P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), *Protocols, Flows and Glitches, Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, 863-873.

ROBOTIC SIMULATION OF TEXTILE AS CONCRETE REINFORCEMENT AND FORMWORK

XIAO LU[1], THEODOROS DOUNAS[2], BENJAMIN SPAETH[3], CHITRAJ BISSOONAUTH[4] and ISAAC GALOBARDES[5]
[1]*University College London, United Kingdom*
[1]*luxiao931206@163.com*
[2,4,5]*Xi'an Jiaotong-Liverpool University, China*
[2,5]*{theodoros.dounas|Isaac.galobardes}@xjtlu.edu.cn*
[4]*Chitraj.b12@student.xjtlu.edu.cn*
[3]*University of Cardiff, United Kingdom*
[3]*spaetha@cardiff.ac.uk*

Abstract. New possibilities of concrete constructions in architecture, the traditional formwork can be gradually replaced by the use of flexible textile. At the same time textile reinforcement combined with fabric formwork, introduces an innovative integrated solution in the fabrication of concrete. Based on a simple understanding of the textile weaving and knitting techniques, this project concentrates on the architectural production and the structural optimization of the textile as both concrete reinforcement and formwork. Furthermore, we present a robotic simulation of the process that develops using a series of computational experiments to research the sequence of weaving and/or knitting. Through the computational process and the design simulations, the research is firmly rooted in analog and digital exploration of material and its implementation in architecture, with particular emphasis on the convergence of robotics and computation. Note that the paper deals mainly with the software and weaving simulation as part of a larger research project, without dealing with the production of physical artefacts.

Keywords. Robotic weaving; textile-reinforcement; parametric design; lightweight structure; textile-reinforced concrete.

1. Introduction

Technology for robotic fabrication has developed since the 1980s. Simultaneously, an extensive scope of intrinsically architectural themes of fabrication and technique is developing onto the current agenda (Fereos & Tsiliakos 2014). At the same time recent advances in textile fabrication showed the advantage of using textile-weaving techniques to create structural shells. Due to the high cost and the complexity of construction, the applications of shell like structures have been limited. Therefore, it is necessary to develop robotic fabrication to achieve geometric freedom and decrease the budget. Within 3D modeling software Rhino and Graphical algorithm editor software Grasshopper, a parametric system of simulating weaving of textile was introduced, and an investigation of several approaches to address the stresses on the shells and the external forces by using Grasshopper's plugin Millipede based on Finite Element Methods (FEM). Finally the robotic fabrication of the weaving was simulated related to previous experiments.

Notice that, the structural performance and durability of concrete systems may be improved by introducing high-strength textiles with different permeability, interlacement structure and load-bearing capability. And besides, the use of textile may reduce the use of timber in vertical supporting formwork and, therefore, minimize reliance on timber resources (Mcquaid & Beesley 2015). Hence, the work presented is novel in the following regards: the production of lightweight, continuous, textile reinforcement and in tandem formwork for concrete shells will reduce waste and increase the economy of concrete structures by creating smaller lighter building cross-sections.

2. Background

One of the streams of robotic fabrication in architecture has been the novel combination of computational techniques into integrated design, test, adapt and fabricate systems. Some studies have ventured into adaptive stacking of architectural elements, in an exploratory open framework (Narahara 2013), or attempted to create an integrated framework of computationally driven, robotic actuation and fiber-stiffening process of shell-like inflatable structures (Poinet et al. 2016), after a critique of post-rationalized geometry input into fabrication methods, where the focus is on saving material, being economical due to constraints. Again shell geometries seem to be a good target selected by the CAAD community for robotic fabrication, for example integrating behavioral design and adaptive robotic fabrication of a compression shell, with the aid of a pneumatic formwork (Doerstelmann et al, 2015). Double curvature surfaces are also the subject of integrated approaches in creating special machines to form them, for example by custom presses of a material, with the press actuated by robot (Fereos & Tsiliakos 2014). Integrated processes can be shown also to be efficient when developed into a dynamic direct framework, such as in the study of (Braumann & Brell-Cokcan 2015) who developed direct, dynamic, bi-directional, parametric controls of robots instead of the packaging and sending of tool paths to robots at the end of the parametric design process. Within this field, this research integrates design, simulation and physical material constraints.

