Robotic Fabrication of Structural Performance-based Timber Grid-shell in Large-Scale Building Scenario

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ABSTRACT

This paper investigates the potential of a digital geometry system to integrate structural performance-based design and robotic fabrication in the scenario of building a large-scale non-uniform timber shell. It argues that a synthesis of multi-objective optimization, design and construction phases is required in the realization of timber shell construction in architecture practice in order to fulfill the demands of building regulation. Confronting the structural challenge of the non-uniform shell, a digital geometry system correlates all the three phases by translating geometrical information between them. First, a series of structural simulations and experimentations with different objectives are executed to inform the particular shape and tectonic details of each shell component based on its local condition in the geometrical system. Then, controlled by the geometrical system, a hybrid process of different digital fabrication technologies, including a customized robotic timber mill, is established to enable the manufacture of the heterogeneous shell components. Ultimately, the Timber Structure Enterprise Pavilion as the demonstration and evaluation of this method is fabricated and assembled on site through a notational system to indicate the applicability of this research in practical scenarios.

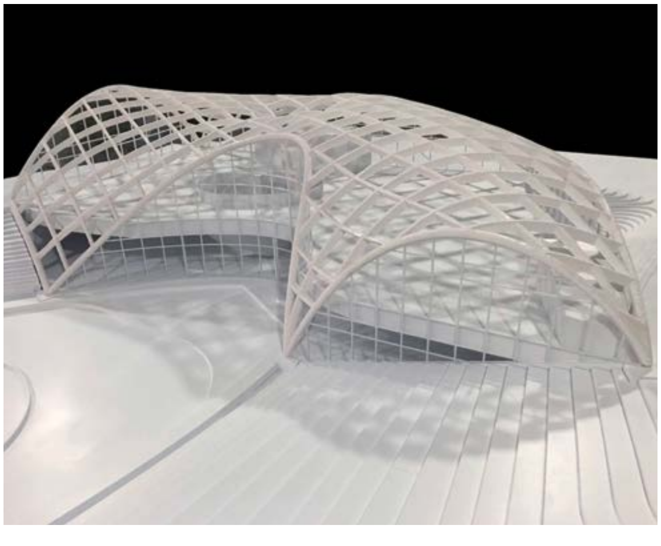
1 Timber Structure Enterprise Pavilion in Horticultural Expo, construction process.

INTRODUCTION

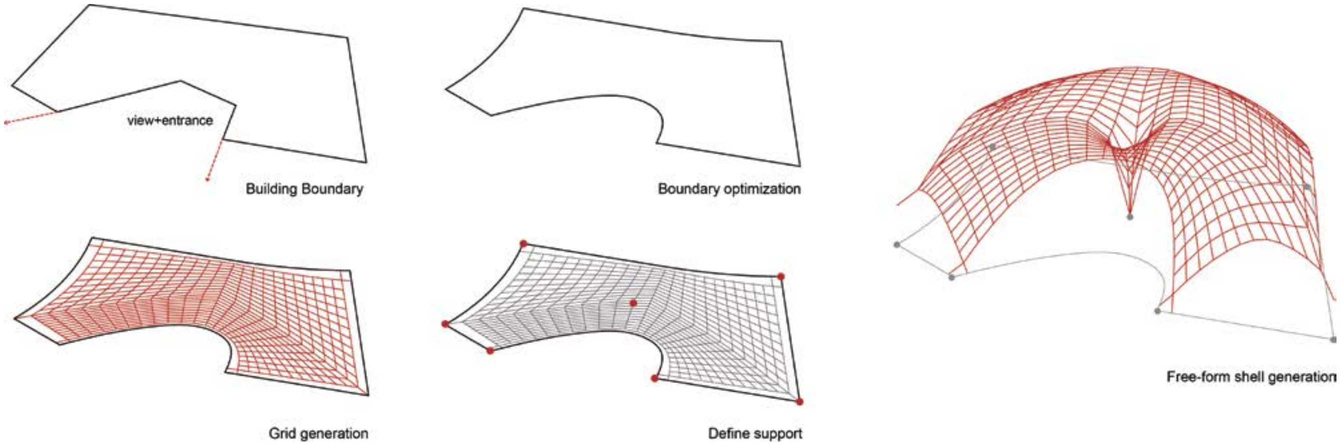
Since the first industrially patented use of glue-laminated timber in the early 20th century of Germany (Muller 2000), modern timber production technology has completely transformed the situation of wood material from its ancient scenario. With technological development, a variety of defects of raw wood material are solved such as knots, heterogeneous density, limited length, corrosiveness, etc., and timber has become a building material with properties of large-scale adaptability, high structural performance and long durability, which are all highly required in building construction. Moreover, with the great awareness of environmental issues in our society, wood as a renewable resource with negative carbon footprint and low embodied energy (Kolb 2008), has been broadly reconsidered to establish a low carbon emission pre-fab construction process in architecture practice. And due to its natural color, light reflection and material texture, timber has been applied into various building types to create glamorous interior experiences. With the development of structural engineering in the 20th century, timber has become a material frequently utilized for grid-shell structures to realize enormous large-span buildings. In the early stage of the development, in examples such as Weald and Downland Open Air Museum designed by Buro Happold and the Multihalle (multi-purpose hall) in Mannheim by Frei Otto, timber material was usually fabricated into small-dimension components to form a double layer or even multi-layer shell system. By utilizing the flexibility of timber, the components can be easily assembled into free-form structure. Nevertheless the timber shell composed by small-dimension components will not only require more time in fabrication and assemblage, but also conflict with current fire regulations in timber building.

