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Design of Bamboo-Steel Hybrid Spacial Truss Roof for a Utility Facility

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ABSTRACT

This paper reports the design and construction of a relatively large scale bamboo and steel hybrid spatial truss for covering the roof of a utility facility. The hybrid truss was invented by the last two authors with pyramid configurations of glubam (glued laminated bamboo) upper chords, web elements, and steel pipe lower chords. The paper describes the details of the design and analyses and provides an update about the construction.

1. INTRODUCTION

Bamboo is a green material that is gaining more and more attention in the current worldwide trend towards sustainable development. Though having been used by mankind for thousands of years, bamboo is not fully explored in the construction of modern buildings and bridge structures. The last author's group has been working on modern bamboo structures for the last two decades. Targeting as a substitute for wood-based glubam, or glued and laminated lumber, the last author has developed glued laminated bamboo, glubam. Studies are also carried out on the performance of a glubam-steel hybrid spatial truss system. Test results show that this type of truss has high structural bearing capacity. This paper presents a design case of a bamboo-steel hybrid spatial truss, acting as a shield for a waste treatment and management facility.

2. OVERVIEW

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The building is located at the northeast corner of the international campus of Zhejiang University in Haining city, Zhejiang province, as a waste gathering, treatment, and transfer center. Fig.1 shows the plan and the perspective view of the facility designed by a team led by Prof. Lao, of the Zhejiang University Design Institute. The authors are responsible to collaborate with the architect to optimize the structural system, providing the design of the bamboo-steel truss.

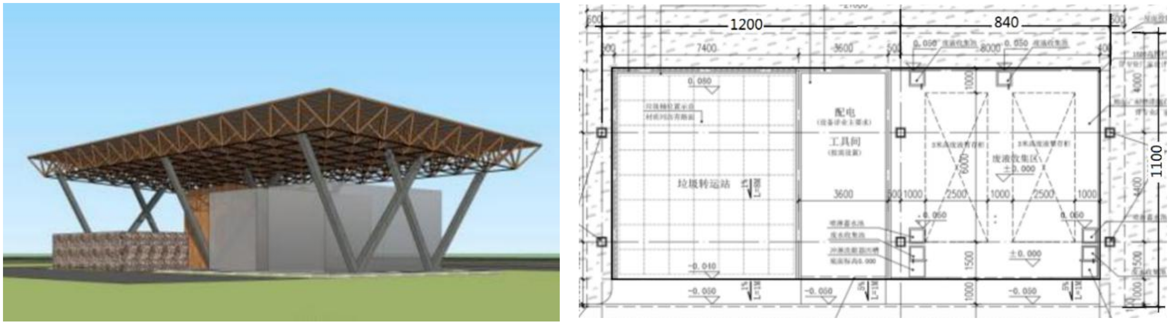

Fig.1 Plan and perspective view of the waste management center

3. STRUCTUAL DESIGN

As shown in Fig.2, the structural system consists of three W-shape steel frames that are bolted to the independent concrete foundations, through anchoring bolts. The bamboo-steel spatial truss system is supported on the W-shape frame with pinned and roller connections. On top of the bamboo-steel truss, light-gauge steel roofing panels are connected.

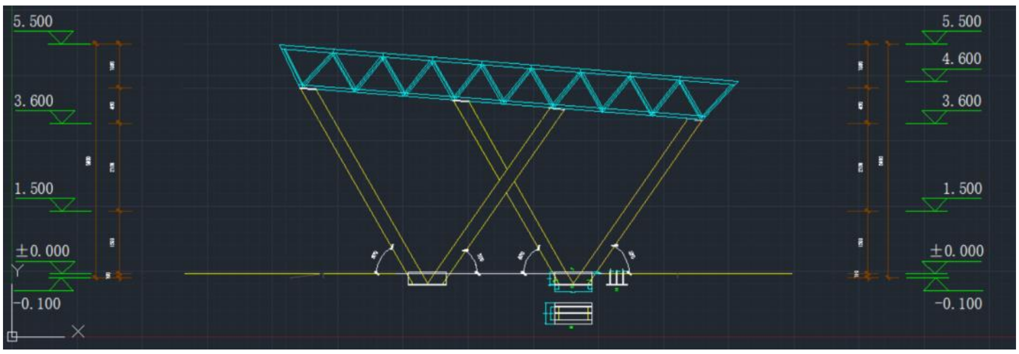

Fig.2 Steel frame and bamboo-steel upper truss.

