CURVED GLULAM ARCHITECTURE DESIGN OPTIMISATION FOR LOW-TECH CONSTRUCTION

The Fabrication and Construction of KATENARA

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Abstract. This paper reports on the research findings from the fabrication and construction of "KATENARA" (弦閣), a prototypical, hyper-lightweight, wooden pavilion built in the Dongshi Forestry Cultural Park, Dongshi, Taiwan in November 2023. KATENARA uses a suspended roof structure system optimised for low-tech production from glue-laminated (glulam) timber. The pavilion’s geometry is based on near-catenary-shaped glulam beams that are evolutionary algorithmically optimised for manufacture from a single mould. Structures based on suspended beam geometries substantially reduce material needs when compared with those relying on straight beams, as catenary beams operate in pure tension throughout, avoiding inefficient neutral fibres along the centreline and removing risk of buckling. Yet, their manufacture from glulam typically requires costly bespoke individual hardware setups. Shape optimisation for fabrication efficiencies substantially increases the tectonic system's applicability, as it facilitates more affordable implementation in low-tec fabrication environment.

Keywords. Catenary, Timber Shell, Evolutionary Algorithm, Glue-laminated Timber, Low-tech, Affordable Construction.

1. INTRODUCTION

Catenary structures are a type of hyper-lightweight structure popularised by architect Frei Otto (Otto, 2005). Their main components follow suspended cable geometries operating in pure tension. Therefore, catenary structures are characterised by their

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minimal material use, geometric elegance, and structural efficiency, making them ideal for a variety of construction projects. Catenary structures were originally introduced and gained popularity in the post-World War II period. The Dorton Arena (Maciej Nowicki, Raleigh, North Carolina, USA, 1952), was the first large-scale shell structure to use (near) catenary suspension beams, which created a hyperbolic paraboloid geometry (Sprague, 2013). The typology quickly gained recognition and influenced pioneering architects like Eero Saarinen and Kenzo Tange in seminal projects like the Dulles International Airport Terminal Building (Chantilly, United States, 1962) and the Yoyogi National Gymnasium (Tokyo, Japan, 1964) respectively. Frei Otto's four Wilkhahn factory pavilions (Bad Münder, Germany, 1987) elegantly applied the typology to glulam timber.

Designs that use beams with differing bending radii, when made from glulam, typically require multiple individual jigs for their fabrication, which can quickly become cost-prohibitive (Fast, 2017). In response, this research developed an evolutionary algorithm that minimises the number of required jigs, making the construction of such timber structures more practically and financially feasible (Author, 2019). This paper discusses KATENARA, a prototype pavilion, built in the Dongshi Forestry Cultural Park, Dongshi, Taiwan in November 2023, as a demonstrator project of the design opportunities made possible by introducing evolutionary algorithms to simplify the construction of non-standard, light-weight catenary wood structures.

Figure 1. KATENARA (Dongshi, Taiwan, 2023)

2. BACKGROUND: OPTIMISATION ALGORITHM

Earlier publications reported on the evolutionary algorithm that was introduced to derive, from input geometry, a single jig setup that allows the closest manufacturing approximation of any given set of input curves (Wong and Crolla, 2019). This algorithm uses the standard Galapagos© add-on to Rhino’s Grasshopper software, which allows for straightforward evolutionary optimal solution identification within a multi-dimensional field (Rutten, 2013). Five parameters (three x-coordinates and two y-coordinates) are used to define the four control points (including origin) of the NURBS curve that will define the eventual jig (see Fig. 2). The evolutionary solver adjusted input parameters until the cumulative distances between each curve and its respective NURBS curve segment were minimal.