Actually, the timber shell structure is a complicated system in architecture design and construction. Unlike concrete or steel material, which can be easily shaped by a customized mold, the fabrication of wood material usually involves a complicated drilling and cutting process and a relatively more sophisticated joint system, which can lead to a variety of difficulties in its realization. In timber shell structures, the aim for high structural performance of the shell geometry at the macro scale and the simplification of the design and fabrication of its internal joint system at the micro scale are usually two mutually contradictory pursuits. In the geometrical optimization process of pursuing a uniform stress distribution along the shell, the geometrical result usually tends to be a free-form surface with heterogeneous curvature conditions, which results in a great variety among the shell components. And this heterogeneity within both shell components and their joints has no doubt deeply challenged traditional methods of timber construction. Even more, in an architectural practice scenario, unlike relatively small-scale installations, the design and construction of timber shell structures is highly restricted by building regulations. The shell structure not only has to distribute the gravity into all the components evenly, but also has to have enough structural stability to confront wind and seismic load. This multi-objective design requirement brings different types of parameters into the structural evaluation of timber shell systems. The shape, dimension and orientation of each timber component will be determined by both the local curvature of the shell geometry and the particular requirements of structural performance on stability. As a consequence, more variation will be brought into the structural components, which are difficult to simplify by a geometrical rationalization process and can only be fabricated and assembled through a highly customized construction method.

Since the digital turn in the field of architecture, the innovative development of digital fabrication technology has brought great advancement to traditional ways of building construction. Compared with the standardized mechanical approach, digital construction is characterized by customization and personalization. In the digital paradigm, code becomes a medium translating geometrical information directly between performance simulation, virtual shell modeling and material fabrication, which breaks the limitation of mechanical construction and offers a new possibility for the heterogeneous fabrication of timber shell structures. With this development, the construction of shell structure in contemporary timber buildings, like Centre Pompidou-Metz and Nine Bridges Golf Club designed by Shigeru Ban and supported by design-to-production, can be controlled with high precision and efficiency. However, the deployment of digital technology involved in these cases only occurred in the construction phase and rarely supported the design process by an interactive network.



