Effect of additional grid installation on the stress-strain state of a three-hinged arch

I S Inzhutov¹, V I Zhadanov², I A Polyakov¹, E A Chaikin¹ and D A Ukrainchenko²

¹ Siberian Federal University 82 Pr. Svobodny, Krasnoyarsk, 660041 Russia
² Orenburg State University, 13 Pr. Pobedy, Orenburg, 460018 Russia

Polyakov_ilya@bk.ru

Abstract. The authors of the article have analyzed the stress-strain state and design of a new rational circular tie-arch. In the article the arch stress-strain analysis of symmetric and asymmetric loads and the comparison of the new design with the classical one are studied. The most rational position of the struts of the new arch is established by varying their geometric parameters. The calculation of arches is performed taking into account the compliance of joints, and consumption of building materials for the production of structures is determined. As a result of research it is established that the use of a new design of the arch allows to reduce the bending moment in the top chord that results in the general decrease in consumption of wood for the production of an arch.

1. Introduction

Arch structures are rather rational in the perception of loads evenly distributed along the length, in the upper zone of the arch there appear bending moments of small magnitude [1-4]. However, during the action of the same uniformly distributed load on the tie-arch, there are moments of much greater value in comparison with the moments from the action of uniformly distributed loads.

To reduce the bending moments Professors Zhadanov V. I. and Dmitriev P. A. have proposed a new rational scheme of arch design (Figure 1 (b)) [5]. Therein, through the struts and flexible rods the reduction in the bending moments under the action of the roof of uniformly distributed loads is provided. A timber-metal circular arch with an additional lattice is a structure of the roof including the upper circular chord, the tie, connecting the bearing joints of the arch, strut and flexible rods. The struts are installed symmetrically in the 1/4 of the span and directed along the radius perpendicular to the chord. The connection of the struts with the upper chord and tie is hinged.

In modern standards regulating snow loads on arched surfaces the following schemes of loads are given: option 1-parabolic load distribution with maximum intensity in the middle of the span and zero intensity at a point with a 60°slope of the arch; option 2 – linear load distribution with zero intensity in the middle of the span and maximum intensity on one side of the arch at a point with a 30°slope; on the other side the intensity at a 30°slope point is half of the maximum (Figure 2) [6].
Figure 1. Schemes of classical (a) and rational arches (b), 1-the upper circular chord, 2-tie, 3-suspensions, 4-struts, 5-flexible rods.

Figure 2. The scheme of distribution of snow loads on the arched floor.

This nature of the distribution of snow loads in modern regulations necessitates studying stress-strain state of a new design of the arch, depending on its geometric parameters of the layout, in particular, the location of the struts.

The purpose of this research is to study the stress-strain state of a new timber-metal arch with varying geometric parameters.

2. The method of numerical research

SCAD software package was used for the purpose of the research. The elements of the three-hinged circular arch with a lifting boom of 3.6 m and a curvature radius of 13m were modeled on the design scheme by the finite rod elements. The design has a span of 18 m. The struts were located at the distance of 4.5 m (scheme 1), 5.5 m (scheme 2) and 3.5 m (scheme 3).

The arch was divided into 8 equal sections; for schemes 2 and 3 one of the sections was further broken at the intersection with the strut. The design schemes are shown in Figure 3.
Figure 3. Calculation schemes of the classical (a) and new (b) arches.

Previously, the section of the classical arch is assigned to $175 \times 858$ mm of pine lamellas with a moisture content of 10%, tie is made of $90 \times 7$ paired steel rolling corners. In the new arch the section is $175 \times 759$ mm, tie is made of $70 \times 5$ paired steel rolling corners, flexible rods are made of round bars with a diameter of 44 mm, struts - $99 \times 175$mm solid timber. Steel grade for all metal elements is C345.

In the analysis of the arch stress–strain state three different options for loading were considered:

1. Dead load of load-bearing structures, including roofs. The load, evenly distributed along the length of the arch, the value of the loads from the dead load of the enclosing structures was collected from the width of the cargo area - the step of the arches - 6 m. The dead load of the bearing elements of the arch was assigned using the internal tools of the SCAD based on the pre-assigned sections of the elements;

2. Snow loads. The intensity of snow loads adopted for the VI snow area is 3.0 kPa:
   - Option 1, the value of the load is calculated for each node of the arch. The evenly distributed load is trapezoidal. The load intensity was calculated for the extreme points of each arch element, the load value between the points was determined by linear interpolation.
   - Option 2, the values of loads were calculated at points with a 30° slope and at the extreme points of the arch; intermediate values were determined by interpolation. The load distributed for the arch rods was set similarly to the first variant.