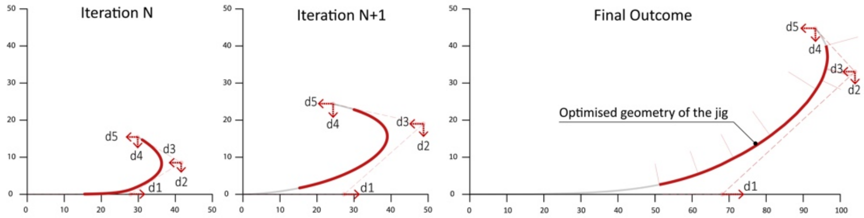

Figure 2. Jig geometry optimisation using a multi-parameter evolutionary solver

3. **PROJECT DESIGN**

3.1. CONCEPT

To facilitate future architectural applications of this structural typology, a collaborative research project was set up between The University of Hong Kong (HKU) and National Yang Ming Chiao Tung University (NYCU) to build a small demonstrator pavilion, titled "KATENARA" (弦閣). Programmatically, the pavilion was specified to be a minimal shelter-providing catenary roof structure placed in an open park landscape. It covers an area of 25.3 sqm with a double curved wooden roof surface that stands 3.9m tall. The symmetrical roof structure consists of two glulam ring beams that hinge at the bottom. These are kept in place by ten near-catenary-shaped glulam beams suspended between them and tension cables anchoring the whole to the foundations. On these, a doubly-curved roof floor from wooden planks is installed that is finished with a waterproofing layer and asphalt tiles for rain protection. Along its perimeter, a protective metal edge profile detailing was implemented.

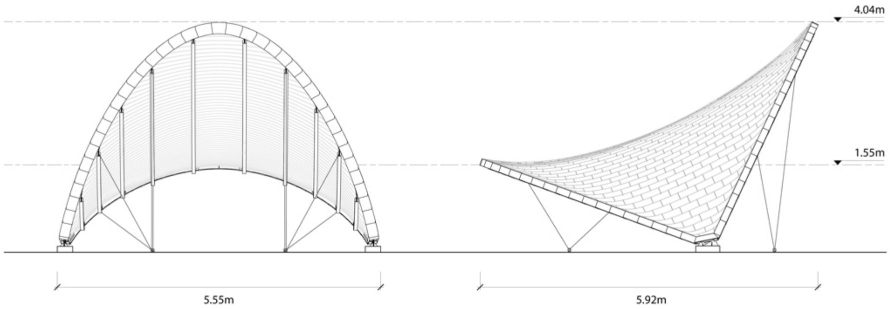

Figure 3. Elevation drawing

The pavilion's design process followed both an iterative prototype design process through scale models and a rigorous analysis of historic precedents that used suspended glulam structures, from which construction detailing concepts were extracted as starting points (Crolla and Wong, 2023). By designing and realising KATENARA, the study aimed to identify and resolve common construction and implementation challenges and opportunities associated with the structural systems.

3.2. MATERIAL USE OPTIMISATION

The number and spacing of the catenary beams were designed and structurally optimised using the Karamba3D parametric engineering plugin for Rhino. Local structural engineering partners further refined and assessed the model using structural analysis software MIDAS/Gen V851. For this, Taiwanese building codes for architectural design, timber structure design, and seismic design were used. Wind resistance design was based on an "open architecture with a single-slope roof" building type, sitting on a "Flat and open ground with scattered obstacles less than 10 meters high" terrain type (Ministry of the Interior, 2014). Domestic Japanese Cedar wood, a locally available timber species donated by the Forestry and Nature Conservation Agency, was used as the main material. Ring beam sections were optimised to 160mm x 100mm using E105-F300 grade Japanese Cedar, while E85-F255 grade Japanese Cedar were selected for the suspended beams which were sectioned at a mere 60mm x 90mm.

3.3. TIMBER FABRICATION SIMPLIFICATION

The cost of timber fabrication includes various elements, like jig manufacture and set-up, timber preparation, lamination, trimming and sanding, weatherproof coating, consumables, mock-up installation, and transportation. Within this, the cost of setting up custom jigs can be substantial and varies according to required quantities and overall size.

To minimise construction cost, KATENARA's geometry was optimised to allow pre-fabrication of all curved glulam elements from only single jig. The symmetrical ring beams were broken up into two parts each to allow for easy road transportation and a reduction in the size of the prefabrication jig. Even then, quotations provided by our local manufacturing partners revealed that the custom jig set-up still accounted for 19% of the total amount of the timber works, or 10 % of the total construction budget, highlighting the significance of the employed optimisation strategy (see Fig. 4).

