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A research of stress/strain condition of reinforced timber structures with natural weakenings

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Abstract. In recent decades building structures are faced with more serious demands in a broad sense of this term, but in this case the lumber quality is gradually lowered due to large volumes of consummation along with sufficient time, needed to reproduce a stock lumber. As a result, there is a need for a more detailed and in-depth study of the influence of low-grade wood defects on the work of wooden structures. One of the methods to improve characteristics of structures, made with low-grade lumber is a reinforcement of these. The objective of the research below is to determine a degree of influence of a cross-sectional natural weakenings (such as knots) to a stress/strain condition of reinforced timber beams. The main research methods are as follows: mathematical calculations, computer modeling in the software "Cosmos/M" and an experiment. The methodic of an experiment planning is based on the "Latin Squares" principle [1]. The square is designed for three primary factors, each of which consists of three variants. The results of the research work are shown in form of graphs and tables. The main conclusions made after the research: the deformation of the reinforced beams is from 15 to 20% lower, as compared with non-reinforced; crushing of reinforced beams with weakened cross-section takes place without a sharp state of a former because of a supporting influence of reinforcement in tensioned zone and reliable connection of reinforcement with wood, which is ensured by a glued joint until the crushing of the timber. The safety factor of reinforced timber structures varies from 3 to 5.07.

1 Introduction

Wood is a material that finds wide application and a variety of uses in life. Forests unlike fossil resources (coal, oil, etc.) are able to recover (the average age of maturity of trees in the stand is 20-50 years, depending on the breed [2]). The suitability for use is determined by the quality of the wood, which consists of a set of physical and strength properties. In any wood there are some defects. International standards ISO 1029, ISO 1030, ISO 1031, ISO 2299, ISO 4475, Russian Federation State standard GOST 2140-81 [3] classify, introduce

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terminology, regulate the norms of restriction and indicate methods for determining visible defects.

In view of the fact that the quality of wood is influenced by a wide variety of defects, it is divided into several groups (varieties) for each of which the norms of restriction or application of defects are described in detail and regulated. According to Russian Federation State standard GOST 8486-86 [4], the lumber is distributed to the 1st, 2nd, 3rd and 4th grades, however, the production of glued constructions does not practically use wood of grades 3 and 4. Timber defects have a great influence on the process of bonding, deteriorating the quality of the adhesive joint and construction.

Many scientists, who investigated bended laminated glued timber structures proved, that the main reasons of the structures crushing are natural defects of timber. Mainly on the quality of timber structures influences knots, which reduce several times the strength of a timber, reduce functional cross-section of a structure, and therefore it load-bearing capacity, because crushing of structural elements very often takes place along the most weakened parts, i.e. along a zone with knots [5, 6, 7, 8, 9.10]. To reduce the impact of natural defects on the strength and load-bearing capacity of structures, researchers are proposing a large number of options for strengthening and hardening of glued wooden structures in order to expand the scope of such structures. One of the types is reinforcement - both steel and composite reinforcement.

Analysis of studies conducted over the past decade [11- 18], the most common material is carbon fiber or carbon plastics, having a number of advantages: high specific strength, corrosion resistance, low heat and electrical conductivity, as well as environmentally friendly material - non-toxic. Strengthening of wooden structures is carried out either by gluing the rods at different angles to the structure, or by layers, between the glued layers of planks, or by external reinforcement. According to the data of [18], in experimental studies of models of wooden beams reinforced with carbon plastics, an increase in the bearing capacity in the range of 21...79% was observed. However, despite these advantages, carbon plastics in wooden structures in the Russian Federation are rarely used in view of the insufficient study of composite structures, the lack of a broad regulatory framework for their application and design, and the cost of manufacturing such structures [18].