All loads except snow were applied perpendicularly to the support line. The load value was calculated for the pitch of the arches - 6 m.

One of the important conditions that determine the work of rod structures is the consideration of the real work of the interfaces of elements, since the ductility of the joints of rod systems has a significant effect on the stress-strain state of the structure as a whole. To take into account the compliance of the nodal joints of the arches, the calculations were carried out in 2 stages.

At the first stage, forces and deformations were determined without taking into account the compliance in nodal connections, and at the second stage the compliance of joints was considered in accordance with recommendations [7-13].

To account for the deformability of joints in the design scheme in the areas of joint connections finite elements have been provided, for which at the second phase conditional modules of elasticity [9] were introduced.

\[ E_y = \frac{E}{1 + \delta_0 \cdot E \cdot A/(N \cdot l)} \]  \hspace{1cm} (1)
where \( E = 10000 \) MPa is the initial modulus of elasticity of timber elements; \( \delta_0 \) is the calculated limit value of the yield stress, taken depending on the maximum value of local plastic compression (on the frontal felling and the end of the end \( \delta_0 = 1.5 \) mm; on the dowels of all types \( \delta_0 = 2.0 \) mm; in the junction across the fibers \( \delta_0 = 3.0 \) mm) and the degree of use of bearing capacity, respectively: \( A \) is the cross-sectional area of the rod, \( \text{m}^2 \); \( N \) is the force acting in the rod, \( \text{kN} \); \( l \) is the length of the rod, \( \text{m} \).

Calculation of limit values of deformations gives

\[
\delta_0 = \delta_1 + \delta_2,
\]

where \( \delta_1 \) is the compliance’s deformation of the bolted connection, mm; \( \delta_2 \) is the shear deformation of timber elements, mm.

3. Analysis of the results

It was found that the most unfavorable combination of loads for all variants of arches was the combined effect of snow load option number 2 with its own weight of the bearing structure including the roof. Under combination of loads given, the flexible rod which adjacent to the upper zone of the arch at the site of action of the maximum load (in our case on the left) appears to be compressed. Since the flexible thrust was not intended for the perception of compressive forces in the design scheme of the arch, it was excluded at the next stage of calculation.

In the case of classical structural solutions of the three hinged thrustless arch with steel tightness the maximum bending moment equal to 179.23 kN · m was obtained. In the new schemes of the arch calculation without taking into account the compliance, the following values of the bending moments were set:

- Scheme 1 (distance from the support to the strut – 4.5 m) – 121.25 kN · m
- Scheme 2 (distance from the support to the strut - 5.5 m) – 123.51 kN · m
- Scheme 3 (distance from the support to the strut - 3.5 m) – 114.58 kN · m

Diagrams of moments in the arch of the new technical solution are shown in Figure 4.

![Figure 4](image.png)

**Figure 4.** Diagrams of the moments of the new arch.

To identify the consumption of materials for each variant according to [12], the cross-sections of the elements were calculated and the nodal connections were designed. The cross-sections of the elements obtained are given in Table 1.
Table 1. Dimensions of cross sections of different variants of arches.

| 18m structure with a 3.6 rise | The upper circular chord | Tie | Flexible rods | Struts |
|-----------------------------|--------------------------|-----|---------------|-------|
| Classical structural solutions | 175×891 mm | 70×5 paired corner | - | - |
| Scheme 1 | 175×759 mm | 70×5 paired corner | ø 44 | 99×175 mm |
| Scheme 2 | 175×759 mm | 70×5 paired corner | ø 35 | 99×175 mm |
| Scheme 3 | 175×726 mm | 70×5 paired corner | ø 55 | 99×175 mm |

The coupling of the arch with the tie is designed through a steel shoe (Figure 5). The thrust from the arch is transmitted to the steel shoe through the front stop. The attachment of the shoe to the arch is carried the on steel pins. Fixing the tie angles to the steel shoe is performed by welding.

Figure 5. Arch support joint.

Struts are held in the arch and are attached to it by means of timber slips and steel cylindrical dowels (Figure 6). To limit the movement of the strut on the arch a timber bar is provided. The
flexible rod is connected to the arch through a steel U-shaped plate, for which the cutting is performed at the junction of the plate in the arch.

Figure 6. The node of coupling of the strut and flexible rod with the upper chord.

The node of coupling of flexible rods with the lower chord is made through a metal inverted U-shaped element. The inverted U-shaped steel element represents a plate welded on one side; here is a hole in the plate with a flexible pull passing through it. At the end of the flexible rod threading is carved for locking nuts. The corners of the lower chord are fixed on the sides of the inverted U-shaped element by welding. On top of the inverted U-shaped element a timber strut rests through the front stop.