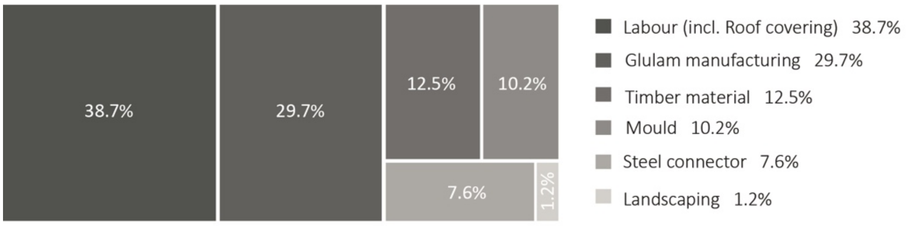

Figure 4. Construction cost break down

3.4. STRATEGIC DETAILING

To allow for the easy connection with the roof floor, the suspended beams were rounded at the top to provide for a connection point regardless of the angle between the beams and the roof surface. Steel connection details were optimised for ease of fabrication and minimal onsite installation complexity. A parametric model allowed incorporating the connection's geometric variations along the ring beams (see Fig. 5).

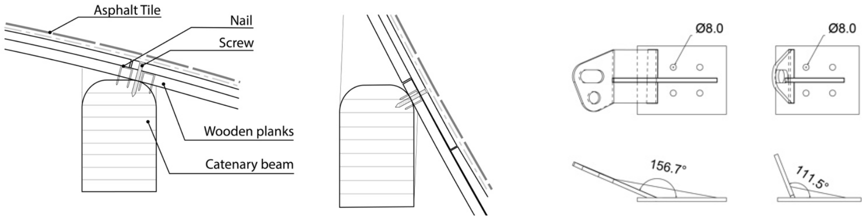

Figure 5. a) Roof floor to beam connection detail at high point and low point; b) Parametric connection detail design

4. PRE-FABRICATION

4.1. JIG SETUP

Rather than relying on fully computer-numerically-controlled (CNC) jigs, which are rare in most construction contexts, this project used more common and traditional means to produce its curved glulam elements (see Fig. 6a). The wooden jig, measuring 6.6m x 1.3m, had its base template geometry crafted from plywood using a 3-axis CNC milling machine. This was placed inside a series of wooden pressure vices made from wood blocks and steel bars with nuts and bolts on both ends. Reference markings denoting start- and endpoints of each glulam beam were marked on top (see Fig. 6b).

Figure 6. a) Wooden jig, b) Marking of end points of individual beams

4.2. TIMBER PREPARATION

All beams were fabricated by laminating layers of 10mm thick Japanese cedar in between which polyurethane adhesive was manually applied. Layers of wooden planks were then pushed towards the wooden jig and immediately pressed with a series of high-pressure vices (see Fig. 7).

Figure 7. a) Manual application of polyurethane adhesive, b) Layers of Japanese cedar are manually pressed into the jig, c) High-pressure vices are used to clamp the geometry

Upon drying of the adhesive, individual beams were sanded to eliminate any superfluous adhesive and to ensure correct beam widths. Since all beams followed only two-dimensional curvature, they could easily be inserted into standard sanding machines. Subsequently, slots and holes for the connectors were manually incised into the beams following fabrication drawings. A protective coating was applied to the wood surfaces to avert potential termite and mould infestations, as well as to confer weatherproofing properties (see Fig. 8).

Figure 8. a) Ring beam prior to sanding, b) Ring beams with steel plate slots, c) Catenary beams with rounded top profile

4.3. METAL CONNECTOR FABRICATION

Simultaneously to the wooden elements, the metal connectors were fabricated from 5mm thick steel plates parts that were laser-jet cut following parametrically generated production drawings, point-welded, and coated with protective metal spray paint (see Fig. 9).

Figure 9. a) Prefabricated steel connectors, b) Installed steel connectors

5. INSTALLATION

5.1. MAIN STRUCTURE

A mock assembly was conducted adjacent to the wood factory to ensure precision and ease of installation of each element and to test the proposed installation sequence at full scale. Step one was connecting the ring beam halves on the ground to form the two symmetrical ring beams. These were then loosely secured to the bottom metal hinge joint using nuts and bolts that allowed rotational movement. Prior to lifting the ring beams, steel connectors were affixed in accordance with the markings pre-applied in the factory. Then, the first ring beam was lifted to the desired height and temporarily held in place by a steel pole at the lower end (see Fig. 10a). At first, only two suspended catenary beams were connected to both ring beams to lock in their intended height. Then, the remaining beams were installed to solidify the whole. The entire assembly process was completed within 2.5 hours.

