Optimization Analysis of a Long-span Glulam Beam String Structure

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Abstract. The force analysis for a long-span glulam beam string of a swimming pool roof was made by SAP2000 finite element software. It was found that the long-span glulam beam string structure is reasonable, which can significantly reduce deflection and improve the structural performance. In the preliminary design, the stress of the glulam beam string is uneven. The structure is optimized with balanced struts and better performance.

Keywords: Long-Span Structure, Glulam, Beam String Structure

1. Introduction

The original roof of a swimming pool in Changchun adopts the steel grid structure. After having been used for 20 years, due to the high chloride ion content in the water vapor of swimming pool, the condensation and moisture environment, the members and connecting bolts are rusted. The serious corrosion reduced the effective cross section of the members and connecting bolts. Due to the difficulty of steel grid repair, the owner decided to upgrade the original structure with wood structure.

Compared with original wood, Glulam has the advantages of small timber, reducing defects, layering and optimization, and is widely used in modern wood structures [1]. Because of the large span of the roof, the glulam beam needs a large section size, which has poor visual effect, and has the problem of high cost.

The beam string is a common structural form in large span buildings, which is composed of the upper beam, the middle strut and the lower flexible high-strength cable [2]. It has large stiffness and strong bearing capacity [3][4]. The glulam beam is used for the upper chord, steel tube for struts and high-strength steel strands for cable. Making full use of the material properties of the components, Glulam beam string structure avoids the disadvantages of large consumption, high cost and large deflection of wood beam.

The swimming pool is a concrete frame structure, with a span of 30m and a spacing of 6.38m. See Figure.1 for the preliminary design of the beam string facade.
In this paper, the finite element software SAP2000 is used to optimize the 1/3-scale beam string [5], which provides support for experiment research and engineering design.

2. Finite Element Analysis Model
Beam string is divided into three parts: the glulam beam upper chord, the square steel pipe strut and the lower flexible PE cable. The glulam beam is divided into three parts according to the radian: oblique straight section, positive arc curved section and reverse arc curved section [6]. For the convenience of description, the top chord is divided into 5 sections named 1-5 section according to the strut, the strut is numbered 1-4, the left high-end sliding hinge is support A, and the right fixed hinge is support B. As shown in Figure.2.

2.1 Material Definition
The upper chord of the scaled beam string is two pieces of TCT24 glulam [7] with a section size of 67x200mm, and the joist is TCT21 with a section size of 67x135mm. SAP2000 focuses on the analysis of the overall structure, so the end splint of wood beam, steel connectors and bolts between the primary and secondary beams do not include in the model, only the boundary conditions present[8][9]. The strut is Q235 square steel pipe, the cable is φ18 PE cable (fptk = 1720MPa), and the fixed rod at both ends is φ70 Q420 steel pipe. See Table 1 for detailed material properties. Poisson's ratio of all materials is 0.3.

| Parts          | Material  | Density (kg/m³) | Modulus of elasticity (N/mm²) |
|----------------|-----------|-----------------|-------------------------------|
| glulam beam    | TCT24     | 800             | 9500                          |
| glulam joist   | TCT21     | 800             | 8000                          |
| cable          | JTG-fptk 1720 | 7850          | 1.95×10⁴                      |
| strut          | Q235      | 7850            | 2.06×10⁴                      |
2.2 Load Definition

The dead load and live load of the model are applied in the way of uniform load, the snow load is arranged in half span considering the unfavorable arrangement factors, and the cable pretension is applied in the way of negative temperature stress.

The dead load D1 is the self-weight of the beam string, which is calculated automatically by the program. D2 is the external dead load, the roof dead load value is 1.0kN/m2, and the calculated line load for each upper beam is 1.07kN/m.

The live load of non-accessible roof is 0.5kN/m2. A uniform line load of 0.53kN/m is applied to each upper beam. The basic snow pressure is 0.45kN/m2. Only the half span snow pressure is considered in analysis.

The prestressing force of the cable is applied by -96 ℃ temperature with a preaching of span’s 1 / 500, i.e. by applying negative temperature to the cable, the mid span preaching is 20mm.

