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EXPERIMENTAL STUDIES OF THE WORK OF NAILED CONNECTIONS

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Abstract

This study is devoted to one of the most common types of wooden structural elements joints - nailed connections. The article presents the results of experimental studies of two types nailed connections on metal plates: traditional connections without bushings and connections, reinforced (modified) with pressed-in fiberglass bushings. The methods of mathematical planning of the experiment were used during the test. That allowed to significantly reduce the number of tested samples of connections and to obtain mathematical dependences in the form of response functions for such characteristics as breaking load N_t and load N_{I-II}, corresponding to the upper boundary of the elastic behavior area of the compound from three factors: the angle between the direction of the acting force and the direction of the wood fibers, the dowel diameter and the wall thickness of the fiberglass bushing. The obtained dependences allow us to evaluate the values of the loads N_t and N_{I-II} for the nailed connections with bushings without testing.According to the experiment planning matrix, 15 types (series) of connections with pressed-in fiberglass bushings and 9 types (series) of traditional nailed connections without bushings were tested.According to the test results, the authors made a comparison of the load bearing capacity and deformability of two types of nailed connections, with bushings and without bushings; the nature of the damage has been established; the analysis of stress-strain state of the middle wooden element in the area of mortise strengthened with pressed-in fiberglass bushing is performed; the conclusion about prospects of *application of a pressed-in fiberglass bushings to enhance mortises of new structures and when reconstructing wooden structures in operation.*

Keywords: Nailed connection, wood, load bearing capacity, deformability, experiment planning, fiberglass bushing.

I. Introduction

The nailed connections are the most common among joints of wooden structures. They are distinguished by ease of manufacture, unification, compactness and reliability. There are many types of nailed connections. A lot of researches have been devoted to the study of nailed connections. In [IX], nodal connections of trusses are investigated. The authors of [XV-X] have investigated the possibility of using nailed connections in laminated bamboo panels, for panels designed to improve the seismic resistance of the building framework. The authors [XVIII] have proposed a new type of compounds for the light spatial structures of the bamboo tree. A lot of research has been devoted to the study of compounds of elements of metal-wooden structures, structures made of LVL-timber, glued timber [I-IV]. Methods of computer modeling of the operation of nailed connections in the elements of real structures are considered in [III-XIX]. The authors of the article [V] propose to strengthen the mortises of laminated wood in order to reduce brittle fracture modes. In the researches [VII-VIII] the work of nailed connections is studied using the methods of fracture mechanics.

To increase the load bearing capacity of compounds, to reduce their deformability and increase the anticorrosive protection of metal dowels, glued and screwed-in glued rods are used [XX-XIV].

It is much more effective to use pressed-in fiberglass bushings, proposed by the author of the article Okolnikova G.E. [XII]. The load bearing capacity of traditional joints of wooden elements on the dowels is largely dependent on the resistance of wood to crushing in the hole area.

Pressing the fiberglass bushings into the hole of wooden elements significantly increases the strength of the material of the edge of the hole to collapse, draws into work a stretched zone of wood around the hole, changes the design pattern of the work of the dowel on bending, increases the density of the connection. Bushings are pressed into wooden elements prior to assembly. The material of the bushings can be made of laminated glass-fibre sheet AG-4c, fiberglass DSV (metered fiber) and GSP-4 (granulated fiberglass based on chopped fiber).

This work is a continuation of the research started by the authors earlier [XII-XI].

II. Materials and Methods of Research

The authors have carried out short-term tests of two types of nailed connections on metal plates:

- traditional joints without bushings;
- joints, the mortises of the middle elements of which were reinforced with pressed-in fiberglass bushings (Fig. 1).

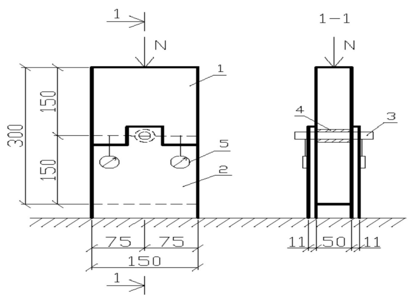

Fig. 1: Nailed connection with pressed-in fiberglass bushings drawing:

