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Innovative Truss Design for Long-Span Timber Vaults: The Tianfu Agricultural Expo

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Abstract

At over 75,000m^2, the new Tianfu Agriculture Expo will be the largest timber structure in Asia, and one of the largest timber structures in the world. Working closely with one of China's most renowned architect, Cui Kai, StructureCraft designed this series of 5 vault enclosures using unique Vierendeel inspired trusses to achieve clear spans up to 110m and heights up to 44m.

By integrating a cutting-edge parametric workflow into the design process, the design team achieved the ambitious architectural vision and freed the design from common fabrication and timeline constraints.

Keywords: long-span, mass timber, glulam, arches, hybrid truss, timber-steel hybrid, parametric, Cui Kai, vierendeel truss, structural efficiency

1. Introduction

The Tianfu Agricultural Expo Park is part of a major development program in the greater metropolitan area of Chengdu, which aspires to compete with other major economic hubs in China. As Sichuan's capital, Chengdu seeks to showcase the importance of rural areas while transitioning from a traditional farm-based state into the agricultural and technological powerhouse of southwest China. Located on the west border of the Sichuan Basin, where up to 5000m high mountains meet Sichuan's great plains, the wide views and mountain peaks on the horizon inspired the architect Cui Kai with the concept for the curved timber enclosures.

The unique wave of the building ensemble blends gently into the landscape, but also provided challenges for StructureCraft's engineering team to materialize the architectural scheme into a bold project on a very tight schedule.

Figure 1 Overview

2. Project Overview

Tianfu Agricultural Expo's five main buildings create the space for a variety of different venues ranging from a museum to a convention center, with a total footprint of over 75,000m^2.

The largest timber vault (G1, fig. 2) spans over 110m and is emphasized by a 3000m^2 LED screen above the main entrance to the convention center. Each of the 5 vaults is semi-enclosed with a light, cable-supported LED screen at front and a full opening on the back. Some of the structures are filled with inner buildings to support the agricultural expo, and some are open to house flexible spaces and temporary structures. A pre-tensioned translucent ETFE membrane clads the irregular roof surface and protects the timber elements from weather.

Cui Kai 's vision of the building ensemble translates into 3500 unique singly curved timber members and a total Glulam volume of 6000 m^3. The ability to create an integrated design workflow based on parametric geometry definition, as well as automated generation of fabrication drawings and CNC files, freed the architecture from common fabrication and timeline constraints.

Figure 2: Vault overview

3. Geometry

The core geometry of each vault is defined by two base lines on the ground to define the axis and span, and the first/last truss height. All vault arch curves (except G1) are catenaries to reduce truss moments and increase structural efficiency. Even though G1 is the largest span and therefore has the highest loads, it was constrained by clearance to the interior buildings and a maximum height, and the trusses in that vault follow a more rounded geometry.

Each arch truss is formed by two bottom chords and one top chord (double glulam section) with structural truss depths of 1.3m – 3m. The general arch geometry tapers from deep trusses and sections near the base to shallow truss and section depths at the apex. The diagonal webbing consists of a light 'pyramid' of laser cut Q355 plate members, allowing very slender web elements which almost disappear, minimizing the visual connection between top and bottom truss chords.

Purlins sit on top of the truss bottom chords and support ETFE membranes, which are pretensioned against the two neighboring arches. Enabled by a scripted geometry, extensive optimization studies were conducted in Grasshopper to find a purlin distribution which allows for a minimum of individual cladding support members. A reduction in production time and cost was achieved by relating the purlin spacing to the louvre openings.

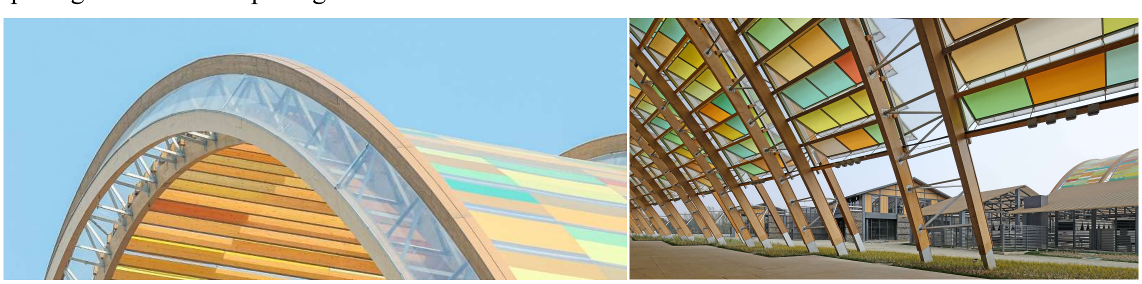

Figure 3: Vierendeel inspired laser cut truss webbing and optimized purlin spacing in louvre zones