According to the results of numerous tests [1, 19- 26]] - reinforcement allows reducing the cross-sectional height of wood elements by 25-30%, cutting wood consumption by 30-40%, reducing by 15-25% assembly mass, 12-18% cost, and also allows the use of 3 grade wood, due to the perception of the valve by a significant part of the load, and over time, the value of the proportion of the perceived load, in the armature, from the acting bending moment only increases. But when using steel reinforcement there are a number of drawbacks, the main one is the corrosion of the reinforcement over time. However, the rigidity, ductility and thermal stability of steel reinforcement allow it to occupy the leading positions to this day in the creation and production of reinforced wooden structures.

2 Materials and methods

For research, the beam was taken as a basis, by a span (l) of 1.8 m, with cross-sectional dimensions 125 (h) x 30 mm. The planning of the studies was based on the method of the Latin (combination) square, taking into account three main factors: the factor h - takes into account the influence of the height of the wooden beams, expressed in relative values l/h = 1/16, 1/17, 1/19; factor μ - takes into account the effect of the reinforcement factor on the strength and rigidity of wooden beams and varies μ = 0; 0.027; 0.042; Factor C - takes into account the influence of the grade of wood: Class I, Class II, Class III [27]. This method made it possible to reduce the number of beams investigated from 27 to 9, with a slight decrease in the accuracy of the dependencies. For the testing, three series of beams were made, the beams were made from pine wood 1, 2, 3, grades K26, K24 and K16 [28]. The first series of beams was without reinforcement; in the other two series of beams, the reinforcement was carried out with reinforcing bars of AIII class (A400) which were pasted into grooves of a rectangular cross-section, using an epoxy-sand compound [1, 22, 23, 25]. Series of beams: I series - unreinforced beams: B I-1 (1), B I-2 (3), B I-3 (2); I Series I - reinforced beams, diameter of reinforcement 8mm: B II-1 (2), B II-2 (1), B II-3 (3); III series - reinforced beams, armature diameter 10mm: B III-1 (3), B III-2 (2), B III-3 (1).

Arabic numerals 1, 2, 3 - in the marking of beams mean the height of the section, h = 115 mm, 105 mm, 95 mm - respectively. Roman numerals I, II, III - series of tests: I - unreinforced beams, II - reinforced, reinforcement 8mm in diameter, III - reinforced, reinforcement with a diameter of 10 mm, the numbers in parentheses - grade: 1 grade, 2 grade, 3 grade.

For these beams, mathematical calculations were carried out based on the method of calculating reinforced wooden structures according to the given geometric characteristics, which is based on the idealized diagram of the elastic-plastic work of wood, with the hypothesis of flat sections provided that the steel-wood glue joint ($\varepsilon d = \varepsilon a$) at all stages of the design work until destruction [29]. To verify the engineering calculation method, an analytical model was created based on the finite element method (FEM) with the help of the finite element analysis program "COSMOS / M" that performs linear and nonlinear static and dynamic analysis and allows solving stability problems. In the program "COSMOS / M" the matrix of elastic characteristics for each element with a different modulus of elasticity.

For the elements of the pine wood panel the following characteristics were specified:

EX = 16600 MPa, GXY = 1180 MPa, NUXY = 0.42.

To simulate the attenuation of artificial origin, the elements of the pine wood group are selected from the region of the partition, at the point of weakening.

To model the attenuation of natural origin (knots), the material directions of the mechanical constants of the elements of the pine wood group change:

EZ = 16600 MPa, GXZ = 1180 MPa, NUXZ = 0.42.

In accordance with [30], full-scale testing of beams was performed in two stages: At the first stage, the stress-strain state of reinforced and unreinforced beams was investigated, with natural weakening, the nature of failure was determined depending on the design parameters and the nature of the location of the weakening in wooden beams.

In the second stage, the integral modulus of the beam without reinforcement was determined, which, in contrast to the design elastic modulus, takes into account the heterogeneity of the wood and defects, at this stage a selection of beam blanks according to similar parameters was performed.

The moisture content of wood was within 10%, the air temperature in the room was within 18-22ºC, and the relative humidity was 50-60%.

The physical and mechanical characteristics of wood and reinforcement were determined in accordance with the requirements of GOST. The values obtained were used in the processing of the test results. The load was applied in thirds of the span; such a decision was made in order to obtain a pure bend.