1-middle wooden element

2-metal plates

3-metal cylindrical nail

4-pressed-in fiberglass bushing

5- dial indicator for deformations measuring

The tests were carried out according to the loading scheme with steps with periodic loading and unloading with a constant loading and unloading rate, in accordance with [XVI]. The magnitude of the increase in force during the loading of the sample was assigned 0.08-0.1 of the destructive force N_t, determined from the test until the destruction of the test samples of the compound (3-6 *kN*). The hydraulic machines R-5 and P-10 were used for tests. To measure deformations, dial gauges with a scale value of 0.01 mm were used. Testing of samples was carried out until the loss of load bearing capacity. Pine wood with the width of annual layers of 1-5 mm and humidity not higher than 12-18% was selected for manufacturing of wooden elements of samples. For dowels, A240 reinforcing steel was used. Plates were made of steel brand VSt.3, bushings - of fiberglass GSP-4 on the basis of chopped fiberglass (granular). The study of compounds was carried out according to the theory of experiment planning. Using the methods of mathematical planning of an experiment allows one to obtain much more information than with a sequential experiment. The number of samples and testing time is reduced by about 4 times.

Three factors that have the greatest impact on the load bearing capacity and deformability of nailed connection were considered:

X_1- is the angle α between the direction of the acting force N and the direction of the wood fibers;

X_2- is the diameter of the dowel d;

X_3- is wall thickness of fiberglass bushing t_w^b.

Each of the factors was varied at three levels:

$X_1(\alpha)$ – 0°; 45°; 90°
$X_2(d)$ – 14; 18; 24 (mm)
$X_3(t_w^b)$ – 4; 6; 8 (mm)

As the parameters of the experiment were considered:

- load N_{I-II}, corresponding to the upper boundary of the elastic behavior of the joint and characterizing the load bearing capacity of the joint under short-term load action;

- destructive load N_t.

Since the relationship between response functions and factors is non-linear, and the factors were supposed to vary on three levels, a three-level Box-Benkin plan was applied. The matrix of experiment planning in dimensionless and natural values of factors is presented in the table. 1.

Table 1: Experiment Planning Matrix

Planning matrix			**Squares of variables**			**Interaction of factors**			**Natural values of factors**		
X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_1X_2	X_1X_3	X_2X_3	$(X_1)a$	$(X_2)d, mm$	$(X_3)t_w^b, mm$
+1	+1	0	+1	+1	0	+1	0	0	90°	24	6
+1	-1	0	+1	+1	0	-1	0	0	90°	14	6
-1	+1	0	+1	+1	0	-1	0	0	0°	24	6
-1	-1	0	+1	+1	0	+1	0	0	0°	14	6
+1	0	+1	+1	0	+1	0	+1	0	90°	18	8
+1	0	-1	+1	0	+1	0	-1	0	90°	18	4
-1	0	+1	+1	0	+1	0	-1	0	0°	18	8
-1	0	-1	+1	0	+1	0	+1	0	0°	18	4
0	+1	+1	0	+1	+1	0	0	+1	45°	24	8
0	+1	-1	0	+1	+1	0	0	-1	45°	24	4
0	-1	+1	0	+1	+1	0	0	-1	45°	14	8
0	-1	-1	0	+1	+1	0	0	+1	45°	14	4
0	0	0	0	0	0	0	0	0	45°	18	6
0	0	0	0	0	0	0	0	0	45°	18	6
0	0	0	0	0	0	0	0	0	45°	18	6

The load bearing capacity of the nailed connections with the pressed-in fiberglass bushings on the metal plates under long-term load was estimated by the value of the reliability coefficient according to the method of Yu.M. Ivanov [XVI]. For this purpose, in the process of testing, in addition to the destructive load, the duration of a short-term test of samples *t* was determined.

The required reliability coefficient was calculated by the formula:

$$k = 1.38(1.94 - 0.116 \lg t) \quad (1)$$

The load bearing capacity of the joint was estimated by inequality: the ratio of the destructive load to the calculated load bearing capacity should be greater (or equal) to the required reliability coefficient:

$$N_t / N_n \geq K \tag{2}$$

III. Results and Discussion

According to the experiment planning matrix, 15 types of joints with pressed-in fiberglass bushings and 9 types of traditional joints without bushings were tested. To obtain reliable test results, the number of repeated experiments in the row of the matrix was assumed to be 3. The total number of tested samples was: for joints with bushings - 45, for joints without bushings - 21.

The results of short-term tests of samples of two types of nailed connections on metal plates with pressed-in fiberglass bushings and without bushings are shown in the Table 2.

