Strength and stiffness of wood structures for compounds of gang nail plate "Steelcap"

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Abstract. The article is devoted to research of strength and stiffness properties of wood structures on a new type of gang nail plates. The relevance of the study is due to the need to meet the requirements of modern design standards SP64.13330.2017 with respect to new types of wood structures. In this regard, the purpose of this article is to determine the estimated carrying capacity and stiffness of joints of wooden structures "Steelcap". The main method of studying this problem is the analysis of experimental data on the basis of short test compounds with the gang nail plate at the angle of 0°, 45° and 90° the fibers of wood.

1. Introduction
The main purpose of the research is to determine the estimated carrying capacity of joints of wooden structures performed using gang nail plate of the new type "Steelcap". The need for this research is dictated by the fact that in the domestic design standards [1] such compounds are considered superficially and it is recommended to determine the carrying capacity of the compounds at various minimum wage levels individually.

According to the data on the industrial production of wooden structures in almost all countries of the world, the most widely used today are joints of toothed connection type and, above all, connections on cylindrical metal nails [2–4]. The main advantage of such compounds is the relative simplicity of manufacture and their functional versatility, which predetermines the possibility of sufficiently efficient production of knot joints of wooden structures, which creates conditions for the production of various core structures of sufficiently high consumer quality.

In the process of manufacturing of toothed connections, two main ways of placing the dowels in the wood massif of the elements are used: placement of cylindrical pegs into pre bores; introduction of the pointed dowel at the solid wood, incl. groups of dowels on a common plate of MNP type.

It is considered that connecting elements in the form of metal plates stamped in their modern form Gang-nail connectors (in Russia the term “metal toothed plates”, MNP is more often used) were developed and proposed by D. Juraite (USA) in 1953. In USSR and Russia development of compounds on MNP were conducted mainly in ZNIISK named after Kucherenko, Moscow, VNNGASU, Nizhny Novgorod and TGASU, Kazan. Studies [5-8] consider the issues on the development and refinement of the method for calculating the connection of wood structures on MNP, including taking into account the duration of load action [9-10]. In foreign practice there is a large
number of different plates like Gang-nail connectors, which are used for various purposes. Works [11-13] consider the possibility of strengthening wood elements, butt-joint, the comparison of work with other tooth connection types.

The simplicity of basic technological operations and the high productivity of manufacturing processes for both plates and structures have led to their wide distribution in almost all developed countries of the world. This is where the main advantages of these connecting elements are manifested, stimulating attempts to develop new types of plates.

The main disadvantage of nail plates stamped is their limited carrying capacity. It should be noted that their shear and normal carrying capacity are interconnected with each other. For example, an increase in shear strength, which is achieved by increasing the number of teeth or their dimensions, inevitably leads to a decrease in the cross section of the plate and, consequently, to a decrease in the normal strength of the plate.

Therefore, the carrying capacity of currently used stamped plates with a maximum thickness slightly exceeding two millimeters is close to its limiting values [14-15]. The calculated shear strength \( T_c = 0.05 - 0.14 \text{ kN/cm}^2 \) (with the most favorable orientation of the teeth relative to the wood fibers) is also close to its possible maximum values.

In terms of their work under load, MNPs are practically the same as any other tooth connection. It makes possible to apply the methods for determining the carrying capacity developed by V.N. Kochenov based on the limit equilibrium method [16] in the development of theoretical solutions by A.V. Lenyashin and being basic for modern design standards [1].

In conclusion, we should note that the question of the estimated carrying capacity of joints is key in solving subsequent issues, since if it is successfully solved, further problems acquire an arithmetic order of complexity.

2. Preliminary data

This theoretical approach is supposed to be used at the first stage of the calculation of the carrying capacity, and then (after experimental studies) we are to clarify its values, based on the work of V.A. Ivanov regarding connections on the metal plates in combination with cylindrical rod nails [17], and KirPI studies in Kirov [18] regarding nails fixed to rigid plates.

Let us turn to the question of determining the estimated carrying capacity of the tooth connections in relation to "Steelcap" in the framework of current design standards. Fig. 1 shows the general view and photo of the plates. The "Steelcap" plates are characterized by rather short teeth of the original shape.

Given that for the MNP there is only the extreme part of the nail, we get the following values: \( a = 7.0 \text{ mm} \), taking into account the sharpening of the tooth. The transverse dimensions of the tooth are 3.5x1.0 mm. The approximately equivalent diameter is 2.1 mm.

