Experimental Studies of the Strength and Rigidity of Screw Connections of Covers with Wooden Ribs

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Abstract. The results of a study of the shear stability of single-slice joints on screws of wooden ribs and wood-composite covers of structural plywood (SP) and oriented-strend boards (OSB) are presented. The plastic behavior of the destruct of the joint is established, the coefficient of safety during plastic fracture is determined, the bearing capacity and stiffness coefficient are calculated. A plan for a 2-factor experiment with varying factors at 3 levels has been compiled, regression equations have been obtained that made it possible to calculate the stiffness coefficient of screw joints as a function of the diameter of the screw and its embedment in the rib, and response graphshave beendrawn. The scientific conclusions and recommendations based on the performed experimental studies are formulated. It can be used in design of plate-ribbed structures of floors and walls with covers from wood-composite materials.

1. Introduction. The relevance of the issue

House building is one of the main consumers of structural wood and wood-composite materials. These materials have become especially relevant recently, since their use is effective in far regions due to low weight, in emergency situations due to the quick response and relatively low cost of materials, for providing people in dire need of housing, as well as during the new settlements construction in the Arctic and Subarctic areas.

The technologies used in industrial production for building of structures and construction elements made of wood have been improved and developed constantly. Various wood-composite materials and mechanical connectors are used as elements of the joints of wooden structures: nails, inserts, dowels, metal nail plates, dowel groups, etc. This variety types of connections is associated with variety of structural solutions and anisotropic properties of structural wood. A number of researches of domestic and foreign scientists are devoted to the study of the dowel joints of elements of wooden structures.

The article [1] contains the results of studies of the shear resistance and rigidity of nail connections of wood-composite covers to wooden ribs in wall panels. The [2] presents the results of experimental studies of the bearing capacity and stiffness of metal staples that may be used as fasteners for covers of cement–bonded particle boards (CBPB) with wooden frame ribs.

The pattern of crushing stress distribution of screw holes instructural wood and mathematical model for the calculation of the single-cut screw with reinforcement of the crushing area by a metal dowel plate bearing capacity are presented in [3, 4].
The article [5] presents the study of the multi-dowel joints «group effect». In [6] some ways for reinforcing screw joints are presented such as additional fasteners for prevention splitting of wood along the fibers by dowel.

In [7] shear resistance of structural wood and concrete compounds made with reinforcement of wood by pressed metal dowel plates in the area of the dowel hole. The relation «load – strain» were obtained as a result of the test, which shows that metal dowel plates as a hole reinforcement allows significantly increase joints shear resistance.

The article [8] presents the results of studies of the shear and angular ductility of the dowel joints of studs and beams in lightweight frame structures of wooden buildings. A variant of local wood reinforcement at the place of introduction of the dowel by impregnation with a special chemical composition is considered in [9], which allows to obtain a new composite material with increased strength and elastic modulus. Obtained results show a positive effect of changes in the strength and stiffness of the material around the connecting element on the joint.

The behavior of dowel connection during a cyclic load in wood biodegradation conditions is investigated in [6]. The article [10] presents the results of the influence of humidity changes on the behavior of the dowels in the tensile joints of wooden structures. The behavior of the screw joints of frame wooden panels under static and dynamic loads is considered in [11] and [12] respectively. The article [13] presents the results of shear tests of screw connections of wooden elements with an inclined arrangement of screws to the plane of shear.

Actually, the issues of rigidity and strength of some types of mechanical joints, one of which are the screw joints of wood to wood-composite covers, have not been sufficiently studied despite the widespread use and extensive research of dowel joints of wooden structures in common. The ductility of such joints of wooden structures leads to significant errors in the estimation of their stress-strain state and must be considered in the static calculation of panel and volume-modular wooden structures. This is also applies to planar wooden structures and for spatial systems such as cross beams, tents, domes, in which enclosing structures or their elements (covers) can be involved in the main load-bearing elements work [1, 2, 14, 15, 16].

Current calculation and design of wooden structures norms and rules [17, 18, 19] don’t allow to determine the strength and stiffness of screw connections of wood with covers. There are also not any researches in the field the strength and stiffness of such joints, therefore, the issue of studying the shear stiffness and bearing capacity of screw joints is relevant.