Experimental studies of structures spanning 1.80 m were carried out on a test bench (Fig.1). The distributing beam provided a correct division of the load in half and transfer it to the tested structure. The stability of the beams from the plane was provided by vertical struts attached to the responding beam.

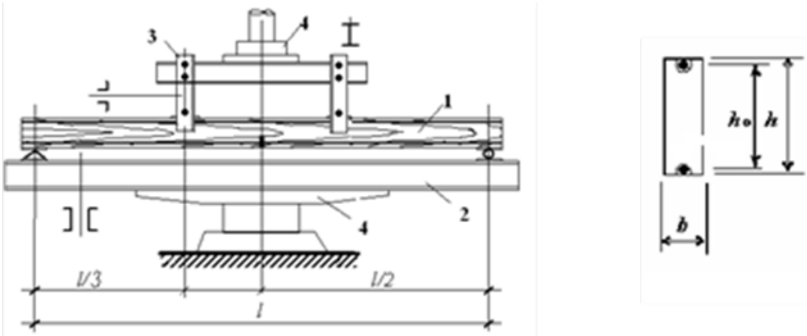

Fig. 1. The scheme of the experimental installation for testing beams with a span of 1.8 m: 1 - reinforced wooden beam; 2 - reactive beam (channel 14 according to GOST 8240-97); 3 - distributive traverse (I-beam # 10 in accordance with GOST 8239-89); 4 - hydraulic press.

3 Results

In Table. 1 shows the values of theoretical and experimental deflections in the course of the experiment; in parentheses, the ratio of the experimental to the theoretical values is indicated.

In Table. 2 presents the results of beam research (theoretical, with the help of FEM and practical on the experimental installation).

Table 1. The main results of experimental and theoretical research of beams.

No	Series of beams	Cross-section		Design load in KN	An experimental camber under deskin load , mm	A theoretical* camber under design load, mm	Crushing load, KN
		h, mm	b, mm				
1	BI-1(1)	110.0	30.0	4.93	0.6378	0.8558 (34%)	8.0
2	BI-2(3)	105.0	30.0	3.63	0.2935	0,5518 (88%)	5.2
3	BI-3(2)	95.0	30.0	2.02	0.5844	0,5703 (2,4%)	5.8
4	BII-1(2)	11.0	30.0	4.3	1.0266	0,8419 (18%)	16.0
5	BII-2(1)	105.0	30.0	5.27	1.8081	0,7165 (60%)	15.8
6	BII-3(3)	95.0	30.0	3.21	0.9558	0,4538 (53%)	13.0
7	BIII-1(3)	115.0	30.0	5.85	0.877	0,6679 (24%)	21.0
8	BIII-2(2)	105.0	30.0	5.07	0.9373	0,7036 (25%)	16.0
9	BIII-3(1)	95.0	30.0	5.59	1.1562	0,588 (49%)	15.0

* - Theoretical deflection is calculated by the formula 3.4, % - the ratio of the experimental deflection to the theoretical deflection.

Table 2. Comparison of beam research results.

No	Beams	Factors	Camber, mm	Modulus of elasticity E×103
1	Non-reinforced	Theory	0.5442	1,0
		“Cosmos/M”	0.5477	1,0
		Experiment	0.5052	0,997
4	Reinforced, with reinforcing steel diameter da=8 mm	Theory	0.578	1,0
		“Cosmos/M”	1.1876	1,0
		Experiment	1.2635	0,971
7	Reinforced, with reinforcing steel diameter da=10 mm	Theory	0.5436	1,0
		“Cosmos/M”	1.0863	1,0
		Experiment	0.9902	0,987

4 Discussions

The weakening of the cross section significantly reduces the strength and deformability of the wooden structures.