3.1 General requirements

Referring to Chinese Code, GB 50009-2012 Code for Load of Building Structures, the standard value of the live load of non-human roofs is 0.5kN /m^2, basic wind pressure 0.45kN /m^2, basic snow pressure 0.45kN /m^2, basic air temperature minimum of -4 ℃, maximum of 38℃ (referring to Hangzhou, take the 50-year recurrence period). The seismic fortification intensity is 6 degrees. In the first group, the designed basic acceleration is 0.05g.

3.2 Bamboo-Steel Hybrid Spatial Truss Design

The roof has an overall plan of 21m * 11m, as shown in Fig. 3. The main unit of the top trusses is a rectangular square pyramid space truss, with glubam material for the upper chord, web elements, and steel pipe for the lower chord. Fig.4 shows an example of the bamboo-steel hybrid spatial truss system. All the connecting parts are specially designed steel brackets. On the premise of considering the structural performance and manufacturing efficiency, the dimension of the element is optimized by adopting the combination of the upper chord of various dimensions (length and thickness) to improve the mechanical performance of the trusses and reduce the difficulty of its installation and maintenance as well. Besides, considering the wind load and snow load, the top trusses are designed to be thinner and inclined to enhance its resistance.

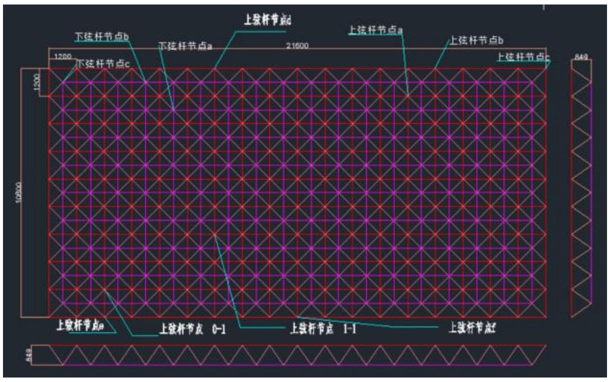

Fig.3 Plan of the bamboo-steel truss

Fig.4 Bamboo-steel truss[1]

(1) Material

The glubam is a thin-strip form with a density of 850.7kg /m^3. Mechanical properties have been given in Xiao et al., Wu and Xiao. Table 1 provides the typical dimension chosen for the roof truss.

Table 1 Dimensions of structural elements

	Sectional dimension	Length	Material	Mass
Upper chord (not mid-span)	56 mm×56 mm	1200 mm	glubam	2.83 kg per bar
Upper chord (mid-span)	56 mm×112 mm	1200 mm	glubam	5.66 kg per bar
Diagonal bar	56 mm×56 mm	1200 mm	glubam	2.83 kg per bar
Lower chord	φ42 mm×4 mm	1200 mm	Q345 steel tube	4.28 kg per bar

(2) Load combination and calculation

To make calculation easier, we use a simplified equivalent truss model, as shown in Fig.5. The consideration and calculation of the dead load is shown Table 2. For the simplified model, the dead weight is approximately 69kN, the upper chord plane area is 142.56m^2, and the constant load is 0.49kN /m^2. The live load and the combination coefficients are shown in Table 2. The most adverse load combination calculation:

(2.1) Ultimate limit state

Combination controlled by variable load: 1.2 * constant load + 1.4 * live load of roof + 1.4 * 0.7 * snow load = 1.2 * 0.49 + 1.4 * 0.5 + 1.4 * 0.7 * 0.45 = 1.73kN /m^2 (for the bearing capacity)

Combination controlled by permanent load: 1.35 * constant load + 1.4 * 0.7 * roof live load + 1.4 * 0.7 * snow load = 1.35 * 0.49 + 1.4 * 0.7 * 0.5 + 1.4 * 0.7 * 0.45 = 1.60kN /m^2

(2.2) Extreme state in normal use

Combination of nominal load: Constant load + roof live load + 0.7 * snow load = 0.49 + 0.50 + 0.7 * 0.45 = 1.305kN /m^2. (For checking deformation)

Combination of frequent load:Dead load + 0.6 * snow load = 0.49 + 0.6 * 0.45 = 0.76kN /m^2

Combination of Quasi-permanent load: Dead load = 0.49kN /m^2.

