Experimental and Theoretical Investigation of Wooden Construction Elements’ Connections on Dowel Plates

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Abstract. Improvement of dowel joints in order to increase their load-carrying capacity and reliability at the present time remains actual one. A special place among them is occupied by connections with the use of dowel plates. In order to increase the bearing capacity of metal nailed plates developed in NGASU (Sibstrin) with the use of reinforced dowel it is suggested to strengthen the nailed plates in metal plates by means of tight installation on the last metal stamped gear washers. In order to determine the strength and deformability of the developed connections they were prepared and tested under the action of short-term loads along and across the fibers. On the basis of the received data the analysis of short-term bearing capacity and deformability of the offered joints has been carried out. The method of calculation of such connections on limiting states of the first group is offered. The interaction of the limiting load-carrying capacities obtained on the basis of the proposed method with the results of short load action tests of the compounds under consideration was performed.

1. Introduction

Researches of work of connections of wooden elements on dowel plates, executed both domestic scientists, and foreign [1-8], have been directed basically on study of work of connections of wooden elements with stamped and cylindrical teeth. Thus work of cylindrical teeth (including dowels) with tightly mounted on them stamped gear washers, in connections of wooden elements, has not been studied till now.

One of the ways to develop wooden constructions is to increase reliability and strength of their knots. Nowadays a great variety of dowel plates is known: stamped toothed plates [9, 10, etc.], metal plates with teeth-dowels [11], nail plates with welded cylindrical teeth [12], and others. Particular attention should be paid to the above mentioned metal plates with teeth-dowels. For their improvement it was suggested to install the dowel gear washers tightly on the teeth of the metal plate dowels (Figure 1) [13, 14]. The expediency of the decision is confirmed by the results of the study of wood buckling work in small diameter holes [15], which show the need to increase the dispersal of toothed dowels to the wooden element. It should be noted that the proposed coatings have not been studied so far. In order to determine the short-term bearing capacity and deformability of such joints, tests were carried out on specimens with different angles between the direction of force and the direction of wood fibers, as well as types of toothed elements.
2. Mathematical processing of the research result

The strength characteristics of pine wood were determined before the main tests began. In accordance with (State standard 16483.10-73 Wood. Methods for determining compressive strength along fibers. - Moscow: IPK Standards Publishing House, 1999. - 6 c.) standard samples-cubes determined the compressive strength of wood along the fibers. Samples-cubes were made of pine wood with 8 % humidity (GOST 16483.7-71 Wood. Method of moisture determination. - Moscow: Standartinform, 2006. - 3 p.), according to requirements of norms (State standard 16483.0-89 Wood. General requirements for physical and mechanical testing. - Moscow: PKI Standards Publishing House, 1999. - 10 c.) They were tested 28 pcs. The compression test of the specified specimens was carried out before failure on the universal breaking machine "R-5". By results of tests statistical characteristics determined in accordance with the abovementioned GOST 16483.0-89 is given in Table 1.

Smooth dowels (Execution 1) with length \((L)\) of 60 mm and diameter \((d)\) of 4.5 mm [16], made of structural steel of 70 grade (State standard 14959-79) were used in manufacturing of connection samples. Metal plates 3 mm thick and stamped gear washers 2 mm thick \((b_{g,w})\), casting were made of sheet steel C 245 (State standard 27772-2015) (see Figure 1). Suggested washers have six stamped and bent in one direction at right angles to the surface of the tooth washer on the edges. Tooth height \((l_t)\) is 19 mm and width \((b_t)\) is 2 mm. In the center of the washer there is a 4.4 mm diameter hole for the dowel \((d_{d,w})\), which ensures its tight fit on the 4.5 mm diameter dowel \((d)\).

![Figure 1. General view and a fragment of a metal toothed plate with a dowel and a stamped gear washer (RF patent for utility model No. 40772 MKI 7 F 16 V 13/00 Fastener for connecting wooden elements (options) / P.A. Dmitriev, V.V. Purtov, A.V. Pavlik. - Publ. September 27, 2004. Bul. No): \(\delta_{g,w}\) - thickness of a gear washer; \(b_t\) - width of a tooth; \(\delta\) - thickness of a metal plate; \(d_{g,w}\) - diameter of a toothed washer; \(d_{d,w}\) - diameter of an aperture under a dowel; \(d\) - diameter of a dowel; \(l\) - full length of a dowel; \(l_t\) - height of a tooth of a washer taking into account the pointed part of a toothed plate.](image-url)
Table 1 Statistical characteristics.

| Statistical characteristics                                      | Indicators |
|------------------------------------------------------------------|------------|
| Compressive strength of wood along the fibers $\sigma_{12}$, MPa | 44.90      |
| Humidity of samples $W$, %                                       | 8.00       |
| Average square deviation $S$, MPa                                | 6.70       |
| Arithmetic mean error $S_r$, MPa                                 | 1.27       |
| Selective coefficient of variation $v$, %                        | 14.90      |
| Relative accuracy $P_r$, %                                       | 5.86       |

Parameters of the toothed washer were determined on the basis on the results of studies of proposed compounds by polarization-optical method [17]. The optimal tooth length of the washer was also determined by analytical method from the condition of achieving the maximum load-bearing capacity in the formation of two plastic joints (in the base and along the tooth length of the washer). In view of all of the above requirements, the stamped gear washers were manufactured with a diameter $d_{g,w}=38$ mm.