2 Physical Model of Timber Structure Enterprise Pavilion.



Building Boundary

Boundary optimization

Grid generation

Define support

Free-form shell generation

3 Form Finding Process of Free-form Structure.

Based on this situation, the research in this paper addressed the design and construction of the Timber Structure Enterprise Pavilion in the Horticultural Expo (Figure 1,2). Confronting the difficulties of non-uniform timber shell structures in architecture practice discussed above, the aims of this research are as follows:

- to establish a design-fabrication platform for large-scale building scenarios, in which all the architectural regulations and requirements, like stability in multiple loading situations, the fire-proofing of structural components (limiting the minimal size of each component), waterproofing, etc., can be balanced and fulfilled in a single system.
- to correlate the structural performance-based design with the construction process in timber shell building, in which the structural simulation and experimentation are utilized not as a mere evaluation tool, but as a design driver to generate and optimize both shell geometry and the joint system.
- to create a parameter-based feedback loop to integrate the simulation, design, digital modeling and physical fabrication of shell structures, in which all the phases can inform each other.

In order to accomplish the research aims, the approach was subdivided into three parts. The first part was a series of structural simulations, experiments and optimizations, studied through a gravity-based shell form-finding method, to improve the structural stability in confronting horizontal loads. In the process, a particular grid-beam system was set up for the shell structure first, and then experiments on a series of joint prototypes were performed to test their structural performance and to use the results to determine their distribution on the shell. Second, according to the local geometrical condition of the shell surface and the dimension requirement for structural strength, prototypes of steel joint and timber beam, which were chosen in the first phase, were then transformed into different variations through a geometrical information system to construct a virtual model of the shell structure in a digital environment. Third, the geometrical system in the digital model was translated into different types of information through a coding process to instruct both CNC timber lamination and robotic fabrication. Further, as the result of this research, all the shell components were assembled on site based on a notational system to accomplish the construction of the pavilion. As such, the structural performance-based design and fabrication provided a solution for the construction of a timber shell pavilion, and reciprocally the realization of the pavilion became a proof of concept to demonstrate the performance of the working system developed in the research.

BACKGROUND

Two scenarios define the research scope in this paper: non-uniform timber shell structure design and large-scale architecture practice. In the former scenario, digital technology was requested to establish a platform for the design and fabrication of the heterogeneous components. In the latter context, the digital platform then has to be turned into a geometrical information system to coordinate all the aspects of realizing a large-span timber building. Facing the two scenarios together, the first challenge is that the structure's performance has to fulfill the multiple requirements of structural regulation. A timber shell usually must be simulated and evaluated on different objectives like strength and stability, and in different scopes like overall shape and particular joints. So the performance-based design process is no longer linear, and the parameters extracted from the result of different simulations have to be balanced and coordinated to generate the geometry system of the timber shell. The second challenge is that the structure usually cannot be constructed by a homogeneous fabrication and assemblage logic due to the large building scale and complicated regulation demands. The large span of the structure and fire-proofing regulations of wood material limit the minimal size the wooden component, so the large scale timber shell is usually designed by using a grid-beam system, which might contain different scale components according to stability requirement. Consequentially, the different scale components in the timber shell require a hybrid of various manufacturing methods, requiring the digital geometrical system to be turned into an adaptive medium, through which the virtual model can be translated into different languages for instructing different types of machines. In general, according to these challenges, what this paper explores is not merely a particular method or workflow of digital design and fabrication, but a hybrid and adaptive system that could combine different methods and workflows into an integrated entity.

METHODS

Research on the Joint System of Structural Performance-Based Timber Grid-Shell

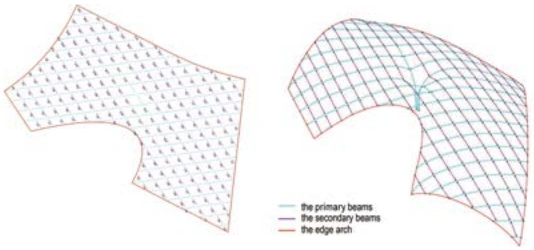
Due to the large amount of interconnections in a grid-shell, the joint system usually plays the most important role in determining its structural performance. In this phase, starting with a free form shell geometry generated by a gravity-based form finding process, the mechanical properties of different joint systems were examined through digital simulations and physical experiments to inform the distribution of different joint prototypes into a hybrid grid-shell system.