![Figure 1. General view and photo of nail plates "Steelcap".](image)
Consequently, it is possible to determine the theoretical estimated carrying capacity of the connection in relation to one “slice” (plane of the joint) from the working conditions of the wood nail center on crushing and nagging on transverse bending at different loading angles relative to the wood fibers: $\alpha = 0^\circ$, $\alpha = 45^\circ$, $\alpha = 90^\circ$. Next, we define the estimated carrying capacity per cm$^2$, taking into account that, according to the type of these plates, there are 1.17 pins per 1 cm$^2$. The results of the calculations are shown in table 1.

| Load carrying capacity of compounds | $\alpha = 0^\circ$ | $\alpha = 45^\circ$ | $\alpha = 90^\circ$ |
|------------------------------------|--------------------|--------------------|--------------------|
| Crushing wood $T_{cw} = 35adK_s$ (kN) | 0.0515 | 0.0438 | 0.0361 |
| Bending nail $T_{bn} = 250d^2 + a^2 \leq 400d^2$ (kN) | 0.1152 | 0.1062 | 0.0964 |
| Crushing wood (kN/cm$^2$) | 0.0603 | 0.0512 | 0.0422 |
| Bending nail (kN/cm$^2$) | 0.1348 | 0.1243 | 0.1128 |

From the above data, it follows that the smallest in magnitude is the estimated carrying capacity of MNP, determined from the conditions of work for crushing wood. Note that the calculations performed are very approximate (estimated).

- $\alpha = 0^\circ$, $T_{cw,\min} = 0.0603$ kN/cm$^2$
- $\alpha = 45^\circ$, $T_{cw,\min} = 0.0512$ kN/cm$^2$
- $\alpha = 90^\circ$, $T_{cw,\min} = 0.0422$ kN/cm$^2$

3. Experimental studies

The method of testing samples was developed in accordance with the Recommendations for testing joints of wood structures [19]. Experimental studies of compounds aimed to identify the nature of the deformation and the limit carrying capacity were carried out on samples of three series. The series consisted of 4 ... 6 samples, each sample contained 4 nail plates on both sides, which allowed us to obtain two results on each sample.

Wherein:

- in samples of the 1st series, oriented to loading by stretching in the longitudinal direction ($\alpha = 0^\circ$), the MNP were located on both sides of the sample, the direction of the applied force coincided with the direction of the wood fibers;
- in samples of the 2nd series, also oriented to loading by stretching, the MNP were located on both sides of the sample, the angle of the applied force to the wood fibers was $\alpha = 90^\circ$;
- in samples of the 3rd series, also oriented to loading by stretching, the MNP were located on both sides of the sample, the angle of the applied force to the wood fibers was $\alpha = 45^\circ$.

Figure 2 shows a general view of samples of 3 series.

The relative humidity of the wood at the time of testing ranged from 4.6 to 6.0 %.
Mechanical tests of samples were carried out using the hydraulic machine Breaking P-10, which was tested by the Federal State Institution of the Kirov Center for Standardization, Metrology and Certification just before the production of the specified works.

Of all the possible loading methods (i.e., variation with loading parameters), we have chosen a stepwise mode— with an exposure of the achieved load at each of the indicated steps. The main advantage of this method of loading is the fact that it is most relevant to the characteristics of mechanical testing of load-carrying structures as a whole.
The magnitude of the loading step is assumed to be 4.0; 2.0 and 3.0 kN for series 1, 2, 3, i.e., approximately the third part of the estimated carrying capacity of the connection; the specified level of loading was achieved within 1 min; immediately after this, counts were taken on indicators, then after a two-minute exposure repeated counts were taken. A similar operation was repeated at each stage of loading. At the final stage of testing, the load was reduced to breaking at a constant rate of increase.

Figure 3 shows the process of testing samples with the location of measuring devices - the dial gauge ICH10 with a division value of 0.01 mm.

The principal feature of the “destruction” in all cases was its ductile failure mode, which expressed in an increase in deformations without an increase in load. The destruction occurred on all samples of all series due to the collapse of wood under the teeth of the MNP, followed by the destruction of wood from cutting fibers.

The final deformation diagrams (load N kg - total deformations Δ mm) of samples of individual series are presented in Figure 4.
4. Results

To assess the quality of wood used for the manufacture of wood samples, the strength and stiffness parameters of wood were determined in accordance with the applicable GOST [20-21]: the short-term flexural modulus and short compressive resistance of wood under compression along the fibers and in the transverse bend.

The results are as follows: $E = 11200 \text{ MPa (13000)}$; $R_u = 61.7 \text{ MPa (80.0)}$; $R = 46.5 \text{ MPa (44.0)}$; $R_n = 36.5 \text{ MPa (33.0)}$.

On the basis of the data obtained and the average statistical values given in the norms [1] (indicated in parentheses), we can conclude that the presented wood has an average statistical quality.

In order to determine the tensile strength of the MNP themselves, 11 samples were tested. According to the test results, the estimated tensile strength of the plates was determined taking into account the weakening of the holes from the teeth. The estimated resistance is determined by dividing the likely least destructive resistance by the safety factor for the metal $K = 1.53$.

