Design and modeling of towering tower structures considering horizontal vibration

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Abstracts: *This document describes in detail the design and modeling scheme of the towering tower structure in the seventh national college students' structural design competition in Hebei Province. For the towering tower structure with horizontal vibration, this paper firstly interprets the competition problem and clarifies the design requirements and loading conditions, including three levels of loading: horizontally excited vibration, hydrostatic calm load and horizontally excited vibration of higher frequency and amplitude. Subsequently, the final model scheme was optimized and determined through material performance testing, component design and testing, structural modeling and analysis. In terms of materials, bamboo veneer and bamboo strips were used as the main materials in this paper, and their mechanical properties were tested in detail. The structure was modeled and analyzed by Midas finite element software, and the strength, stiffness and stability of the structure were comprehensively evaluated. During the modeling process, the focus was placed on the connection method of nodes, material treatment and detail construction to ensure that the model can safely carry and meet the design requirements during actual loading. After several rounds of design optimization and loading tests, the model of the towering tower structure in the form of truss structure is finally determined, and the model shows good force performance and load carrying capacity at all levels of loading conditions. The whole process of model design, fabrication and testing is recorded in detail in this paper, which provides valuable experience for the design of similar structures.*

Keywords: *towering tower structure, horizontal vibration, structural design, finite element analysis, modal analysis*

1. Program conceptualization

1.1 Interpretation of the competition questions

The competition is entitled Design and Modeling of Tower Structures Considering Horizontal Vibration, which takes the tower structure as the basic unit and conducts force analysis, structural design, modeling and loading test for the complex working conditions of horizontal load, vertical load and horizontal vibration. The three levels of loads are horizontal excitation vibration, water calming load, and horizontal excitation vibration of higher frequency and amplitude, which require the designed tower structure to have good load carrying capacity and at the same time can withstand the horizontal loads and horizontal vibration, in addition to the actual use of the model and the appearance of the model are also taken into account.

According to the requirements of the competition, the group conducted a series of intense and orderly experiments to explore and analyze: firstly, the performance of the material was analyzed, and the self-resonance frequency of the bamboo model was determined to avoid the resonance region as much as possible, to make a preliminary design model, and through a series of experiments and calculations, a reasonable structural model was selected, and finally a calculation manual was formed.

1.1.1 Basic Configuration of the Contest

Model structural form: towering tower structural model, the top of the tower is flat, the number of structural floors and forms are not limited.

Model size requirements: the tower outside the circumvention limit for the bottom diameter of 300mm, the tower inside the circumvention zone for the bottom diameter of 100mm, which means that the model outside the boundary size can not be greater than 300mm; in the height range of H-200, the inner boundary size can not be less than 100mm, and the model height can not exceed the specified height H, the height of the model in the competition before the drawing of lots to determine, for 800mm. The specific requirements are shown in Figure 1-1.

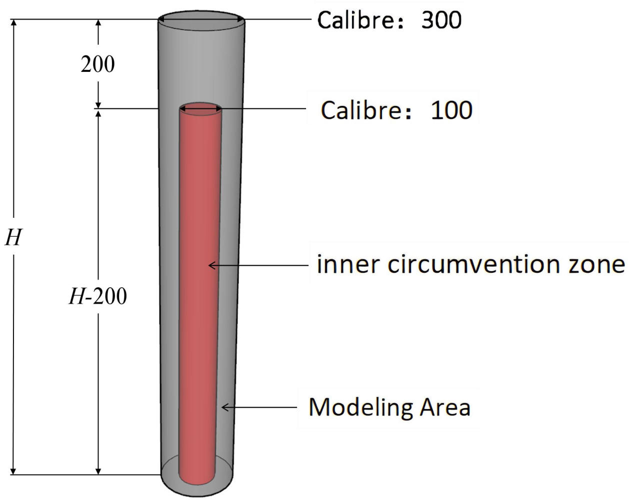


Figure 1-1 Model Size Requirements in the Competition

Materials: bamboo veneer, bamboo strips, glue, etc. The specifications of the main materials and the upper limit of usage are shown in Table 1-1. It is specifically stipulated in the competition that the model itself can only be made of the given bamboo material, and not of the given auxiliary materials, such as thick cardboard and non-woven fabrics in the paper veneer.

Table 1-1 Bamboo specification and upper limit of use

	Bamboo specification (unit: mm)	Bamboo Name	dosage
bamboo skin	1250 x 430 x 0.20 (+0.05)	Integrated bamboo sheet (single layer)	1 sheet
	1250 x 430 x 0.35 (+0.05)	Integrated bamboo sheet (double layer)	1 sheet
	1250 x 430 x 0.50 (+0.05)	Integrated bamboo sheet (double layer)	1 sheet
bamboo stick	930 x 6 x 1.0 (+0.5)	bamboo	20 roots.
	930 x 2 x 2.0 (+0.5)	bamboo	20 roots.
	930 x 3 x 3.0 (+0.5)	bamboo	20 roots.

Model column foot condition: the model is fixed to the model base plate of 15mm thickness by self-tapping screws and mounted in the specified parts, the specific connection method and parts are relevant requirements.

Loading devices: loading ropes, horizontal vibration exciters (shakers), weights, top mass systems, auxiliary pulleys, additional mass blocks, displacement measurement systems, loading auxiliary frames, etc.Calculation software: Midas

1.1.2 External load requirements

The applied loads of the structure are dynamic and static loads, which are divided into three levels, so as to examine the force performance of the model structure under the complex working conditions of horizontal load, vertical load and horizontal vibration. After the first level of loading is passed, the next level of loading can be carried out.

The first stage of loading was a horizontal excitation of the shaker, through which a unidirectional sinusoidal wave with a duration of 20 s was fed to the model. The frequency of the sinusoidal wave was determined by drawing lots before the competition and was 4 Hz; according to the supplemental notice of the competition question, it was known that the model's top mass system was 3 kg.

The second level of loading is water calming load, horizontal load is applied on the top of the structure, the direction of the load, which is determined by drawing lots after the model is finished and the dimensional check is passed, the size of the load is 6kg, and the duration of the horizontal load is more than 10s. The displacement limit of the model was determined by lot before the competition as 25mm.

The third level of loading was vibratory loading, in which a unidirectional sine wave with a duration of 20 s was input to the model via a shaker with a frequency of 3 Hz. For the third level of loading, the top mass of the structure had to be adjusted or not as determined by the team members prior to loading in the field.

1.1.3 Modeling

The production of the model requires the team to divide the work and work together, within the stipulated 12 hours, using the materials provided by the Organizing Committee of the competition, according to the pre-designed model of each team, according to the design of the processing and production. The Organizing Committee will provide a certain amount of raw materials during the production of the model, and no replacement materials will be given if the model is damaged due to the participating teams' own reasons.

Structural scoring is based on a total score of 100 points, which includes:

Theoretical program score: 5 points

Points for models made on site: 10 points

Points for live presentation and defense: 5 points

Loading Performance Score: 80

Among them, the loading results account for the main score, and if one of the following situations occurs during the loading process, the loading will be terminated, and the score for this and subsequent levels of loading will be zero:

If one of the following five conditions occurs during the loading process, it is determined that the loading is invalid, and the loading is terminated, and the loading at this level and the following levels are loaded.

A grade of zero:

There were non-equipment reasons for the second stage of loading that prevented the displacement meter from reading effectively, including a large difference between the height of the bottom of the top weight disk after installation and the required height of the top surface of the structure, H (800 mm);

During the loading process, the model exceeded the qualifying indicators for each level of loading requirements, including the overall tipping collapse of the model, the straightening of the protective ropes, and the model touching the loading frame;

The top weight disk or additional mass block fell off during loading;

Participants touch the model at a time other than the time of model adjustment before the third level of loading;

Other cases where the Group of Experts determines that loading cannot continue.

1.2 Programmatic comparison

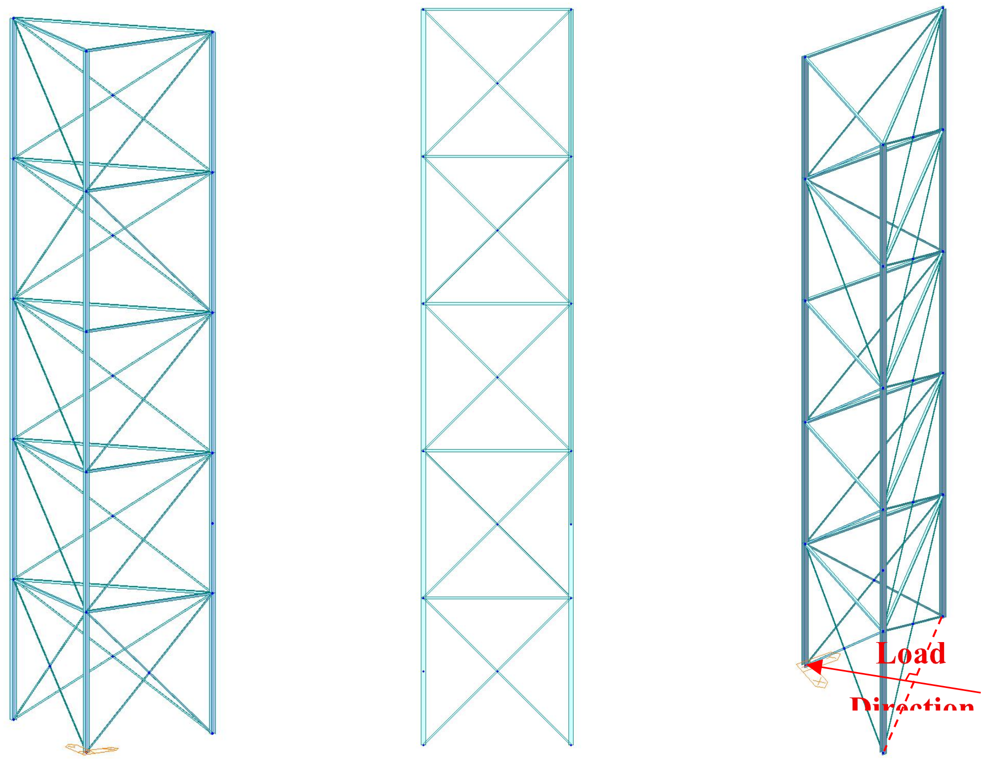
First of all, for the model design requirements, external load form, the given material, using bamboo strips and bamboo veneer as raw materials, according to the mechanical properties of the material: bamboo strips tensile capacity is about twice its compressive capacity, bamboo veneer can withstand larger tensile force, and the shortcomings of the bamboo strips is the bending capacity of the weak, so in the use of bamboo strips should be avoided as much as possible to appear "long and thin poles Therefore, the use of bamboo strips should avoid the "long thin poles" and focus on the problem of instability. Design race entitled towering structure, bear vertical load, horizontal load and vibration load, that is to say, the structure is required to have enough stiffness and deformation capacity, at the same time, the selection should be reasonable.