2.3 Load Condition and Combination

D1 is defined as the initial condition. The load case which cable pretension through negative temperature, is defined as pre, and the analysis type is non-linear. Pre is defined continued from D1. Load combination D1 + pre + D2 that is, the load combination of self-weight, cable pretension and dead load, chooses to add D2 condition, which is defined as nonlinear analysis, and continues from the end of pre-condition. Load combinations D1 + pre + D2 + live, D1 + pre + D2 + snow are added.

In force analysis of the structure, the basic combination D1 + pre + 1.35D2 + 0.98live and D1 + pre + 1.2D2 + 1.4live should also be considered.

3. Preliminary Analysis

According to the preliminary design, the modeling analysis of glulam string beam is carried out.

3.1 Displacement and Deformation

The vertical displacement at the strut and in mid-span of beam under various load conditions are shown in Figure.3. The abscissa is the relative position of the beam string (0 is support A, 0.2, 0.4, 0.6, 0.8 represent strut 1-4, 0.5 represent midspan, 1 is support B), which lists the deflection of the beam when the self-weight, cable pretension, dead load and live load conditions are applied.

When the negative temperature of -96 ℃ is applied to the cable, the cable is tensioned to achieve the pre work condition. After the self-weight deflection is overcome, the midspan upper arch is 20.5mm, the x-direction displacement of support a is 3.13mm, and the upper arch of strut 2, midspan and strut 3 is obvious, reaching 19.54mm, 20.58mm and 19.86mm respectively.

When the dead load D2 is applied, the pre camber of the beam string is mostly offset by the deflection, and the pre camber of the midspan is 4.84mm. When the live load is applied, the deflection is eliminated the pre camber. The upper arch displacement of 2.16mm is still retained at strut 1, the deflection in mid-span is -2.75mm, and the x-direction displacement of support A is 1.68mm.

The analysis shows that when the high-strength cable is combined with the top chord glued wood beam, the cable can exert the required pretension to greatly reduce the deflection of the beam and improve its mechanical performance.
3.2 Upper Glulam Beam

The axial force of the upper glulam beam is basically uniform. Under pre + D1 + 1.2D2 + 1.4live load combination, the maximum axial force is 28.3kN, and the bending moment of each section of the top chord wood beam is uneven (see Figure 7). The maximum negative bending moment is -1.96kN.m at strut 1 position. The mid span bending moment is 1.24kN.m, and the maximum positive bending moment appears in the fifth section of the beam, which is 1.56kN.m.

Under the combined action of bending and compression internal forces, the maximum normal stress is applied to the first and second sections of the main beam, which are -6.51N/mm² and -6.49N/mm² respectively, but lower than the design value of wood strength by 24 N / mm².

The shear force of the top chord timber beam under the corresponding working condition has a sudden change at the action position of each strut. At one strut, the left and right shear force of the beam is 3.00kN, -3.14kN. The maximum shear force of timber beam at strut 2 and strut 3 is -2.26kN and 1.44kN respectively, and the maximum shear force of timber beam corresponding to strut 4 is 3.14kN.

3.3 Strut

The strut mainly bears the axial force and transmits the vertical component force generated by the cable pulling force at the strut due to the cable turning at the strut. The axial force of strut can balance the moment and shear produced by the upper load, which is the main factor of the stress efficiency of the beam string. The results show that the axial force distribution of strut is very uneven, the strut 1 is the largest and the strut 3 is the smallest. In the Figure, the axial force of strut 1 in sequence 1 is -5.19kN, while strut 3 is only -0.78kN. The axial force of strut 1 in sequence 3 is -6.38kN, the axial force of strut 2 is -3.43kN, the axial force of strut 3 is only -1.00kN, and the axial force of strut 4 is -3.22kN. From this analysis, it can be seen that the force gap between the struts is too large, and the strut 1 is close to the support while its axial force is the largest. In order to improve the mechanical performance of the beam string, it is necessary to adjust the strut and optimize the cable shape so that all the struts are stressed uniformly.

