DIGITAL DESIGN AND CONSTRUCTION OF LIGHTWEIGHT STEEL-TIMBER COMPOSITE GRIDSHHELL FOR LARGE-SPAN ROOF

A Practice of Steel-timber Composite Gridshell in Venue B for 2018 West Bund World AI Conference

JINXI JIN¹, LI HAN², HUA CHAI³, XIAO ZHANG⁴ and PHILIP F. YUAN⁵
¹,²,³,⁴,⁵ Tongji University
¹,²,³,⁴,⁵{jinjess|1810137|chaihua|1732145|philipyuan007}@tongji.edu.cn

Abstract. Timber gridshell is an efficient structural system. However, the feature of double curved surface result in limitation of practical application of timber gridshell. Digital technology provides an opportunity to break this limitation and achieve a lightweight free-form gridshell. In the practice of Venue B for 2018 West Bund World AI Conference, architects and structural engineers cooperated to explore innovative design of lightweight steel-timber composite gridshell with the help of digital tools. Setting digital technology as support and restrains of the project as motivation, the design tried to achieve the realization of material, structure, construction and spatial expression. The digital design and construction process will be discussed from four aspects, including form-finding of gridshell surface, steel-timber composite design, digital detailed design and model-based fabrication and construction. We focuses on the use of digital tools in this process, as well as the role of the design subject.

Keywords. Timber Gridshell; Steel-timber Composite; Digital Design and Construction; Lightweight Structure; Large-span Roof.

1. Introduction

Timber gridshell structure is an efficient structural system, which gains its strength and stiffness through its double curvature and covers large-span space with relatively small amount of materials. However, the feature of double curved surface result in complexity of design, analysis, fabrication and construction, which leads to the limitation of practical application of timber gridshell.

Digital technology provides an opportunity to break this limitation and achieve a lightweight free-form gridshell. This problem can be discussed from the perspective of design and construction. On one hand, structural algorithm tools can easily find the optimal form of a shell. Digital simulation and analysis tools
support non-standard form of grid shell. On the other hand, the transformation of industrial production from roughness to refinement promotes the construction mode of “customized fabrication in the factory + on-site assembly” (Y. ZHANG, 2018), which allows lightweight free-form gridshell can be materially realized. The change of construction mode also influences the architectural design process and broaden the thinking way of architects. Comparing the design and construction process of Mannheim Multihalle and Wood Structure Theme Pavilion in Jiangsu Province Horticultural Exposition (YUAN et al, 2016), we can find a flexible adaptability of timber gridshell under the latest digital tools (see Figure 1).

![Comparison of design and construction of Mannheim Multihalle and Wood Structure Theme Pavilion](https://example.com/image1)

This flexible adaptability provides an innovative possibility. If we look at the possibilities of innovation from a practical perspective, we will find more motivation (PICON A, 2011). In practice, besides appropriate, structurally efficient, the shape of the shell is also defined by other constraints (Sigrid, 2014). The design and fabrication of steel-timber grid shell in Venue B for 2018 West Bund World AI Conference provides us an opportunity to explore the possibility.

![Lightweight steel-timber composite gridshell of Venue B](https://example.com/image2)

In the practice of Venue B, we explore digital design and construction of
DIGITAL DESIGN AND CONSTRUCTION OF LIGHTWEIGHT STEEL-TIMBER COMPOSITE GRIDSHELL FOR LARGE-SPAN ROOF

lightweight steel-timber composite gridshell, which is used for the roof structure of courtyard (see Figure 2). Under digital technology, large-span timber structure is developing towards composite structure (K.LIU, 2012). Steel-timber composite structure, as a modern timber structure, is one of the most promising composite structures (HOU, 2016).

2. Method

Under digital technology, the main emphasis of the work has shifted from computing to design strategy. In the practice of Venue B for West Bund World AI Conference, setting digital technology as support and restraints of the project as motivation, the design tried to achieve the realization of material, structure, construction and spatial expression.

The unique constraints of the project lies in the limited time and spatial relationship: firstly, we had only 100 days to conduct design and construction. Secondly, the courtyard was limited to the triangular space defined by three rectangular meeting space and the relationship of surroundings should be taken into consideration (see Figure 3). The following sections show the digital design and construction process of the lightweight steel-timber composite gridshell roof for the main courtyard of Venue B. The process will be discussed from four aspects, including form-finding of gridshell surface, steel-timber composite design, digital detailed design and model-based fabrication and construction.

