КРАТКИЕ СООБЩЕНИЯ И ОБМЕН ОПЫТОМ

UDC 624.011.2+674.028.3/9
DOI: 10.37482/0536-1036-2020-4-178-189

CONTACT INTERACTION OF A CLAW WASHER WITH WOOD AT LIMITING SHEAR

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When designing, manufacturing and maintaining of woodworks and elements of wooden structures it is necessary to solve the problem of providing the calculation of strength, stiffness and their bearing capacity. This problem becomes particularly relevant while reconstructing and new wooden house building, as the correct choice of connection type influences the technical possibility to use wood in the elements of structures. Such types of special connectors as claw washers, gang nails, dowel connections, etc. are used for these purposes. The existing range of claw washers implies different diameters, thicknesses, and claw configurations depending on the required bearing capacity and cross-sectional dimensions of sawn timber. The accepted physical model of wood is a transtropic body. The forces transmitted in the joints of the elements of wooden structures are perceived by the total contact surface of the mating elements. However, the work of individual teeth of claw washers has been poorly studied: research on influence of geometrical characteristics of the tooth on the bearing capacity of the connector is absent; variation in thickness of the connector is not assessed. A double-sided claw washer of the Bulldog type (prototype) with the diameter of 50 mm was adopted as the object of study. Various schemes of cutting of the claw washer with predetermined dimensions (width and height) of a triangular tooth are considered. The influence of dimensions on the bearing capacity of the thickness of claw washers is estimated within 1–1.5 mm. The main criterion for the selected cutting patterns is the ability to produce the washers by single-impact stamping without additional trimming. Double-sided claw washers of 5 different types with the number of cog-teeth from 8 to 12 items on each side were studied. A differential equation of the 4th order is accepted as a mathematical model of cog-tooth action. The equation describes the behavior of a dowel on an elastic base with a fixed value of bending stiffness EI. The transition to which was carried out from the variable value $EI = f(x)$ by searching for the equivalent width of the cross-section from the bending conditions of the element of the triangular section of a variable directed normal to the frontal surface and a constant directed normal to the lateral surface.

For citation: Popov E.V., Ruslanova A.V., Sopilov V.V., Zdralovic N., Mamedov S.M., Labudin B.V. Contact Interaction of a Claw Washer with Wood at Limiting Shear. *Lesnoy Zhurnal* [Russian Forestry Journal], 2020, no. 4, pp. 178–189. DOI: 10.37482/0536-1036-2020-4-178-189

Keywords: wood, wooden structures, anisotropy of wood, strength, deformability, claw washers, gang nails.

Introduction

Wood is a self-renewing natural resource with special strength, technological and anisotropic properties, which must be taken into account when designing and calculating of the connectors. The most responsible issue is the interaction of wood and the connectors in the contact zone. V.M. Vdovin [6], M.S. Galakhov [7], D.S. Ishmaeva [10], A. Karelskiy [11], B.V. Labudin [14, 16, 17], Xu Yun [21], E.V. Danilov and A.G. Chernykh [8], A.O. Orlov [27, 28], J.N. Karadelis and P. Brown [24], E.-M. Meghlat, M. Oudjene and H. Ait-Aider [25], H.J. Blaß and P. Schädle [22], Čechavičius R. [23] and others were engaged in designing and calculation of the connections of wooden structures with the help of metal connector plates and washers.

Various types of connections on dowels, Lennov's claw washers, glued steel corrugated gang nails, Bulldog claw washers, and others have been developed from the whole variety of joints used in wooden structures [1–3]. Such connections are used in manufacturing roof trusses, compound beams, columns and flat ribbed panels, in the amplification of wooden structures of different purposes, and also in fitting connections.

A wide variety of connectors [15] was presented and metal connector plates were considered (Fig. 1) in our research [18].