2. Formulation of the problem
Before experimental researches have been started, the results obtained by other authors: I.M. Linkov, A.S. Chernykh, A.S. Kavelin, V.G. Kotlov, A.K. Naumov, R.B. Orlovich, V.Y. Terentyev [16, 20, 21, 22, 23, 24] and others – were analyzed. The Recommendations of the Central Scientific Research Institute for Scientific and Technical Research named after V.A. Kucherenko [25] have been applied as a basis of the experimental studies. Fastened composite packages of wood (a fragment of a rib) and two plates (covers) have been taken as samples for shear tests. The plates are located with an offset of 20 mm relative to wood for the displacement possibility of the elements relative to each other. Shear resistance in the sample is provided by a single-slice screw. The shape and size of the samples are shown in Figure 1.
The «Shimadzu 50 kN» test machine in the laboratory of the Department of Forestry Production and Materials Processing of NArFU named after M.V. Lomonosov has been used to carry out the tests. The moisture content of the samples at the testing time ranged from 10 ... 12%. Room temperature and humidity was 22±1 °C and 38±2% respectively.

According to recommendations of TsNIISK \[25\], the screw connection belongs to the II group of connections, with a non-linear dependence «elastic deformation – force». However, after a series of preloads from the constructed diagrams, it was not possible to determine the required parameters due to the significant scatter of the obtained values. It was decided to analyze the results according to the standard load «strain relation».

Samples loading was carried out at a speed of 5 mm/min until automatic fixation of failure or achievement of ultimate deformation (10 ... 20 mm). The graphical documentation «load – strain» relationship was carried out automatically; the dependency graphics were imported into the graphic editor. After the scaling of the obtained curves, the failure force \(N_t\) has been determined, as well as the upper region of elastic deformations \(N_{I-II}\) force and the strain value \(\delta_{I-II}\) corresponding to this force.

### 3. Theoretical part

The determination of the stiffness coefficient of the connections is considered in \[14\]. It is determined by the graphical dependence «load – strain» and in the elastic behavior of the joint or with small deformations it is enough to keep only the first term in this polinomial, which leads to the linear condition:

\[
C = \frac{P}{\delta}.
\]  

(1)

In fact, according to experimental curves, the compliance of the joints is a non-linear function of the loads:

\[
P = C \cdot \delta \pm C \cdot \delta^2 \pm C \cdot \delta^3 \pm ... \pm C \cdot \delta^n,
\]  

(2)

where \(P\) – is the force applied to the sample, kN; \(\delta\) – is the linear deformation of the compound, mm.

The reliability coefficient of the wooden structures joints is determined by the TsNIISK methodology \[25\] with plastic pattern of failure:

\[
k_{pl} = 1,38 \cdot (1,94 - 0,116 \cdot \log t).
\]  

(3)

Estimation of the bearing capacity of the group II connections is calculated by the inequality:

\[
\frac{N_{I-II}}{N_p} \geq 1,3,
\]  

(4)
where \( N_{I-II} \) is the value of the upper region of elastic deformations force; \( N_p \) — bearing capacity of the connection.

If the destruction of the samples occurred with a violation of the solidity of the materials, checking the additional condition is calculated by the inequality:

\[
N_t / N_p \geq 1,38 \cdot (1,94 - 0,116 \cdot \lg t),
\]

where \( N_t \) is the value of the destructive force.

If inequality (4) is not satisfied, the design bearing capacity \( N_p \) should be reduced to a value of \( N_p' \) determined by inequality (6), and if the inequality (5) is not fulfilled, the calculated bearing capacity \( N_p \) should be reduced to a value of \( N_p' \) determined by inequality (7).

\[
N_p' \leq N_{I-II} / 1,3,
\]

\[
N_p' \leq \frac{N_t}{1,38 \cdot (1,94 - 0,116 \cdot \lg t)}.
\]

The dependences «load – deformation» are shown in Figure 2. The test results and calculations are presented in table 1.

**Figure 2.** The graph «load – shear deformation» of the samples of the screws connections:

a — «wood – SP»; b — «wood – OSB».

The behavior of ductility wooden structures joints with influence of creep is reflected in the works of D.K. Arleninova, V.M. Kochenova, A.K. Shangelia. The results of their research in this direction are summarized in [14], in which it have been established on the basis of regression analysis that under constant loading over time the deformation process obeys the function:

\[
\delta(t) = \delta_0 [1 + \varphi(t)],
\]
where $\delta_1$ is the deformation of the compound at the initial moment of loading; $\varphi(t)$ is the creep characteristic of a connection, which depends from the ratio of creep to $\delta_1$.