3. Research and Analysis: Importance of Fabric Structure

With the advancement of new techniques for material inventions and constructions, the possibility for freeform geometries make it timely to review the design and fabrication techniques in not only architectural design but also structural engineering. This computational revolution made possible a massive improvement in complexity and freedom, widening the collection of architectural shape (Grasser & Brueck 2011). The form finding process based on computational algorithms is consisted of three crucial principles: modeling of desired geometry, transformation from pattern to structural elements and optimization of force distribution (Ahlquist & Menges 2011). In this project, the vital part is simulating the weaving and knitting pattern and conducting the textile parametric experiment. On the basis of the prototype analysis, the project further studied the role and significance of structural performance-based tools in structural design.

3.1. OVERVIEW OF THE EXPERIMENTS

We introduced a series of experiments to test material recognition in the computational design process, and create the overall textile structure considering form, loads and material properties integrated. The parametric generative form finding aims to explore the material nature and entire of an architecture arrangement, a valuable process in comprehending the connection between geometry, material and force. Consequently, we started creating weaving patterns and interlocking structures to test how they may be utilized in both concrete reinforcement and formwork. After applying the weaving pattern to the different geometries such as a surface, a column, a falling mesh and a vault, we used Grasshopper's plugin Kangaroo to conduct a series of physics-based experiments to understand the relationship between the geometry and the exterior forces. Through applying and simulating different forces on the surface, the reinforcement geometry can be changed in relation to the stress analysis, and therefore, optimized. Moreover, considering the use of textiles as structural formwork, we used an advanced plugin Rhino Vault based on Thrust Network Analysis to modify the horizontal and vertical force diagram in real-time. The final step was finding stress and strain lines in the loaded surface and optimize the shape of loaded surfaces by using another Grasshopper's plugin Millipede based on Finite Element Method (FEM) to define the material, loads, supports, deformation axis and vector where is load is being applied. The robotic fabrication simulation following as the last experiment in line simulates the tool path of the robot and optimizes the final artifact production. Note that the process we present at this paper deals mainly with the software and weaving simulation as part of a larger research project, without dealing with the production of physical artefacts.

3.2. WEAVING AND KNITTING SIMULATION

Our logic to create interlocking structure using now is based on weaving, knitting, braiding, and sewing. Each of this process with different methods and techniques to create knots and each of these methods can be made available for industrial fabrication by using specific machines such as, looms to weave, knitting needle to knit, braiding machine for braiding. Borrowing and learning these methods that already have been put into manufacturing can combine the simulation and fabrication tool repository combined to create new prototypes.

The experiment of the simulation work focuses on the application of tools, exploration of the technique, and subsequent development of an informed design intuition for generating the weaving pattern in a fabric. Specifically, we will examine how the Grasshopper with physics engine plugin Kangaroo explored the design process for form finding, geometric articulation and structural optimization. Figure 1 shows the procedure is creating a weaving surface like fabric. The first step is to set one surface on Rhino and then divide it to create perpendicular grids. For each intersection points on grid, the normal is found. Therefore, the interpolate curve through the points can be weaved.

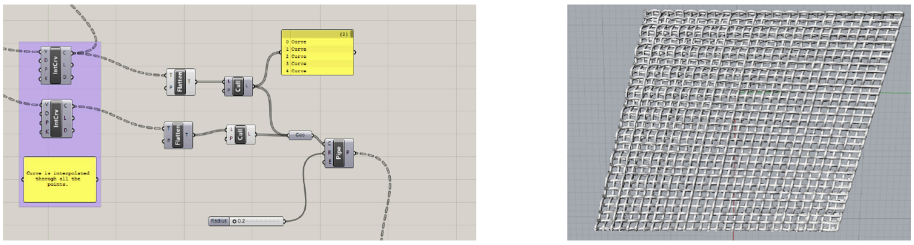

Figure 1. Creating weaving surface like fabric.

The introduction of Kangaroo as a physics-based simulation engine has further extended the software program to include a dynamic physics algorithm, thus allowing designers to visualize the physical forces interacted with their designs (Huang & Lewis 2014). The following stem aimed to see how the weaving changes under a load of gravity. So in a way, the stress and strain and elastic deformation of the weaving itself can be seen. This may actually help, as many fabrics, such as polymers or carbon and glass fibers, present a small region of elastic deformation (Calister 2007). When setting surface on grasshopper and dividing to generate points, which are going to be used to produce weaving. The normal of points is going to be used in order to control the amplitude of weaving. From the amplitude points generated, curves are interpolated and then further piped and baked (figure 2).