4. Structural Engineering

4.1 Concept Phase

The initial architectural concept from Cui Kai used planar "trusses" with 2 chords and only vertical webs connecting them – no diagonals – signaling the architectural desire to create a minimalist truss maximizing transparency and focusing on exposing a timber top chord on the exterior of the vaults. It was clear from the beginning that simply triangulating this truss structure not only visually distracted from the flow of the curved Glulam elements, but also created challenges for assembly of pre-fabricated truss segments in the air.

Early design sessions with Cui Kai yielded the concept of turning the planar trusses into an "expanding" arch with a continuously varying triangular cross section comprised of double bottom chords and a single top chord. The deeper and wider truss near the base creates fixity into the foundations, enabling the truss to cantilever both in-plane and out-of-plane for lateral loads.

During design meetings, StructureCraft discussed the idea of using a true Vierendeel truss scheme to connect the three chords, but it was discarded due to the need of a complicated and expensive moment-fixed web connection. The following discussions led to the unique Vierendeel-inspired concept of using two leaning triangles (fig.4) connecting the bottom- with top chords. The shear induced in the system by global moments on each truss is translated into a triangular push-pull, which is structurally more efficient than a bending-active Vierendeel web.

Structurally, this system induces only axial forces into the single top chord, but both axial and significant shear forces into the bottom chords. The Larch double top chord is outside the ETFE cladding and exposed to the weather, creating the need for a carefully developed weather protection and flashing concept throughout the project.

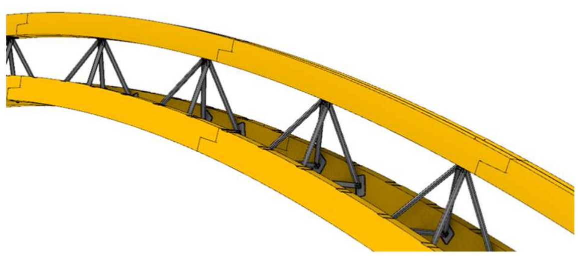

Figure 4: Vierendeel inspired truss webbing

4.2 Structural System and Loads

All vaults have the same structural system, which consists of independent truss arches, laterally tied together by purlins and global cable bracing. The cable bracing with the purlins forms the longitudinal lateral system to withstand seismic- (PGA: 0.1g) and wind forces on the semi enclosed structures. Each individual arch forms the lateral system in transverse direction and supports just the load tributary to that arch.

Vertical and local orthogonal forces (due to wind) are transferred by the purlins to the bottom chords where they are translated into axial and bending chord forces. The steel base connections transfer the chord forces through steel embed plates into the massive concrete foundations which were designed by the LDI. Depending on the load distribution and geometry, the arches are subjected to global bending. This leads to high axial chord and web forces near the base where the arch moment and shear is the highest.

In addition to the loads transferred by the purlins, the second arch of each vault is vertically loaded by pre-tensioned 24mm open spiral strand steel cables, which support the LED screen substructure. The cable pre-tensions vary dependent on the cable location, and sequence of pre-tensioning. Adding tension into one cable changes the pre-tension in the surrounding cables, so the installation and tensioning sequence needed to be carefully planned through staged finite element analysis, monitored, and executed.

4.3 Design

All five buildings have a great geometrical variation of the same structural system. This fact makes it a prime application for automation and parametric generation. The center lines for the structural models were generated simultaneously with the geometry exploration in the main grasshopper script, which allowed a direct model export (including member sizes and loads) for structural analysis. Later in the project the grasshopper plugin *Parametric FEM Toolbox* was used for smaller geometry exports/adjustments. All surface loads were automatically applied onto the purlins based on their changing tributary areas.

The design process for all vaults utilized the same workflow: Simple section checks were efficiently done within the finite element software based on nonlinear internal forces. Due to the relatively low curvature, timber members were regarded as straight for local buckling checks, while global buckling behavior was captured by nonlinear calculations. Additionally, a nonlinear buckling analysis was conducted to understand the factor of safety against global buckling, and to ensure a safe structural performance.

Two governing global buckling shapes were identified during the analysis:

1. Buckling of bottom chord in the region with splices.

2. Buckling of the top chord in the ridge area due to high bending forces introduced by the LED screen in G1.

Besides the global design, many small analyses were conducted to capture different construction phases such as de-propping, lifting, screen pretension procedure.