One of the important conditions determining the work of rod structures is the account of the real operation of the connection of elements, as the ductility of the joints of rod systems has a significant effect on the stress-strain state of the structure as a whole.

In the case of the classical design of a three-hinged thrustless arch (classical scheme), the maximum bending moment in the arch increases from 18.27 t·m to 19.19 t·m (by 4.8%). In the new arch:

- Scheme 1 (the distance from the support to the strut - 4.5 m) – with 121.25 kN·m to 134.69 kN·m (by 10%);
- Scheme 2 (the distance from the support to the strut - 5.5 m) – 123.51 kN·m to 132.83 kN·m (by 7%);
- Scheme 3 (the distance from the support to the strut – 3.5m) – 114.58 kN·m to 121.45 kN·m (by 5.6%).

In view of the reallocation of efforts, the dimensions of the cross-sections of the various arch variants are shown in Table 2 and the material consumption is shown in Table 3.
Table 2. Dimensions of cross sections of different variants of arches, taking into account the redistribution of effort in the account of the compliance of nodal connections.

| 18 m structure with a 3.6 rise | The upper circular chord | Tie | Flexible rods | Struts |
|--------------------------------|--------------------------|-----|---------------|-------|
| Classical structural solutions | 175×924 mm | 70×5 paired corner | - | - |
| Scheme 1 | 175×792 mm | 70×5 paired corner | Ø 44 | 99×175 mm |
| Scheme 2 | 175×759 mm | 70×5 paired corner | Ø 35 | 99×175 mm |
| Scheme 3 | 175×759 mm | 70×5 paired corner | Ø 55 | 99×175 mm |

Table 3. Consumption of materials for the production of different variants of arches.

| 18 m structure with 3.6 rise | Timber, m³ | Steel (C345), kg |
|----------------------------|------------|-----------------|
| Classical structural solutions | 3.24 | 294.3 |
| Scheme 1 | 2.79 | 483.99 |
| Scheme 2 | 2.69 | 346.87 |
| Scheme 3 | 2.68 | 682.19 |

4. Conclusions
The study resulted in founding that the use of the new design of the three-hinged arch allows reducing the calculated bending moment in the upper chord section at asymmetric loading by 36%.

As a result of varying the location of the struts, it is found that the most rational (from the point of view of the stress-strain state), is the installation of the strut at the distance of 1/5 L from the support node. Timber consumption compared to the classic solution of the arch has decreased by 17%.

Consideration of the yield of joint connections is required. It is found that the actual moment calculated in the cross section of the arch is greater than the one calculated without taking into account the compliance by 6%.

References
[1] Kashevarova G G, Zobacheva A Yu and Faizov I N 2010 Bulletin of Perm State Technical University. Construction and Architecture Issue 1 22-31
[2] Cannizzaro F, Greco A, Caddemi S and Caliò I 2017 Intern. J. Solids Struct. 121 191–200
[3] Fedorova F O 2013 *Architecton Proceedings of Universities* **41** 107–18
[4] Naichuk A J 2006 *News of Higher Educational Institutions. Forestry Journal* **3** 141–4
[5] Zhadanov V I, Dmitriev P A, Mikhaylenko O A and Arkaev M A 2012 *Arch Construction for Building Covering* Patent RF 2498026/20 Bul 31
[6] Set of regulations 2016 *Loads and Impacts* (Moscow: Publishing House of Standards) p 80
[7] Inzhutov I S 1995 *Block farms on the base of timber for buildings* (Novosibirsk: Novosibirsk State Academy of Construction) p 282
[8] Inzhutov I S, Deordiyev S V, Buchel K V, Zhadanov V I 2004 *News Higher Educ. Inst. Construc.* **8** 12–6
[9] Inzhutov I S, Loktev D A and Rozhkov A F 2015 *Proc. Higher Educ. Inst. Construc.* **4** 24–32
[10] Deriglazov O Yu 2007 *Development, design and research of the timber-ribbed dome ring with blocks of rigidity and collapsible nodes* (Tomsk: Tomsk State University of Architecture and Construction) p 183
[11] Rozhkov A F 2006 *Controlled Block Sections with Prestressed Timber Elements* (Krasnoyarsk: State Academy of Architecture and Construction) p 191
[12] Tur V I and Tur A V 2014 *Fundam. Res.* **6** 1165–68
[13] Kalinin S V, Zhadanov V I, Ukrainchenko D A and Lisov S V 2012 *Herald Orenburg State University* **9** 184–90
[14] *Timber structures* 2017 RF Set of Regulations (Moscow: Ministroy RF)