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Experimental Study of Timber-Steel Arch with the Support Joints on Glued-in Steel Rods

***[1]Dmitry D. Koroteev, [2]Farid A. Boytemirov, [3]Makhmud Kharun**

* [1 3] Department of Architecture & Civil Engineering, Peoples Friendship University of Russia (RUDN University), Moscow, Russia

[2]Department of Metal & Wooden Structures, Moscow State University of Civil Engineering (MGSU), Moscow, Russia

* Corresponding Author: d241184@gmail.com

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Abstract

Vital problem, occurring in the operation process of bearing timber structures, is improvement of their durability in conditions of aggressive environment. Another aspect of this problem is the increase of fire resistance of timber-steel structures. One of the possible design solutions of this problem is given in the research work.

The aim of the research is study of experimental arch with support joints on glued-in steel rods. The arch was developed based on typical timber-steel arch with span length 11.8 m. Geometric shape and sizes of the arch were kept without changes, but steel elements were replaced by timber elements. Design features of the arch and calculation methods, taking into account bearing capacity of the joints on glued-in steel rods, are given in the research work.

The experimental arch showed enough reliability during the test and stiffness during transportation and mounting. The arch loading was carried out in laboratory bench by using hydraulic jacks. The load increased until the arch destruction. Deflection and deformation of glued-in steel rods were measured during the test.
Information about vertical deformation in the arch and stretching tensions along the length of the rods under the load were obtained in the test results. The results show that shear tensions in the joints spread along the bonding length unevenly and they have maximum value on the surface of timber elements. The arch showed perceptivity of practical using in the mild chemical-aggressive conditions and bearing structures with high requirements of fire resistance.

Keywords : Timber-Steel Arch, Corrosion Resistance, Fire Resistance, Bearing Capacity, Steel Rods

I. Introduction

Vital problem, which rises during the long-time operation of timber-steel structures, is the save of bearing capacity in conditions of mild chemical-aggressive environment (Li et al., 2017; Loss et al., 2016;Gavalli et al., 2014). It is the common knowledge that mild chemical-aggressive environment, which is characteristic of the reagent and fertilizer storehouses, stock buildings, does not influence destructively on softwood of the bearing structures (Cheung, 2016; Asdrubali et al., 2017).

However, chemical-aggressive environment is dangerous for unsheltered steel elements and joints in timber-steel structures (De Luca et al., 2012; Reynolds et al., 2014). Moreover, the use of unsheltered steel elements in structures and their joints reduces significantly aggregate fire resistance of timber-steel structures. It is connected with the steel feature to change physical-mechanical characteristics in condition of the increase of the steel elements temperature up to 550-650 °C. The significant reduction of elastic modulus and the slight reduction of the steel strength occur in such condition. It affects the fire resistance of the completelytimber-steel structure (Audebert et al., 2011; Erchinger et al., 2010).

One of the ways to increase the operation properties of timber-steel structures, especially corrosion and fire resistance, is the use of the joints, where steel elements are covered by timber (Bradford et al., 2017; Custodio et al., 2009). One of the types of such joints is joints on glued-in steel rods (Gattesco et al., 2017;). The glued-in steel rods are usually used for longitudinal and angular joints of timber elements, which withstand longitudinal force and bending moment. They are able to withstand longitudinal stretching and compressing forces (Gonzales et al., 2016; Yeboah et al., 2011). The steel rods, covered by timber, become sheltered from chemical-aggressive environment and quick heating during fire (Barber, 2017;Di Maria et al., 2017; Dietsch, 2011;Sandhaas et al., 2017).

Simple manufacturing and the low steel consumption characterize the joints on glued-in rods (Steiger et al., 2015). Adhesive layer covers the rods and timber hides them in such joints. The short steel rods, made from reinforcement, are glued in groovesoftimber elements with using of rather strong waterproof and heatproof compound based on epoxy resin. Epoxy compounds provide strong adhesive bond between steel and soft wood (Koroteev et al., 2017).

The joints on glued-in steel rods can be effectively used in the support joints of timber structures, such as truss and arch, especially operated in places with humid and mild chemical-aggressive environment and high requirements of fire resistance.

However, the absence of enough information about reliability of timber structures with the joints on glued-in steel rods slows down the distribution of such structures. The aim of the research work is to study the experimental arch with the support joints on glued-in steel rods to obtain the information about corrosion and fire resistance of such structures.

II Research Methodology

The design of typical timber-steel triangular arch with span length 11.8 m and height 1.48 m, which is used as a cover structure in small industrial and agricultural buildings, was taken as a basis for the experimental timber-steel structure. The new designed structure was triangular arch with the joints on glued-in steel rods.

