The Design of a Timber-Metal Arch with an Additional Lattice Taking Ductility of Nodal Joints into Account *

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Abstract. The article is dedicated to the rational efficient design of a three-hinged arched coating. It is noted that as a result of a significant decrease in the bending moment under asymmetric snow load the structure possesses a good rate of basic materials consumption. The numerical analysis of the arch stress-strain state has been done. The results of the arch stress-strain state under asymmetric and symmetric loads, comparison with the stress-strain state of a classical three-hinged arch included, have been given.

Keywords: Arched structures, Ductility, Timber construction.

1 Introduction

In the Russian and international construction practical experience arched coverings are widely used [1]. This is caused by such advantages of supporting arches as a lack or insignificant values of bending moments (depending on the structure geometry) under uniformly distributed load along the length [2]. However, in case of one-side or asymmetric loads of the same strength significant bending moments occur.

This peculiarity makes designers to search for a solution that will allow reducing the effect of asymmetric loads significantly.

The analysis of patents on inventions has revealed the following techniques [3-5]:

- installing a pre-stressed metal tightening into the structure of a three-hinged arch;
- installing additional inclined flexible rods and rigid bars of the lattice;
- installing a diaphragm with the stiffness of 10 to 20 times bigger than the upper belt linear stiffness in the middle of the arch span;
- increasing the height of the cross section of the upper belt by using lattice section made of still elements.

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We should note that along with the arch technological loads (such as crane and equipment loads) asymmetric loads occur as a result of snow uneven distribution along the arch length. In the modern standards regulating snow load on arched surfaces there are the following unloading schemes: Option No. 1 – parabolic load distribution with the maximal intensity in the middle of the arch span and zero intensity at the point of 60° slope of the arch; Option No. 2 – linear load distribution with zero intensity in the middle of the arch span and maximum intensity on one side of the arch at the point of 30° slope; on the other hand the intensity at the 30° slope point is half of the maximum (Figure 1) [6].

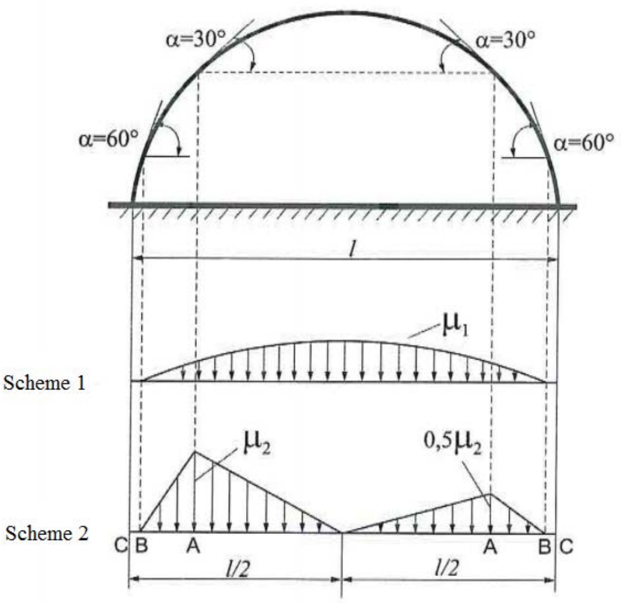

Fig. 1. The scheme of snow load distribution on the arch structure.

Widely spread one-sided and asymmetric loads for various types of buildings with arched coverings causes the necessity of designing new technological solutions that will allow reducing arch bending moments and thus decreasing material consumption and increasing economic attractiveness of applying arched structures.

To decrease bending moments Prof. V. I. Zhadanov and Prof. P. A. Dmitriev have proposed a new rational scheme of an arched structure (Figure 2, b) [7].

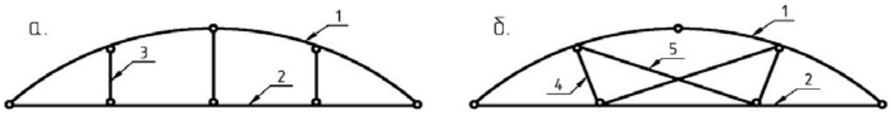

Fig. 2. The schemes of classical (a) and rational (b) arches: 1 – upper circular belt, 2 - tightening, 3 - suspensions, 4 - struts, 5 – flexible rods.