Structural Performance-Based Form-Finding and Optimization

The compression-based shell form-finding could be traced back to the pre-digital age in architecture. For example, in the works of Antoni Gaudi, Heinz Isler and Frei Otto, the forming process of shell geometry could be conducted through a series of physical experiments. In contemporary design, lots of digital simulation tools for compression form finding are available, such as “Rhinovault” designed by Philippe Block, to be able to conduct the process precisely in the digital environment. In this research, the initial geometry of the timber structure was generated through a gravity-based form finding process in Rhinovault1 (Figure 3). Then, according to the fabrication methods for timber material and the fireproof regulation, the initial geometry was translated into a particular grid-beam system.

Based on the site boundary, the two axes in the grid shell were designed to intersect with a particular angle, rather than being perpendicular to each other. In this situation, as the stability of the whole shell was relatively low, the structure was optimized into a primary-secondary beam system to increase the internal rigid connectivity. In the beam system, the cross-section of both primary beam and secondary beam were defined as rectangular, which is inherent in glue-laminated timber production technology. Generally, the primary beams were comprised of long and continuous curved timber, and each adjacent pair was connected by a row of short straight beams (Figure 4). In order to balance the simplification of the assembly process and the smoothness of shell geometry, the primary beams were defined as always being perpendicular to the ground while the orientation of secondary beams varied according to the local surface norm along the shell.

The form-finding process in Rhinovault mainly calculates the static equilibrium of stress distributed along the geometry based on gravity, regardless of the performance of structural stability including buckling, bending and shear (Adriaenssens, et al. 2014).



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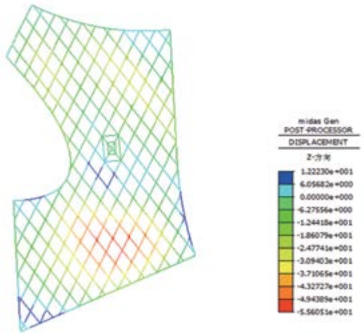

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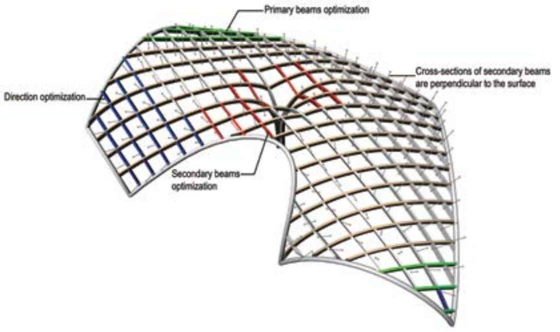

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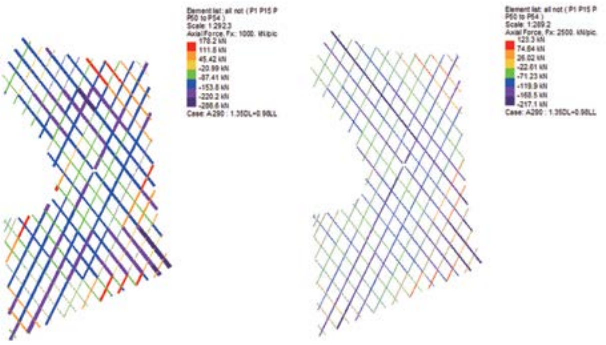
4 Primary-Secondary Beam System within Oblique Grid.

5 Structural Displacement Simulation with Multi-Directional Payload.

6 Optimization of Beam Dimensions.

However, in architecture practice, the structural stability in confronting horizontal loads, like wind and seismic, is also a main aspect in evaluating shell structure performance. So a series of multi-objective structural simulations with material properties were conducted in the subsequent optimization process (Figure 5), and the parameters extracted from their result were then correlated together to adjust the dimension of each beam to reinforce its local structural stability (Figure 6). After the optimization process, the dimension of the beam sections were set in a continuous variations from 650 mm x 250 mm to 350 mm x 250 mm.