Geometric shape of the arch and cross section of its upper part were kept the original, but steel elements were changed by timber. The glued-in steel rods were used in the arch joints and laminated timber was used in other elements of the arch (fig. 1)

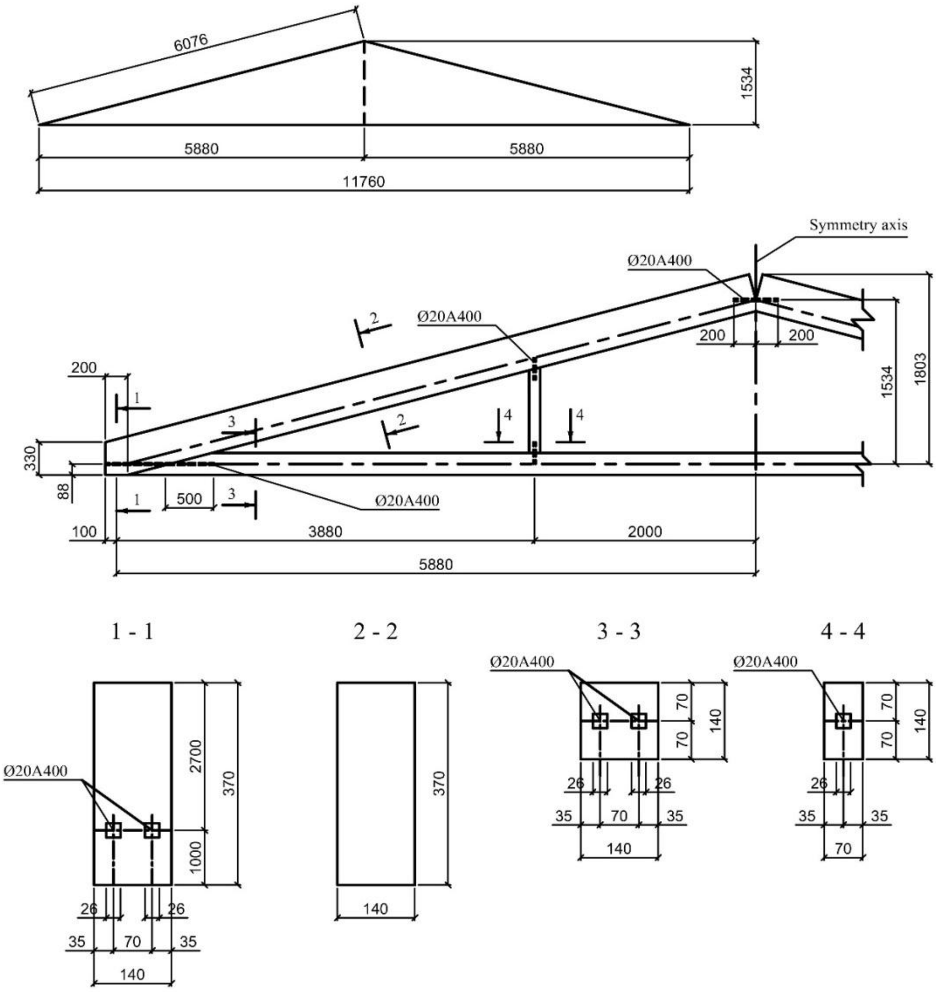

Fig. 1. Scheme of experimental timber-steel arch with the joints on glued-in steel rods

The experimental arch was made in laboratory conditions. The timber elements were made from sawn softwood (pine and fir threes), which is used for production of timber structures, with section 150x40 mm and the average limit of compressive strength 40 MPa and humidity 8-10%. The elements bonding was made by synthetic waterproof glue.

The cross section of laminated timber for upper part of the arch was with size 140x370 mm, for other parts – 140x140 mm. Support joints of the arch were designed as twin rods with diameter 20 mm and length 1 m from reinforcement A400, strengthened up to yield point 454 MPa. The rods were glued-in by epoxy-cement compound in rectangular grooves with width 25 mm. The rods were cleaned from corrosion and degreased by acetone in advance.

The channels to place strain gauges were made in the grooves. The ridge joint was also made with using glued-in steel rods.

The estimated load on the arch was determined under condition of bearing capacity of the rods, glued in the support joints, according to equation (1).

$$T = R_{sr}\pi(d + 0.005)l_b k_d \qquad (1)$$

wherel_b – bonded length, equal to 0.5 m; d – diameter of the rod, equal to 0.02 m; k_d – coefficient of uneven distribution of tensions in timber along the bonded length; R_{sr} – estimated shear resistance of timber, MPa.