According to the competition question and actual theoretical analysis, it is known that the structure selection arrangement should adopt regular shape, symmetrical structural form, and clear structural form of force transmission system to avoid stress concentration and torsion effect. Therefore, according to the stress characteristics of the structure and the actual needs, our group firstly proposed three types of selection arrangements.

The first, isosceles triangle plan layout, vertical use of I-beam cross-section rods, horizontal use of box section rods, layer to layer using diagonal rods for fixing, the structural model is shown in Figure 1-2.

The advantage of this type of selection is that the plane layout is triangular, solid in the plane, stiffness, can provide a larger bearing capacity of bamboo are very high tensile and compressive strength, but the model for the towering structure, easy to pressure rod stabilization problems, can not give full play to the compressive capacity of bamboo, so in the static loading of the two vertical rods are subjected to tension, a compression, can give full play to its tensile strength, good lateral force resistance; at the same time, the quality of the At the same time, the quality is light and can be safely carried under the excitation of sinusoidal seismic wave.

The disadvantage is that the model requires a high level of production technology, and if there is a slight error, it will result in asymmetric structural form, which is easy to appear eccentric force under the action of load, resulting in structural damage. Especially under the vibration load, the production error will cause the structure to torsion effect is obvious, and the components are seriously damaged by torsion.



(a) 3D view (b) Side view (c) Loading direction

Figure 1-2 First Selection

The second is polygonal plan layout, the plan layout form used is hexagonal, six layers of transverse supports are set up along the height direction to increase the stiffness of the cross-section, diagonal rods are used to support between the layers, and box section supports are used on the top surface to increase the stiffness. As shown in Figure 1-3.

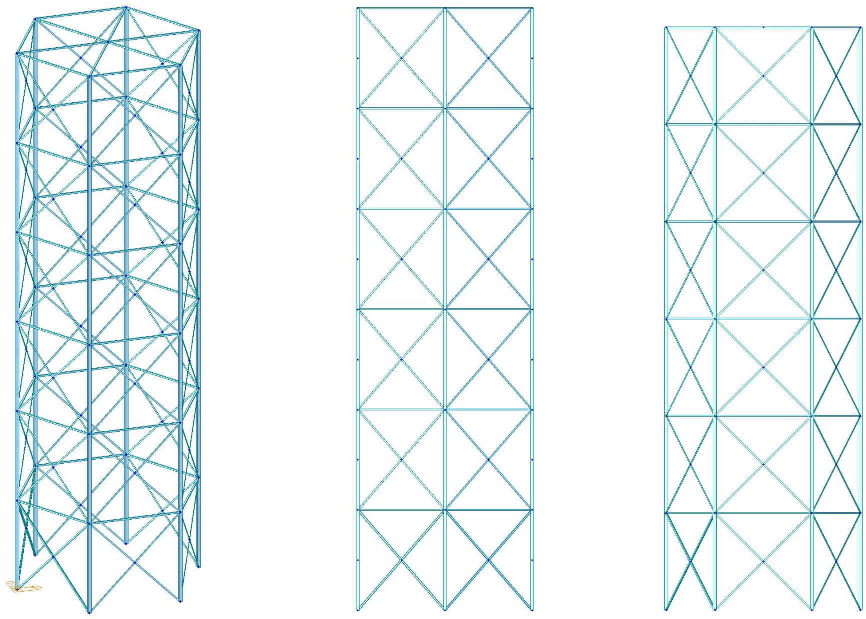
The advantage of this type of selection is that there are six loaded rods in the vertical direction, which can make the structure uniformly stressed, uniformly transfer loads, high redundancy in structural safety, more coordinated deformation under vibratory loads, and large flexibility. In addition, the structure is safe under secondary loads with large displacements.

The disadvantage is that the hexagonal plane stiffness is small, the production is more complex, the production process requirements are relatively high, the production error on the structure of the force has a greater impact on the force is likely to cause weak force, torsion effect; in addition, the structure of the self-weight will be relatively high.

The third rectangular cross-section arrangement. The plan layout form of the structure is rectangular, four columns are set up in the vertical direction to bear the vertical load, the bars are all symmetrically arranged, and 1-3 layers of transverse supports are set up along the height direction, with tie bars and tie rods set up between each layer. When bearing the top static load, two columns are subjected to tension and two columns are subjected to compression. As shown in Figure 1-4.

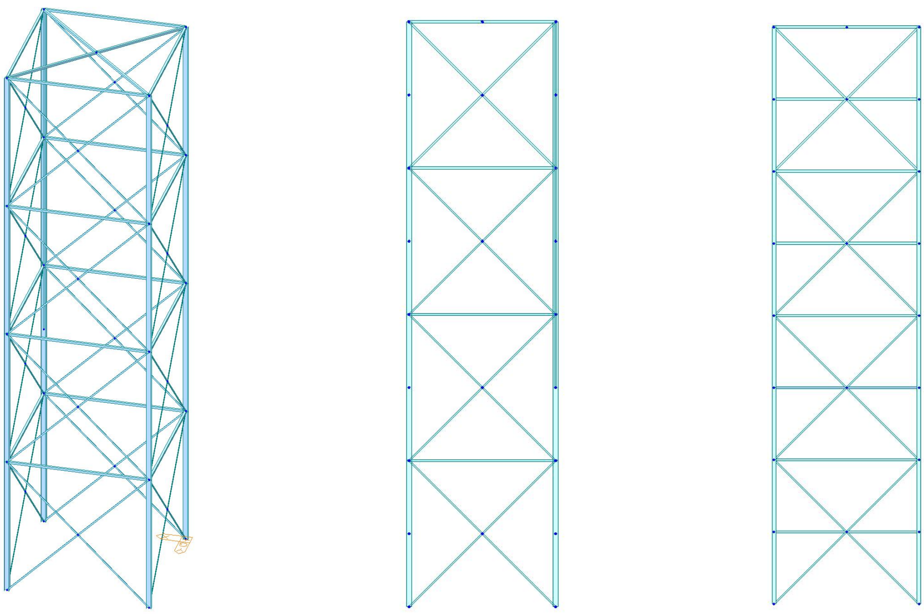
The advantage of this type of selection is that the structural plane stiffness is moderate, the structural arrangement is simple and regular, the force is uniform, the number of rods is moderate, and the production will not be too complicated. Under static and dynamic loads, the deformation is more uniform, basically no torsion effect, simple materials, easy to produce, and light weight.

The disadvantage is that if the structural form is not properly arranged, it is easy to produce excessive stiffness and small displacement under secondary loads, which requires repeated calculations and adjustments.



(a) 3D view (b) Side right view (c) Side left view

Figure 1-3 Second Selection



(a) 3D view (b) Side right view (c) Side left view

Figure 1-4 Third Selection

The actual material is abstracted into three mechanical models, i.e., bending member, axial compression member and tensile member, and the load is applied through Midas modeling to analyze the internal force, stress-strain, node displacement and other related mechanical characteristics, combined with the mechanical properties of the raw materials, to gradually improve the local structural combinations, so that the stresses and deformations can meet the requirements. Because the mechanical properties of the model under the same loading condition are obviously better than that of Model I, Model III is finally selected for model design and fabrication.

After that, the model was modified and optimized once again, and after many discussions, we came up with a model that meets the requirements of load-bearing capacity. On this basis, we shifted the focus of our thinking to reducing deadweight, saving materials, and structural form towards aesthetics and art. We optimize the model as much as possible to get the best design solution. Now the model is a truss structure, and the optimization process is as follows:

We first set up the I-beam bar at the bottom of the model, and set up the T-beam bar at the top of the model (the top 300mm is T-beam, the bottom 500mm is I-beam, all assembled with 0.8×6 bamboo pieces) to make a model with the bottom cross-section of 180×100, the top cross-section of 100×100, and the layer spacing from the bottom to the top of 250mm, 250mm, and 300mm, and after the The actual measurement of the first and third level of loading did not have problems, the second level of loading, the T-bar weak axis direction of buckling, after strengthening in the weak axis direction, the displacement reaches 13mm, the displacement is too small.

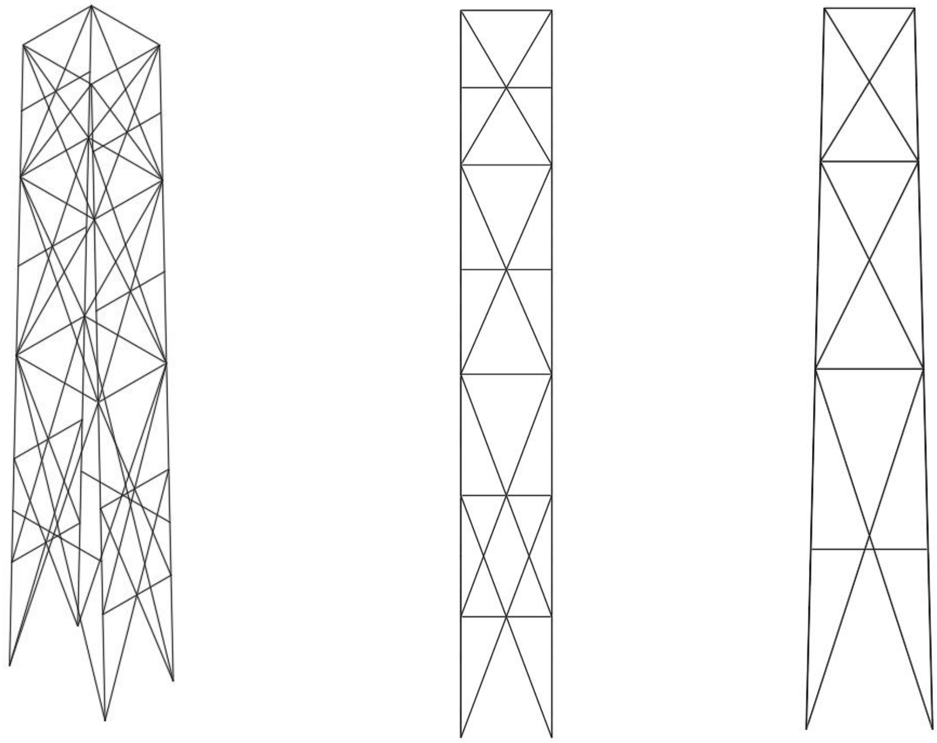
1.Further, in order to increase the secondary displacement under secondary loading and improve the problem of severe buckling in the weak axis direction of the structure, we reduce the bottom size of the structure from the original 180 × 100 mm to 160 × 100 mm cross-section, and at the same time, we reduce the moment of inertia of the bars in the loading direction by decreasing the width of the bar webs in order to achieve the effect of increasing the displacement. After the actual measurement, the model appeared obvious torsion when loading in the first stage, and finally the model was damaged under the vibration load in the first stage. After later analysis of the damaged rods, it was found that the top T-bars were prone to torsion, and the height of the top T-bars was 300 mm, which exacerbated the torsional effect of the structure.