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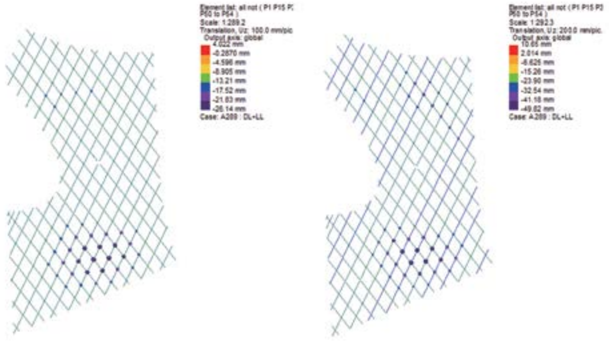

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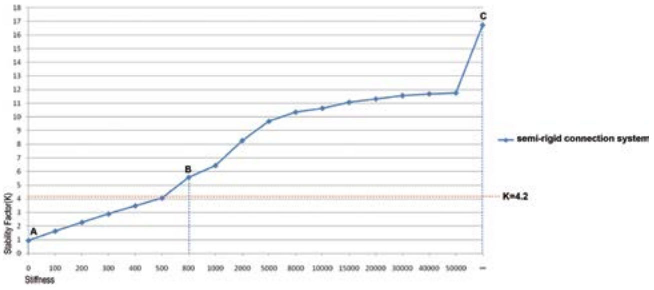

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7 Simulation of the Axial Stress of Semi-rigid Joint System (left) and Rigid Joint System (right).

8 Simulation of the Structural Deformation of Semi-rigid Joint System (left) and Rigid Joint System (right).

9 The Relationship between Joint Stiffness and Structure Stability (A: Hinge Joint, B: Semi-rigid Joint, C: Rigid Joint).

Experimentation on Joint Prototypes

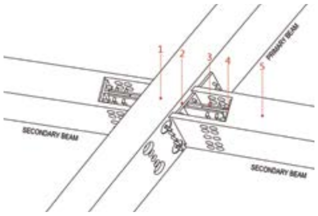
According to structural regulation, the joint between two timber components can only be considered as a semi-rigid or articulated connection. For grid-shell structures, the level of joint stiffness has a direct impact on the overall structural stability. Therefore, a series of digital simulations and physical experimentations were conducted to demonstrate the requirement in order to meet the level of overall stability. The result of these experiments became the main parameter to inform joint prototype design and distribution.

In the design of the timber joints, the simulations of structural stress and deformation were conducted to compare the shell structure with the ideal condition of full rigidity and the current condition of semi-rigidity (Figure 7). Taking the full rigidity condition as a contrast sample, the stress simulation result showed that the difference between the two systems is in an allowable range, which indicated that the stress was already evenly distributed along the beams in the current condition. However, structural deformations in the two systems were only close in several areas, where the local curvature of shell geometry was relatively large (Figure 8). So in order to fulfill the overall stability requirement of the semi-rigid system, an appropriate joint stiffness had to be achieved to control deformation within the allowable design range (Figure 9). As a result, to meet the building regulations, the average joint stiffness had to be more than 500 kNm/rad, and if considering the situation of a hybrid of semi-rigid joints and articulated joints, the minimal stiffness would have to be over 850 kNm/rad.

According to the stiffness requirement, three typical joints were designed for further physical experimentation: bolt plate joint, overlapping plate joint and planting bar joint. In the stiffness tests of full scale joints carried out in the structures laboratory, five measuring devices were placed on different parts of each joint prototype to record the amount of deformation under a payload ranging from 5 kN to 50 kN, and then the joint stiffness was calculated based on the test result (Figure 10, 11). As the calculation shows, the joint type with the best stiffness performance was the planting bar joint (Table 1). Through a feedback loop between comparative experimentation and joint prototype adjustment, a series of optimizations were made to improve

	displacement meter 1(mm)	displacement meter 2(mm)	displacement meter 3(mm)	displacement meter 4(mm)	displacement meter 5(mm)	Stiffness（kNm/rad）
5KN	115	118	108	99	71	1727.62
10KN	182	190	174	165	115	2195.64
15KN	276	286	263	247	175	2237.27
20KN	411	420	385	365	257	2163.66
25KN	542	551	506	488	337	2209.34
30KN	673	682	626	602	419	2157.77
35KN	855	865	791	765	529	1996.92
40KN	1175	1183	1083	1046	728	1711.67

