Research of the Stress-Strain State of Glued Wooden Structures After Prolonged use in Various Extreme Conditions

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Abstract. Glued wooden structures for example beams, frames, archs had been used in the territory of the Arkhangelsk region in the period since the 70s to the 90s years of the XX century for the purpose of industrial and agricultural assignment as load-bearing structures of the coating. Today their age is 30-40 years. Such a period of time makes it possible to evaluate the technical condition of structures from the point of view of durability and to identify the main errors and shortcomings when design, construction and operation of glued wooden structures. The article presents the results of the survey of wooden glued structures coatings for various purposes: Ice rink, swimming pool, production hall with challenging temperature-humidity conditions. The survey was identified damage in beams in the form of degradation of the wood due to lesions wood-destroying mushrooms, longitudinal cracks in the glue seam, and damage by fire. In most cases, the cause of damage is the improper operation of buildings. Are most common damage have been identified longitudinal cracks in glue lines. Influence of cracks on the stress-strain state of glued wooden structures is addressed. The method for solving a problem of accounting for disbonds in a glued wooden structures is invited.

1. Introduction

The history of application of laminated wood structures (LWS) in the Arkhangelsk region is associated with construction of 2 factories in the region: Pilot Production Plant the Red October in Arkhangelsk and the Velsky laminated wood structure plant in Velsk.

The Velsk laminated wood structure factory specialized in production of load-bearing and enclosing structures for construction of Minselstroi facilities. The factory produced rectilinear beams, laminated wood three-hinged arches and laminated wood three-hinged lancet arches, curved laminated frames, roof slabs, wall panels, and others LWS for agricultural enterprises.

Pilot Production Plant the Red October in Arkhangelsk mainly specialized in production of laminated structures for the timber industry complex. Large number of beams of rectilinear contour for the roof slabs of production buildings were manufactured here.
At present, the age of the majority of the LWS is 30-40 years, and the question of determination of their technical condition after long-term operation under different operating conditions, as well as an estimate of the remaining life time of such buildings is now very important.

2. Urgency and formulation of the problem
In the Arkhangelsk region, a number of objects made of LWS were surveyed in accordance with the norms [1]. Let us show the two most typical objects [2-7].

a) Inspection of roof beams of the Palace of Sports in Arkhangelsk.

The indoor skating rink in Arkhangelsk is one of the first unique structures with a large span of wooden laminated structures built in our country. The building was put into operation in January 1981. The gym, in which the ice rink is located, is covered by three-hinged wooden arches with a rise of 11 m and a step of 6 m. The wooden arches have solid straight section 360x1600 mm. In the arches there are many cracks in the form of non-glued adhesive joints up to 1 m long, up to 30 mm deep and 1 mm opening width (Figure 1).

![Figure 1. Palace of Sports in the city of Arkhangelsk. Longitudinal crack in the bearing part of the roof arch.](image1)

b) Roof arches of the dryer and stacking line of the timber mill No. 26

Bearing structures of the roof of the timber dryer and stacking line of the timber mill No. 26 in Arkhangelsk are laminated wood beams. The beams have single-slope span 15.3 m with a console of 3.4 m. The cross-section of the beams is 1260x215 mm. One of the beams has collapsed. Other beams have longitudinal cracks.

![Figure 2. Collapse of the roof beam of LWS No. 3 shop in Arkhangelsk. Cracks in the glued joint of the roof beams](image2)

The above examples show that the most common defects are crack in the glued joints. And for massive wooden structures (consisting of several layers of boards across the width), the cracks are usually superficial, associated with the opening of cracks in the upper layer of the laminated pack. Basically, such cracks do not affect the load-bearing capacity of the structure. For high beams
with h/b>5 ratio the cracks can be through and reduce the bearing capacity of the LWS, which must be restored.

According to the analysis the strength and rigidity parameters of the LWS with cracks have not been sufficiently studied. In the current regulatory documents and recommendations for inspection of building structures, there is no system and algorithms for assessment the influence of the cracks on the stress-strain state (SSS) of the laminated wood structures. In order to properly perform the reinforcement of the structure, it is necessary to know the degree of influence of the crack on the construction SSS. Some issues of the influence of cracks are described in the works of M.L. Birichevsky, A.Y. Naychuk, A.B. Schmidt et al. [8-12].

3. Theoretical part and practical significance
The cracked laminated structure essentially represents a system of composite rods connected together by glue joints in undamaged areas.

One of the first scientists who calculated the compound rods was Friedrich Engesser (1848-1931) [13]. He considered the composite rod monolithic, but lowered the shear modulus of the material, as a result he derived the formula for the reduced elastic modulus. R. Mises and R. Rattsendorfer have further developed the theory. In modern norms, the calculation of composite wooden structures is carried out according to this theory [14]. This technique is reliable and fairly simple for designers. The known formulas of structural mechanics for the monolithic body are applied taking into account the compliance coefficients kw and kz, ie, reducing not the shear modulus but the geometric characteristics of the cross section. N. Müller-Breslau, A. Längberg, L. Grüning [15-17] proposed to define the forces in the composite elements considering the composite rod as a frame system. I. Arnovlevich carried out work aimed at examination of shear forces during their distribution along the length of the beam. His research was continued by Phyllunger, Govgard, Ezek, Sokolov, Zhukovsky. For the wooden composite rods, the effect of the compliance of the joints was first studied by V.G. Pischikov. The first simplified theory of compound rods was developed by P.F. Pleschkov.