2.In order to further reduce or eliminate the torsional effect, we optimized the top T-shaped vertical rod into an I-beam with gradually decreasing wing edge from bottom to top, gradually decreased the width of the wing plate on one side of the I-beam, and decreased the layer spacing at the top of the model and increased the layer spacing at the bottom of the model. Through simulation and actual testing, it was found that the improvement method was effective, but the displacement of the structure was still less than 20mm under secondary loading.

3.Under the premise of ensuring the safe bearing of the structure and increasing the displacement of the structure under secondary loading, we further optimized the model. The bottom section of the structure is reduced to 140×100mm, the width of the web of the vertical rod is increased to 0.8mm, the height of the section is reduced to 4.5mm, and the position of the tie bar is optimized so that it is fixed 20mm away from the node of intersection between the horizontal and vertical rods.The optimization scheme is effective through actual testing.

4.Final calculations and test results show that the model is able to safely carry the load at three levels of loading, while the weight of the structure is less.

The optimized structural model is shown in Figure 1-5



(a) 3D view (b) Side right view (c) Side left view

Figure 1-5 Optimized structural model

The following three structural design concepts were tried in order to design the structure to avoid the resonance cycle of an earthquake, while ensuring the strength, stiffness and stability of the structure.

1.By reviewing relevant data, analyzing the competition questions and studying the winning models of similar competitions in the past, we finally concluded that the convergent rectangular tower structure is the optimal solution and verified its performance by using midas software, and concluded that in terms of seismic performance, the convergent rectangular tower structure has better performance than the non-convergent tower structure and convergent square tower structure in terms of vibration resistance, stability, and dispersal of wind load method. tower structure.

2.The structure pursues a simple and clear structural form, which can maximize the performance of the material; and the structural design needs to be both rigid and flexible, interacting with each other, to ensure its load-bearing capacity and seismic capacity while reducing the self-weight.

3.Reduce the top acceleration by using some vibration-damping and energy-consuming constructions or seismic isolation measures in the basic structure.

2. Experimental aspects

2.1 Material testing

1.bamboo

The bamboo materials used in this competition are all natural color re-pressed bamboo veneer with three specifications: 1250 × 430 × 0.50mm, 1250 × 430 × 0.35mm and 1250 × 430 × 0.20mm, the bamboo material has a smooth grain and transverse grain, and its smooth grain mechanical properties are better, with a tensile strength of 60MPa, while the bamboo material's bending and shearing resistance is poor; in addition, its transverse grain Mechanical properties are poor. In the process of design and production, we should make full use of the tensile and compressive properties of bamboo smooth grain, and adopt the smooth grain in the main direction of force, while minimizing the damage to the bamboo fiber. Compared with other materials, the ductility of bamboo is better, so we also made full consideration in the design. The bamboo poles used in this competition are made of integrated bamboo material with three specifications: 930×6×1.0mm, 930×2×2.0mm and 930×3×3.0mm, with a density of 0.8 g/cm3, a tensile strength of 60 MPa in the smooth grain, a compressive strength of 30 MPa, and a modulus of elasticity of 6 GPa. Table 2-1 gives the upper limit of specifications and dosage of the materials used in the competition, and the model of the competition Table 2-1 gives the specification and upper limit of the material used in the competition, and the model of the competition needs to be selected and made according to this requirement.

Due to the discrete nature of the material of bamboo, in addition to referring to the specifications of bamboo and its material properties given in the competition question, the tensile properties of bamboo were tested briefly, as shown in Table 2-2. Since bamboo veneer cannot be subjected to compression and bamboo strips are mainly subjected to destabilization damage mode, the compressive strength of bamboo veneer and bamboo strips are no longer tested.

Table 2-1 Specification and upper limit of bamboo material usage

	Bamboo Specification	Bamboo Name	usage ceiling
bamboo skin	1250mm×430mm×0.20 mm	Integrated bamboo sheet (single layer)	2 sheets
	1250mm×430mm×0.35mm	Integrated bamboo sheet (double layer)	2 sheets
	1250mm×430mm×0.50mm	Integrated bamboo sheet (double layer)	2 sheets
bamboo shank	930mm×6mm×1.0mm	bamboo	Twenty.
	930mm×2mm×2.0mm	bamboo	Twenty.
	930mm x 3mm x 3.0 mm	bamboo	Twenty.

Table 2-2 Reference and Measured Mechanical Indexes of Bamboo Material

material (that sth is made of)	numerical value	Physical and mechanical properties			
		Density g/cm^3	Parallel grain tensile strength/MPa	Compressive strength/MPa	Modulus of elasticity/GPa
bamboo	theoretical value	0.8	60	30	6
Bamboo veneer 0.2mm	measured value	0.75	48	-	4.6
Bamboo veneer 0.35mm	measured value	0.83	64	-	5.3
Bamboo veneer 0.5mm	measured value	0.85	69	-	6.2
Bamboo strips 6 x 1 mm	measured value	0.85	68	-	6.5
Bamboo strips 2 x 2 mm	measured value	0.85	72	-	6.9

Bamboo strips 3 x 3 mm	measured value	0.85	75	-	7.1

Table 2-1 Bearing capacity of columns of different cross-sectional forms (39 cm length as an example)

	material (that sth is made of)					
	bamboo strips	bamboo skin			Bamboo Strips + Bamboo Veneer	
cross-section view						
carrying capacity	40kg	34kg	39kg	38kg	39kg	37kg
conduct oneself with dignity	11.5g	7.2g	7.4g	7.8g	9.5g	8.6g
vantage	High moment of inertia	Utilizing the tensile properties of bamboo veneer	good stability	High efficiency ratio	Utilizing the tensile properties of bamboo strips	Utilizing the tensile properties of bamboo veneer and bamboo strips
drawbacks	efficiency ratio is low	Weak-axis orientation is susceptible to instability	lack of rigidity	Highly discrete	efficiency ratio is low	Highly discrete

2.glue

The competition stipulates the use of 502 glue for the connection between the model structural components, and the amount and quality of glue applied directly affects the performance of the whole structure. Since 502 glue is very brittle, if a large amount of it is applied to the bamboo pieces, it will affect the ductility of the bamboo pieces and improve the quality, as well as affect the bonding of the joints. Therefore, the glue should be applied in small amount and evenly. In addition, the volatility and corrosiveness of 502 glue is strong, be careful when using it, and it should be pasted immediately after applying the glue, otherwise the bonding strength will be seriously affected.

3.Hot Melt Adhesives

Hot melt adhesive is used for fixing the top iron box with the model. According to the requirements of the competition, the top iron box falling off belongs to the structural damage, so it is significant to study the adhesive performance of hot melt adhesive. According to the experiments of our group, the hot melt adhesive has a better bonding effect with bamboo and water tanks, but the bonding effect with iron blocks is poorer, in the modeling, our group specially takes constructive measures to strengthen the connection between iron blocks and the model.

2.2 Component testing

Table 1-2 Model Component Dimensions and Illustrations

name (of a thing)	Pillar 1 (work-type cross-section)	Pillar 2 (tapering section)	first floor beam (T-section)	Intermediate floor beams	Upper middle and lower middle beams
illustrate					
Selection of bamboo materials	930×6×1.0mm	930×6×1.0mm	930×2×2mm	0.35mm thick bamboo veneer	930×3×3mm
sizes	Web 630×4.5×0.8, wing 630×6×0.7	Web: 170×4.5×0.8 Wing 1: 170 x 6 x 0.7, Wing 1: 170 x 3 x 0.7	100×2×2mm	120×4×0.35mm 100×4×0.35mm	108.5×3mm 100 x 3mm
quantities	4	4	4	4	4
name (of a thing)	Lower and middle horizontal support rods 1	Upper middle horizontal support bar 2	Diagonal bar 1	Slash 2	column foot
illustrate					
Selection of bamboo materials	930 x 2.5mm	930×2×2mm	930×3×3mm	930×2×2mm	930×6×1.0mm
sizes	100 x 2.5mm	100×2×2mm	3×0.5mm	2×0.5mm	20×1×0.5
quantities	4	4	4	24	4

With the same length, different cross sections will have different effects on the mechanical properties of the column, we tested the load carrying capacity and self-weight under different cross sections, and under the condition of ensuring the load carrying safety, structural stability, and seismic capacity, we choose the cross sectional form of the member with the lightest self-weight, and take the cross sectional form with a length of 39cm as an example, and the load carrying capacity of the different cross sectional forms is shown in Table 2-1.

On the basis of obtaining the material properties of bamboo, the finite element model analysis was carried out using Midas software to maximize the material properties of the components by setting up a reasonable structural system. In this process, no individual component testing was carried out, and the main purpose was to optimize each component through actual loading. The dimensions and illustrations of each member in the model are shown in Table 1-2.

2.3 Structural testing

According to the race question, the structural test loading system is shown in Figure 2-1.