The value of $\varphi(t)$ is determined by the formula:

$$\varphi(t) = \varphi_\infty [1 - e^{-\gamma t}], \quad (9)$$

where $\varphi_\infty$ is the ultimate creep characteristic of the joint at the moment of deformation stability; $\gamma$ is a coefficient of the rate of development of creep strain in time $t$ (days).

The parameters $\varphi_\infty$ and $\gamma$ mainly depend from the type of connection, orientation of the forces with respect to the main axes of wood anisotropy and environmental humidity. With a loading duration of $t \geq 50$ days, the graph goes into a straight line parallel to the X axis, which indicates a creep «attenuation». Thus, the effect of creep of bonds at each loading stage can be estimated by formula (10), i.e. the stiffness over time will decrease in proportion to the deformation increase of the connection, caused by creep of the wood:

$$C(t) = P / \delta(t), \quad (10)$$

where $C(t)$ is the value of the rigidity of the connection for a certain period of time. Substituting formulas (8) and (9) into (4), we obtain formula (10), which allows to obtain the value of the stiffness coefficient of the connection in each periods of time:

$$C(t) = P / (\delta_1 + \varphi_\infty [1 - e^{-\gamma t}]). \quad (11)$$

The pattern of the samples destruction is shown in Figure 3. The failure of almost all samples occurred before reaching the established ultimate deformation of the compounds (20 mm). For «wood – SP» connections, the destruction of the samples is characterized by insignificant indentation of the screw heads into the cover (in some cases), local crushing of holes in the wood and the covers, and bending and shearing of some screws. The destruction of the «wood – OSB» connections is characterized by a significant (in all cases) indentation of the screw heads into the cover, significant crushing or local destruction of the cover in the area of the screw holes, crushing of the holes in the wood, bending and cutting of the screws.

![Figure 3. The pattern of the destruction of samples and screws: a – «wood – SP»; b – «wood – OSB».](image)

According to the tests results the diameter and embedment length of the screws in the wood is rather significant factors for shear stability and stiffness coefficient of connection «C». For «wood –
SP» connections, the increase of this coefficient is 220 ... 250% with a changing in the screw diameter from Ø4 to Ø6 mm, for «wood – OSB» connections— 165 ... 175%. Increasing the embedment length allows increasing of this coefficient by 30 ... 80% in «wood – SP» connections, by 20 ... 40% in «wood – OSB». Large values of the stiffness coefficient correspond to «wood – SP» joints, exceeding the value of this coefficient compared to «wood – OSB» joints is observed in the range of 40 ... 90% depending on the pinch depth and screw diameter.

Table1. The results of shear tests.

| Diameter / embedment length of screw into wood, mm | Destructive force, kN | The force corresponding to the upper region of elastic deformation, \( N_{\text{II}} \), kN | Deformation corresponding to the upper region of elastic deformation, \( \delta_{\text{II}} \), mm | Test duration, \( t \), sec | Reduced to invariable action of destructive force, \( N_{\text{II}} \), kN | Reliability coefficient of connection, \( k_{\text{R}} \) | Estimated bearing capacity of the compound, kN | Rigidity coefficient of connection, C, kN/mm |
|-----------------------------------------------|---------------------|--------------------------------|--------------------------------|-----------------|--------------------------------|-----------------|-----------------|-----------------|
| Ø4 \( l_{\text{emb}}=30 \)                    | 2,202               | 1,40                          | 3,32                          | 117,96          | 3,09                          | 2.50            | 0.88            | 0.42            |
| Ø4 \( l_{\text{emb}}=40 \)                    | 2,577               | 1,55                          | 3,04                          | 163,20          | 4,27                          | 2,44            | 1.05            | 0.51            |
| Ø4 \( l_{\text{emb}}=50 \)                    | 2,796               | 1,59                          | 2,88                          | 197,04          | 5,16                          | 2,41            | 1.16            | 0.55            |
| Ø5 \( l_{\text{emb}}=30 \)                    | 2,804               | 1,32                          | 1,83                          | 128,40          | 3,36                          | 2,48            | 1.01            | 0.72            |
| Ø5 \( l_{\text{emb}}=40 \)                    | 3,080               | 1,40                          | 1,39                          | 178,44          | 4,67                          | 2,43            | 1.07            | 1.00            |
| Ø5 \( l_{\text{emb}}=50 \)                    | 3,353               | 1,50                          | 1,16                          | 213,12          | 5,58                          | 2,40            | 1.16            | 1.30            |
| Ø6 \( l_{\text{emb}}=30 \)                    | 3,589               | 1,91                          | 1,41                          | 141,24          | 3,70                          | 2,47            | 1.45            | 1.35            |
| Ø6 \( l_{\text{emb}}=40 \)                    | 3,869               | 1,65                          | 0,94                          | 194,28          | 5,09                          | 2,42            | 1.27            | 1.75            |
| Ø6 \( l_{\text{emb}}=50 \)                    | 4,082               | 1,78                          | 0,91                          | 240,00          | 6,28                          | 2,38            | 1,37            | 1.95            |