By using struts and flexible rods the reduction of bending moments under one-sided loads has been assured. A timber-metal circular arch with an additional lattice is a coating structure that includes the upper circular belt, tightening that connects the arch bearing joints, struts and flexible rods. The struts are installed symmetrically in the 1/4 of the arch span and directed along the radius perpendicular to the belt. The connection of the struts with the upper belt and tightening is hinged.

2 Materials and Methods

The arched covering with a span of 10 m has been designed for the region with the following climate characteristics: a snow area - V (2,5 кPa), a wind area – III (0,38 кPa). The distance between the arches is 3 m. Laminated plywood wooden plates have been used as roof structures: they have been insulated with mineral wool; the roof covering has been made of metal composite panels.

The design of the new three-hinged arch (Fig. 3, a) includes the upper belt, assembled of two curved wooden beams, wooden struts attached to the upper belt in the quarters of the span and installed in the arch plane in the direction perpendicular to its axis, metal flexible rods that connect the neighbor struts' tops and bottoms, the lower belt made of steel products of circular cross-section.

The main nodes of the structure are shown in Fig. 3, b - f.

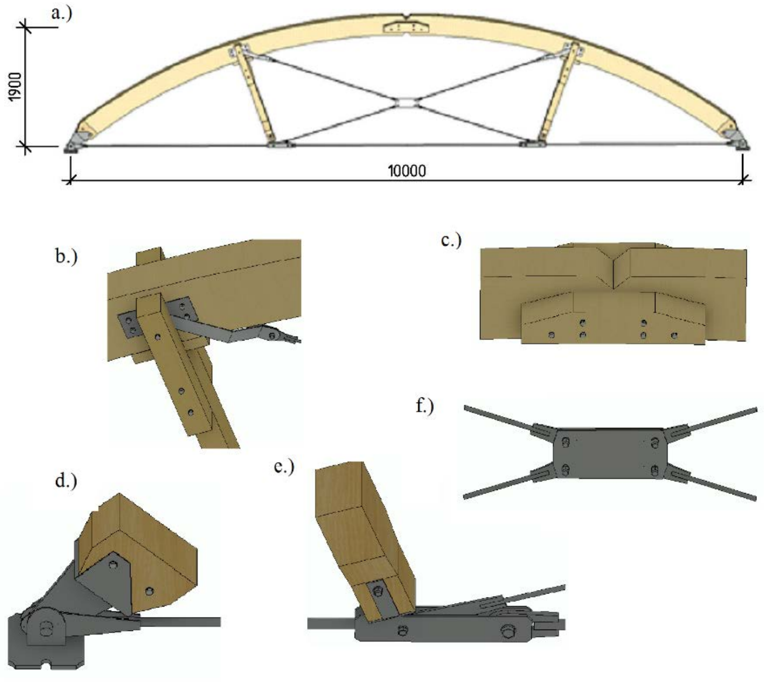

Fig. 3. The structure and nodes of the new arc.

The proposed arch design with the span of 10 m has been developed before the album stage of working drawings and it is characterized by the following values of main materials consumption: the mass of metal elements per one arch is 89.64 kg; the amount of wood needed to produce one arch is 0.545 m^3

To study stress-strain state of the arch the SCAD software has been used. The elements of a three-hinged circular arch with a span of 10 m, a lifting boom of 1.9 m and a curvature radius of 13 m has been modelled on the design scheme by the finite rod elements. The struts positions have varied, taking distance a from the reference node to adjunction to the upper belt where: a= 2.5 m (scheme 1), a=3 m (scheme 2) and a=2 m (scheme 3).

On the design scheme the upper belt has been divided into 8 equal sections, for scheme 2 and 3 one of the sections has been additionally divided at the point of the intersection with the strut. The upper belt on the design scheme has been divided into 8 equal sections, for scheme 2 and 3 one of the sections has been additionally divided at the point of the intersection with the strut.