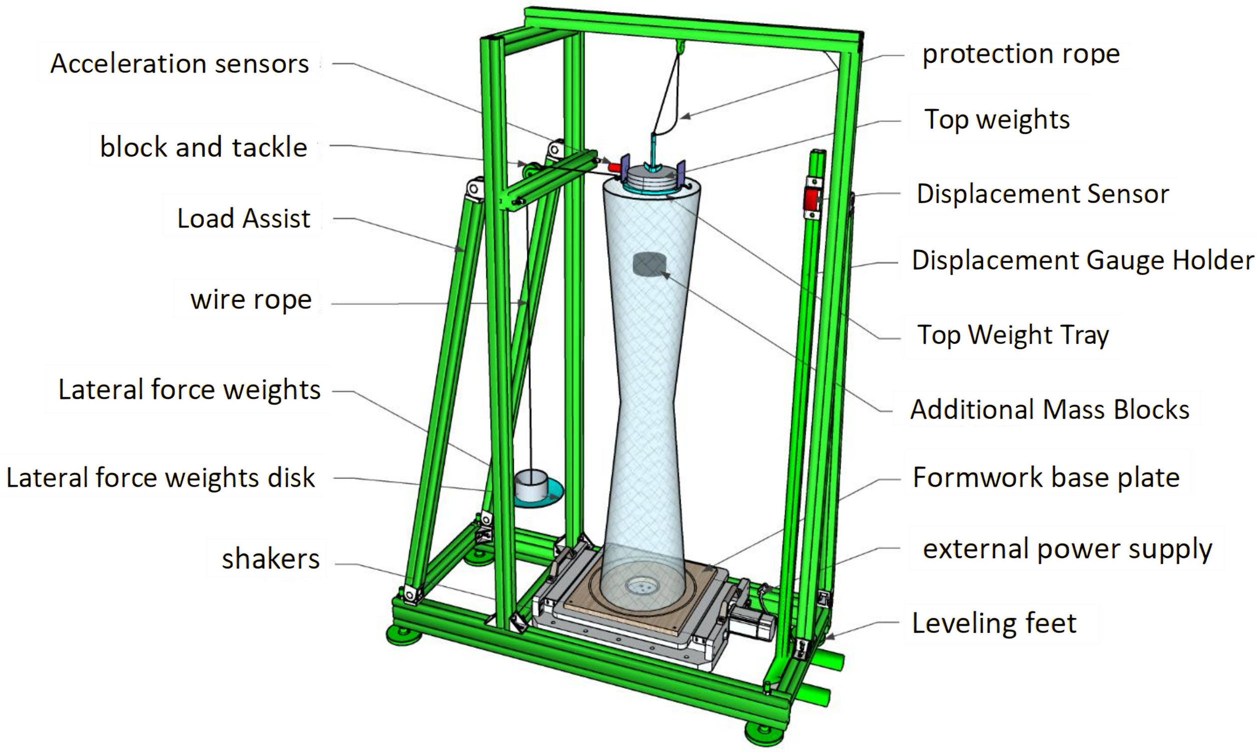


Figure 2-1 Loading Schematic

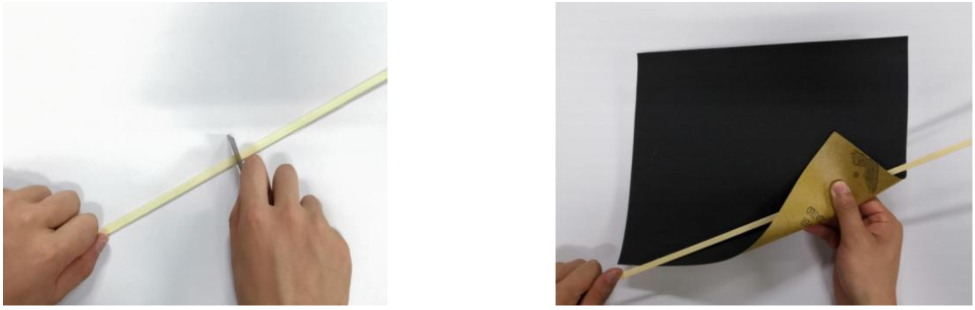
Then through the loading of the designed model, analyze its force characteristics, discuss and analyze the unreasonable local range of force, use different cross-section arrangement form and rod cross-section to make the local force of the structure more reasonable, the main investigation of the deformation of the structure, the displacement of nodes, structural components of the stress situation, which is the controlling strength index of the bamboo strips is the tensile performance and compressive properties, through multiple loading tests. The design scheme of the model is gradually improved through several loading tests and continuous optimization of the structural design.

2.4 Detailed construction

This model adopts truss structure form, node connection is the key and important part of this model, which is an important part to ensure the structural integrity and safety.

As there is a certain gap between the actual model nodes and the rigid nodes simulated by Midas, the node connection parts of the actual modeling need to be connected by glue and bamboo powder, which is more demanding for manual operation. If the amount of bamboo powder is not enough, it may cause the nodes to be not firmly connected, affecting the structural performance; if the amount is too much, it will increase the node stiffness, further increase the stiffness of the whole model, so that the model deformation will be reduced under the secondary loading, and at the same time, it will also increase the weight of the model. Therefore, when making the model, the team made a large number of models, and repeated simulation calculations and loading, to improve the accuracy of modeling, as far as possible to ensure that the strength of the node connections to meet the requirements, while controlling the quality of the model.

1.Material handling



(a) Thinning of bamboo poles (b) Sandpaper treatment

Figure 2-2 Material Handling

For weight reduction considerations, we need to thin the bamboo poles, using a hobby knife to scrape both sides of the bamboo material to reduce the weight of the structure, and then use sandpaper to finish its surface to ensure that its mechanical properties are uniform and reliable, as shown in Figure 2-2.

Figure 2-3 Node Connection Figure 2-4 Bamboo Patch Reinforcement

2.Node processing

Use glue to connect the nodes at the connection nodes of horizontal and vertical bars, and use bamboo powder to reinforce the nodes to prevent gluing. For the tensile bars and tie bars, the ends can be directly glued to the vertical bars; for the pressurized bars, the concentrated force is dispersed by covering the bamboo sheet at the pressurized position, as shown in Figure 2-3. For the existence of bamboo joints of the rod, easy to fracture at the bamboo joints, the formation of weak parts, so there are bamboo joints in the location of the paste one to two layers of 0.2mm bamboo skin for reinforcement, as shown in Figure 2-4.

3.Vertical rod connection

Model vertical bars, variable cross-section connection part of the extended bonding design to enhance the node stability, as shown in Figure 2-5.

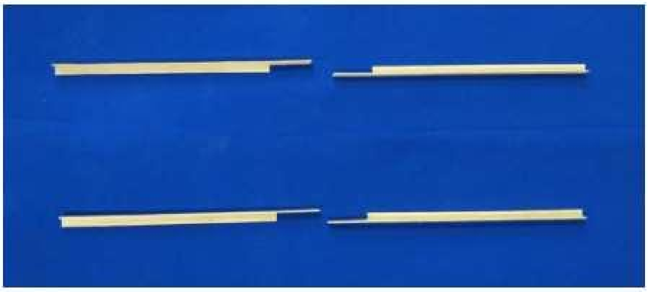


Figure 2-5 Variable Section Connection

4.Column foot connection

In order to prevent the destruction of the bottom of the column, the bottom section of the column needs a larger bonding surface, we used to expand the foot of the column to increase the contact area between the column and the bottom surface, and use screws to fix the connection between the foot of the column and the bottom plate, as shown in Figure 2-6.

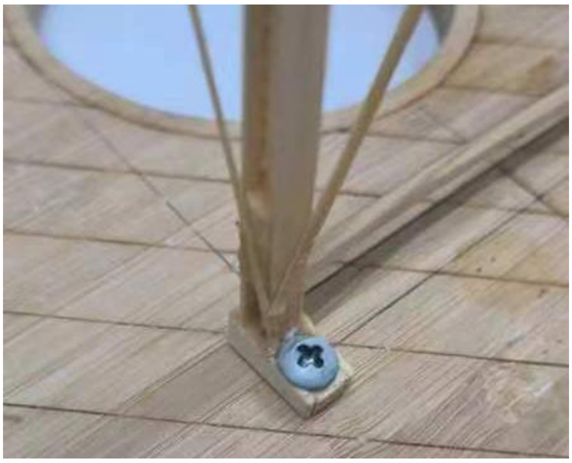


Figure 2-6 Leg Connection

3. Computational aspects

3.1 Modeling methodology

An analytical model of the structure was developed using the finite element analysis software Midas.

Theoretical mechanics, mechanics of materials, structural mechanics, finite elements and other knowledge are applied in the mechanical analysis of structural models to comprehensively analyze the strength, stiffness and stability of structures.

1.Strength analysis

We mainly use the knowledge of mechanics of materials to design the structural model and optimize and adjust the structure. The basic forms of deformation of structural bars include: axial tension and compression, and torsion. The strength calculation mainly includes stress calibration problems such as bending stress and shear stress. The bamboo material is used in the model, which has superior tensile and compressive properties. Moreover, this model is a truss structure, and the vertical rods mainly bear the role of internal forces such as tension, pressure, bending moment, etc. The other rods are basically tensile and compressive members, and they mainly bear the tension and pressure as the two-force rods. According to the calculation and analysis, the internal force of each member under different working loads is obtained, and it is examined whether each internal force is within the allowable range of material strength.

2.Stiffness analysis

Structural stiffness analysis to check the stiffness by calculating the deformation indexes such as positive strain and tangential strain of the members. According to the design strength of the materials used (stress strength conditions), the maximum displacement and maximum deformation that can be produced by the rod is calculated, so that the actual deformation produced by the member can be calculated according to the specific stress conditions during the actual stressing process of the rod, and the actual displacement of the structural member can be controlled within the corresponding range by designing and modifying the structural member when subjected to external loads.

3.stability analysis

Considering the small cross-sectional area of the structural member, its moment of inertia is small, resulting in small bending stiffness, and according to the "compression rod stability" problem, there are "slender rods", "large-kneed rods" and other poorly stabilized rods in the model, so for our model, the stability problem is the focus of the study. Therefore, for our model, the stability problem is the focus of research. The stability problem can be divided into the overall stability of the structure and the local stability of two parts, the overall stability refers to the gradual increase of the load, the original equilibrium state of the structure into an unstable state, which can be divided into two basic forms: the extreme point of instability and the branch point of instability. The local analysis is to analyze the specific compression member, which is the specific realization process of the overall stability analysis. Considering that what is studied is mainly a small displacement analysis, the branch point instability principle is adopted, based on Euler's instability theory. As for the elastic rod, which is an infinite degree of freedom problem when it is destabilized by pressure, its equilibrium equations are differential equations rather than algebraic equations, which are difficult to calculate by hand, and the number of rods and frames in the whole structure is relatively large. Therefore, we apply the advantage of computer and use finite element analysis method to analyze. Specifically, the buckling analysis function of Midas is used to realize the stability analysis of the model. From the stability theory, it is known that under the action of external load, if the rod is in equilibrium at this time, when the axial pressure on the rod is less than the critical load, the slight interference will occur bending, deviating from the original equilibrium state, when the interference disappears, the compression rod back to the original equilibrium state; when the axial pressure on the rod is equal to the critical load, the original equilibrium state is no longer the only state, and there will be two kinds of tendencies, when there is no interference, the member In the linear form of the equilibrium state, slight interference will occur bending, deviation from the original equilibrium state, when the interference disappears, the compression rod will not return to the original equilibrium state, but to maintain a slightly curved equilibrium state; in the extreme case, when the axial pressure on the rod is greater than the critical load, theoretically the rod can still be in the form of a straight line of the equilibrium state, is not stable equilibrium state, a slight interference will occur drastic bending The slightest disturbance will cause sharp bending and deformation, leading to damage. In Midas, by applying the corresponding vibration load, vertical static load and horizontal tensile force, the software simulation analysis is carried out.