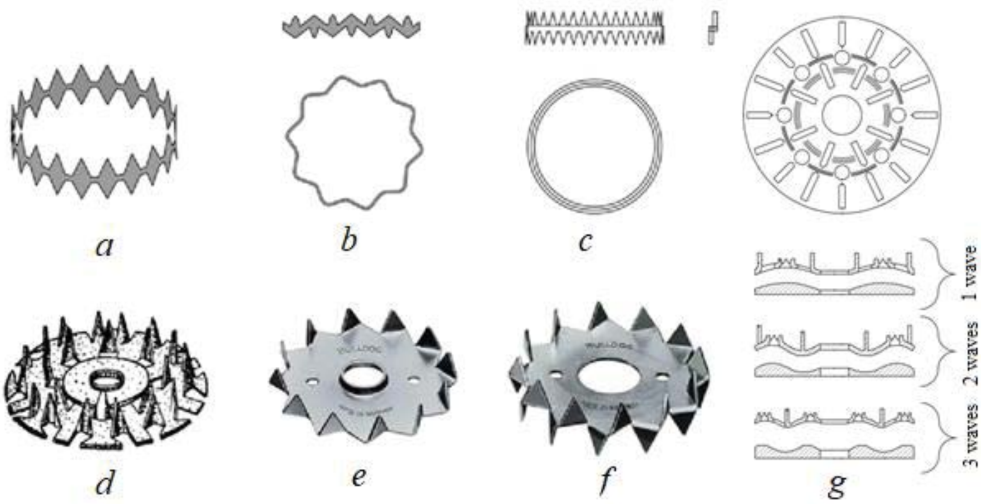

Fig. 1. Varieties of gang nails and claw washers: *a* – Alligator gang nail; *b* – Engineer Khorkov's gang nail; *c* – Kabakov's gang nail; *d* – Lennov's claw washer; *e*, *f* – Bulldog claw washers; *g* – glued steel corrugated gang nails

Bulldog claw washers consist of low-carbon steel with or without cold-rolled covering. Types of steels from DC01+C390 to EN 10139, or cold-rolled high-strength cold stamped steel from N320M to EN 10268 are used as a body material. Claw washers are round plates made of thin (from 1 to 1.2 mm) steel with triangular shaped claws bent perpendicular to the plate plane. They are made with one-sided (Fig. 1, *e*) and two-sided (Fig. 1, *f*) bending of teeth. The advantages of these claw washers include the simplicity of pressing the connection, the lack of necessity of preliminary drilling of holes, and the high bearing capacity of the connection. Bilateral Bulldog washers can be used not only in nodal connections, but also for improvement of shear stiffness of dowel connections of wooden structures [16]. The calculation of connections with these claw washers is performed according to [20].

Research objects and methods

The range of washers of the Bulldog type manufactured by the Bova-Nail company [26] is shown in Table 1.

Table 1

The range of the Bulldog claw washers

Diameter of a claw washer, mm	50	75	95
Diameter of a bolt, mm	17	23	36
Minimum pitch of washers, mm	70	110	140

A double-sided Bulldog claw washer with a diameter of 50 mm is taken as a research object. It was made of a steel plate of 50 mm diameter, 1 mm thick, in which 12 notches were cut in advance. The number of notches is equal to the number of teeth on each side of the washer; the angle between the notches is denoted by α.

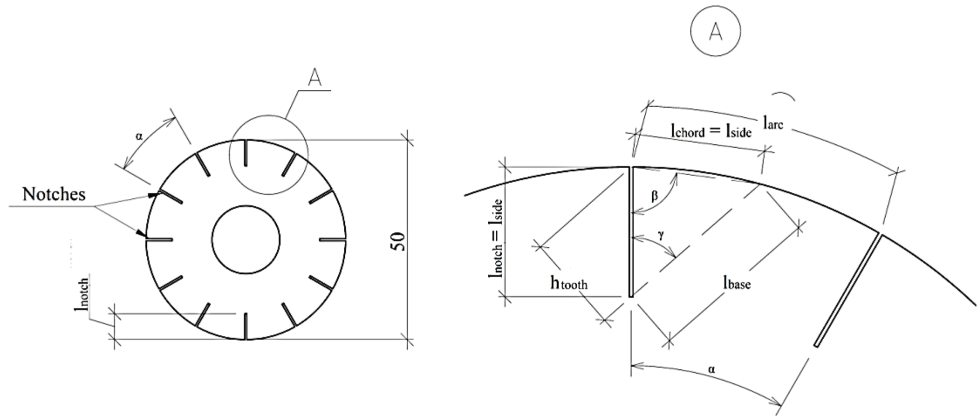

Fig. 2. Scheme of a workpiece for stamping out the Bulldog claw washer with a diameter of 50 mm and the values that determine the tooth dimensions

The notch length l_{notch} determines the value of the side of the washer tooth. The tooth height h_{tooth} equal to the product of the length of side l_{side} of a triangle to the cosine of half the angle β between the inner side of the tooth and the chord of the arc outer side of the tooth. The length of the tooth base l_{base} is equal to twice the product of the length of the side l_{side} by the cosine of the angle between the side and the base of the tooth γ.

The production efficiency of claw washers is based on the possibility of their manufacturing by single-impact stamping from a round steel workpiece, and the tooth dimensions should determine the possibility of making the washer without the need for additional undercutting, which is important for the purposes of rational material consumption.

It is necessary to consider several options of washers with different number and sizes of teeth should in order to select the rational shape of the claw washer.