In order to study load-bearing capacity and deformability of connections on metal plates and dowels with stamped gear washers, samples of single-cut connections of glued wooden elements of MDSH-0 series (metal face plate with dowels and toothed washer - interface angle $0^\circ$) and MDSH-90 series (the same, with interface angle $90^\circ$) were manufactured and tested for short-term static load. For comparison, similar samples were tested on dowels without gear washers (MD-0 and MD-90 series). In all of four samples in each series were tested.

To study the influence of stamped toothed washer on the bearing capacity of the investigated co-sections samples of connections on metal plates and stamped gear washers (series MSh-0 and MSh-90) have been additionally produced.

Testing of specimens was carried out on tension (breaking machine P-5) at continuous loading. Some samples were tested with periodic unloading. Shear deformations during testing of specimens were measured with the help of time type indicators "ICH-10" with the price of division of 0.01 mm installed on them.

Figure 2 shows one of the results of short-term tests of single-cut specimens of MD, MSh and MDSH series along fibers.

As a basis for development of a method of calculation of investigated compounds the theory of calculation of the pegged connections based on a principle of limiting states and on representation about wood as about elastic-viscoplastic material which destruction occurs with occurrence of plastic deformations and considers the time factor is accepted. Peg is considered as a beam lying on the elastic and viscoplastic base, to which loads are applied in order to crush the base and bend the beam. Percentage of use for buckling the peg hole in the steel plate and wood is taken into account by means of the bed coefficients proposed by Professor P.L. Pasternak.

The above method of calculation was confirmed and used by a number of researchers (A.K. Naumov, A.M. Durnovskiy, V.A. Tsepaev, N.T. Andreiko, Yu. Purto, L.A. Maximenko, V.G. Kotlov, A.V. Kritsin, G.A. Stolpovsky, M.A. Arkaev, etc.).

The conclusion of the calculation formulas for calculating the limit state by one conditional "cut" of the dowel reinforced by a stamped toothed washer was based on the assumptions previously used by other authors (A.V. Lenyashin, V.L. Nikolai, V.M. Kochenov, P.A. Dmitriev, V.V. Purto, etc.) in order to create practical methods for calculating dowel compounds.

Taking as a basis the calculation method for pressed tooth developed by A.K. Naumov, and taking into account the above general prerequisites, the authors first determined the load-bearing capacity of connections of wooden elements on metal plates only with stamped gear washers.
Figure 2. Load displacement curves for MD-0, MSh-0 and MDSh-0 series samples.

Destruction of connections of wooden elements on metal plates only with stamped gear washers can occur: from buckling of wood under the tooth of the washer; from formation of plastic hinge at the tooth base or from formation of two plastic hinges, at the base and along the length of the tooth of the washer. After inserting the dowel into such a joint, a fourth failure pattern is possible due to one-sided metal buckling in the bore of the washer under the dowel.

The maximum load-bearing capacity of connections with metal plates and stamped gear washers was determined as the minimum of the calculated:

1. Uniform buckling of the wood under the tooth of the washer without formation of plastic joints in the tooth itself:

   \[ T_{g.w.crust} = R_{\text{crush.c.}}^{\text{live}} \cdot d_t \cdot l_{\text{work.t.}} \]

   where \( l_{\text{work.t.}} = 0,71 \cdot d_t \cdot \sqrt{R_{g.p.}^{\text{live}}} \)

   \[ \frac{R_{g.p.}^{\text{live}}}{R_{\text{crush.c.}}} \]

2. Double-sided buckling of the socket wood and bending of the tooth at its base:
\[ T_{g.w} = R_{\text{crush},c} \cdot d \cdot x_1 \quad \text{where} \quad x_1 = \sqrt{2 \cdot l_{\text{work},t}^2 + \frac{R_{y,p}}{R_{\text{crush},c}} \cdot d^2 \cdot l_{\text{work},t}}. \]

3. The formation of a second plastic tooth joint along the length of the tooth:

\[ T_{\text{g.w,bend}} = d^2 \cdot \sqrt{R_{y,p} \cdot R_{\text{crush},c}}. \]

4. Crush in the hole of the washer:

\[ T_{g.w,\delta} = k_\delta \cdot \delta_{g.w} \cdot d \cdot R_{\text{crush},\delta} \quad \text{where} \quad k_\delta = 1. \]

For all analyzed fracture diagrams according to the obtained formulas, the authors made graphs for determining the limit and calculated carrying capacity of stamped gear washers with thickness of 1.5, 2 and 2.5 mm.