Table 2. Dead load of members

Type	Number	Mass	Total mass
Upper chord (not mid-span)	188	2.83 kg per bar	616.94 kg
Upper chord (mid-span)	30	5.66 kg per bar	169.80 kg
Diagonal bar	396	2.83 kg per bar	1120.68 kg
Lower chord	178	4.28 kg per bar	761.84 kg
Upper chord node	120	12 kg per node	1440.00 kg
Lower chord node	99	8 kg per node	792.00 kg
Roof	142.56 m^2	14 kg/m^2	1995.84 kg
Total mass			6897.1 kg

Table 3. Combination coefficient

Load type	Load standard value	Combination value coefficient φc	Frequency encounter coefficient φf	Quasi-permanent coefficient φq
Live load of roof	0.50 kN/m^2	0.7	0.5	0.0
Wind load	-0.27 kN/m^2	0.6	0.4	0.0
Snow load	0.45 kN/m^2	0.7	0.6	0.0

(3) Modeling and Analysis of Bamboo-Steel Truss

As shown in the Fig. 5, the supports are distributed on both sides of the long span of the grid frame, with fixed hinge supports on one side and rolling hinge supports on the other side. The span between supports is 12m. In the calculation of the structure, the load on the uniform surface is converted to node load for load checking, and all load on the upper chord plane. The middle member of the upper chord span of the grid frame (the thick member added in the figure) is 56 mm * 112 mm, that is, it is composed of two 56 mm * 56 mm members. The rest of the upper chord members are 56 mm * 56 mm.

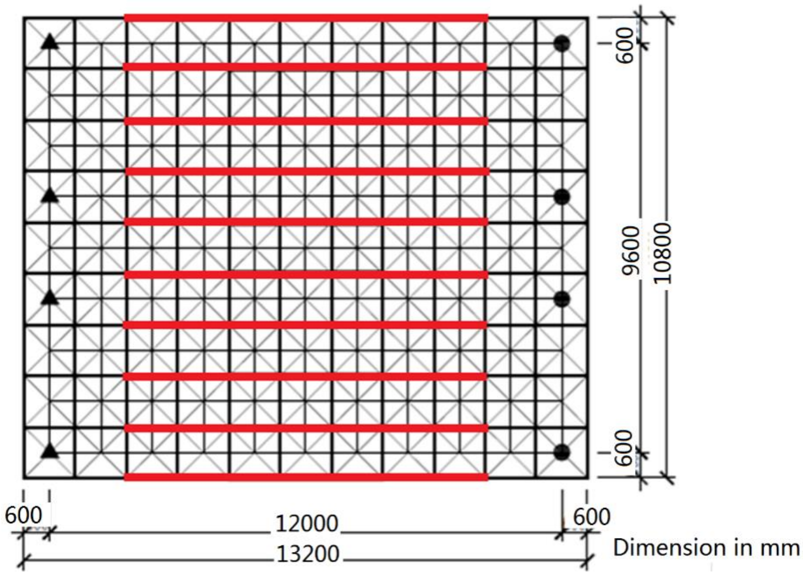

Fig.5 Analytical model for the longer span roof truss

When checking the load carrying capacity, the uniformly distributed load of the roof was converted into node load, the load of the center node was 2.50kN (1.73kN /m^2 * 1.2m * 1.2m), the load of the edge node was 1.25kN (1.73kN /m^2 * 1.2m * 0.6m), and the load of the corner node was 0.63kN (1.73kN /m^2 * 0.6m * 0.6m).

During deformation checking, the load of the central node is 1.88kN (1.305kN /m2 * 1.2m * 1.2m), the load of the edge node is 0.94kN (1.305kN /m^2 * 1.2m * 0.6m), and the load of the corner node is 0.47kN (1.305kN /m^2 * 0.6m * 0.6m).

Using the software SAP2000, under the most unfavorable load combinations (not consider seismic load and temperature effects), the maximum pressure of the upper chord (mid-span) is obtained as 40.98kN and the maximum pressure of the upper chord (not mid-span) is 34.90kN. The maximum tension corresponding bar for bottom chord across inside span steel pipe and is equal to 49.86kN. The maximum pressure of the oblique ventral bar is 19.12kN and the maximum mid-span deformation was 19.74mm.

(4) Component Check

Since the glubam is a new material which has not been fully specified in design codes, the timber design code is followed[i].

(4.1) Check calculation of upper chord compression rod (56 mm×56 mm)

Slenderness ratio: $\lambda = \frac{l}{i} = \frac{1200}{\sqrt{\frac{\frac{1}{12}\times 56\times 56^3}{56\times 56}}} = 74.23$

Stable bearing capacity under compression：

$F = \varphi f_c A = 0.43\times 26.75\times 56\times 56 = 36.07kN > 34.90kN$ (Refer to the design specification of wooden structure, set φ equals to 26.75kN /m^2)

Therefore, the designed bearing capacity of glubam rod is 36.07kN, which is greater than the maximum pressure of the compression rod, and the empirical calculation member meets the design requirements.