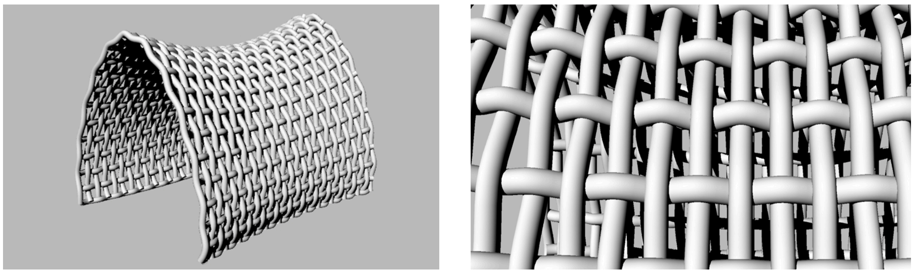

Figure 2. Design vault and applying weaving definition.

3.3. TEXTILE PARAMETRIC EXPERIMENT

In order to create a fabric as a structural reinforcement surface, we considered the analysis of primary forces: tension, compression, bending, shear and torsion. The designers cannot define the form before they understand the relationship of geometry, material and force, thus, the route need to be studied to simulate the performance accurately at the final and full scale (Grasser & Brueck 2011). Therefore, we applied the Grasshopper's plugin Kangaroo to create physics-based simulation environments and see the results virtually. For example, in physical-based modeling, there is a usually used parameter 'spring', which followed the linear equation called Hooke's law of Elasticity (Neville 1996). It consists a strength factor and relates the displacement of an object from its initial length to force. Although materials do not always behave in a linear equation under force, the equation is still enough for an elastic simulation. In fact, the Kangaroo is contained large amount of information cannot produce accuracy completely; it offers a practicable guide to deal with the collaboration of material characteristics and primary forces (Ahlquist & Menges 2011). Based on the interacting forces, the computational process contributed significantly to form finding.

The experiment is generating a double curved shell to explore the textile parametric. Using attractor force command on kangaroo, a sphere mesh is created on kangaroo. The mesh surface is made to be attracted to the sphere size and distance from it (figure 3). Then using weaverbird command, the mesh can be smoothed and the grids on the relaxed state shell are found and the intersections point is baked. Consequently, the knitting style is done using different numbers of wefts. The more increased value for wefts, the more knitting there will be.

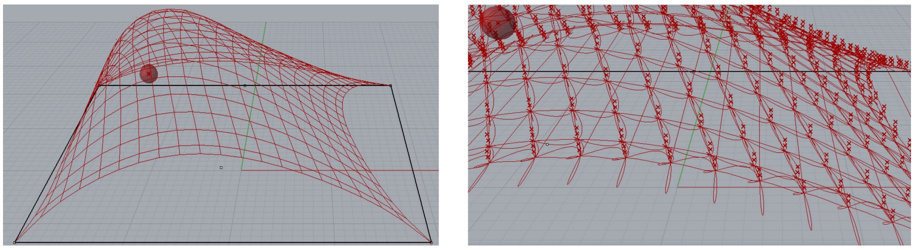

Figure 3. Grid generation and wefts control.

4. The Structural Simulation with Geometry

Not only the fabric can be used as a formwork, but also the textile can be utilized in order to act as reinforcement. The interlacing fabric formwork can minimize the penetration of air bubbles improve the surface texture quality of the concrete (Cauberg et al, 2012).

4.1. THE RELATION OF GEOMETRY AND FORCE

When considering the use of textiles as structural surfaces, where a force of tension is applied to develop stable structures, this condition is the most critical to consider. For the sake of discovering novel vaulted geometries and exploring these constrained structural systems, we used a plugin named Rhino Vault to express the stress dependencies visually between distinctive segments of the structure. By using the Thrust Network Analysis, the process of form finding can modify the stress diagram in real-time, which have an access to blur the difference between freeform surface structures and geometry with typical tension or compression-only forms (Rippmann & Block 2013).