Table 2: Comparison of the load bearing capacity and deformability of nailed connections with bushings and without bushings according to the results of experimental studies

Force N_t, kN		Force N_{I-II}, kN		Increase in bearing capacity		Full deformations D_n under force N_{I-II}, mm		Reduceindeformation	Full deformations D_n under force N_t, mm		Reduce in deformation
Without bushings	With bushings	Without bushings	With bushings	By N_I	By N_t	Without bushings	With bushings		Without bushings	With bushings	
25	34	16	24.5	1.53	1.36	1.903	0.7875	2.42	5.893	2.165	2.72
16	30.5	8.5	18	2.12	1.9	2.701	1.12	2.41	10.54	5.882	1.79
46	76	25	49	1.96	1.65	1.75	0.8125	2.15	2.017	1.605	1.257
28	50	16	38	2.375	1.786	2.183	1.573	1.39	6.675	2.77	2.41
19	32	13	22	1.69	1.68	0.838	0.76	1.1	8.065	5.57	1.45
19	31	13	20	1.53	1.63	0.838	0.6038	1.39	8.065	5.955	1.35
28	56	19	44	2.32	2	1.32	0.74	1.78	3.05	2.675	1.14
28	54	19	40	2.1	1.93	1.32	1.29	1.02	3.05	2.728	1.12
31	45	22	36	1.64	1.45	1.573	0.63	2.496	4.713	1.16	4.0625
31	43.7	22	34	1.545	1.4	1.573	0.634	2.48	4.713	1.1	4.28
20	34	10	29	2.9	1.7	2.2	0.73	3.03	7.023	5.69	1.03

						1					
20	32	10	27	2.7	1.6	2.21	0.6875	3.21	7.023	4.56	1.54
22	40	16	31	1.94	1.82	1.678	1.3525	1.24	6.465	2.663	2.43
22	43	16	31	1.94	1.95	1.678	0.5725	2.93	6.465	5.57	1.16
22	41	16	31	1.94	1.86	1.678	1.0625	1.58	6.465	4.275	1.51
				2.1	1.7			2.04			1.96

According to the test results, the dependences of the permanent residual deformation for the *do* cycle on the elastic strain D_y were (Fig. 2). The $D_y - d_o$dependence was used to determine the upper boundary of the elastic behavior of the joint and the $N_{I\text{-}II}$ load corresponding to it.

According to the test results were determined:

- characteristics of the load bearing capacity in the form of a load $N_{I\text{-}II}$, corresponding to the upper boundary of the elastic behavior of the joint, and the destructive load N_t;
- deformability characteristics in the form of absolute values of total deformations (deformations with $N_{I\text{-}II}$ force and maximum deformations with or without destructive force N_t);
- the values of complete, elastic, residual deformations at each step of loading;
- required reliability factor;
- the nature of the destruction of the joint.

The loads of $N_{I\text{-}II}$ and N_t were subjected to statistical processing, which consisted in assessing the significance of the coefficients of the regression equations and checking the adequacy of the model. The resulting response functions have the following form:

- for$N_{I\text{-}II}$ effort (kN):

$$Y_{N_{I-II}} = 31 - 10.8125X_1 + 3.94X_2 + 1.25X_3 \quad (3)$$

- forN_t effort (kN):

$$Y_{N_t} = 41.33 - 13.5625X_1 + 6.25X_2 + 1.0625X_3 - 5.625X_1X_2 \quad (4)$$

From the response functions, it can be seen that the factors of importance (degree of ranking) are arranged in the following sequence: angle between the direction of force and direction of wood fibers (X_1), the dowel diameter (X_2), the wall thickness of the bushing (X_3). The obtained response functions allow us to determine the values of the $N_{I\text{-}II}$ and N_t forces for the nailed connections with pressed-in fiberglass bushings on the metal plates with different combinations of three factors (X_1, X_2, X_3) without testing.Tests of traditional joints without bushings were carried out simultaneously with the tests of the nailed connections, modified by the pressed-in fiberglass bushings.

As can be seen from the table. 2, the load bearing capacity of the nailed connections with the pressed-in fiberglass bushings on the metal plates, compared with the traditional nailed connections without the bushings, increases by an average of 2.1 times, and the deformability decreases by 2.04 times.