The value of the estimated load, determined by equation (1), taking into account two rods, is 104 kN. The section of the arch was designed under condition of its uniform strength with the joints. The estimated constant evenly distributed load on the arch, equal to 8.85 kN/m, was determined by formula (2).

$$q = \frac{8Hf}{l^2} \qquad (2)$$

where$H$ – estimated stretching of arch; f – estimated height of arch; l – estimated span length of arch.

The average shear tension, equal to 2.1 MPa, the stretching tension in the arch, equal to 6.7 MPa, and the stretching tension in the steel rods, equal to 180 MPa, were assumed in the support joints under that load. These values show that the primary shear destruction of the adhesive joints is theoretically guaranteed under the expected destructive load, which is 2.4 times more than the estimated load.

The arch assembling was made in vertical position when the ridge was down. The grooves of the support joints and the ridge joint were filled by the epoxy-cement compound on the half of the rods diameter. Then, the rods, greased by the compound, were interred and the wooden slats with rectangular section covered the grooves. The arch was in that position during the day after the rods bonding, and then, it was transported to the testing area. The load on the arch joints was not allowed in that time and it was planned not earlier than 3 days after the beginning of the polymerization process of the epoxy-cement compound. The arch was transported in horizontal position and mounted by overhead traveling crane in the design position. It showed rather adequate mounting stiffness.

The arch was placed on moving and stationary roller stands, providing the movement freedom of the support joints. The upper part of the arch was fixed between four triangular wooden counterforts.

Static test of the arch was carried out by using four hydraulic jacks, working synchronously from joint pump unit. Those jacks were placed on the arch upper part in the quarter of arch length and fixed in the main beams of the laboratory bench by using double steel tension bars. Such scheme of loading satisfied the recommended design double-side load with the required accuracy.

The load on the arch increased with constant speed. It was the stepwise process with step, which was equal to a quarter of the design load with keeping each step during 10 minutes.Such scheme of loading satisfied the above-accepted loading scheme of the support joints with glued-in rods in laboratory conditions.

The following measurements were made during the arch test. The deflection of the arch upper and lower part in the joints and one third of the arch length was measured by using deflection gauges with scale 0.1 mm and test gauges of line type with scale 1 mm. The deformation of glued-in steel rods in the support joints was measured by using the deformation and strength gauges with scale 10 mm, fixed in the gutters.

Safety timber cross elements with small controlled clearance between them and the upper part of the arch were placed with aim to provide safety in the test process.

III. Results and Discussion

The arch destruction occurred 3 minutes after the destruction load making and, as we expected, the destruction was brittle in the result of shear of the rods, glued in the support joints in timber part of the arch and partly on the surface, bordering with the adhesive layer of the bonded rods. The rods bended considerably in the result of load and their surface cleared from timber and the adhesive layer almost completely.

The destruction of the support joints and the arch collapse were divided by some period, which was necessary for the complete rods pulling from the arch. The whole period of the arch loading was 90 minutes.

The value of the complete destructive load on the arch was P_p=291.6 kN.It satisfies the distributed destructive load q_p=24.7 kN/m, which was determined by formula (3).

$$q_p = \frac{p_p}{l} \tag{3}$$

Safety factor in this case was 2.8 in respect of the estimated load q=8.85 kN/m. It was determined by formula (4).

$$k_p = \frac{q_p}{q} \tag{4}$$

The arch reliability under its long-time loading in the operation process was determined according to equation (5) for safety factor.

$$k = 1.48(1.88 - 0.106 \log t) \tag{5}$$

where$t$=0.02t_1+t_2 – time characteristic; t_1=90x60=540 sec – time of loading;t_2=3x60=180 sec – time of withstanding of the destructive load.

Safety factor k=2.4, in this case we can assume that the arch will have enough reliability under long-time loading in the operation process because the safety factor, obtained in the test result, is k_p=2.8.