2.1. FORM-FINDING OF GRIDSHELL SURFACE

With the help of the structural algorithm tool, which can quickly realize form-finding of high-efficient shell surface (YUAN, 2014), the design is presented as a judgment problem for a reasonable “design solution”. In space, the boundary condition of triangular courtyard space was nearly restricted (see Figure 3). Gridshell should be coordinated with the supporting conditions on both sides and meet the structural size of components.

In order to achieve an elegant form under the restrictions, we try to find suitable form by using structural algorithm plug-in Kangaroo (see Figure 4). Firstly, the geometric boundary of the gridshell is defined according to the site relationship; secondly, the vertical support is defined considering the distance.
of columns. Then, by defining the mechanical boundary in Kangaroo, we can have structurally optimal form under uniform load. Two different possible forms are explored. One is taking the triangular geometric boundary and the support columns as mechanical boundaries, and the other is taking the triangular geometric boundary as mechanical boundaries and ignore the support columns. Considering the relationship between the gridshell and the surroundings, the form ignoring the mechanical relationship between gridshell and column is more harmonious and achieve an open space for the city. Moreover, it is also beneficial for timber fabrication for its flat curvature.

![Figure 4. form-finding of Kangaroo.](image)

### 2.2. STEEL-TIMBER COMPOSITE DESIGN

The form-finding process separates roof system and vertical support system, which results in a gridshell roof that is structural optimized itself but not uniform with columns. Vertical columns cannot bear horizontal thrust resulted from gridshell roof. One common solution is to balance the horizontal thrust with a diagonal column, such as the Palazzetto Dello Sport of Rome by Nervi and the Auditorium in Tongji University (see Figure 5). But this solution obviously does not apply to the sites for the spatial constraints.

![Figure 5. Palazzetto Dello Sport of Rome by Nervi and the Auditorium in Tongji University.](image)

Beam string structure is a common type to achieve large-span timber structure (Qian, 2017). Besides improvements of strength, stiffness and stability, string can achieve self-balancing of the structure and balances horizontal thrust. Structural engineer proposed two types of beam string structure. However, the steel string
affect the net height of courtyard, further affecting the transparent space. Finally, the steel string and steel beam are set in the three corners of the roof. The horizontal force of grid shell is balanced by the steel truss in the outer ring and steel string at three corners (see Figure 6).

The position of the beams were projected by plane lines which are parallel to the three sides of the triangle. Diamond and square mesh can be obtained by the projection of the lines that are parallel to the long side of the triangle. Diamond and square mesh is suitable for the transparent space. However, it ignores the beam system parallel to the short side of triangle, which is structurally optimal. The triangular mesh takes short beam as the main direction of the force transmission. Also, the triangle units work well for a stable overall structure. However, the short beam system affects spatial transparency and its complex joint system increases the time of construction. Finally, we decided to adopt Diamond and square mesh as main structure and retain short beams partially.

Faced with the contradiction between form and structure, a final structure that mixed timber beams, steel beams, steel trusses and steel strings was realized (see Figure 7). The structure combined the advantages of different solutions. The main
part of gridshell is diamond and square mesh timber beam, and the lateral thrust of gridshell is balanced by the steel trusses arranged in the outer ring and the three prestressed steel strings at the corner of triangle. The timber beams corresponding to steel strings are replaced with steel curved beams. Also, diagonal short timber beams in the middle improve the structural integrity. The arrangement of timber and steel enhances the overall stability and vertical stiffness and realizes original shell surface at the same time.

Finally, we achieve coherent form and rich space of a gridshell in a balance of complex forces. The steel beams and the steel trusses are covered by wood and achieve an overall atmosphere. The structural system and space system can be clearly read: steel trusses and steel strings that resist horizontal force present a heterogeneous form. Timber beams in central space highlight the central space of gridshell roof, echoing the 3D printing coffee bar in the middle of the courtyard (see Figure 8).

![Figure 8. steel-timber composite grid shell of Venue B for West Bund World AI Conference.](image)

2.3. DIGITAL DETAILED DESIGN

Generally, there are two ways to decompose a timber gridshell. The entire glued timber beam has high joint stiffness but complex and time-consuming to fabricate. If we fit surface with short single beams that are divided by joints, joint stiffness will be weakened, the amounts of components will rise and the type of joints will increase. In contrast, the staggered arrangement of beams can achieve semi-rigid connection of the joints, which also optimize the number of components and the difficulty of fabrication. Lamella roof (or Zollinger roof) (see Figure 9) is single-layer grid shell system named after the German architect Friedrich Zollinger, which achieves large-span wood structure by staggered timber beams. Lamella roof was usually used for cylindrical shells or spherical shells. With the help of parametric model, Lamella roof can easily and flexibly fit free-form shells.
Considering that the overall flat curvature and limited construction time, we proposed further optimizations of Lamella roof, including fit the shell surface with straight beam, and use vertical hollow double beam as unit beam (see Figure 10). The joint is rigid connection in the continuous direction and hinge connection in the other direction.