Having determined the formulas for finding the limiting load-carrying capacity of stamped gear washers, the limiting load-carrying capacity of the whole connection (metal plate with a dowel and a stamped toothed washer) was calculated taking into account the supporting action of the washer. To determine the calculated load-carrying capacity of the whole connection, it is necessary to replace the time limits of strength \( R_{\text{crush},\delta} = R_{\text{crush},c} \cdot R_{y,p} \) with the calculated resistances \( R_{\text{crush},\delta}, R_{\text{crush},c}, R_{\text{bend}} \) in the above mentioned formulas.

The calculated load-carrying capacity of connections with metal plates and dowels, reinforced with stamped gear washers, was determined as the minimum of the calculated:

1. From the condition of wood buckling

\[ T_c = k_c \cdot l_{\text{work}} \cdot d \cdot R_{\text{crush},c} + T_{g.w}. \]

2. From the crushing condition of the steel lining

\[ T_\delta = k_\delta \cdot \delta \cdot d \cdot R_{\text{crush},\delta}. \]

3. Under the condition of the dowel bend in the thickness of the wooden element.

\[ T_{\text{bend}} = k_\delta \cdot \delta \cdot d \cdot R_{\text{crush},\delta}. \]

4. Under the condition of bending the dowel in a thicker metal lining.

\[ T_{\text{bend}} = k_c \cdot l_{\text{work}} \cdot d \cdot R_{\text{crush},c} + T_{g.w}. \]

5. From the condition of bending the dowel with the formation of two hinges

\[ T_{\text{bend}} = \delta_{\text{bend}}. \]

6. From the condition of cutting the dowel in the plane of the elements' fusion

\[ T = \delta \cdot k_\delta \cdot \frac{3 \cdot (\delta \cdot k_\delta)^2}{2 - R_{y,p} \cdot d^3 + \frac{8 \cdot R_{y,p}}{3 R_{\text{shear}} \cdot \pi^2 \cdot d}}. \]

For revealing the working scheme of the limiting balance of connections on metal plates and dowels, strengthened by the stamped gear washers, it is offered to use the step-by-step algorithm developed by the authors which block diagram is presented in figure 3. At working out of the step-by-step algorithm of revealing of the true scheme of limiting balance of knot connections the position of a static theorem of limiting balance was used and a problem of definition of a maximum of limiting loading was put and solved as a problem of nonlinear mathematical programming [18].
The proposed method allows calculating the maximum and calculated carrying capacity of connections under the action of a short-term force at different angles to the direction of the fibers.

3. Results
On the basis of the tests it was found that the short-term carrying capacity of dowels across the fibers in the samples of MD-90 series is significantly less (≈ 25 %) than in the joints along the fibers (MD-0 series). For the samples of the MSh-90 series the short-term load-carrying capacity was less ≈27% than in the samples of the MSh-0 series. In turn, the short-term load-carrying capacity of the MDSH-90 series is less than that of the MDSH-0 series by ≈ 14 %.
Analysis of the results of the experiment showed that dowels reinforced with stamped gear washers have, on average, a higher carrying capacity by \( \approx 41 \% \) (along the fibers) and \( \approx 48 \% \) (across the fibers) than dowels without such washers.

4. Discussion
The use of connections on metal plates and dowels reinforced with stamped gear washers in wooden constructions is a rather promising direction.

Firstly, widely available materials (sheet steel with thickness of 2 and 3 mm, thermally hardened and chipped dowels nails) are used to create such toothed plate.

Secondly, the presence of a toothed washer reduces the deformation of the joints along and across the fibers. This can be explained by the fact that the forces acting in the joint are perceived by a large number of teeth and dispersed on a large working surface of wooden elements. Putting a toothed washer on the tooth plate reduces the deformation in the tooth base within the elastic range of the wood. This increases the load-bearing capacity and viscosity of the joint in comparison to similar joints on dowel nails.

The results of theoretical and experimental studies allow us to formulate further directions for the development of the above topic:

- development of the calculation method for the second group of limiting states for such compounds;
- investigation of their long-term bearing capacity;
- development and research of knot connections made with the help of metal plates and dowels, reinforced with stamped gear washers, working together with metal plates inserted into cuts of wooden elements;
- development and research of connections of thin sheet materials (steel profiled sheets, etc.) with wooden elements, made with the help of a mounting part in the form of a single dowel and a tightly placed pressed toothed washer;
- development and design of industrial folding wooden constructions using the above-mentioned plates and recommendations for their calculation, production, transportation and installation.

The researched connections can be successfully used in solid wood and glue trusses of middle spans, as well as in spatial combined coating trusses [19]. At the same time, first of all, it is expedient to use them in the construction of support units of structures capable of absorbing significant tensile forces.

5. Conclusion
The results of the experiments clearly showed the advantages of the proposed metal plate with teeth dowels, reinforced with stamped gear washers.

The developed method of calculation is universal and allows determining the bearing capacity:
- connections on metal plates with teeth dowel;
- connections on metal plates with stamped gear washers;
- connections on metal plates with dowels, reinforced with stamped gear washers.

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