Table 1



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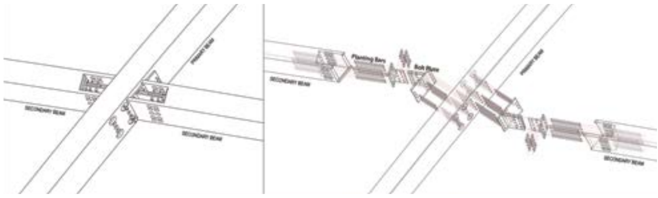

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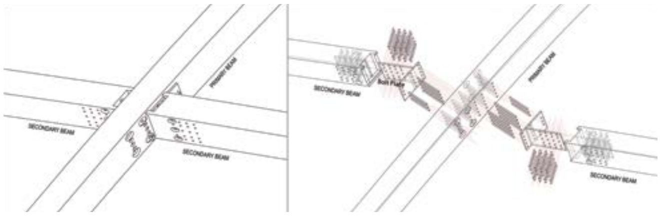

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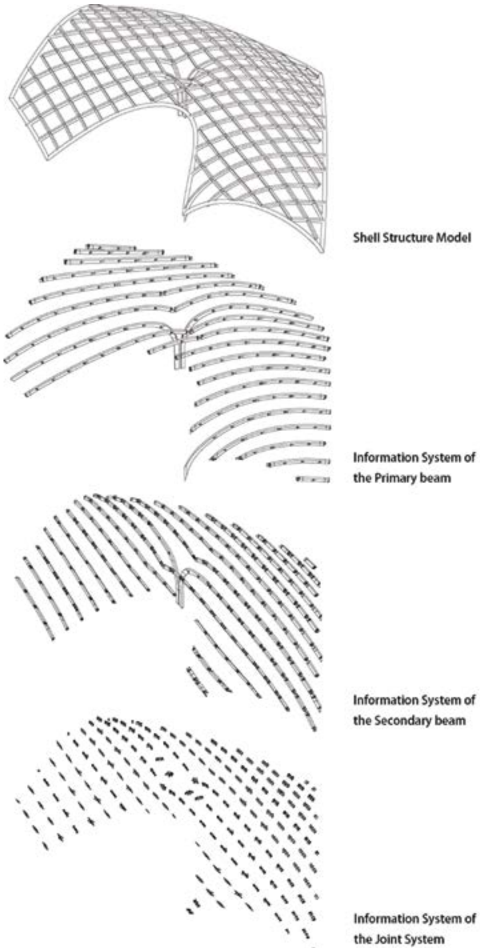

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the stiffness of this joint type further, including the planting bar length, etc. Finally, by combining the planting bar joint with the overlapping plate joint, the connection stiffness was enhanced to 1500 kNm/rad, which was considerably larger than the design value 850 kNm/rad, to ensure a certain degree of safety redundancy for the structure.

In the optimized joint, two T-shaped plates were connected together with high strength bolts. One of the T-shaped plates was fixed to the primary beam by high strength bolts, while another T-shaped plate was fixed to the secondary beam by planting bars (Figure 12). Due to the heavy steel components in the new joint, although the stiffness was highly enhanced, the large weight of the joint would introduce more load to the shell itself. In the structural experimentation, the bolt plate joint performed with much lower stiffness. However, because it connects two beams together only by bolts and clamping members (Figure 13), its weight would be much lighter too. So, in order to balance the structural load and stability, these two types of joint were distributed into the structural system according to the result of structural analysis; in the areas requiring only low joint stiffness, the bolt plate could effectively meet the rigidity requirement as well as reduce the structure weight.

In addition to joint stiffness experiments, several other experiments regarding different aspects of structural performance were also conducted during the research process, such as material properties testing, moisture control testing, coating durability testing, etc. The results from all the simulations and experiments were correlated together to inform the establishment of the geometrical system of the grid-shell structure.