The first experiment is to design a simple vaulted structure by using RhinoVault. At the beginning, the surface on Rhino was rebuild and the control points were adjusted. For further exploring the connection between form and force, a double curved shell structure was designed using precise tension elements. The experiment showed how creates the funicular structure and how to change support settings. In this experiment, the shape of the structure and the local stress distributions were effortlessly adjusted (figure 4). Thus, the structural optimization model could be selected by defining the specific material to conduct the further physical test that simulates exterior forces such as tension, compression, and gravity and so on by Millipede.

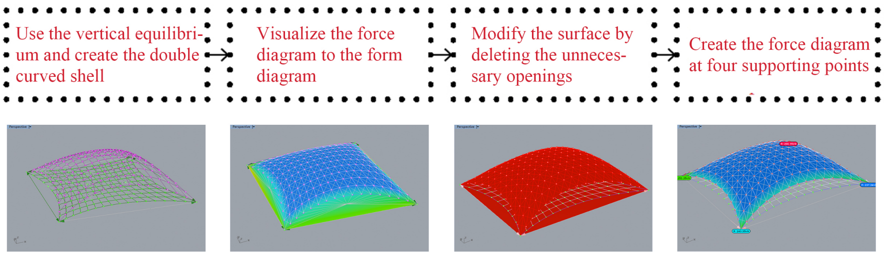

Figure 4. A double curved shell structure designed by Rhino Vault.

4.2. METHOD OF STRESS ANALYSIS - MILLIPEDE

The interlock logic of weaving gives us a way to organize individual fibrous material into an integrate structure. Based on topology optimization tools, the Grasshopper's plugin "Millipede" developed by Michalats used the Finite Element Method became an efficient structure optimization tool for linear elastic systems. In order to obtain the stress and strain lines of the resultant surface under external and self-load forces, and apply weaving to the loaded surface, a series of experiments were conducted (figure 5). First of all, with the help of grasshopper plugins such as Paneling, Lunchbox, and Weaverbird, different types of surface were created and divided to achieve grid deformation and densification according to the vector point. Surface points were moving towards the attractor point-using vector between the points as direction and curve is interpolated through points.

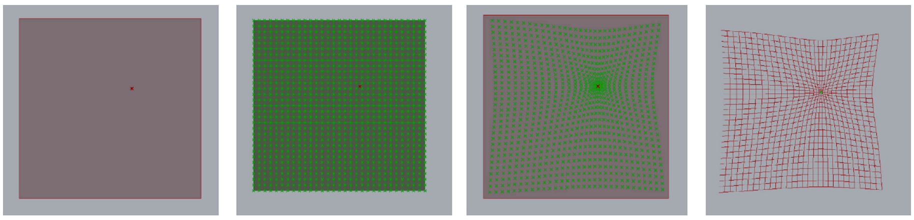

Figure 5. Grid deformation and densification on surface.

The material component in Millipede enables the user to select a stock material including concrete, steel and glass. In addition, each time the cross section type is changed, the input parameters of the component are changed so as to reflect the different geometric properties of each section. Thus, the numerical range of the results for the mesh visualization component can explicitly be set. Taking advantages of the shape and material size optimization of Millipede, we used the previous vault as the geometry to be analyzed in order to generate a network of curves. Curves are automatically intersected and discretized by the Finite Element Method (FEM) system builder (figure 6).

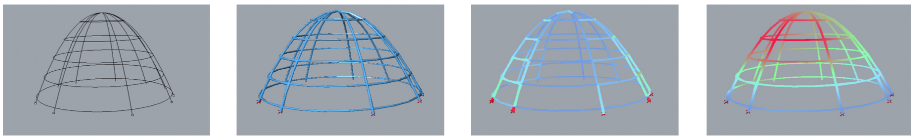

Figure 6. Basic structural analysis of vault frames.

With just 5 numbers we can explore a large family of surfaces and observe how the different shapes fair with the applied boundary conditions. Furthermore, the parameters can also be reset and connected to search for the optimization solutions. Within a fixed mesh, force is resolved individually at each fixed node. The stress can only flow and travel through the path of the open mesh material. Thus, tension force goes across the whole surface until it achieves equalization in force in a woven or knitted surface and a mesh work with a regular grid horizontal and vertical springs are used to find a balanced equilibrium of forces. An open mesh can achieve many variations in topology and still realize a tension-equilibrium form (Grasser & Brueck 2011).

