

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 glulam 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.

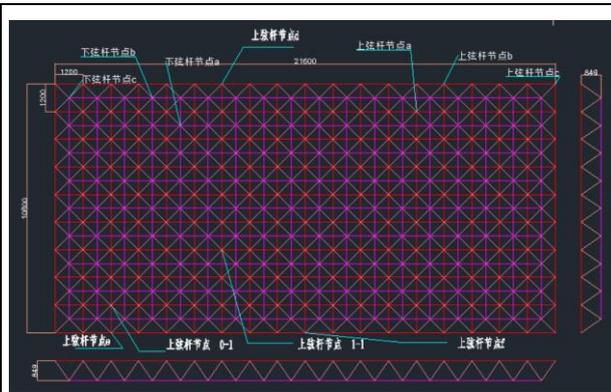


Fig.3 Plan of the bamboo-steel truss



Fig.4 Bamboo-steel truss¹

(1) Material

The glulam is a thin-strip form with a density of 850.7kg /m³. 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	glulam	2.83 kg per bar
Upper chord (mid-span)	56 mm×112 mm	1200 mm	glulam	5.66 kg per bar
Diagonal bar	56 mm×56 mm	1200 mm	glulam	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

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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 142.56m², and the constant load is 0.49kN /m². 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: $1.2 * \text{constant load} + 1.4 * \text{live load of roof} + 1.4 * 0.7 * \text{snow load} = 1.2 * 0.49 + 1.4 * 0.5 + 1.4 * 0.7 * 0.45 = 1.73\text{kN /m}^2$ (for the bearing capacity)

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

(2.2) Extreme state in normal use

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

Combination of frequent load: $\text{Dead load} + 0.6 * \text{snow load} = 0.49 + 0.6 * 0.45 = 0.76\text{kN /m}^2$

Combination of Quasi-permanent load: $\text{Dead load} = 0.49\text{kN /m}^2$.

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 φ_c	Frequency encounter coefficient φ_f	Quasi-permanent coefficient φ_q
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.

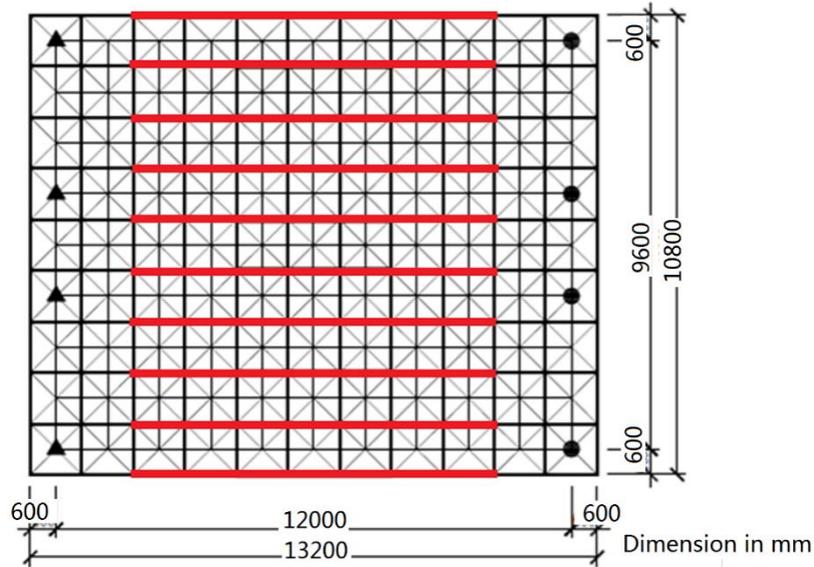


Fig.5 Analytical model for the longer span roof truss

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 ($1.73\text{kN}/\text{m}^2 * 1.2\text{m} * 1.2\text{m}$), the load of the edge node was 1.25kN ($1.73\text{kN}/\text{m}^2 * 1.2\text{m} * 0.6\text{m}$), and the load of the corner node was 0.63kN ($1.73\text{kN}/\text{m}^2 * 0.6\text{m} * 0.6\text{m}$).

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

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 glulam is a new material which has not been fully specified in design codes, the timber design code is followed¹.

(4.1) Check calculation of upper chord compression rod (56 mmx56 mm)

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

Stable bearing capacity under compression:

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

Therefore, the designed bearing capacity of glulam 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)

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

Stable bearing capacity under compression:

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

(Refer to the design specification of wooden structure, set φ equals to 26.75kN/m²)

Therefore, the designed bearing capacity of glulam 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:

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

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

$$75 \sqrt{\frac{235}{f_{ay}}} = 61.89 \text{ and less than } 85 - \frac{120N_b}{Af}$$

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.

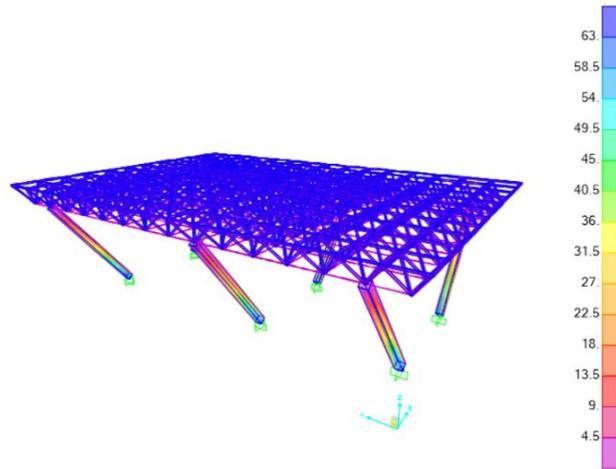


Fig.6 Structural system model

3.4 Foundation

The base connections of the columns are designed as fixed ends with bolted end plates of $900 \times 500 \times 20$ (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.

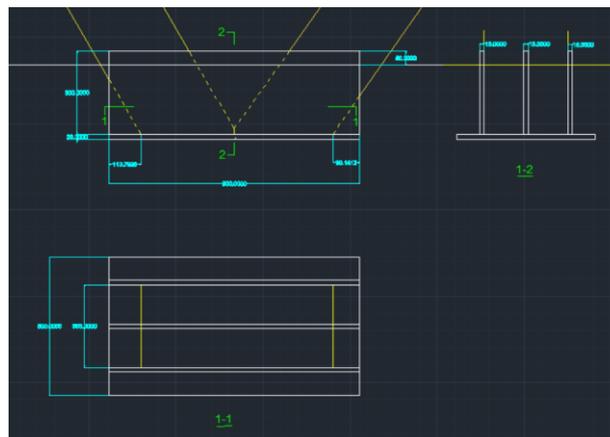


Fig.7 Column base

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.



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

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REFERENCES

- Y. Xiao.; Shan, B.; Chen, G.; Zhou, Q.; and She, L.Y. (2008), "Development of A New Type of Glulam – GluBam," *Modern Bamboo Structures*, Xiao et al. edited, CRC Press, UK, 299p.
- Y. Xiao, Q. Zhou, and B. Shan (2010). Design and construction of modern bamboo bridges. *Journal of Bridge Engineering*, 15(5):533–541, 2010.
- Y. Wu, Y. Xiao, (2018) "Steel and glulam hybrid space truss," *Engineering Structures*, 171, 140-151.
- Xiao, Y.; Yang, R.Z.; and Shan, B., "Production, Environmental Impact and Mechanical Properties of Glulam," *Journal of Construction and Building Materials*, Vol. 44 (2013) 765–773.
- GB50005-2017. (2017). Code for design of timber structures. Beijing: China Building Industry Press (in Chinese).