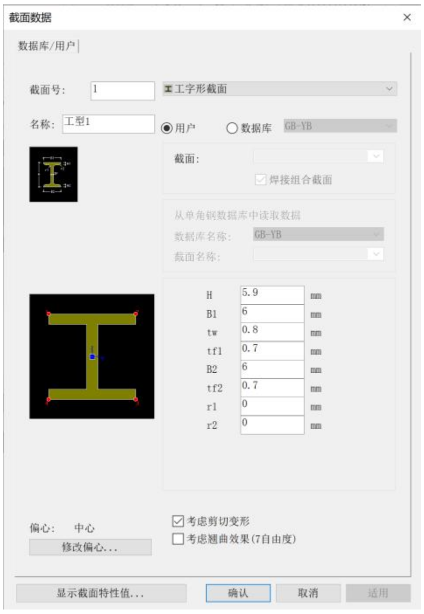
3.2 Modeling parameters

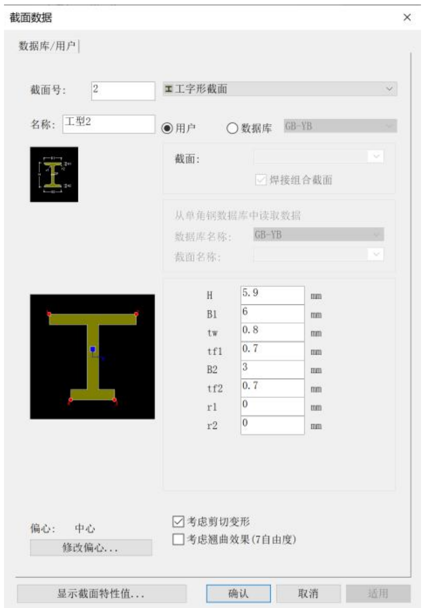
In the Midas modeling analysis, the main parameters were defined as follows:

1.Mechanical property parameters of the material used: the modulus of elasticity of bamboo is set to 6000 N/mm2. as shown in Figure 3-1.

Figure 3-1 Model Materiality Definition

2.There are various kinds of cross sections in this model, respectively, according to the actual model size, the corresponding cross sections are built in Midas. Among them, there are three kinds of I-beam sections, with specific dimensions and material properties such as material cross-section properties as shown in Figures 3-2 to 3-4. The I-beam sections with different cross-section sizes are arranged along the height so that the structure can be deformed in a coordinated manner with appropriate stiffness and flexibility to ensure that the strength of the structure in bending, compression, tension, etc. meets the requirements.





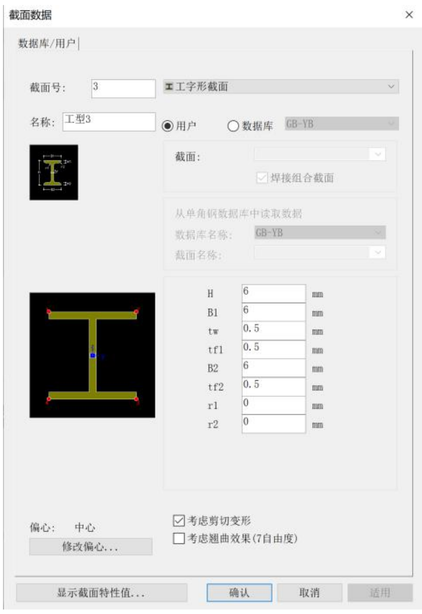
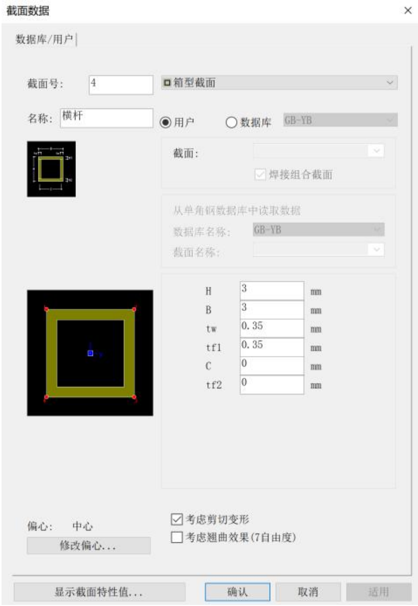
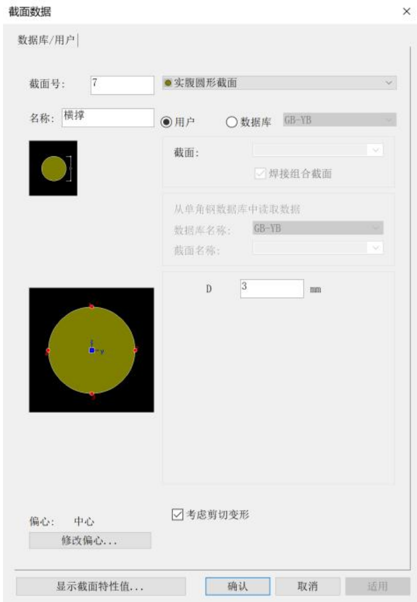


Figure 3-2 I-beam Section 1 Figure 3-3 I-beam Section 2 Figure 3-4 I-beam Section 3

The structure was arranged with box sections in the transverse and longitudinal directions to increase the structural stiffness, as shown in Figures 3-5. Circular rods were arranged in the middle of the structure to form a closed rectangle, dividing the structure as a whole into upper and lower layers. A number of transverse, longitudinal, and diagonal braces and tie bars are arranged between the layers. The specific cross sections are rectangular and circular, as shown in Figures 3-6 through 3-9.





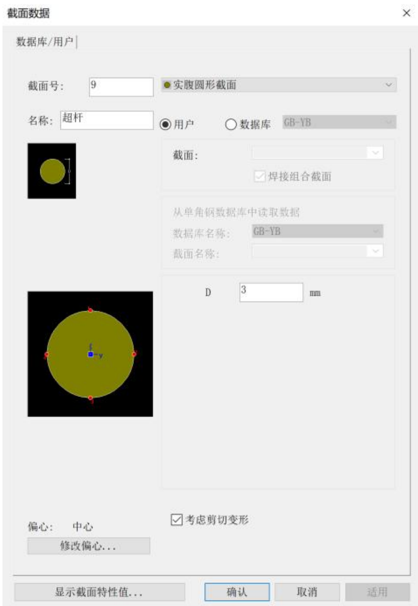
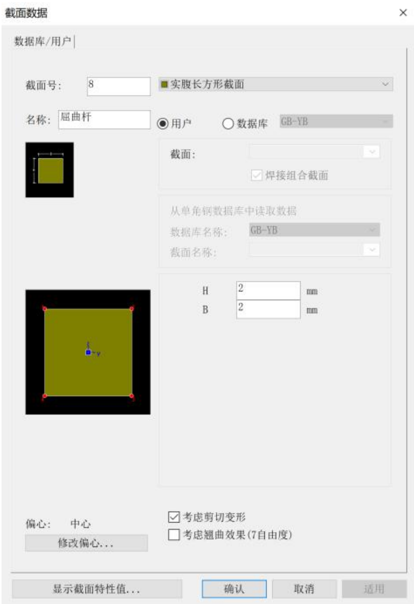
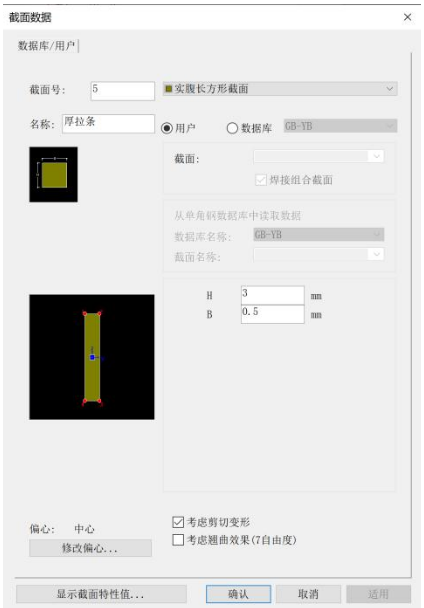


Figure 3-5 Box Section Figure 3-6 Circular Section 1 Figure 3-7 Circular Section 2





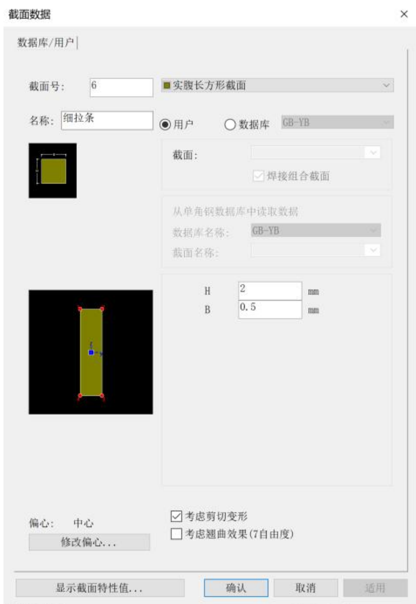


Figure 3-8 Rectangular section bar Figure 3-9 Tie bar 1 Figure 3-10 Tie bar 2

1.In order to make the model and the actual more close, need to set the boundary conditions reasonably, the model of the boundary conditions is relatively simple, the column foot through the bolt fixed on the base plate, for fixed connection, so in the Midas model using constraints on the foot node of all degrees of freedom to simulate the fixed connection, as shown in Figure 3-11.

2.According to the race question, the appropriate loads are applied to the finite element model, which are sinusoidal vibration load, top horizontal load and top vertical load.

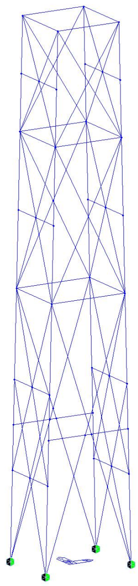


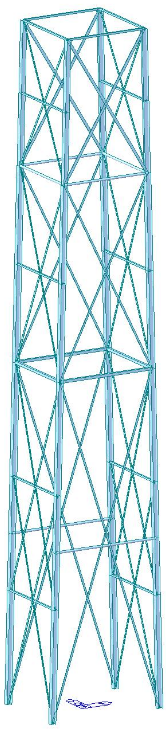
Figure 3-11 Setting of boundary conditions for column footing

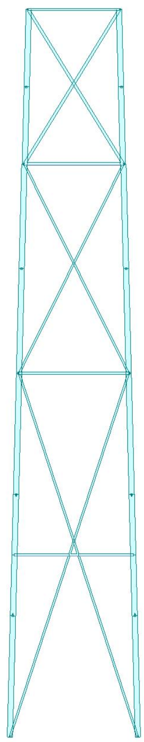
4. Structural modeling and main parameters

The model was structurally modeled and analyzed using Midas finite element software.

4.1 Midas structural model

An analytical model of the structure was developed using the finite element analysis software Midas, as shown in Figures 4-1 through 4-4.