3.4 Cable

The pretension of the cable produces upward component force at the turning point of the strut, which balances the load on the upper glulam beam, so the pretension of the cable is very important for the load of reverse balance. For glulam beam string, because of the small self weight of the structure, the large pretension will make the top chord beam reverse arch, so when the roof dead load is large and the deflection control is strict, it can be tensioned by stages to control the amount of prearching. Because of small roof load, the pretension produced by the initial tension can control the deflection of the beam string. Under all working conditions, the tension of the last four sections of the cable is relatively uniform, and the first section is significantly greater than the other four sections. The most unfavorable basic combination - under the condition of pre + D1 + 1.2D2 + 1.4live, the maximum
tension of the first section of the cable reaches 60.07kN, and that of the other sections is about 56kN, which is far lower than the allowable tension of the cable, so the cable has a high safety margin. The main reason for the difference of cable tension is that the angle of the cable between each strut is different. So the longer the length of strut 1, which makes the angle of the cable at strut 1 larger, the larger the tension of the first section of the cable and the axial force of strut 1. It is necessary to optimize the cable shape.

4. Optimization and Reanalysis
According to the preliminary analysis results, on the premise that the total height of the beam string remains unchanged, the cable type is optimized by adjusting the length of each strut. Optimization idea 1: pressure balance of each strut. The optimization result of idea 1 is not good for the beam string shown in this paper, which leads to the increase of bending moment and deflection of the beam string, so idea 1 is not suitable for the beam string in this paper. Finally, the optimization idea 2 is adopted: the bending moment of the top chord wood beam is the minimum. By properly reducing the length of strut 1, adjusting the cable shape, and carrying out step-by-step optimization analysis, it is determined that when the length of strut 1 is reduced to 550mm, the stress of each strut is relatively balanced, the cable tension is uniform, the peak moment of the top chord wood beam is reduced, and the mid-span deflection is slightly reduced [10]. The optimization can improve the bearing capacity and mechanical performance of the beam string. The elevation of the optimized beam string is shown in Figure 4.

![Figure 4](image4.png)

**Figure 4.** Struts length of the optimized strut string beam

Under the most unfavorable working condition of the basic combination, the deflection before optimization is 2.75mm, the maximum deflection appears in the middle of the span, the maximum deflection after optimization is 2.12mm, and the maximum deflection appears in the strut 1. See Figure 5 for comparison.

![Figure 5](image5.png)

**Figure 5.** Comparison of deflection before and after optimization

See Figure 6 for the axial force of strut before and after optimization, and the maximum difference of axial force of each strut before optimization is 5.48kN. After optimization, the maximum axial force of strut is transferred to strut 2, which is -4.86kN, and the axial force of strut 3 is still the minimum, which is -1.28 kN.
Figure 6. axial force of struts before and after optimization

From the stress system of the beam string, the wood beam at the top chord is mainly in compression, and the bending moment makes it in compression bending state, which will reduce the compression bearing capacity of the wood beam, so the smaller the bending moment of the wood beam at the top chord, the better. See Figure 10 for the moment distribution of the top chord timber beam before and after optimization. Under the action of the most unfavorable load combination, the maximum negative bending moment of the wooden beam appears at the strut 1, which is -1.98kN.m, and the maximum positive bending moment is 1.58kN.m in the fifth span of the wooden beam; after optimization, the bending moment distribution of the upper chord wooden beam is uniform, and the peak value decreases. The maximum bending moment of straight section of wood beam is 0.93kN.m, and the bending moment of the fifth section is basically the same as that before optimization.

Figure 7. Bending moment of upper beam before and after optimization

5. Conclusions
The finite element analysis of the glued wood beam shows that the stress of each component of the beam is reasonable. The glued wood beam can cooperate with the steel strut and high-strength prestressed cable, greatly improve the rigidity of the long-span wood beam, and obtain good mechanical performance.

The finite element analysis results of the scale model of the long-span timber structure show that the cable type of the beam string in the preliminary design drawing is not reasonable, which leads to a great difference in the axial force of each strut and a large internal force of the top chord timber beam.

The optimization idea of the balance of the axial force of each strut is not suitable for the beam string in this paper. After adopting the idea of internal force balance of top chord timber beam to optimize the cable shape, the phenomenon of unbalanced stress of strut and top chord timber beam is effectively improved. After optimization, the maximum axial force of strut decreases, and the peak value is transferred from strut 1 close to support to strut 2 close to midspan, which reduces the maximum bending moment of top chord timber beam, and the stress of all parts of chord beam is more balanced after optimization.

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