Two single timber beams connect to each other through timber connector and crew to form a vertical hollow double beam. Screw is also used as connection of the beam in the other direction with the help of steel connector and self-tapping nail. Steel connector is manufactured by customized molds. The double curved gridshell is the projection of the parallel plane line, which means the angle of steel connector is consistent. So the steel connectors can be optimized to the same size. Using self-tapping nail to connect steel connector and timber beam can realize
adjustment of assembly error (see Figure 11). The design of joint and timber beams reduces the difficulty of fabrication and assembly, reduces the weight of the roof. The screws at the joints are well concealed and the gridshell presents the futures of simplicity and lightweight.

Computational analysis shows that 400 height timber beam can meet the structural requirements of the overall gridshell. We evaluated the joints under the parametric model since each joints of the double curved gridshell are different. In order to reduce the type of joints, the height of the timber beams are uniformly adjusted to 500mm, which ensures the height difference at the beam end to achieve staggered rhythm. The parametric model of gridshell was slightly adjusted to achieve the coordination between the overall form and the joint performance. SAP 2000 is used for structural analysis of the gridshell.

The parametric model shows a flexible adaptability in the design process, and connects design data and construction data. Although the geometric conditions are continuously optimized during the design process, 562 non-standard beams are updated quickly under parametric model. Therefore, the design process achieve real-time feedback during structural optimization, component optimization and joint optimization.

2.4. DIGITAL MODEL-BASED FABRICATION AND CONSTRUCTION

Digital model directly guides factory prefabrication and on-site construction. Prefabrication and on-site assembly of the 2000m2 steel-timber composite roof was completed in less than two months. Reasonable evaluation of relevant manufacturing attributes in the design phase is one of the main reasons for the completion of the construction in limited time. In the process of on-site construction, reasonable design greatly improves speed and accuracy of the gridshell. Lightweight single timber beam can be easily carried by 3-4 workers on site. The timber joints have a higher degree of pre-assembly before on-site assembly. The self-tapping screw is punched on site, which eliminated on-site assembly error, realized accurate and rapid construction of gridshell structure (see Figure 12).

Another important reason for the successful construction is that a design-construction process based on data model is explored. Digital factory fabricate and numbered non-standard components based on the parallel data guidance of the data model. On-site construction is based on the data model and scaffolding platforms were erected. Firstly, the steel structure was installed. As for the installation of bulk assembled wooden structures, the assembly process was measured by the total station, which measure the construction data and returns message to the software platform to update model in real time to feedback to the error adjustment. After the installation of the whole structure, the steel strings are prestressed, then the whole structure unloaded to achieve the final form of gridshell.
3. Result, Discussion and Outlook

We explore a digital workflow for lightweight steel-timber composite gridshell in the design and construction process in Venue B for West Bund World AI Conference (see Figure 13). Finally, with the help of digital tools, 2000 square meters steel-timber grid shell was completed in less than 100 days, which realizes diversified demands of material, structure, construction and space. The project shows great potential of digital design and construction of lightweight steel-timber composite gridshell for large-span roof.

The discussion includes the following points. Firstly, as a large-span structural form, the innovative design of steel-timber composite structures requires architects and structural engineers to work in a highly interactive way. Under the real-time feedback of the visual model, an efficient collaborative working mode of between architects and structural engineers is worth exploring (MA, 2016). Secondly, the practical project faces complex constraints, which makes us to further consider the relationship between people and technology. Technology opens a door for innovation. People, as design subject, should fully play the role of perception of space and form, logical reasoning and decision planning of the design subject.

In recent years, steel-timber composite structure has become a trend of practice in the large-scale public building including stadium, exhibition hall, conference center (LIU, 2012). For steel-wood composite grid shell, which is a high-performance lightweight long-span structure, there will be more opportunities for innovative practice under digital technology in the future. The
digital workflow of this project provide a useful reference for innovation practice of steel-timber composite structure.

Acknowledgements

This research is funded by the National Natural Science Foundation of China (Grant No.51578378), the Special Funds for State Key R&D Program during the 13th Five-year Plan Period of China (Grant No.2016YFC0702104), the Sino-German Center Research Program (Grant No.GZ1162), and Science and Technology Commission of Shanghai Municipality (Grant No.16dz1206502, GrantNo.16dz2250500,GrantNo.17dz1203405,GrantNo.18dz1205604).

References