5. Robotic Fabrication Simulation

With the advantage of visual programming systems for accessible robot simulation, the users can change the geometry, adjust the sequence of tool path and simulate the movement results intuitively (Braumann & Brell-Cokcan 2015). In this part, the graphical algorithm editor Grasshopper plugin named HAL was chosen as the parametric programming tool for controlling industrial robots, which supporting ABB, KUKA and Universal Robots. In addition, an ABB IRB 1600 robotic arm that payload is 10kg and the reach is 145cm was selected as an exemplary robot to simulate the sequence of tool path (Schwartz 2013). Simultaneously, we are developing fabrication methods with the research of previous various computational experiments such as interlacement woven structure on double curved shell to research the sequence of weaving.

5.1. ROBOTS AND END-EFFECTOR OVERVIEW

On the basis of Grasshopper, the HAL plugin was the vital platform to simulate and program the robots, which covering a large number of creative instructions such as multi-tasking, milling, hotwire cutting and so on. This software included a large number of libraries of different robot types such as KUKA KR10, KR120, KR 1000, Universal Robots UR 5, UR 10, ABB IRB 120, IRB1400 and so on. Begin with creating the robot, we chose the flexible ABB-IRB 1600 robot that can be mounted on the wall and the floor. We selected the Robot Creator command to define the working range, the rotation value, the payload and the maximum speed. Besides, it is necessary to set the plane of base, six axis, rotation points and rotation center. A six-axis robot has different working range because each axis has its own rotation value in order to define the location of the end-effector such as milling spindles, gripper and weaving equipment. In this project, we create the customized weaving tool and transferred the mesh information to the robots (figure 8). For designing the specific end-effector, the first step is to create the 3D model in Rhino and convert the surface to mesh in Grasshopper. Besides, defining the center point of the tool and creating fixed plane through the original point of the tool.

5.2. TOOL PATH FOR SIMULATING THE MOVEMENT OF ROBOTIC ARMS

Like CNC machines, the subsequent task is to create tool paths that translate the data to control a robot. The plugin HAL connected the geometric model, the generation of tool path and the simulation simultaneously. We started from simulating a simple control point curve in the robot-working environment. The vital step is to confirm the start position and the end position of the movement through dividing the curve into several segments. Then the sequence of the movement can be defined by generating the position of each segment and we put the all of the positions as targets to the Tool path Creator command. Finally, all the data can be transferred to Inverse Kinematics Solver to compute the rotations of the robot joints and generate a log of movements in order to reach the target. Then we simulated the movement of robotic arms to build a woven surface and a vault. Through controlling the slider from the start point to end point, the movement of robotic arms can be simulated visually (figure 7). Notice that, when the target is out of the range of the working reach of the robotics arm, the program will produce an error log and the theoretical robot will turn to the red, thus, it is necessary to to check the working range carefully while simulating.

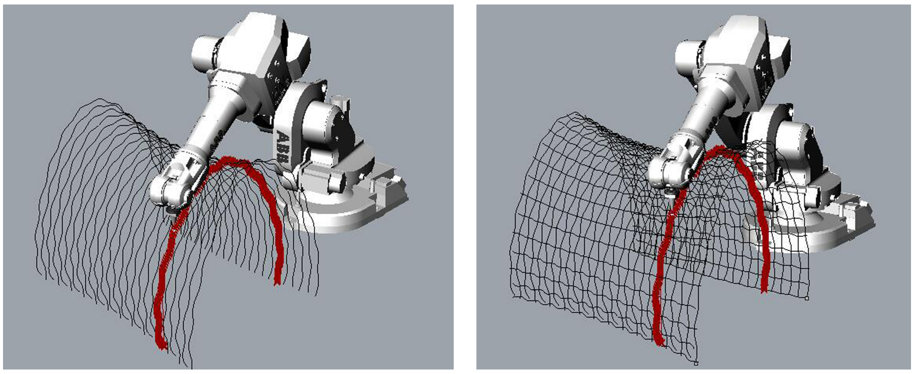

Figure 7. The sequence of weaving the vault structure though robotic simulation.