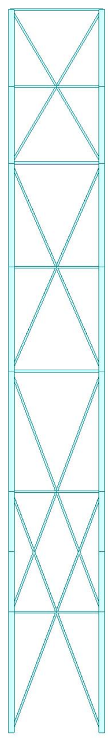


Figure 4-1 Three-dimensional axonometric drawing of the analytical model Figure 4-2 Longitudinal elevation of the analytical model Figure 4-3 Cross-sectional view of the analytical model

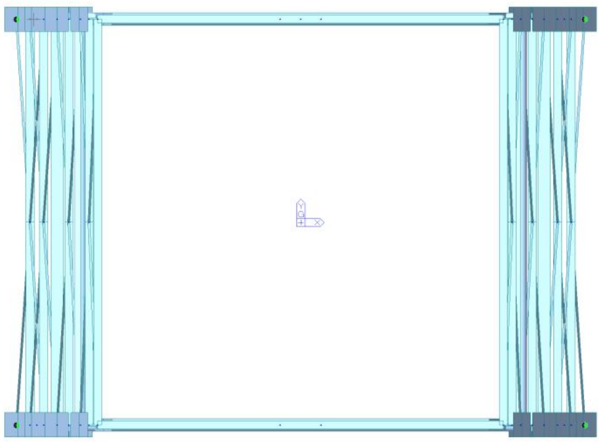


Figure 4-4 Structural analysis model plan view

4.2 Main parameters in structural analysis

In the Midas modeling analysis, the main parameters were defined as follows:

1.Material part: the modulus of elasticity of the bamboo veneer is set to 6000N/mm2 and the tensile strength is 60MPa; the density is 0.8g/cm3 and the compressive strength is 30MPa.

2.Geometric information part: the bottom surface size of the structure model is 100×140 mm, and the top surface size is 100×100 mm. the structure vertical rod arrangement is shown in Figures 4-5 to 4-6. The vertical rod member work section size is 7×5×0.8 mm; the vertical rod member T section size is 6×5×0.8 mm; the horizontal rod member top horizontal rod is 15×7×5 mm; the horizontal rod section size in the middle of the modeled structure is 15×4×4 mm; the horizontal support size in the other parts is 50×4×4 mm; the diagonal tie bar on the side of the structure has a size of 300×3×0.2 mm ; the size of the front diagonal bar of the first layer of the structure is 300×3×0.5mm; the cross-section size of the rest of the diagonal bars is 300×3×0.3mm; the information of the bar dimensions in the finite element model is shown in Figs. 3-2 to 3-10.

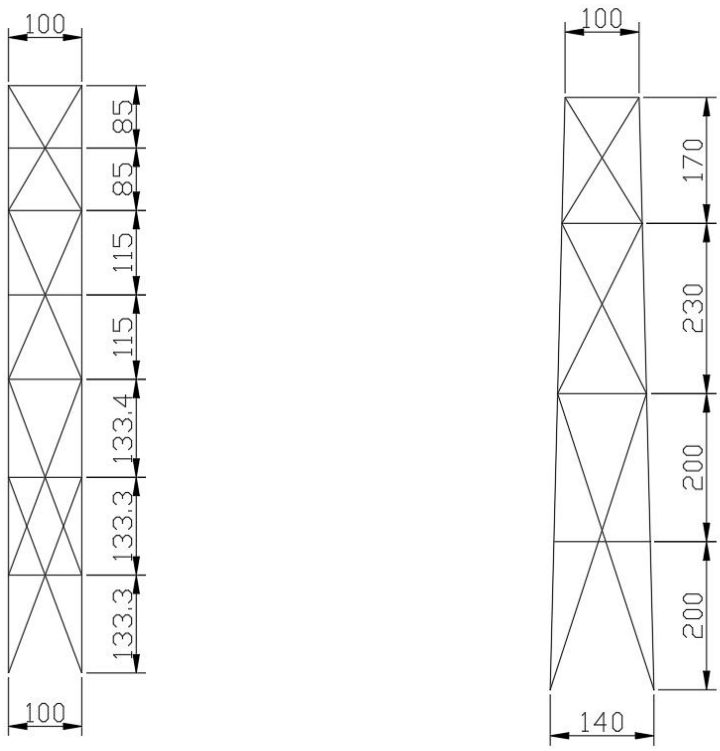


Figure 4-5 Right Side Face Dimensions Figure 4-6 Left Side Face Dimensions

Load condition part: The load applied condition in the finite element model is consistent with the loading method in the structural design competition, and the load condition in the model is shown in

Figures 4-7 to 4-9.

The primary load is horizontal excitation vibration. The vibration table was vibrated with a sine wave of frequency 4Hz in one direction, amplitude 10mm, vibration holding time 20s. the secondary load was a water calming load applied to the top of the structure, size 6kg. the tertiary load was a horizontally excited vibration. The shaker was vibrated with a sinusoidal wave of 3 Hz unidirectional vibration with an amplitude of 20 mm and a vibration duration of 20 s. The secondary load was a water calming load applied to the top of the structure with a size of 6 kg.

Structural support section: in the actual model, the connection and fixation between the column footing and the base plate is done through bolts, so a fixation constraint is applied between the bottom of the structure and the base in the Midas model.

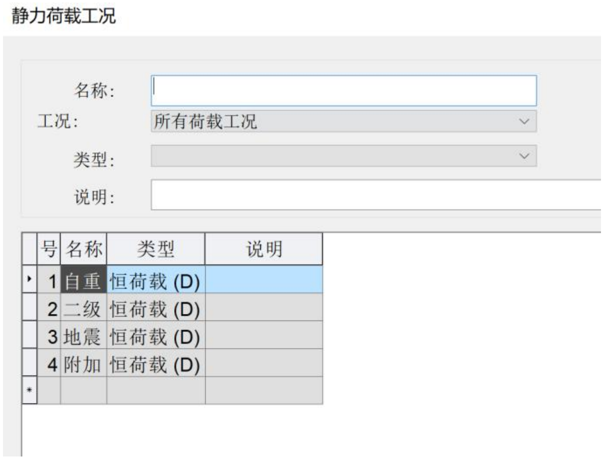


Figure 4-7 All Load Conditions

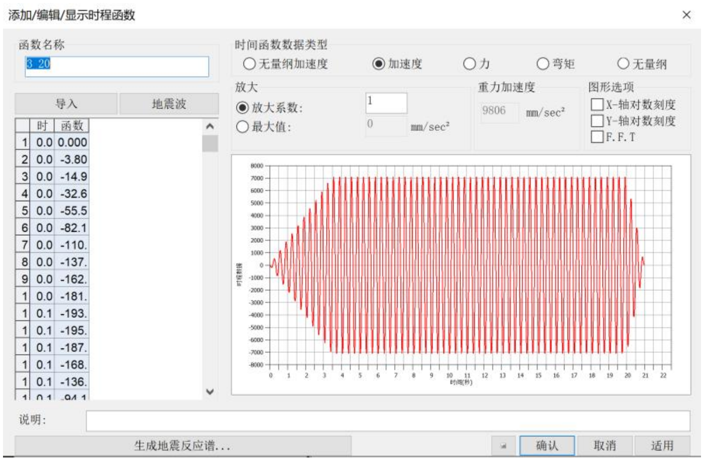


Figure 4-8 Primary vibration load

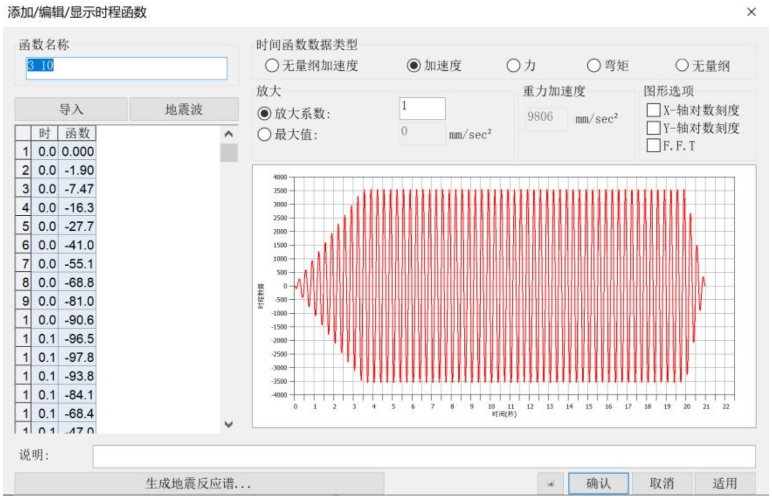


Figure 4-9 Vibratory Load Level 3

4.3 Tertiary Loading Response Strategies

1.Primary loading

The first stage of loading is the horizontal excitation of the shaker, and a unidirectional sine wave with a duration of 20 s is input to the model through the shaker, with a frequency of 4 Hz and an amplitude of 10 mm; according to the supplemental notification of the competition, the top mass system of the model is 3 kg.

After analysis, the working condition is characterized by vibration in the presence of vertical loads, and the structure is characterized by a towering structure with a large aspect ratio, large structural stiffness, and susceptibility to buckling damage. In order to prevent damage such as member fracture, node instability, and tower torsion, the following response strategy is adopted:

Increase the strength of diagonal tie bars perpendicular to the direction of vibration to reduce the deformation of the structure in the direction of vibration; change the vertical bar section to a variable section system to realize the gradual change of the structure's stiffness from the bottom to the top, with the use of work-type sections at the bottom and the middle, and the top with the gradual change of the width of the wing plate on one side; and add patches at the nodes connected by the horizontal support bars in order to increase the torsion resistance of the structure.

2.Secondary loading

The second level of loading was a water calming load with a horizontal load applied on the top of the structure with a magnitude of 6kg and a horizontal load duration of 10s or more. The displacement limit of the model was determined as 25mm by drawing lots before the competition.

After analyzing, the load is static load, the load is larger, the bending moment borne by the vertical rod is large. Moreover, the structure is a towering tower structure, the horizontal support rods are easy to bend and the vertical rods are easy to flex. In order to enhance the bending capacity of the structure and adjust the structure to the appropriate stiffness, the following coping strategy is adopted:

The tower body is horizontally arranged as a rectangle, the long side of the rectangle is arranged along the vibration direction, and the wide side is placed perpendicular to the vibration direction; the vertical rod at the bottom of the structure is a box section, the long side of the section is arranged along the vibration direction, and the wide side is placed perpendicular to the vibration direction.

3.Tertiary loading

The third level of loading was vibratory loading, in which a unidirectional sine wave with a duration of 20 s was input to the model via a shaker, with a frequency of 3 Hz and an amplitude of 20 mm. For the third level of loading, the top mass of the structure had to be adjusted or not, as determined by the team members prior to loading in the field.