During the arch stress-strain state four different versions of the load have been considered:

1. Dead load of the load-bearing structures, including the roof. The load is evenly distributed along the length of the arch; the values of the loads from the dead load of enclosing structures have been measured at the width of the load area – the distance between the arches of 3 m. The dead load of the arch bearing elements has been assigned by the SCAD internal tools based on the pre-assigned sections of the elements;

2. Snow loads. The intensity of snow loads has been adopted for the V snow area that is 2.5 kPa:

- Option 1, the load value has been calculated for each node of the arch. The evenly distributed load is trapezoidal. The load intensity has been calculated for the extreme points of each arch element; the load value between the points has been determined by linear interpolation.

- Option 2, the load values have been calculated at the points with a 30° slope and at the extreme points of the arch; the intermediate values have been determined by interpolation. The distributed load for the arch rods has been set similarly to Option 1.

3. Wind loads. The wind load intensity for snow area III is 0.38 кPa:

All the loads, except for the snow load, have been applied perpendicular to the support line. The load value has been calculated for the distance between the arches in the longitudinal direction of 3m.

The stress in the considered arch has been compared to the stress in a classical three-hinged circular arch for the schemes of snow and wind loads regulated by Construction Rules and Regulations 20.13330.2016 «Loads and affects».

Figure 4 shows the schemes of load cases.

a has been measured in the following values: $a_1 = \frac{1}{4}$L (2,5 m), $a_2 = \frac{1}{3}$L (3 m), $a_3 = \frac{1}{5}$L (2 m).

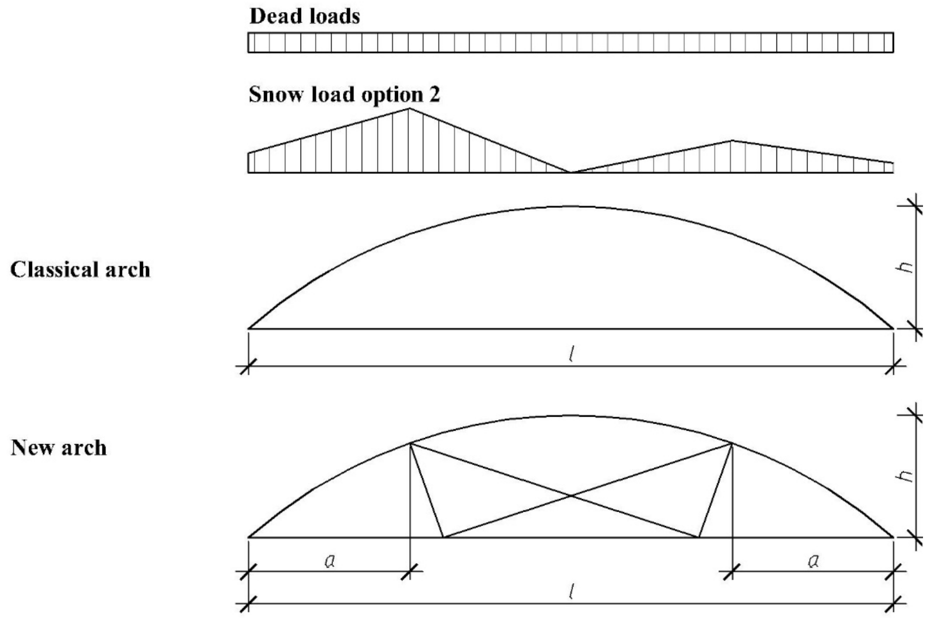

Fig. 4. The scheme of load cases. *h* – a lift boom, *l* –spa*n*, *a* – distance from the supporting node to the connection point of the strut and the upper belt.

$$E_y = \frac{E}{1+\delta_o \cdot E \cdot A/(N \cdot l)} \tag{1}$$

where E is the initial modulus of timber elements' elasticity (E = 10000 MPa); δ_o is the calculated limit value of the ductility deformations that is taken in accordance with the limit deformation of the nodal joint (which is 1.5 mm at the frontal felling and end to end; 2.0 mm at the dowels of all types; 3.0mm in the junctions across the fibers) and the degree of the bearing capacity use, respectively; A is a cross-sectional area of the rod, m2; N is a force effecting the rod, кN; l is a length of the rod, m.

The calculation of the limit ductility deformation value δ_o:

$$\delta_o = \delta_1 + \delta_2 \tag{2}$$

where δ_1 is a ductility deformation of the bolted connection, mm; δ_2 is a shear deformation of timber elements, mm.