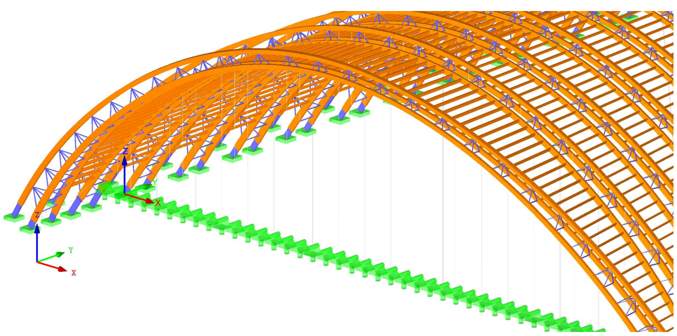

Figure 5: G4 analysis model

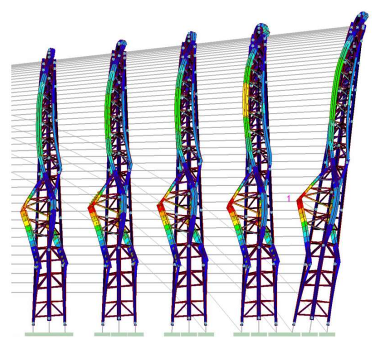

Figure 6: Mode shape case 1

The assembly line nature of the project had a special role for efficient detailed design. Efficiency in this case was a fine balance between saving through material cost reduction and easy to install repetitive connections to ensure a smooth preassembly process. This balance was achieved by exporting the detail forces to Excel, which was then used to map connection forces, decide on an efficient amount of connection types, and conduct the detail design.

Following the load path, 45° fully threaded screws transfer the shear from the double top chord via a bolt and 4 shear planes into the triangle below (fig.7). The welded vertical top plate has two functions: On one hand it acts as a stiffener for the horizontal plate, and on the other it stabilizes the top double chord.

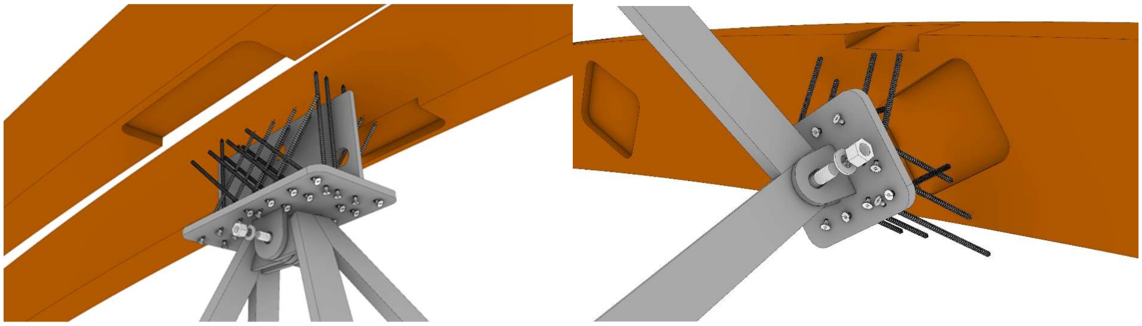

Figure 7: Example top (left) and bottom (right) chord connection

The shear transfer force between the chords is translated into a push-pull in the steel triangles. The axial triangle forces travel through a single bolt in shear via 45° screws into the bottom chords. The countersunk screws always point inwards to allow for a compact detail, which was crucial in areas with shallow bottom chords but relatively high shear transfer (e.g. ridge region due to unbalanced wind loads). The chord splice connections are an integral part of the truss design. Splice locations were driven by shipping constraints, triangle distribution, and axial forces. Each splice is mainly loaded by axial forces. Tension is transferred by 45° screws and compression by end grain bearing. Additionally, notch reinforcement and shear screws are used. The moments are very small due to the global structural system and low rotational splice stiffness.