On the basis of the test results, the value of the calculated tensile strength along the plate felling can be taken as 11.5 MPa, across the plate felling (taking into account their dimensions) 4.0 MPa.

The final diagrams $(N - \Delta)$ of Figure 4, constructed by the end points of the deformations, taking into account the holding of the samples at each load stage, combined with the value of the ultimate (breaking) load, serve to clarify the estimated carrying capacity of the compounds.

The sequence for determining the estimated carrying capacity of the compounds is as follows:
- statistical processing of the received ultimate loads for groups of samples of different batches is carried out in order to determine the minimum individual value (at the level of confidence $\alpha = 0.95$).
- on the basis of data on the speeds and mode of loading the samples, the reliability compound factor of the connection is determined [22]; with ductile failure mode

$$K_n = 1.38 \left(1.94 - 0.116 \log t\right)$$

$t$, loading time, reduced to constant force action with maximum value of the reliability compound factor $K_n = 2.52$;
- the estimated carrying capacity of the connection is determined by dividing the probable minimum value of the breaking load by the safety factor.

Processed results with allowance for rounding are shown in Table 2.

![Figure 4. Final diagrams of deformation of joints for series 1...3.](image)
Table 2. Results of experimental studies.

| Experiment parameters | Series 1    | Series 2      | Series 3     |
|-----------------------|-------------|---------------|--------------|
| Time t, min           | 24.0        | 29.0          | 17.0         |
| $K_n$                 | 2.60 (2.52) | 2.59 (2.52)   | 2.63 (2.52)  |
| Square MNP cm$^2$     | 190         | 190           | 150          |
| Probable min value of load, kN | 23.54       | 13.56         | 14.30        |
| Estimated carrying capacity kN/cm$^2$ | 0.05        | 0.03          | 0.04         |
| Regulatory load capacity kN/cm$^2$ | 0.12        | 0.07          | 0.095        |

Taking into account that the carrying capacity of the compounds is normalized not only by strength, but also by the deformations, at the final stage of the study, we determine the displacement of elements at the level of their estimated carrying capacity using the full strain diagrams. At the same time, the magnitude of short-term deformations for the MNP should not exceed the value equal to $\Delta = 0.3\text{mm}$ (which corresponds to 1.5 mm with long-term load action).

Using the deformation diagrams according to Figure 4, which show the average values of the deformations and the range of their possible variation, we obtain for the series in their natural sequence:

- series 1 $\Delta_1 = 0.018 \text{mm if } P = 9.50 \text{kN}$;
- series 2 $\Delta_2 = 0.046 \text{mm if } P = 4.50 \text{kN}$;
- series 3 $\Delta_3 = 0.056 \text{mm if } P = 7.60 \text{kN}$.

Let us note that the obtained experimental values of the estimated carrying capacity are slightly lower than the theoretical ones, obtained on the basis of the existing design standards. The reason for this is the fact that theoretical solutions require the work of dowels of sufficient length.

Results: during the research we have developed a method for determining the strength and deformation characteristics of joints made with the use of gang nail plate "Steelcap", when loaded at an angle of 0°, 45° and 90° to the wood fibers; we have tested samples and presented in conclusion the results of the strength and deformation characteristics of the compounds.

5. Conclusion

Studies have allowed to establish the carrying capacity and stiffness of the joints of wood structures made with the use of gang nail plates "Steelcap", when loaded at an angle of 0°, 45° and 90° to the wood fibers.

The values of the estimated carrying capacity of the compounds are given in Table 3.

The estimated carrying capacity of the studied MNP is somewhat lower than that given in Recommendations [23], which is related to the design parameters of the teeth, which are 2-3 times shorter than those recommended in [23].

Therefore, plates of this type (with short teeth) work a little differently: under load, only the wood collapses without bending the nail itself, i.e. they work like a hard stamp. The stiffness characteristics of the investigated MNP are much higher, which follows from the above.

Table 3. The estimated carrying capacity of compounds.

| Type of stress                                      | The magnitude of the estimated carrying capacity of the MNP at $\alpha = 0^\circ$ | $\alpha = 45^\circ$ | $\alpha = 90^\circ$ |
|----------------------------------------------------|--------------------------------------------------------------------------------|---------------------|---------------------|
| Stretching the working area of the compounds at an angle $\beta$ (kN/cm$^2$) | 0.05 / 0.12                                                                | 0.04 / 0.095        | 0.03 / 0.07         |
| Stretching the working area of the compounds at an angle $\alpha$ (kN/cm$^2$) | 1.15                                                                      | -                   | 0.40                |
| Slice plate at an angle $\gamma$ (kN/cm$^2$)       | 0.35                                                                      | 0.30                | 0.25                |
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