### 4. Practical significance

The obtained results of researches shows that the use of screws with a diameter of Ø5 and Ø6 mm significantly affect the shear stability of the joint stiffness coefficient instead of using Ø5 mm nails [26] and brackets 40 mm long with a shelf width of 10 mm and a bar thickness of 1,5 mm [16]. This is due to the thread, because of the pulling resistance of screws significantly increases.

An variation of screws diameter from Ø4 to Ø6 mm increases the bearing capacity by 18 ... 65% for the «wood–FC» connections and by 86 ... 126% for the «wood–OSB» connections. With an variation of embedment length of the screw into the wood from 30 to 50 mm, the increase in this values is 14 ... 31% and 9 ... 31%, respectively.

To improvement the reliability and efficiency of experimental studies, the experiment was planned according to the methodology [27].The shear rigidity parameter of connection «C» is assigned as output parameter. As a result of planning, the optimal number of test samples was established with a statistical support of 0.95. Multi-factor method of experiment planning has been adopted. The input
parameters are assigned 2 factors: the diameter of the screw \( (x_1) \) and embedment length of the screw in the wood \( (x_2) \). The number of parallel experiments is 3, determined by the results of previous tests of samples according to [28]. The reliability of the results was checked by calculating the Kochen criteria, the significance of the coefficients according to the Student criteria. The obtained equations have been checked according to the Fisher criteria.

The obtained regression equations have the form:

\[
\begin{align*}
\text{− «wood−SP»: } & \quad y = 1.061 + 0.595x_1 + 0.218x_2 + 0.118x_1x_2 + 0.082\left(x_1^2 - x_1\right) \\
\text{− «wood−OSB»: } & \quad y = 0.627 + 0.287x_1 + 0.082x_2,
\end{align*}
\]

(12) (13)

where \( x_i \) are the encoded values of the factors (\( x_1 \) is the diameter of the screw; \( x_2 \) is the embedment length of the screw into the wood) to conversion to which from natural values the formula is used:

\[
x_i = \frac{x_i - x_{0i}}{\Delta x_i}
\]

(14)

where \( x_i, x_{0i} \) are the natural values of the factor on the desired \( (x_i) \) and base \( (x_{0i}) \) levels; \( \Delta x_i \) is the interval of variation of factors.

The response curves of the regression equations are shown in Figure 4.

\[\text{Figure 4. Graphs of the dependence of the rigidity coefficient of the joint from:} \]

\[\text{a − screw diameter (} x_1 = -1; -0.5; 0; 0.5; 1) ; \text{b − screw lengths (} x_2 = -1; -0.5; 0; 0.5; 1).}\]
5. Conclusions
1. Based on the experimental results, regression equations for the «wood – SP» and «wood – OSB» screw connections are obtained, which allow to determine the shear rigidity coefficient “C” for the connections depending on the screw diameter and the embedment length into the wooden rib.
2. An increase of diameter of the screw affects an improving of shear rigidity and bearing capacity of connections more than increase of the embedment length of the screw in the wooden rib. Thus, if it is necessary to improve shear rigidity coefficient, it is primarily recommended to increase the diameter of the screws.
3. The use of screws with a diameter of Ø5 mm or more instead of nails or staples significantly increases the longitudinal shear resistance of the covers relative to the ribs of wooden wall panels and conduce their more effective inclusion in the work of entire structure. Strength indicators and obtained from the regression equations shear resistance values of screw connections can be used in design of plate-ribbed structures.
4. «Wood–SP» connections have higher values of shear strength and rigidity coefficients than «wood–OSB».

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