Structural Geometry System

In the research, a digital information model was constructed to represent the structural simulation results for design visualization and optimization. Further, the geometrical system, which included the shape, dimension and orientation of steel joint and timber components, was translated into different types of information for different fabrication machines in the construction

10 The Position of Measuring Devices.

11 Physical Experiment on the Stiffness of Typical Beam Joint.

12 Combination of Bolt Plate and Planting Bars.

13 Bolt Plate Joint.

14 Structural Geometry System.


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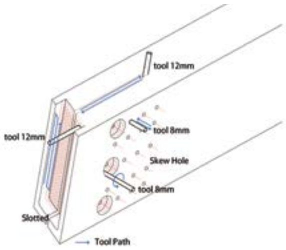

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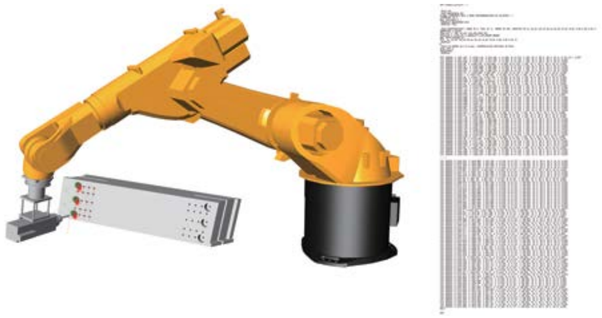
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15 Glue Laminating Process of Curved Beam.

16 Translation from Geometrical Model to Robotic Tool-path.

17 Simulation of Robotic Fabrication Process.

18 Robotic Fabrication Process.

phase. The whole process from form finding and optimization to material fabrication could be integrated and controlled through a digital information feedback loop.

The structural geometry system in this research includes three layers of information (Figure 14). The first is the shell surface, which provides the local geometry condition for orienting structure components. The second layer is the structure model, which stores the geometrical information of the beam and joint components. The final layer is the fabrication processing information, which is the convergence of structural geometry and fabrication methods and includes a series of tool-path generating codes.

In the geometrical system, the numeric information of each structural component was converted into a parametric relationship. For example, the dimension and orientation of each joint was parameterized into the geometrical relation between the initial shell surface and timber beams by using the Grasshopper program. The main bolt plate was always parallel to the side surface of the primary beam; the axis of the planting-bar was always perpendicular to the cross-section of secondary beam, etc. With this parametric system, the initial beam model as input parameters can be processed through code to generate joint variations automatically. And as so, the numeric information of the structural geometry can be easily translated between the three layers.

Digital Fabrication

With the embedded code in the structural geometry system, three types of geometrical information were generated as output to control different digital fabrication machines for three different structural components: primary beam, secondary beam and steel joint. According to the limitations of different fabrication tools, the primary beams and the steel joints were prefabricated by CNC machine in a factory while the cutting and drilling of the secondary beams were implemented by robot.

CNC Prefabrication of Curved Beam and Steel Joint

Limited by the dimension of glue-laminating devices and digital fabrication tools, the fabrication process of the primary beams employed CNC machines to control the shaping and drilling process. At the beginning, geometric information, like the outline of the curved beams and the position of the drilling holes, was first transmitted to cutting machine through G-code to cut templates for the glue-laminated process. The templates were not only used to inform the curvature of timber beams, but also to position the bolt-holes for steel joints. Since the glue-laminating devices can move flexibly to shape the beams with different curvature conditions (Figure 15), a template-based fabrication method with fully adaptivity was established in the factory. In general, although large-scale curved beams have to be fabricated by the glue-laminating devices, the digital information in the geometry system could be effectively transmitted into the process through templates to conduct the indirect translation of geometrical information.

The mass production of the steel joints was accomplished in a factory as well. Due to the variety and complexity of these components, the working planes in the digital environment were first redefined to adapt to the unfolding process for each joint. Then the geometric information was outputted in the form of 2D cutting paths to a CNC machine to fabricate all the plates of the joints. Further, as the plates were melted together according to the angle information, large quantities of joint variations could be produced in a relatively short time.