The credit in development of the general theory of calculation of composite rods goes to the most prominent academic professor A.R. Rzhanitsyn, who compared and analyzed the works of his predecessors and elaborated a mathematical apparatus describing the work of composite rods [18]. Rzhanitsyn proposed to consider the composite structure as a hinged pivot system, where the composite rods are connected to each other by transverse links and shear bonds.

V.V. Bolotin [19] proposed a calculation for composite materials based on the principles of energy continuation, and Professor Labudin B.V. in [20] suggested to assess the long-term shift of the adhesive joint using the energy method.

We proposed to consider the calculation of the composite wooden beam as a hinge-rod finite element model implemented in the software products SCAD Office, Lira Windows, Ansys, etc.

The nature of the design scheme was adopted in accordance with the initial data and assumptions proposed in [8] and [18]:

- The composite rod for the LWS without a defect is a rod consisting of two or more branches that are elastically joined together by gluing.
- The joint is a gap between the composite rods (glued joint). The thickness of the joint is assumed to be infinitesimal.
- The joint is considered to be a supple elastic bond (the adhesive joint itself is rigid for a small thickness, however, due to the compliance of the wood along and across the fibers, the bond can be considered pliable).
- Connections are established continuously along the joint. Shear links and cross links (2.1.1) are considered.
- The shear bonds receive only tensile components of shearing forces.
- Cross-links provide only pressing of one rod to another
- The bending moment is not received by the joint, therefore the joint of the tie beams with the longitudinal bars is assumed to be hinged (Figure 2.1.1)
Wooden beams of rectangular section are considered and it is considered that for the bent stress element in a compressed zone the beams are equal to the stresses in the stretched zone (an ideal beam without defects in the elastic stage).

We consider the composite beam as a hinged-rod scheme (SSS) with continuous bands for the entire length and with pivotal connection to them of columns and braces (Figure 3). The shear links in the SSS are the slope braces, and the cross links are SSS columns. The slope braces in SSS should only take up tensile efforts, that is why up to the middle of the SSS span downward slope braces are used and above the middle - the ascending ones. The tension of the links affects the stress-strain state. Cross links have low compliance, so it can be neglected and absolutely rigid links can be accepted. Shear links are compliant. In order to take account of their compliance, in the general case, the shear stiffness coefficient is introduced into the scheme:

\[
k = \frac{ES}{L}
\]

where E is the modulus of elasticity of the joint, equal in this case to the shear modulus; S is the cross-sectional area of the element; L is the length of the element equal to the distance between the cross links.

We transform (1) with respect to the glued joint [18]

\[
k = \frac{bG}{c}
\]

where b is the width of the beam; G is the shear modulus; c is the distance between the axes of the composite rods.

By changing the shear modulus and the cross-sectional dimensions of the element in formula (2), we can change the compliance of the joint.

The magnitude of the shear forces depends on the distance Y between the SSS belts. To determine the Y consider normal stress diagram in a continuous bend section wooden beam h × b (Figure 4 a). The axes of the SSS belts will coincide with the axes passing through the centers of gravity of the stresses of normal stress diagrams within the rod. The distance Y will be equal to the distance between the centers of gravity of the normal stress diagrams.

For example, if the joint is located in the middle of the height of the beam section, the resultant stress force for the upper rod will be located at the center of gravity of the triangular diagram, and the distance between the axes of the HSS belts will be \(Y = \frac{2}{3}h\) (Figure 4b).

If the joint is above the neutral axis, the resultant stress force for the upper rod is located at the center of gravity of the trapezoidal diagram of the compressed zone. The equal force for the lower rod is located at the center of gravity of the stress diagram of the stretched and compressed section (Fig. 4 c, d).

The shear force up to the cross-section in the hinged-rod scheme with continuous bands is determined (Figure 5) by:
\[ T = \sum_{i} N_{pi} \cos \alpha_i \left( \frac{M_{ani} + M_{uni}}{Y} \right) \]  

(3)

\[ T = N_{ani} + \frac{M_{ani} + M_{uni}}{Y} \]  

(4)

Shear force for a separate part:

\[ T = N_{pi} \cos \alpha_i + \left( \frac{M_{ani} - M_{ani-1} + M_{uni} - M_{uni-1}}{Y} \right) \]  

(5)

Bending moment for the beam:

\[ M = T \times Y \]  

(6)

**Figure 4.** Determination of the distance between the axes of the SSS belts

- a - the diagram of internal stresses in a rectangular beam; b - distance between the SSS belts for a joint located in the middle of the height of the beam section; c - the distance between the SSS belts for a joint located at 1/3 of the beam cross-sectional height; d - is the distance between the SSS belts for the joint located at 1/4 of the cross-sectional area of the beam

**Figure 5.** For determination of shearing forces in SSS with monolithic belts.

In a system with continuous belts and hinged connection of columns and braces, it is possible to remove shear links. It helps to simulate "non-adhesion" in the laminated wood beam and calculate the composite wooden beams with different types of connections. The solution of this problem is quite simple and can be performed by an engineer who does not have in-depth mathematical knowledge.

