich) during the Academic Year 2011-2012. The project is based on the architectural exploration of the bending behaviour of plywood and the use of it in lightweight structural design following a research-by-design approach.

Initially, the pavilion has been conceived as a short-term lightweight sun-shading construction for parts of the grand staircase on the Stefano Franscini Plaza at the ETH Science City Campus. The spatial enclosure generated by the pavilion allowed for the grand staircase to be effectively activated [Fig. 1] and the pavilion soon became a new meeting space for both ETH students and faculty. Thus, the pavilion had been actively employed as an outdoor venue for about nine months (August 2011 to April 2012).

Figure 1. The spatial enclosure generated by the AA/ETH Pavilion allowed for the grand staircaise of the ETH Science City Campus to be activated.

2 Project Description

The structure of the pavilion is based on three bent panels of plywood with non-standard dimensions, up to 2.3m in width and 10.3m in length. Each panel is made up of six cross-banded veneers – four veneers with fibres in longitudinal direction and two veneers in lateral direction - bonded together with phenol resin adhesive. The nominal thickness of the veneers is equal to 3.0mm resulting in a total thickness of the panels of 18mm. Although birch (Betula pendula, hardwood) is usually preferred for structural applications due to its superior mechanical properties, spruce (Picea abies, softwood) has been employed to take advantage of its lower Elastic Modulus in the bending process during the construction phase.

Based on the knowledge gained during the experimentation carried out throughout the design phase, the arrangement of the veneers in each plywood panel is specifically defined to control the overall bending behaviour of the panels. In addition, each panel is cut in a specific triangular shape [Fig. 2] to adjust the flexural stiffness along its longitudinal axis and consequently its bent shape. With the same purpose, cuts in the panels are present which also allow for a sequence of lamellas working as sun louvers to be integrated into the design [Fig. 3]. The bent panels are connected to the ground by means of five pinned supports consisting of plywood forks fixed to steel channels [Fig. 4].

The panels are connected together through a sequence of stainless steel cables [Fig. 5]. The cables stabilize the overall structure and let external forces to be evenly transferred within the system, i.e. the connected panels function as one unique structure. Because of this - contrary to lightweight constructions like membrane surface structures - the overall shape of the pavilion is stable under point loads, like leaning users, or wind and snow loads. Globally, the form-active structure of the pavilion works as a system of self-stabilizing lightweight barrel vaults. The total mass of the pavilion accounts for 326kg while the maximum span is 8.50m.

Figure 2. Two plywood panels after the cutting process.

Figure 3. Detail of the lamellas working as sun louvers integrated into the design. The cuts allows for the curvature of the bent panels to be adjusted.

Figure 4. Detail of the connection of the pavilion to the ground.

Figure 5. Detail of the sequence of stainless steel cables that stabilize the structure.

3 Structural Behaviour

With regards to the design concept, the main idea behind the design of the pavilion has been to explore the opportunities of the use of plywood in lightweight structural design by taking advantage of the material properties as well as by testing unconventional construction processes.

The pavilion is the result of a form-finding process in which each plywood panel, starting from an undeformed flat state, has been deformed and bent around its own transversal axis to its final form-active structural state. Thanks to this operation, the flat surfaces of the panels have been turned into three-dimensional ones, allowing for a spatial enclosure to emerge and revealing the architectural qualities of the structure [Fig. 6].

Figure 6. Sequence of operations showing the bending process of plywood at the base of the design concept.

Precedents to this field of research by design on plywood commenced with the work of A. Aalto and C. Eames [6]. Experimentation on bending plywood has been extensively conducted over the last decades. Recent contributions include the Ornamentation v1.0 by S. Tibbits [8] at the MIT – Massachusetts Institute of Technology (2008) and Datareef by Probotics [5] at the AA DRL - Architectural Association Design Research Laboratory (2010). Nevertheless, the pavilion represents one of the first attempts of exploiting the opportunity of bending plywood to produce a full-scale architectural prototype.

As a first step to understand the structural problem of bending plywood, an analytical approach has been deployed to describe the behaviour of a simple bent lath with constant flexural stiffness (EI) along its longitudinal axis. The shape taken on by thin beams under bending moment has been systematically investigated in previous works. As observed by [1], the curvature (k) of a thin beam of length (L) along its longitudinal axis varies in proportion to the bending moment (M) and in inverse proportion to the flexural stiffness (EI). The bending strain energy for a thin beam with constant flexural stiffness along its longitudinal axis is equal to:

$$U = \frac{1}{2} EI \int_{s=0}^{L} k^2 ds$$

Formula 1. Bending strain energy for a thin beam with constant flexural stiffness along its longitudinal axis.