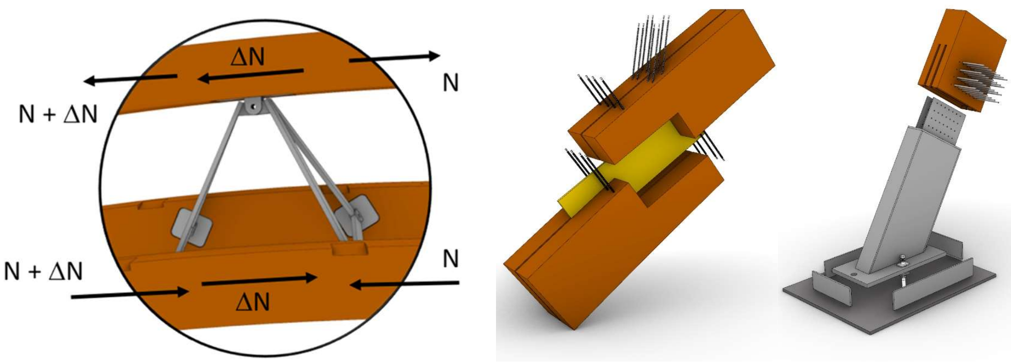

Figure 8: Triangle loadpath, chord splice and base connection

The base connection provided enough flexibility to accommodate high tolerance requirements due to the site welded steel box between hollow section and embed plate (grouted after installation). Levelling nuts on welded threaded studs were used to adjust the arch height during construction. High axial compression forces are transferred from the glulam through end grain bearing via cap plate into the steel box section, while tensions are transferred through the knife plate connections.

5. Automated Workflows

The initial architectural desire to create a smooth enclosure combined with the sloped ridge lines added a unique twist to each arch truss. Consequently, one bottom chord is always slightly lower than its

Figure 9: Sloped ridge lines added complexity

neighbor within the same truss. This design decision affected the whole fabrication process by making every arch, web and therefore truss connection unique.

By deciding early to parametrically generate all aspects of the geometry, StructureCraft enabled an end-to-end workflow that could cope with thousands of unique pieces and connections. The whole project was driven from Grasshopper using custom C# object model and classes and defining all structural members in 3d space including steel details and notches and screw holes into the timber.

A graphical output in Rhino was used to check fabrication data and geometry constraints. Meta data using key-value pairs were automatically assigned to each piece, containing BIM data such as fabrication-, shipping- and construction information (…). This information in conjunction with the 3d geometry was used to generate automated fabrication, shipping, assembly- and erection drawings.

Furthermore, the Grasshopper script drove custom C# scripts for CNC data generation (.bvx files). After a coordination phase to confirm available CNC tooling and ensure output quality, the data was directly used by three different European Glulam mills to machine the truss chords. Not only was the fabrication process substantially shortened by the integrated workflow, but fabrication precision and error rates were improved significantly.

Figure 10: Unique arch segments with notches for purlins

Figure 11: Smooth enclosure, optimized purlin distribution

5.1 Wind Loads

When the first architectural concepts of the project were discussed, it was decided a wind tunnel test should be conducted to capture the complex shielding effects and internal pressure distributions for the semi enclosed buildings adequately. The wind tunnel test was carried out by the China Academy of Building Research (CABR) who obtained the needed wind pressure data for a 50- year return period.

To process the wind data for structural analysis, a Grasshopper script was used to map the distinct wind pressure points onto the vault surface. After the surface pressure distributions was generated, it was translated into line loads based on purlin tributary areas and imported to the calculation software for finite element analysis. The complex intercation between load and geometry required an automated design process.

Figure 6: Wind tunnel vault models

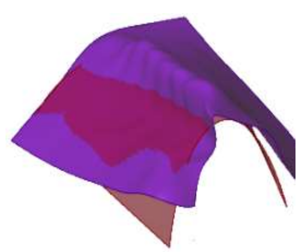

Figure 13: Generated wind pressure on vault

5.2 Generated Analysis Model

All five buildings have a great geometrical variation of the same structural system. This fact makes it a prime application for automation and parametric generation. The center lines for the structural models were generated simultaneously with the geometry exploration in the main grasshopper script, which allowed a direct model export (including member sizes and loads) for structural analysis. Later in the project the grasshopper plugin *Parametric FEM Toolbox* was used for smaller geometry exports/adjustments. All surface loads were automatically applied onto the purlins based on their changing tributary areas.

The assembly line nature of the project had a special role for efficient detailed design. Efficiency in this case was a fine balance between saving through material cost reduction and easy to install repetitive connections to ensure a smooth preassembly process.

This balance was achieved by exporting the detail forces to Excel, which was then used to map connection forces, decide on an efficient amount of connection types, and conduct the detail design through Excel. Critical for this workflow was full control over finite element numbering and orientation when generating the models to ensure correct internal connection forces.