5.3. CHALLENGES OF WEAVING PATTERN FOR ROBOTIC FABRICATION

For textile-based architecture, it is really necessary to consider the reachability, the order of path execution and the possibility of interweaving. Moreover, if the fixed robotic arms are to be employed in the construction site, the designers need take the material systems into consideration to cater for problems and opportunities on the loading capacity. The maximum of reaching area for a stationary robotic ABB IRB 8700 is 3.5m*4.2m and its payload is 500kg-800kg, which it cannot reach to higher vertical distance and may need a platform to support.

6. Conclusion and Further Work

Consequently, the project addressed the simulation of textile as concrete reinforcement and formwork for designing the geometry of a knitted or weaved formwork within given design constraints of dimensions, material, and structural loading. The 3D modeling and structural analysis software indicated in this research can be used to design optimized textile reinforcements to used in both textile-reinforced concrete and formwork, meanwhile, we also envision the future robotic production of such constructions will further reduce costs and increase the quality by taping into the numerical control precision of robotic fabrication. At the present paper the focus is in the stress and form analysis and simulation rather than in the actual fabrication itself. The procedure of combining simulation, fabrication and material science into a generative and parametric methodology may be regarded as a more efficient workflow model. For the future research, we will concentrate on the process of using robots to produce the desired formwork in the actual fabrication and develop a validation framework for the evaluation of the weaving and knitting techniques.

References

Ahlquist, S. and Menges, A.: 2011, Articulated Behavior: computational methods for the generation and materialization of complex force-active textile morphologies., *Proceedings of the Ambience'11 International Conference*, Boras (Sweden), 13-19.

Braumann, J. and Brell-Cokcan, S.: 2015, Adaptive Robot Control: new parametric workflows directly from design to KUKA robots, *Proceedings of the 33rd eCAADe Conference 2015*, Vienna (Austria), 243-250.

Calister, W.D.: 2007, Materials Science and Engineering: an introduction, *John Wiley & Sons, Inc*, **7**, 665-715.

Cauberg, N., Tysmans, T., Adriaenssens, S., Wastiels, J., Mollaert, M. and Belkassem, B.: 2012, Shell elements of textile reinforced concrete using fabric formwork: a case study, *Advances in Structural Engineering*, **15(4)**, 677-689.

Doerstelmann, M., Knippers, J., Koslowski, V., Menges, A., Prado, M., Schieber, G. and Vasey, L.: 2015, ICD/ITKE Research Pavilion 2014–15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web, *Architectural Design*, **85(5)**, 60-65.

Fereos, P. and Tsiliakos, M.: 2014, Isoprototyping: rapid robotic aided fabrication for double curvature surfaces, *Proceedings of the 32nd eCAADe Conference 2014*, Newcastle (UK), 433-443.

Grasser, G. and Brueck, M.: 2011, Textile Qualities: parametric design, simulation and fabrication based on new composite materials, *Proceedings of the Ambience'11 International Conference*, Boras (Sweden), 30-37.

Huang, A., Lewis, S. and Moore, W.P.: 2014, Nearly Minimal: how intuition and analysis inform the minimal surface geometries in the pure tension pavilion, *Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) 2014*, Los Angeles (USA), 209-218.

McQuaid, M. and Beesley, P.: 2015, *Extreme Textiles: designing for high performance*, Princeton Architectural Publishing.

Menges, A., Prado, M., Dorstelmann, M., Schwinn, T. and Knippers, J.: 2014, Core-Less Filament Winding, *Robotic Fabrication in Architecture, Art and Design*, **2**, 275-289.

Narahara, T.: 2013, Adaptive Growth Using Robotic Fabrication, *Proceedings of the 18th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2013*, Singapore, 65-74.

Neville, M.A.: 1996, *Properties of Concrete*, Pearson Education Limited.

Poinet, P., Baharlous, E., Schwinn, T. and Menges, A.: 2016, Adaptive Pneumatic Shell Structures: feedback driven robotic stiffening of inflated extensible membranes and further rigidification for architectural applications, *Proceedings of the 34th eCAADe Conference 2016*, Oulu (Finland), 549-558.

Rippmann, M. and Block, P.: 2013, Funicular Shell Design Exploration, *Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) 2013*, Cambridge, 337-346.

Schwartz, T.: 2012, HAL, *Robotic Fabrication in Architecture, Art and Design*, **2**, 92-101.

Yuan, P.F. and Chai, H.: 2015, Reverse Rafter: structural performance simulation based on wood tectonics, *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2015*, Daegu (Korea), 693-702.