When comparing the results of the experiment (see Table 1), it can be seen that in reinforced beams, the strength and reliability indicators are higher than those for unreinforced beams: the value of the design load increased by 1.19 to 2.77 times, when comparing beams with the same h, but different C and μ and in 1.07 - 2.51 times when comparing beams with the same C, but different h and μ; the value of the destructive load increased by 2.0 - 3.08 times when comparing beams with the same h, but different C and μ and by 1.88 - 4.04 times when comparing beams with the same C but different h and μ. This is due to the fact that the reinforcement absorbs some of the load, which makes it possible to increase the design and breaking load, without increasing the cross-section of the structures.

If we observe the effect of attenuation on each series of beams, we note separately that the strength and deformation characteristics decrease with an increase in the area of attenuation, but with the change in the factor h, these characteristics can be improved: the values of the deflection in a timber of grade 3 at h = 95 mm (B II - 3 (3)) below the deflection in the beam of 1 grade timber at h = 9 5mm (B III - 3 (1)) by 21%.

The percentage of the experimental deflection to the theoretical deflection is on average 38%, because wood is an anisotropic material, and the results of experimental studies were influenced by other attenuation of the natural origin of the beams distributed throughout the span.

A comparative analysis of the results for reinforced beams also showed a good convergence of the results of theoretical and experimental research. The results of calculating the reinforced beams using the COSMOS/M software have a discrepancy with theoretical and experimental data at a design load of up to 14% (Table 2). Such a discrepancy in the values of the research results is due to the fact that wood is an anisotropic material, so it is difficult to predict the results of the experiment with high accuracy. Simulations in the COSMOS/M clearly showed that in reinforced wooden beams with a weakening in the stretched zone (at the point of weakness), a significant concentration of stress is observed. The stress concentration factor is 1.1 - 1.3, which must be taken into account in the design.

It has been experimentally confirmed that when the reinforcement factor is increased to 0.040-0.045, the influence of natural defects and weakening of wood is reduced, and it is also possible to use wood of grade 3, without increasing the cross-section and reducing the load on the structure. Reinforcement makes it possible to compensate for the effect of the weakening of the cross section of structures on its strength and deformability. This fact makes it possible to efficiently use reinforced all-wood structures from 3 grade wood (girders and ribs of coating plates) in construction in exchange for existing constructions from sawn timber of grade 2 and makes it possible not only to reduce wood consumption, but also to reduce the cost of the structures themselves.

5 Conclusion

On the data given above the costs of the same area of a roof from the foamglass produced by various producers can significantly differ. So, a foamglass T4 is almost twice more expensive than at the producer Neotim.

When comparing the methods of beams research, it was found that the convergence of the results is 5-10%. Proceeding from this, it can be concluded that all three methods are sufficiently accurate.

The weakening of the cross section significantly reduces the strength and deformability of timber structures. The reinforcement compensates for the effect of attenuations, while in constructions the strength and reliability against collapse are increased in comparison with non-reinforced ones, which was confirmed by the results of earlier research [1, 22-26].

In reinforced whole- timber structures, it is possible to use wood of the third grade instead of the 2nd grade with equal strength and reliability.

In reinforced timber beams with a weakening in the stretched zone (in the place of weakening), a considerable concentration of stresses is observed.

The deformation in reinforced beams is 15-20% lower than in unreinforced beams. When the reinforced beams with a weakened section of collapse do not break down due to the supporting effect of the reinforcement in the stretched zone and the reliable connection of the reinforcement to the wood that provides the glue line up to the destruction of the wood. The safety factor of reinforced wooden structures varies from 3.00 to 5.07, which is confirmed by a number of researchers [1, 22-26].

The method of calculating reinforced wooden beams, taking into account the attenuations when comparing the results obtained with the results of an experimental study, showed that the difference reaches 14-16%, and when calculating using the COSMOS / M software complex, 5-7%, which is within the permissible deviations.

In view of the fact that, at the present stage, there are more and more modern, more qualitative and relatively accessible materials in subsequent studies, it is planned to study in more detail the issue of increasing the strength and deformation of beams with natural kinds of attenuation with the help of carbon fiber.

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