According to the principle of minimum total potential energy, a bent thin beam, such as the analysed plywood lath, deforms to the shape that minimizes its internal strain energy.

As shown in [2], after assuming a parametric function to describe the deflection (w) of a bent lath, a numerical method can be employed to evaluate for which parameters the total potential energy is at a minimum. In this way, the shape assumed by a regular bent lath with constant flexural stiffness along its longitudinal axis can be calculated.

The analytical approach can be effectively deployed in case of regular geometries and simple boundary conditions as the lath previously described. In the situation of plywood panels with non-regular geometry and changing flexural stiffness along the longitudinal axis the analytical approach cannot be applied easily. In order to investigate the behaviour of the pavilion, therefore, another approach have been employed, namely physical and digital form-finding experiments.

Overall, the shape of the plywood panels after the bending process depends on their initial undeformed geometrical layout (geometrical parameter), the thickness and hierarchical organization of the wooden veneers (material parameter) and the given load conditions (external constraint).

With regards to the physical form-finding experiments, a series of prototypes based on scaled-down plywood panels have been produced as a first approach to the research on the geometrical and material parameters. In relation to the geometrical parameter, as also shown in the research of J. Huang and M. Park under the supervision of A. Menges at Harvard GSD - Graduate School of Design (2009) [3], by gradually varying the cross-section of the panels and as such the flexural stiffness along their longitudinal axis, it has been possible to control the bending behaviour of the panels and their curvature after bending. In addition, after introducing cuts in the panels, the flexural stiffness along their longitudinal axis could be reduced and their bending behaviour could be further adjusted [Fig. 7]. Furthermore, the cuts introduce flexible lamellas into the pavilion that function as sun-shading device and at the same time as system for the dissipation of wind loads through vibration. In relation to the material parameter, different arrangements of the veneers in the plywood panels have been tested in order to control the Elastic Modulus (E) and adjust the overall bending behaviour of the panels.

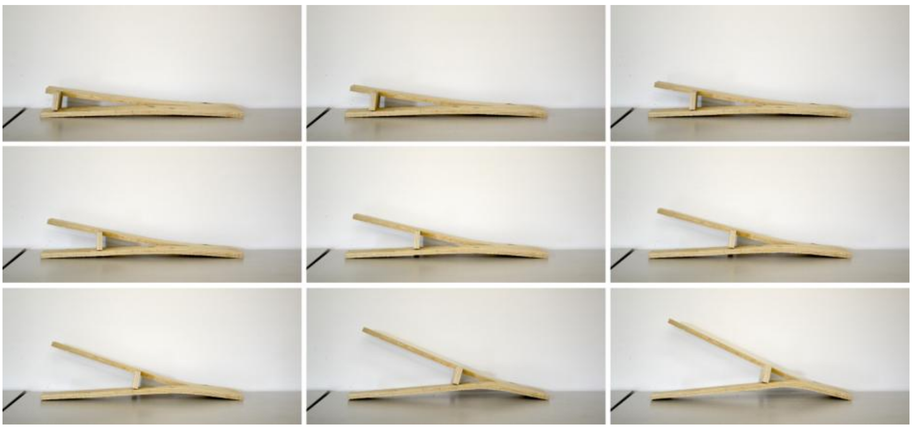

Figure 7. First series of physical tests used to investigate the bending behaviour of the plywood panels.

The physical experiments has been used to calibrate a parametric digital model to efficiently simulate and explore different design solutions at full scale. The model is based on a nonlinear FEM (Finite Element Method) elastic solution to specifically perform the analysis of plates undergoing large deflections. After setting up the material properties (material parameter) and the boundary conditions (external constraints), various geometrical configurations (differing according to the global geometrical layout and the number of cuts in the plate) have been extensively tested until the final curvature of the panels fulfilled the architectural requirements. In addition, due to the irregularities of the site, a final adjustment of the geometrical layout of the panels has proven to be needed after the bending simulation. This modifications to the geometrical parameter in turn affected the bending behaviour of the panels requiring new iterations in the simulation process until a final valid shape has been found.

The final shape of the panels emerged out of the equilibrium of the internal forces (self-weight and stresses introduced by the bending process). Although the panels showed to be stable under their self-weight, due to their high slenderness in the direction of the longitudinal axis, they proved to be highly unstable when subjected to concentrated loads or non-symmetrical distributed vertical and horizontal loads.