Following dismantling and packaging, which was made easy due to the planarity of all the elements, the components were trucked to the site, where the foundations had been cast ahead of time. There, the main structure was assembled and fully anchored within 3 hours (see Fig. 10b).

Figure 10. a) Mock assembly, b) Onsite assembly

5.2. ROOF FLOOR INSTALLATION

The wooden roof floor shell was fabricated using 6mm x 90mm wooden planks, which were bent directly onto the catenary beams and affixed first by nails and then screws. A pre-designed plank pattern was developed to guide their installation, which needed to follow geodesic curvature lines to remove bending outside of the plane of the planks. Onsite notation of this pattern was done using long paper strips with black and white marks indicating planks position and required gaps (Figure 11). A second layer of planks was added to strengthen the whole and to seal gaps of the first layer.

Figure. 11 a) Wooden plank nailing, b) In-situ plank trimming, c) Reference guides for plank pattern

5.3. ROOF TILING

A layered weatherproofing was applied on top of the wooden roof floor consisting of a waterproof membrane and asphalt tiles. The membrane is a self-sealing water barrier composed of a thin asphalt sheet, whose pliability allows it to conform to the curvature of the wooden roof. Subsequently, asphalt tiles were secured atop the water barrier layer, adhering to a predetermined pattern designed based on rainwater flow directions (see Fig. 12a). A metal edge profile, made from 30cm-long aluminium-zinc coated steel sheet segments, protects the ring beams and serves as a safeguard against rainwater dripping from the wooden surface (see Fig. 12b).

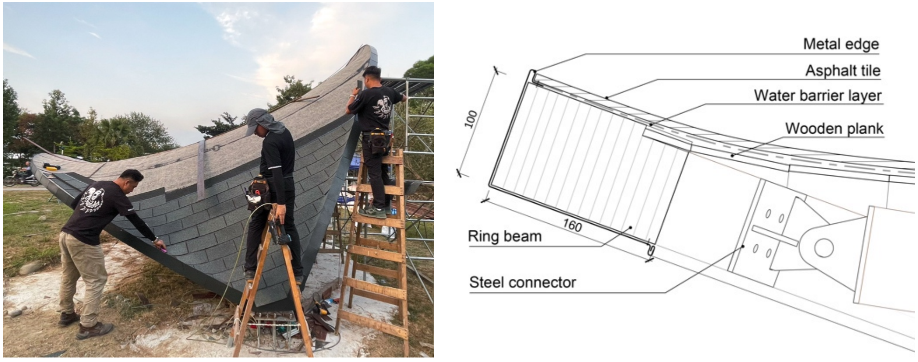

Figure 12. a) Installation of metal edge profile, water barrier and asphalt tiles, b) Sectional drawing of ring beam edge profile

6. DISCUSSION

The prototype was successfully installed as a demonstrator confirming the validity of the concept the research project set out to proof. Simultaneously, it identified issues that present opportunities for future improvement. One such issue related to the rounding of the catenary beam's top surface sections for connection with the roof floor, which resulted in aesthetically too large gaps between the roof floor and the beams on one side at points with steeper slopes. These were resolved by adding narrow wooden strips to conceal the space (see Fig. 13a). Another involved the pre-designed curved plank pattern, which proved challenging during construction, in part, due to the stifferthan-anticipated wooden planks. This was resolved by locally faceting the roof's otherwise smooth surface in segments in the areas of highest curvature, resulting in a slightly visible seam lines and a flat area near the lowest point of the central pair of catenary beams (see Fig. 13b).

Figure 13. a) Sealing of gap between catenary beam and roof planks, b) Discretising the area of highest curvature.

7. CONCLUSION

As global interest in environmentally sustainable modes of construction increases, novel methods are required that allow for the qualitative expansion of their architectural design solution space without increasing construction cost or complexity. KATENARA showcases the design potential evolutionary algorithms and catenary-based tectonic systems bring to common practice, paving the way for spatially innovative future building designs, especially in low-tech or developing construction context (see Fig. 14).

Figure 14. KATENARA during winter solstice sunrise

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