(4.2) Check calculation of upper chord compression rod (56 mm×112 mm)

Slenderness ratio: $\lambda = \frac{l}{i} = \frac{1200}{\sqrt{\frac{\frac{1}{12}\times 112\times 56^3}{56\times 112}}} = 74.23$

Stable bearing capacity under compression：

$F = \varphi f_c A = 0.43\times 26.75\times 56\times 112 = 72.14kN > 40.98kN$

(Refer to the design specification of wooden structure, set φ equals to 26.75kN /m^2)

Therefore, the designed bearing capacity of glubam rod is 72.14kN, which is greater than the maximum pressure of the compression rod, and the empirical calculation member meets the design requirements.

(4.3) Lower chord pole

Stable bearing capacity under compression：

$F = f_t A = 345\times 478 = 164.91kN > 49.86kN$

Therefore, the tensile bearing capacity of the lower chord steel tube is 164.91kN, which is greater than the maximum tensile force of the tensile rod, and the empirical calculation member meets the design requirements.

3.3 Support structure

The type of the inclined support structure is designed as a W-shaped steel column structure, which is welded by hollow square tubes of five different sizes (as shown in Fig.2). The upper ends of columns are connected to the upper trusses by four connecting plates, and the lower ends of columns are fixed to the concrete foundation with threaded bar anchorage.

The design code of the structure is seismic code GB50001-2018.

(1) The length of the column is 5m.

(2) According to seismic code 8.1.3, Haining city belongs to 7 degrees and is classified as the fourth type of buildings.

(3) According to seismic code 8.3.1, the section fineness ratio should not be greater than $120\sqrt{\frac{235}{f_{ay}}}$, according to Q345 Steel Specification take $f_{ay} = 99$, therefore

$b \geq 126.26mm$. (Box section radius of rotation is 0.4b)

(4) According to seismic code 8.3.2, width to thickness ratio limit should less than $75\sqrt{\frac{235}{f_{ay}}} = 61.89$ and less than $85\text{-}\frac{120N_b}{Af}$

The columns are chosen with a box section with $b = 300mm,\ t = 12mm$, which is sufficient compared with the code requirements. The SAP model is established for the overall structural system, as shown in Fig.6. Based on the analysis, the columns have a safety factor of 5.48.

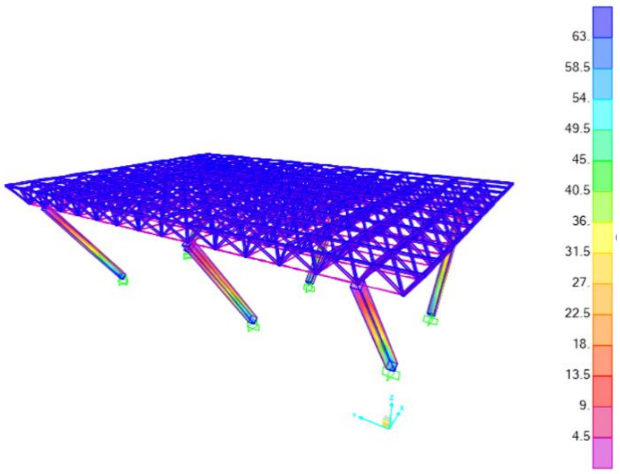

Fig.6 Structural system model

3.4 Foundation

The base connections of the columns are designed as fixed ends with bolted end plates of 900 x 500 x 20 (mm) and vertical stiffener plates. As shown in Fig.7, in these three vertical plates, the mid plate is designed to insert in the two inclined columns and two side plates are used as splints to hold the columns in place. The connection type of plate-to-plate and plate-to-column is welding.

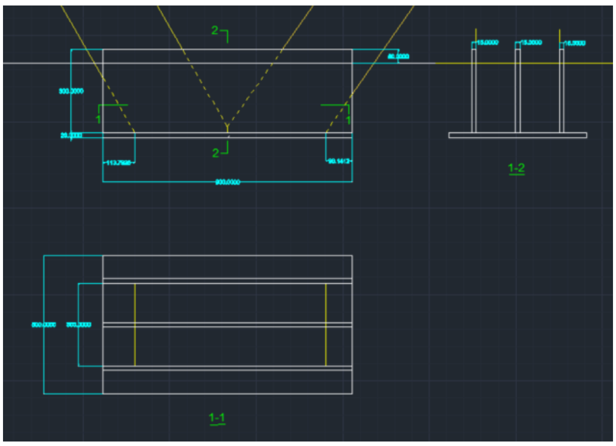

Fig.7 Column base

4. CONCLUDING REMARKS AND CONSTRUCTION UPDATE

As a case study, the design of a building with W-shape steel frames and bamboo-steel hybrid truss roof structure is introduced in this paper. Currently, the construction of the building is underway, though with some delay due to the rainy season. Fig.8 presents some photos of the current stage of the building.

(a) (b)

Fig.8 Construction update: (a) steel frame; (b) bamboo-steel truss assembling on ground.

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