5.3 Automated Site Documents

Due to the necessity of shipping the glulam pieces from Europe to China by rail, single members were constrained by container sizes. In this case, the parametric project tools were used to optimize container packing and shipping sequence. Once the material arrived on site, temporary fabrication facilities took over to assemble the so-called sub-assemblies. These ~11.5m long assemblies consisted of un-spliced glulam chords and associated steel webbing. Between two and four sub-assemblies were connected near the final arch location and formed the up to 35m and 25t heavy lift-assemblies. One arch consists of up to five lift-assemblies.

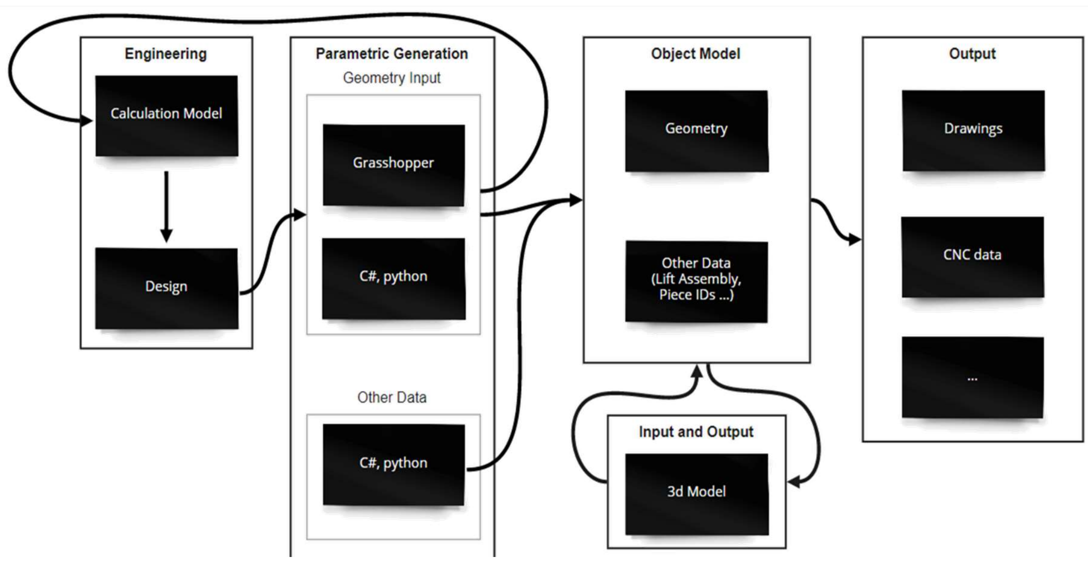

Figure 14: Parametric project workflow

6 Construction

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Figure 15: Lift-assembly and shoring tower

The construction of the superstructures started after all internal steel buildings were finished, to ensure crane access below. After exploring different erection methodologies (e.g. launching arch pieces to avoid shoring onto existing buildings) it was shown that the shoring towers could be supported by the steel structures below where necessary. In addition to providing temporary support, the surveyed shoring towers also played an important role during the construction process by controlling the arch geometry. Each arch erection started with the base lift-assemblies, supported by a shoring tower at the tip. The base connections were temporary fixed to the foundation embed plates during this phase.

After the lift assembly was landed and surveyed, field welds were completed, and the permanent base condition were established. Depending on the arch split points, one or more infill assemblies were lifted in, and finally a keystone section closed the arch. After a sequence of arches got erected and were tied together by purlins, most shoring towers could be lowered and reused for the next arches. Some shoring towers remained in place in conjunction with guy wires to ensure temporary lateral stability of the structure. Finally after a vault completion, the LED screen cables were installed and pre-tensioned in specified load steps and order.

7 Conclusion

Tianfu Agricultural Expo's strictly parametric project approach has enabled architectural creativity to be freed from traditional fabrication constraints, enabling a true batch-size-one approach to manufacture and construction – most of the Glulam and steel pieces (more than 60,000 in total) were unique.

The delivery of the design, fabrication, and construction of this structure in less than 1.5 years was only made possible by combining a unique vertically integrated team of structural engineers, manufacturers, and builders united with a singular purpose of creating this highly complex structure, alongside an architect who created the ambitious project vision. All structural details were designed with fabrication and construction techniques in mind, embedding buildability into the heart of the structural concept. The result is a unique series of long-span timber structures, created through cooperation of team members on three different continents in a year, delivering indeed the owner's desire for a world-class attraction.

The Tianfu Agricultural Expo will show case not only the economic power of the Chengdu agrarian region, but also the stunning structures that can be constructed through innovative timber engineering and integrated design.

Acknowledgements

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Figure 16: G1, second arch (115m)