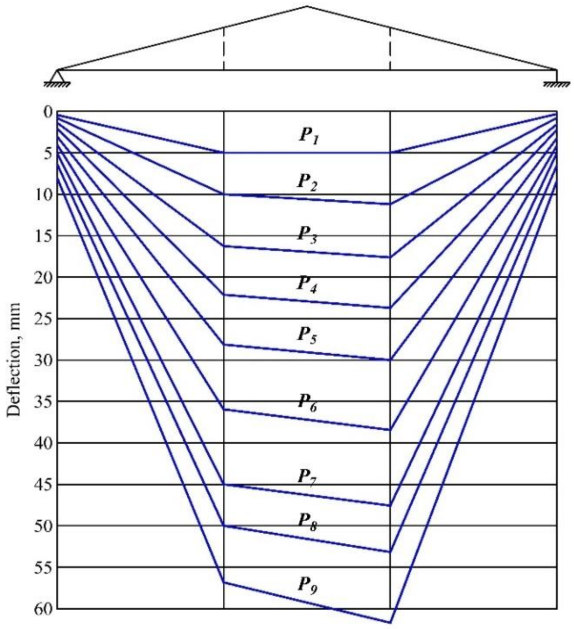

Fig. 2.Deflection of the arch lower part under various steps of loading

The deflection graph in the ridge joint and the lower part of the arch in the middle of span length, as well as the deflection graph along the length of the arch are shown in fig. 2 and fig. 3.

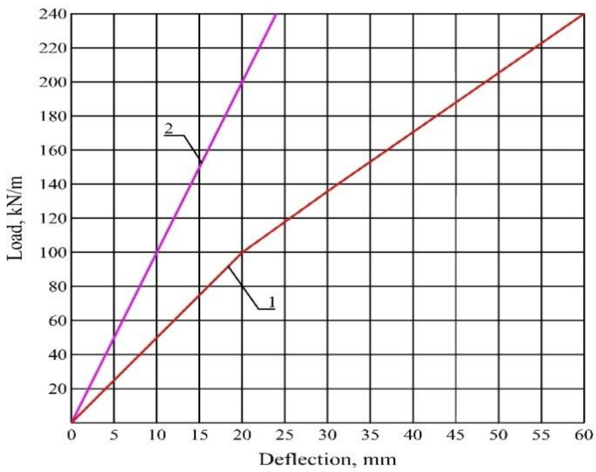

Fig. 3.Dependence of the arch deflection on the load value

1 – in the middle of span length; 2 – in the ridge joint

The increase of deflection, as we can see, has line pattern in the loading process. It testifies to elastic work of the arch elements and joints. The arch deflection under normative load, accepted conditionally equal to 6.8 kN/m, was 1/400 for the arch upper part and 1/800 for the arch lower part. It is less than the deflection value 1/200, accepted by normative documents.

The deflection unevenness of stretching tensions between two bonded rods was about 8%. It is connected with random eccentricity of the stretching tensions, which was identified during the pulling tests of one-rod and double-rod joints.

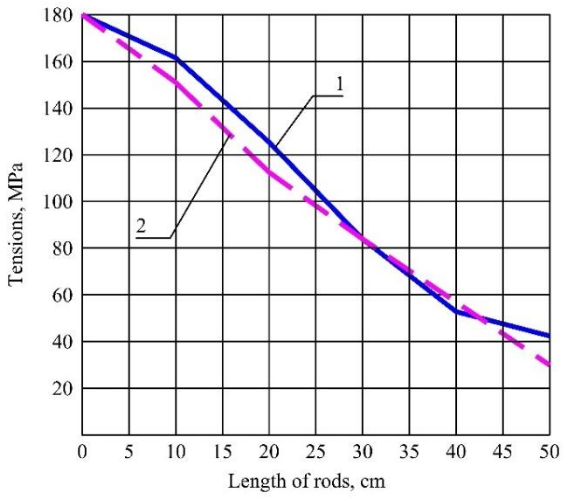

Fig. 4. The tensions distribution along the rods length under the estimated load
1 – glued in the arch lower part; 2 – glued in the arch upper part

The obtained graph of the change of the stretching tensions of glued-in steel rods in the support joints shows that the tensions along the bonding length decrease in four times (fig. 4). Moreover, maximum values, measured in the beginning of the joint, are 164-166 MPa, the average value of shear tension in timber under the arch destruction is 3.74 MPa.

IV. Conclusion

The joints on glued-in steel rods have enough strength and reliability, which are characterized by safety factor k_p=2.8, obtained in the test result of the joints samples and the triangular arch.

The arch strength depends on shear strength of the joints between rods and timber. The break of the samples across the wooden grain is possible under the shear destruction.

The joints on glued-in steel rods have high strength and should not be taking into account in calculations. The slats, bonded in the grooves, increase bearing capacity of the joints in some extent.

The experimental arch showed enough reliability during the test and stiffness during transportation and mounting.

Stretching tensions of glued-in steel rods, and therefore, shear tensions in the joints spread along the bonding length unevenly. They have maximum value on the surface of timber elements.

The experimental arch showed perceptivity of practical using of such structures in the mild chemical-aggressive conditions, which are characteristic of the reagent and fertilizer storehouses, stock buildings. They are also interesting for bearing structures with high requirements of fire resistance.

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