4. Conclusions
The main causes of the destruction of the LWS are improper operation with violation of the design temperature and humidity regime, as a result we see their destruction by wood-destroying fungi and formation of cracks. The most common and dangerous defects and damages are longitudinal cracks in glue joints; registration of their influence on the stress-strain state of the structure is an urgent problem. The developed hinge-pivot system of composite beams helps to determine the shear forces and distribution of shear forces along all beam sections. To model the defects and damages to the glued joint in the beam, the hinge-pivot system is adopted with continuous belts replacing the composite rods of the beam and with hinged connection of the columns and braces simulating the glued joint. By removing the sloped brace imitating a defect or damage we can assess their impact on the beam performance. Substituting instead of a sloped brace imitating a defect or damage, with a brace imitating the reinforcement element, the optimal type and cross section of the reinforcement element will be chosen. Such a model can also be used for selection of bond elements in a composite beam.

References
[1] Recommendations for full-scale inspection of wooden structures 1983 (TsNIISK)
[2] Karelsky A, Labudin B and Melekhov V 2011 Wooden constructions: education, practice, innovations in the countries of the Barents Euro-Arctic region. Collection of proceedings of the international scientific and educational seminar Classification of defects and damages of structures made of laminated wood (Arkhangelsk: Publishing house "Advertising agency" RAD") p. 165
[3] Karelsky A, Labudin B and Melekhov 2010 University Science to the Region: Proceedings of the 8th All-Russian Scientific and Technical Conf. 2 vol. On the urgency of the issue of vitality of buildings and structures made of laminated wood (Volgda: VSTU T.1) pp. 203-204
[4] Karelsky A, Labudin B and Serov E 2010 Building science: theory, practice, innovations to the north-arctic region: collection of scientific papers of the international scientific and technical conf. Inspection of the support areas of roof arches of the Palace of Sport in Arkhangelsk (Arkhangelsk: Northern (Arctic) Federal University) pp. 188-190
[5] Karelsky A 2010 Theoretical bases of construction. Collection of proceedings of the XIX Polish-Slovak-Russian seminar Slovakia, Zilina, September 12-16 Results of full-scale surveys of wooden curved glued arches of covered ice rink in the city of Arkhangelsk after a long operation period (ASV Publishing House) pp. 177-180
[6] Yashkova E, Varfolomeev Y, Popov A and Karelsky A 2007 Environmental protection and rational use of natural resources. Collection of scientific papers. Issue 73 Results of full-scale surveys of structures of swimming pool buildings after long-term operation in the north conditions (Arkhangelsk) pp. 274-277
[7] Karelsky A, Labudin B and Melekhov V 2012 Forest Journal №3 Requirements for reliability and safe operation of large-span laminated wood structures (Arkhangelsk Institute of Higher Education) pp.143-147
[8] Birichevsky M., Varfolomeev Y and Slavik Y. 1986 Construction mechanics and calculation of structures №3 Influence of location and size of cracks on the strength of bent wooden elements (Stroyizdat Publishing House) pp.42-44
[9] Birichevsky M. 1976 Thesis of the Candidate of technical sciences Analysis of strength and deformation of bent elements of structures made from laminated compositions (Leningrad) p.521
[10] Naychuk A 2004 Industrial and civil construction №6 About the bearing capacity of wooden laminated beams with through cracks pp.38-40
[11] Shmidt A 2009 Modern metal and wooden structures (rationing, design and construction): Collection of scientific papers of the International Symposium Operation of laminated wood structures with manufacturing and operation defects (Brest) pp. 377-380.
[12] Reiterer A and Tschess S 2002 Mater, Science Vol. 37 The influence of moisture-content on the mode I fracture behavior; of spruce wood pp. 4487-91
[13] Engesser F Zentralblatt der Bauverwaltung 1891 487p 1907, 609p
[14] SP 64.13330.2011. Wooden constructions. Updated version of SNIp II-22-81 Moscow 2011 p.66
[15] Gruning L 1925 Die Statik des eben Tragwerkes Berlin
[16] Lewicki B 1964 Budynki mieszkalne z prefabrikatow wielkowy miarowych Warszawa p. 602
[17] Muller-Breslau H 1913 Neuere Methoden des Festigkeitslehre Leipzig p.388
[18] Rzhanitsyn A 1986 Composite rods and plates (Stroyizdat Publishing House) p.316
[19] Bolotin V, Goldelblat I and Smirnov A 1972 Structural mechanics. Current state and development prospects (Stroyizdat Publishing House) p.192
[20] Labudin B 2007 Monograph Perfection of laminated wood structures with spatially regular structure (Arkhangelsk: ASTU) p.267