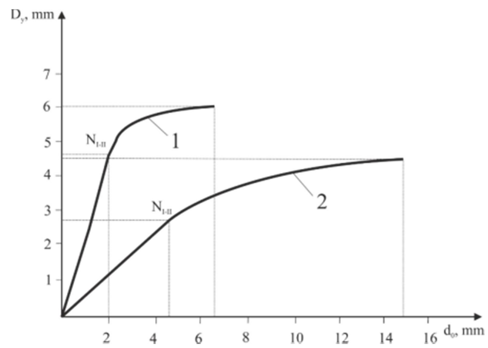

Fig. 2: Graph of residual strain for the do cycle on the elastic Dy for connection with the diameter of the dowel d= 14mm; α=0°:

1- With bushing *t*= 6 mm
2- Without bushing

The work and the nature of the destruction of joints modified with fiberglass bushings have the following features: bushing, which is firmly connected with the wood by pressing, involves a stretched area of wood in the work of the joint. With a subsequent increase in load during the test, the bushing breaks off; upon further loading, the bushing presses into the compressed zone of the wood: an influx of wood forms above the bushing, a gap appears between the bushing and the stretched zone of wood. In the process of further loading, the joint continues to bear (perceive) the load and, in samples with a dowel diameter of 24 mm, destruction occurs due to crushing of the wood of the mortise or splitting of the middle element of the joint. In samples with diameters of 14 and 18 mm, there was no discontinuity in the material of the joint, the load bearing capacity of the joint was exhausted by the bend of the dowel, and the continuous increase in strain was considered as the moment of failure without changing the applied force (without further increasing the load). The bend of the dowel was accompanied by the formation of a plastic hinge in the middle of the length of the dowel.

Since the destruction of the samples occurred at loads higher than $N_{I\text{-}II}$, with a noticeable development of deformations, the work of the joint should be attributed to plastic appearance, and the joint to group II of compounds [XVI].

The results of the evaluation of the load bearing capacity of the nailed connections with the pressed-in fiberglass bushings on the metal plates are shown in Table 3. As can be seen from the Table 3, the actual reliability coefficient is higher than the required one, which indicates that the nailed connections with the pressed-in fiberglass bushings have sufficient load bearing capacity.

Table 3: Evaluation of the load bearing capacity of the nailed connections with pressed-in fiberglass bushings

The load on the sample, kN		Estimated load bearing capacity, kN		$N_{I-II}/N_{п} \geq 1.3$	Reliability coefficient $N_t/N_{п} \geq K$
N_t	N_{I-II}	per one seam	per sample $N_{п}$		
34	24.5	5.042	12.084	2.027	2.81>2.417
30.5	18	5.1756	10.35	1.739	2.94>2.45
76	19	12.084	24.158	2.027	3.14>2.33
50	38	7.049	14.098	2.695	3.54>2.38
32	22	5.2112	10.4224	2.11	3.07>2.44
31	20	5.2112	10.4224	1.92	2.97>2.45
56	44	9.063	18.126	2.427	3.09 >2.36
54	40	9.063	18.126	2.21	2.98 >2.37
45	36	9.063	18.126	1.986	2.48 >2.39
43.7	34	9.063	18.126	1.876	2.411 >2.41
34	29	5.815	11.63	2.49	2.92> 2.44
32	27	5.815	11.63	2.32	2.75>2.44
40	31	7.137	14.274	2.17	2.8>2.41
43	31	7.137	14.274	2.17	3.012>2.4
41	31	7.137	14.274	2.17	2.872>2.41

IV. Conclusions

According to the results of experimental studies, the following conclusions can be drawn:

1. The nailed connections with pressed-in fiberglass bushings have a higher load bearing capacity and lower deformability by an average of 2 times as compared with traditional nailed connections without bushings.
2. The increase in the load bearing capacity of compounds with pressed-in fiberglass bushings is caused by a significant difference in their work in relation to the stress-strain state of wood in the area of the mortise compared to traditional nailed connections. Namely, the pressing of the fiberglass bushings involves the wood, located on the side of its stretched zone, in the operation of the mortise.

3. Due to the increased load bearing capacity of the joints with pressed-in fiberglass bushings, it becomes possible to design more compact nailed connections by reducing the number of dowels and reducing the normative distance between them in the direction along the wood fibers.
4. Reducing the deformability and increasing the load bearing capacity of the nailed connections reinforced with pressed-in fiberglass bushings makes them attractive for use both in the design of new structures and in the reconstruction of existing wooden structures.
5. Mathematical dependences are obtained in the form of response functions for such characteristics as: destructive load N_t and load N_{I-II},, corresponding to the upper boundary of the elastic behavior of the joint from three factors: the angle between the direction of the current force and the direction of the wood fibers, the diameter of the dowel and the wall thickness of the fiberglass bushings. The dependences obtained allow us to determine the values of the loads N_t and N_{I-II} for the nailed connections with bushings without testing.

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