Customized Robotic Fabrication

In order to resolve the difficulties in fabricating the large amount of secondary beam variations, six-axis robotic arms were employed to connect the digital model and the beam fabricating process. The robot was equipped with a milling spindle with speed of 18000 rpm and an ER32 type gripper, which was able to process all the tectonic details on a beam by switching between different cutters (diameters vary from 3.5 mm to 20 mm). Then the Grasshopper plug-in KUKA|prc 2 was utilized to translate the geometric information to robotic motion as machine code to control different tool paths (Figure 16). First, a rough milling tool-path was set to cut out the general shape of each timber beam. Then a series of additional tool-paths were generated to control the fabrication of the tectonic details, such as bolt-holes, slotted openings, etc. The whole process of fabricating beam variations can be done without any sophisticated geometric drawings. The customized robotic fabrication process effectively ensured the large quantities of the shell components, improving the fabrication accuracy, and reducing fabrication time and costs (Figure 17, 18). Even more, the fabrication method also influenced the joint design due to the physical limitations. For example, since the inner corner of the slot openings was filleted in the physical environment according to the diameter of the milling cutters, the joint plate had to be designed smaller than the original geometry.

On Site Assembly

As all the components of the timber grid-shell could be prefabricated in the robot lab and factory, the on-site construction process only involved a series of location and assemblage tasks. At the beginning of construction, all the beams and steel joints were accurately numbered and labeled according to the axis


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19 Assembly Process.

20 Structural Components Assembly.

21 Interior View of Timber Shell System.

notation system in the digital model. Then a full-space scaffolding system with adjustable devices was introduced to enable the three-dimensional location of each beam in real space (Figure 19). In order to reduce the accumulated error, a real-time tracking mechanism was employed into the assembly process. When each beam was located in space and supported by the scaffolding system, a total station was utilized to track and measure the survey points on the beam. The data recorded by the total station was then returned to the digital space and compared with the corresponding data in the geometry system to check the displacement of the actual beam location. Further, the initial dimension generated by the geometry system for the scaffolding would be updated to adapt to the construction errors. In general, the intelligent, data-oriented assembly technology ensured the accomplishment of the project with a high-degree of precision in a fairly short time period (Figure 20, 21).

RESULTS AND REFLECTION

By utilizing the adaptive geometry system, the design and construction of the Timber Structure Enterprise Pavilion in Horticultural Expo was accomplished with a high degree of precision. The building is around 2000 square meters and its maximal span is about 40 meters. The timber shell system of the building contains 27 long curved beams, 184 short beams and 368 steel joints, in which no two components are completely the same due to their different local geometry condition and structural performance (Figure 22). The whole process of structure fabrication and assemblage controlled by the geometrical system only required four months, which is considerably short for a building in this scale. As a result, the accomplishment of the building construction can be considered as proof to demonstrate the adaptivity, capability and efficiency of the system developed in this research to resolve the complicated problems of timber shell structures.

CONCLUSION

The research in this paper reflects the challenges of contemporary digital design and fabrication in the scenario of large-scale architecture practice. According to these challenges, a structural performance-based geometrical system was developed to integrate the multi-objective structural evaluations, the parameter based design and the hybrid of multiple fabrication methods. As the demonstration of the system, the process of design and construction of the Timber Structure Enterprise Pavilion shows that architecture should be interpreted as a balance of contradictory factors in terms of not only form and function but also structure and tectonics. This research proposes that a hybrid of multiple strategies within an adaptive system to solve one problem, rather than a single homogeneous approach to solve multiple problems, would be able to provide an alternative thinking in the contemporary exploration of digital design and fabrication, and might eventually bring advanced digital technologies from the academic context to the practical field of architecture.

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NOTES

1. The Rhinoceros® Plug-In RhinoVAULT which is developed by Block Research Group, emerged from research on structural form finding using the Thrust Network Analysis (TNA) approach to intuitively create and explore compression-only structures.
2. KUKA|prc is a parametric robot control tool developed by Association for Robots in Architecture which enables one to program industrial robots directly out of the parametric modeling environment, including a full kinematic simulation of the robot. The generated files can be executed by the KUKA robot, without requiring any additional software.

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IMAGE CREDITS

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