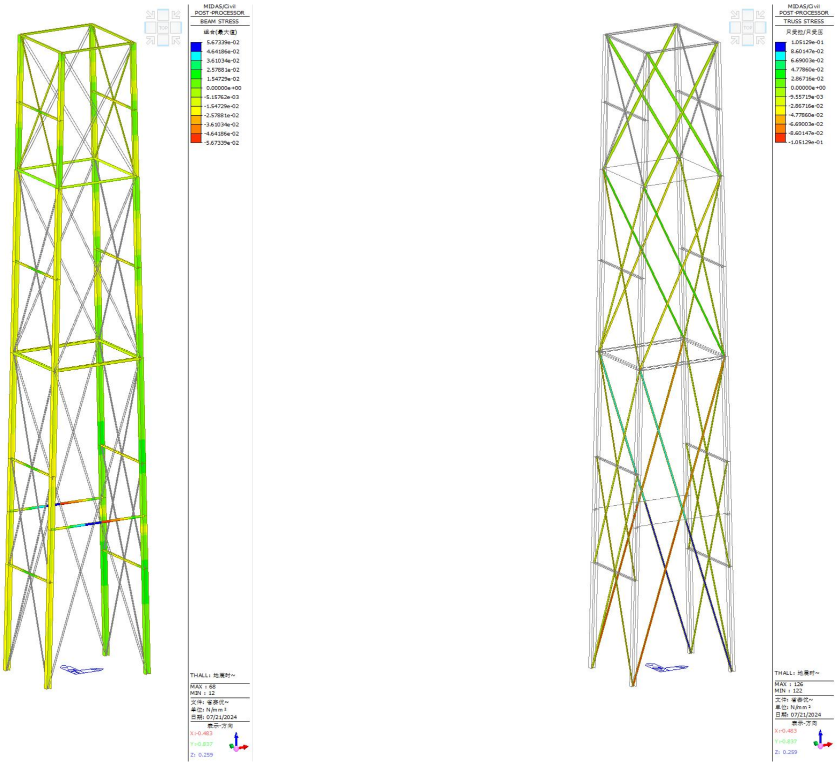
After analyzing, the vibration characteristics of this condition are different from the first level loading, its vibration frequency is reduced and the amplitude is increased to two times of the original. In order to prevent members from fracture, node instability, and tower torsion damage, the following countermeasure strategy is adopted:

Damping blocks are suspended at the top of the tower to reduce the amplitude of the structure; the vertical rods are set at a certain inclination angle from bottom to top, the top plane of the structure is made to be closed, and the plane size of the tower is gradually reduced from bottom to top to enhance its seismic performance; reinforcement measures are adopted at the foot of the columns to share the load at the bottom; the strength of diagonal bars perpendicular to the vibration direction is increased to reduce the deformation of the structure under the action of vibration loading; and the structure adopts the system of variable cross-section in vertical direction, with the stiffness gradually decreasing from the bottom to the top. The stiffness is gradually reduced from the bottom to the top, the bottom and middle part of the structure adopts the I-beam section, and the top part adopts the section that the width of one side of the wing plate changes gradually.

5. Force analysis

5.1 Strength analysis

In the aspect of strength, it mainly includes the checking and analyzing of compressive strength and tensile strength. According to the calculation results, extract the rods with the largest tensile and compressive stresses, and extract the corresponding data to check whether the maximum tensile and compressive stresses of the corresponding rods are within the allowable range of material strength to determine whether the rods and structure can safely carry. If the relevant requirements are not met, the arrangement of the structural members, cross-section size, and the location of the members need to be adjusted and optimized. After repeated adjustments and tests, the strength of the final model meets the relevant requirements and the structure can be safely loaded.

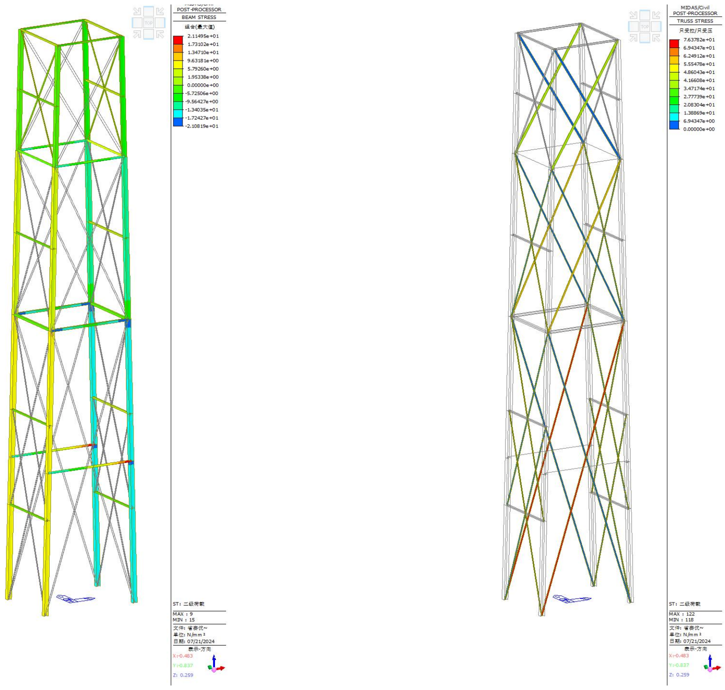


(a) Beam cell stresses (b) Joist cell forces

Figure 5-1 Structural Stress Cloud for Primary Loading

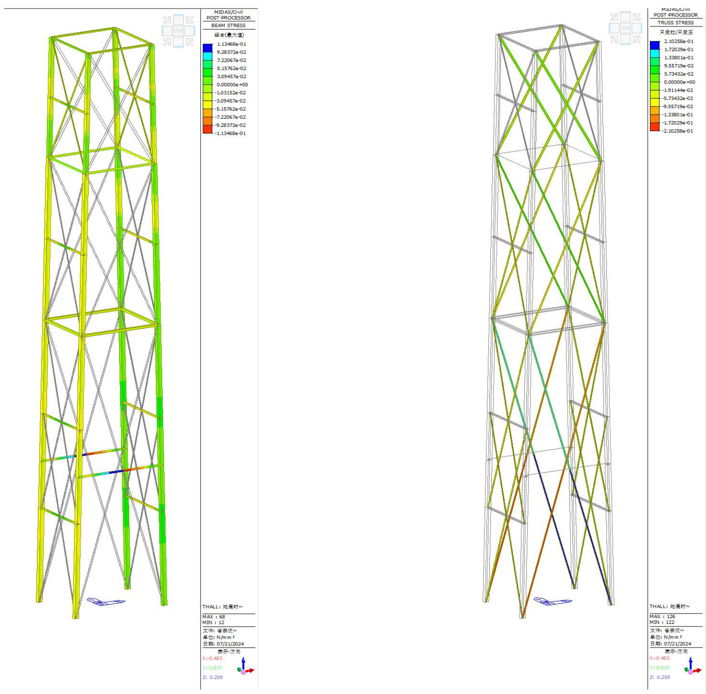
1.first-order load

The primary loads are column top static loads and vibration loads. By adding the time-range function, time-varying static load, and vertical static load in Midas software, the structure is analyzed and the stresses are obtained as shown in Figure 5-1. As can be seen from 5-1, the model shows that the maximum stress of the structure occurs in the compression rod at the bottom, and the maximum compressive and tensile stress is about 56.7 MPa, and the tensile stress is less than the theoretical value of the compressive strength of the bamboo material in Table 2-2, which is 60 MPa. Since the bamboo materials used in the competition are all slender rods, it is not possible to determine the compressive strength of the rods and the bamboo veneer. However, according to GB2005-2017 "wood structure design standard", it can be seen that the general compressive strength of wood in the smooth grain is slightly greater than the tensile strength, so the maximum compressive stress of the rod in the model is 56.7Mpa, which is smaller than the compressive strength of the rod in the smooth grain, and the structure is safe and meets the requirements. And the bar is a flexural bar set up to dissipate seismic energy, which meets the expectation and indicates that the structure can carry the load safely.



(a) Beam cell stresses (b) Joist cell forces

Figure 5-2 Structural stress cloud for secondary loading



(a) Beam cell stresses (b) Joist cell forces

Figure 5-3 Structural Stress Cloud for Three Levels of Loading

2.Second level of loading

The secondary load is vibration load. Through Midas software, the corresponding vertical static load and horizontal load are applied at the top of the model, and the maximum tensile and compressive stresses appear in the middle and lower nodes of the structure, respectively, with a maximum value of about 21MPa, which is smaller than the tensile and compressive strengths of the bamboo material, and the structure can be safely loaded. Under the secondary load, the maximum tensile stress of the tension bar is 76MPa, which is slightly larger than the measured tensile strength of the bamboo material, 75MPa, and it can be seen from the actual measurements that the structure is safe under this load.

3.Tertiary loads

The tertiary loads are static load and vibration load at the top of the column. Figure 5-3 shows that under this loading condition, the maximum stress of the structure occurs at the bottom horizontal compression bar and tension bar, with a maximum value of 21MPa, which is smaller than the tensile strength of bamboo, and the structure can carry the load safely.

5.2 Stiffness analysis

The stiffness analysis mainly examines the deformation of the structure. The structure is a towering structure, and vertical tension rods, horizontal tension rods and tie bars are provided in the structure. The displacements of the structure under different load combinations are obtained by finite element calculation and summarized for analysis.

1.first-order load

The primary load is vibration load and vertical static load at the top of the structure, the deformation diagram is shown in 5-4. From Fig. 5-4, it can be seen that the X-direction displacement of the structure is the largest, that is, the loading direction, which is 40.06mm, and the node number is 50, which is located in the upper part of the structure instead of the top. The whole deformation is in serpentine pendulum, and the deformation is reasonable and able to carry the load safely.

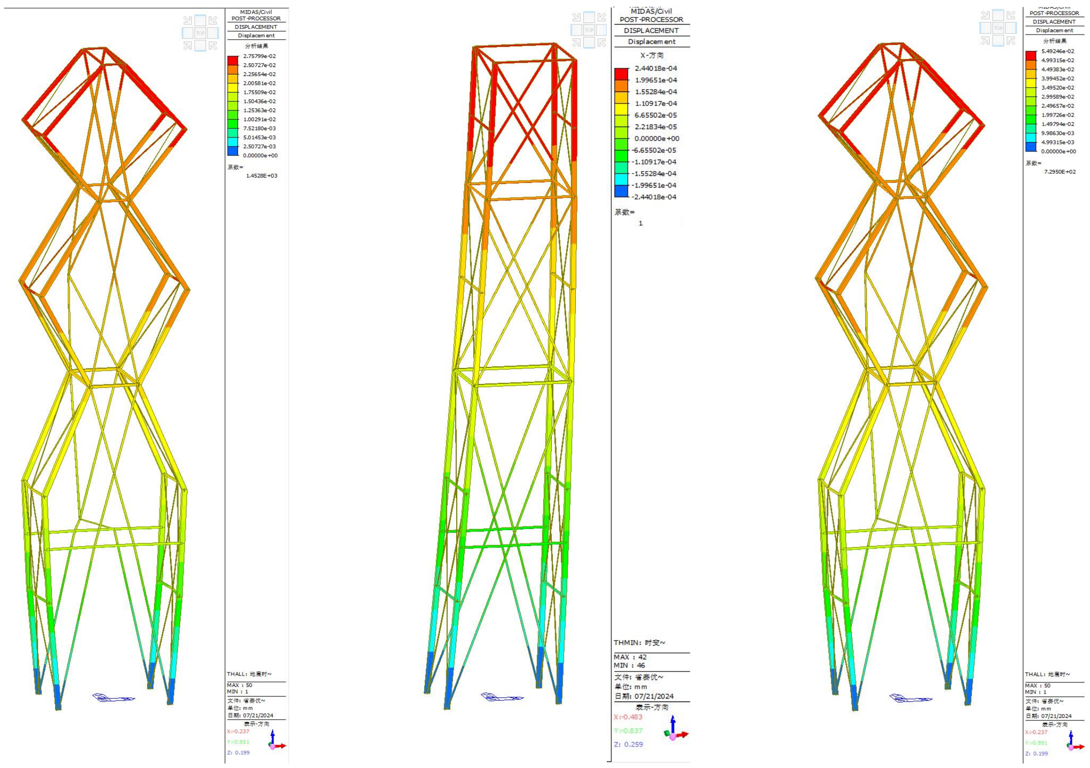


Figure 5-4 Primary Loading Displacement Deformation Figure 5-5 Secondary Loading Displacement Deformation Figure 5-6 Tertiary Loading Displacement Deformation

2.Second level of loading

The secondary load is a static load, in addition to the vertical load applied on the top of the structure, a horizontal load of 6kg is also applied on the top of the structure. The X-direction displacement of the structure is the largest, which is the loading direction, and the top displacement is the largest, which is 24.4mm, and the node number is 42. the whole structure has small deformation in the lower part and large deformation in the upper part, which is in the form of shear deformation, which shows that the whole structure deforms in a coordinated way to satisfy the requirements.