A solution to this problem has been investigated using a graphical static approach [4]. Unless the funicular polygon of the loads falls inside the geometry of the panel, the panels can resist the external loads only through their own flexural stiffness. Thus, in order to increase the global stability of the structure and allow the funicular polygon of the external loads to always be within the geometrical boundaries of the system, a sequences of stabilizing pre-stressed cables has been introduced. By constraining the panels to their initial position, the cables allow for the external concentrated and non-symmetrical distributed loads to be evenly transferred within the structure to the foundations. In addition, employing panels of different lengths has made it possible to partially overlap adjacent elements. By connecting the adjacent panels together through the cables, four main arches has been established, whose structural depth is higher than the ones of the individual panels. In this way, a load-bearing system can be produced within the structural depth of the arches that follows the funicular polygon of the external loads [4]. In particular, a specific geometrical configuration of the cables has been designed that takes into consideration the maximum structural capacity of the plywood panels and their buckling behaviour.

The efficiency of the lightweight structural system has been validated by a final load test [Fig. 9]. For the test, a bag was fixed at six points to the arches and gradually filled with water. At a load of 800kg, that is about 2.5 times the self-weight of the structure, the test had to be aborted due to the dissolution of the structural integrity of the bag. At that point, the maximum displacement of the pavilion reached 3.5cm.

4 Construction

A non-conventional manufacturing process has been employed to produce the plywood panels constituting the main structure of the pavilion in order to address their non-standard dimensions. Standard-sized plywood veneers have been directly glued together and connected by means of half-lap joints in the workshop to produce unique plywood panels with the dimensions required. In spite of their non-standard dimension, thanks to their relative lightweight (around 110kg each), the panels have been easily handled, moved and assembled by a team of twelve students of EmTech during the construction process.

The construction of the pavilion followed a process similar to the one employed in the production of the physical scaled-down model during the design phase. Handmade cut panels have been produced and put in place without employing any crane or mechanical equipment. This has been achieved by manually lifting the panels from beneath while imposing a horizontal displacement along their longitudinal axis to adjust the panels to their final position [Fig. 8]. The geometry of the final structure proved to be very close to the digital model developed in the design phase. Irregularities in the geometry coming from the manufacturing process has been evened out by taking advantage of the material tolerances.

Figure 8. Manually bending the central plywood panel during the construction phase.

Figure 9. Final load test to validate the efficiency of the lightweight structural system.

5 Conclusion

As an experimental construction which follows a research-by-design methodology, the AA/ETH Pavilion is a result of a holistic approach to design where architectural qualities and structural performances are part of the same agenda. In fact, structure and architecture are evenly integrated within the same building.

The design of the pavilion effectively relied on a lightweight structural design approach and successfully took advantage of the opportunity of bending plywood to produce a full-scale architectural prototype. Bending was used in the form-finding process and the final shape of the plywood panels corresponds essentially with the resulting shape under self-weight. This shows, that the bending behaviour can be used in the design of lightweight structures. In addition, a design process based on the combination of analytical, physical and digital form-finding allowed for the goals of the project to be achieved while proving to be a flexible and powerful methodology.

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References

[1] HORN B.K.P., *The Curve of Least Energy. ACM Transaction on Mathematical Software*, Vol. 9, No. 4, December 1983, pp. 441-460.

[2] KUIJVENHOVEN M., HOOGENBOOM P.C.J., *Particle-Spring Method for Form Finding Grid Shell Structures Consisting of Flexible Members*. *Journal of the International Association for Shell and Spatial Structures*, Vol. 53, No. 1, March n. 171 2012, pp. 31-38.

[3] MENGES A., *Material Resourcefulness: Activating Material Information in Computational Design*. *Architectural Design, Special Issue: Material Computation: Higher Integration in Morphogenetic Design*, Vol. 82, Issue 2, March/April 2012, pp. 34-43.

[4] MUTTONI A., *The Art of Structures*, EPFL Press, Lausanne, 2011, pp. 74-76.

[5] PROBOTICS, *Datareef*, http://theprobotics.blogspot.ch, 2013.

[6] SANTI C., *Charles Eames e la tecnica. Domus*, No. 256, March 1951, pp. 11-14.

[7] SCHLAICH, J., SCHLAICH, M., *Lightweight Structures*, Lecture at MIT – Massachusetts Institute of Technology, 4th October 2012.

[8] TIBBITS S., *Sjet*, http://sjet.us/MIT_ORNAMENTATIONv1.html, 2013.