3 Results

The results of the design scheme statistical analysis show that the most unfavorable load combination is the combined effect of the structure own weight and asymmetric snow load (Option 2) . In this case the flexible rod adjusted to the arch upper belt at the point of the maximum load (in our case it is on the left side) turns out to be compressed. Since the flexible rod was not initially intended to perceive compressive forces it has been excluded at the next stage of the calculations in the design scheme.

The maximum values of the moments, transverse and longitudinal forces in the different arch elements are shown in Table 1.

Table 1. Maximum values of the moments (*M, kN·m)*, transverse (*Q, kN*) and longitudinal forces (*N, kN*)

Maximum values of forces *Design scheme*	*M, kN·m*	*Q, kN*	*N, kN*
A classical three-hinged arch consisting of an upper belt and a tightening	25,89	25,52	112,43
Shifting the strut from the support joint by 2,5 *m*	15,55	19,67	126,98
Shifting the strut from the support joint by 3 *m*	15,92	19,88	127,26
Shifting the strut from the support joint by 2 *m*	16,70	20,29	126,44

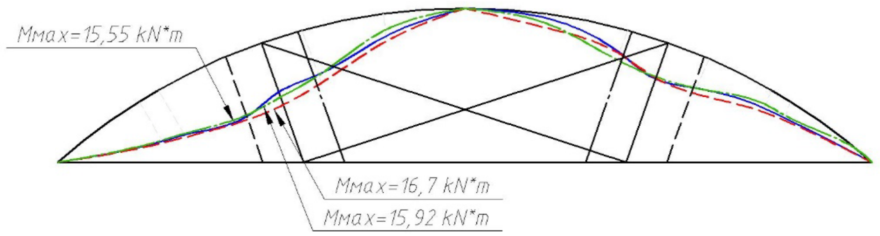

Fig. 5. Diagrams of moments under various arch design schemes.

It has been determined that the maximum values of the moments and transverse forces are observed in a classical arch; when the timber struts and flexible rods are installed the value of the calculated moment reduces by 40…35.5% (depending on the strut location), at the same time the transverse forces decrease by 23…20.5%.

The maximal values of forces in the new design arch occur in the variant when the strut is shifted from the support joint by 2 m. Besides, it has been noted that when the strut is shifted away from the support joint the longitudinal forces in the rods reduce while the stress in the struts increases.

According to the analysis of the diagrams it has been concluded that the most efficient option is shifting the strut away from the support joint by 2.5 m, as it has the most favorable stress values and it is the most relevant in terms of design and esthetics. When the strut is shifted closer to the center of the span the maximum moment is increased by 2.5 %, while shifting it towards to the support joint gives the increase by 7.5%.

To take the ductility of the nodal joints into account the elements with nominal elasticity modulus have been introduced to the design scheme. Figure 6 shows the diagrams of moments My, кN·m, where the dotted line shows the diagram gained taking the ductility calculations into account, and the solid line shows the diagram without taking ductility into account. The calculation has been made under the most unfavorable load combination.

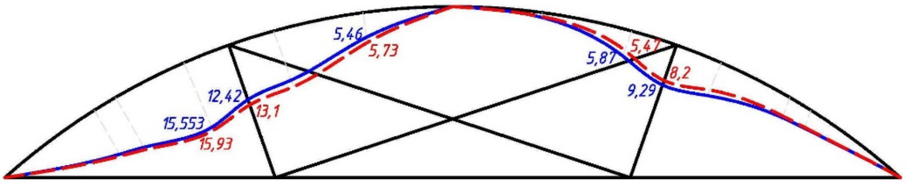

Fig. 6. Diagrams of moments *M_y, кN·m.*

The arch calculation taking the nodal joints' ductility into account shows that the value of the maximum moment has increased from 15.553 up to 15.93 кN·m. The value of the maximum longitudinal force has turned out to be less than the value calculated without taking the ductility into account: 124.333 кN versus 124.548 кN.

4 Conclusion

As a result of the conducted research it has been determined that the use of a new three-hinged arch design allows reducing the calculated bending moment at the section of the upper belt by 40% under asymmetrical load and decreasing timber consumption for the structure production by 18%.

As a result of shifting the struts to various positions it has been determined that in terms of the stress-strain state the struts installed in the quarters of the arch span are the most efficient.

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