3.Tertiary loads

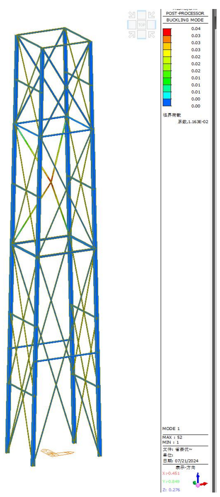
The tertiary load is a vibration load and the top of the structure is a vertical static load, the deformation diagram is shown in 5-4. Compared with the primary load, the vibration frequency of the tertiary load becomes smaller, the amplitude increases to two times of the original, and the mass of the top structure increases. From Fig. 5-6, it can be seen that the maximum displacement of the structure in the X direction, which is the loading direction, is 20 mm, and the node number is 50, which is located in the upper part of the structure instead of the top. The whole deformation is a serpentine pendulum, and the deformation is reasonable and can carry the load safely. Its deformation law is almost the same as the primary loading.

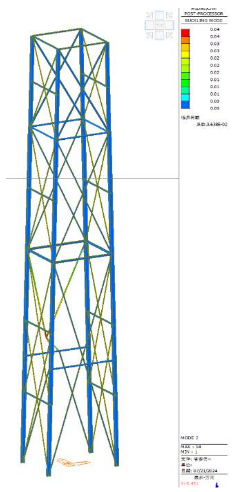
5.3 Stability analysis

In our model, because of the use of elastic bending members, when the eccentric external load is translated to the bending member, the member may be subjected to axial tensile force, bending moment, and shear force together. Considering the small cross-sectional area of the structural member, its moment of inertia is small, resulting in small bending stiffness, according to the "compression rod stability" problem can be known, the model exists in the "slender rod" and other poor stability of the rod, so for the model, the stability problem must be analyzed and studied. Therefore, for the model, the stability problem must be analyzed and studied.

5.3.1 Modal analysis

From the stability theory, it can be seen that under the action of external load, if the rod is in equilibrium at this time, when the axial pressure to which the rod is subjected is less than the critical load, the slightest disturbance will occur bending, deviating from the original equilibrium state, and when the disturbance disappears, the compression rod returns to the original equilibrium state; when the axial pressure to which the rod is subjected is equal to the critical load, the original equilibrium state is no longer the only state, and there will be two kinds of tendencies, when there is no disturbance, the member In the linear form of the equilibrium state, slight interference will occur bending, deviation from the original equilibrium state, when the interference disappears, the compression rod will not return to the original equilibrium state, but to maintain a slightly curved equilibrium state; in the extreme case, when the axial pressure on the rod is greater than the critical load, theoretically the rod can still be in the form of a straight line of the equilibrium state, is not stable equilibrium state, a slight interference will occur drastic bending The slightest disturbance will cause sharp bending and deformation, leading to damage. Therefore, under the action of different loads, in order to make the structure meet the stability requirements, the design of the model, the combination of local structural components, the connection between the rods and the form of bonding need to meet the principles of mechanics, structural requirements, the production process related to the content, extremely test the designer's level of analysis and application of mechanics, structural design skills and manual practice ability. In the model calculation, the five modes of the model under the most unfavorable load combinations were analyzed, as shown in Figures 5-7 to 5-11. After the analysis, it can be seen that the stability of the model in each modal state meets the requirements.





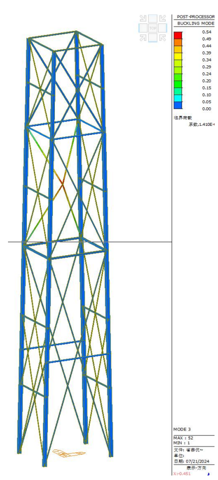
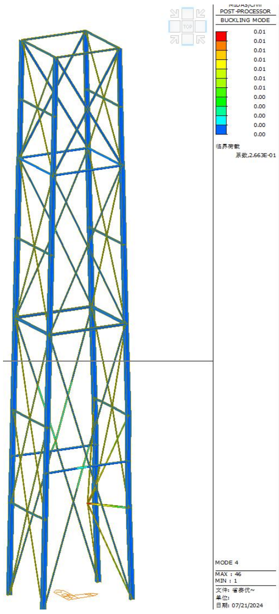


Figure 5-7 Modal 1 Figure 5-8 Modal 2 Figure 5-9 Modal 3



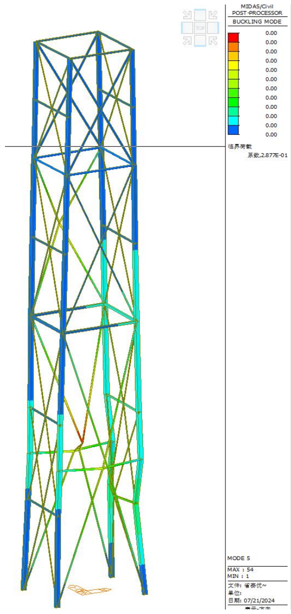


Figure 5-10 Modal 4 Figure 5-11 Modal 5

5.3.2 Stabilization calculations for compression rods

According to GB2005-2017 "Wood Structure Design Standard", it can be seen that: the bearing capacity of axial compression members shall be calculated according to the following provisions:

For strength checking, the following formula shall be used.

$$\frac{N}{A_n} \leq f_c \qquad (5\text{-}1)$$

When the calculation is based on stabilization, the calculation shall be based on the following formula:

$$\frac{N}{\varphi A_0} \leq f_c \qquad (5\text{-}2)$$

Style:

f_c--Design value of the compressive strength of the member material for the smooth grain (N/mm^2).

N - design value of pressure in axial compression member (N).

A_n--Net cross-sectional area of the compression member (mm^2).

A_0--Calculated area of the cross-section of the compression member (mm^2);

φ- - Stabilization factor for axial compression members.

The computed area of the cross-section of a compression member for stability testing shall be used in accordance with the following.

Stabilization coefficient for axial compression members φ shall be determined by the following equation.

$$\lambda_c = c_c \sqrt{\frac{\beta E_k}{f_{ck}}} \qquad (5\text{-}3)$$

$$\lambda = \frac{l_0}{i} \qquad (5\text{-}4)$$

Dang.$\lambda > \lambda_c$ when

$$\varphi = \frac{a_{c\pi}\pi^2 \beta E_k}{\lambda^2 f_{ck}} \qquad (5\text{-}5)$$

when$\lambda \leq \lambda_c$ when

$$\varphi = \frac{1}{1+\frac{\lambda^2 f_{ck}}{b_c \pi^2 \beta E_k}} \quad (5\text{-}6)$$

Style:

λ - length to slenderness ratio of the compression member;

i- - Radius of gyration of the member section (mm); - - - Radius of gyration of the member section (mm); - - - Radius of gyration of the member section (mm).

l_0--Calculated length of the compression member (mm).

f_{ck}- Standard value of compressive strength of the material of the compressed member (N/mm2).

E_k- standard value of the modulus of elasticity of the member material (N/mm2).

a_c,b_c ,c_c --Material correlation coefficient.

β- - Material shear deformation correlation coefficient.

Through modal analysis and model test calculations, it can be seen that the model is easy to be unstable at the bottom and the middle of the horizontal rod intersecting with the vertical rod, so the stability of the rod at this position is mainly examined in the compression rod stability calculations of the structure. The position of the vertical rod for the I-shaped cross-section, its cross-section dimensions shown in Figure 3-2, cross-section area A = 12mm2 , height l_0 = 230mm, radius of rotation i_x =2.14mm, =1.24mm. i_y = 1.24mm. According to GB2005-2017 "wood structure design standards", it is known that the general compressive strength of the wood's smooth grain is slightly greater than the tensile strength, check the relevant parameters, using the formula (5-3) to (5-6) calculated to get the compression bar of$\lambda_c = 91.5$.φ_x = 0.175.φ_y = 0.234, the pressure of the vertical rod is 145 N. According to the formula (5-1) the compressive stress of the rod in the strength conditions is 12.08Mpa, less than the compressive strength of the material 60Mpa, the structure is safe. According to the formula (5-3) calculate the stress magnitude of the rod in the stable condition is 69.04Mpa, which is smaller than the measured tensile and compressive strength of the model material 75Mpa, the structure can carry safely.

5.4 Summary

The strength, stiffness and stability of the model designed by the group was analyzed by Midas finite element software. The finite element model was calculated on the basis of the material property parameters of the main material, and the loads specified in the competition were combined. Especially in the case of unfavorable combination of loads, the force characteristics, internal force distribution, stress magnitude and other strength indexes of the finite element beam unit were analyzed, and it was finally concluded that the load carrying capacity of the model meets the requirements. From the perspective of the overall stress performance of the structure, the overall stress of the model is relatively uniform, and the stresses of various types of rods are relatively reasonable, which can give full play to the advantages of the structure and components, and make full use of the mechanical properties of the bamboo material.

In analyzing the stability problem of the structure, because the material of the model is mainly bamboo strips, and the bending capacity of this material is relatively weak, especially the material of the tensile members is chosen more carefully. According to the Euler instability principle, we try to avoid the appearance of long thin bars, use truss structure and two-force bars to change the long thin bars into short bars, and use the combination of bamboo strips and bamboo veneer to ensure that the structure has enough stability and bearing capacity when it is subjected to external loads. Finally, after ensuring the strength, stiffness and stability of the structure, in-depth analysis is done again to optimize the model with less material and to consider the combination of aesthetics and art, so that the structure not only meets the force requirements, but also makes the structure as a whole beautiful and rich in artistic and cultural characteristics.

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