While the washer is operating in the connection, it is reasonable to evenly distribute the forces along the tooth width, so that the tooth sides forming the angle β (Fig. 2) are equal to each other. Therefore, the reference length of the notch for subsequent stamping should be determined by the following:

$$l_{chord} = 2R\sin\left(\frac{\alpha}{4}\right), \quad (1)$$

where l_{chord} – chord length, mm; R – radius of the round plate of which the washer is stamped, mm; α – angle between the notches, determined by the expression:

$$\alpha = \frac{360}{n},$$

where n – number of notches (teeth).

We obtain an expression that determines the required length of the notch for a given number of teeth taking into account the necessity of equality of the tooth sides, and therefore the equality of the length of the notch and the chord of the half of the arc:

$$l_{notch} = 2R\sin\left(\frac{360}{4n}\right). \quad (2)$$

The small size of teeth, when wood shrinks, leads to their extraction from the contact zone, which greatly reduces the connection strength in moist timber [13]; this is a significant drawback of claw washers. Therefore, it is advisable to consider options of washer design with increased dimensions of teeth, which implies the need to reduce their total number.

The notch depth at a predetermined number of teeth is determined by the equation (2):

n = 8: l_{notch} = 9.8 mm; h_{tooth} = 7.5 mm; b_{base} = 12.4 mm;
n = 9: l_{notch} = 8.7 mm; h_{tooth} = 6.7 mm; b_{base} = 11.2 mm;
n = 10: l_{notch} = 7.8 mm; h_{tooth} = 6.0 mm; b_{base} = 10.1 mm;
n = 11: l_{notch} = 7.1 mm; h_{tooth} = 5.4 mm; b_{base} = 9.3 mm;
n = 12: l_{notch} = 6.5 mm; h_{tooth} = 4.9 mm; b_{base} = 8.6 mm.

Claw washer options are shown in Fig. 3.

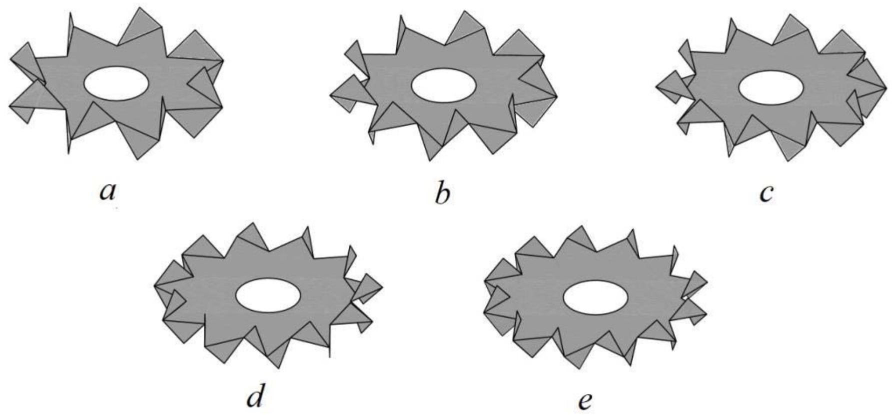

Fig. 3. Options of claw washers with a different number of teeth n, pcs: a – 8; b – 9; c – 10; d – 11; e – 12 (standard washer)

Calculation of a tooth is performed as for a cantilever beam on an elastically deformable base. This assumption is valid under the action of short-term loading and small deformations, when the maximum allowable value for the connections is limited by the requirements of the Code of Practice [19]. Considering the claw material to be elastic and neglecting the influence of lateral forces on deformation and torsion, adopting the hypothesis of flat sections, we accept the Bernoulli's assumption and write the differential equation of the tooth elastic axis as a fixed beam lying on an elastically deformable base [8]:

$$EI(x)y(x)^{\text{IV}} + Cy(x) = 0, \tag{3}$$

where C – short-term bedding value of the base length at an angle to the fibers γ.

To solve equation (3), with a cross-sectional moment of inertia variable in height, we introduce the constant equivalent value $EI(x)$ = const from the condition that the tip moves under the lateral load on the claw. When bending a claw from a plane under the action of a variable load $q(x)$, an equivalent width b_{eq} = = 0.8b is obtained, where b_{base} – width of the tooth base. Since the task of calculating the equivalent width when bending the claw with load q = const in its plane does not have an analytical solution, the values of the equivalent width were selected numerically by approximating the moment of inertia by a replacement function for each option. They are: b_{eq} = 0.011; 0.009; 0.008; 0.0074; 0.0068 with the number of claws n = 8, 9, 10, 11, 12 on one side, respectively.

Equivalent bending stiffness of a tooth EI is determined by the equations (4) when bending from a plane and in a plane, respectively:

$$EI = E_{st}\left(\frac{S^3 b_{eq}}{12}\right); \qquad EI = E_{st}\left(\frac{b_{eq}^3\, S}{12}\right), \tag{4}$$

where E_{st} – modulus of elasticity of steel, $E_{st} = 2{\cdot}10^8$ kPa; S – thickness of a tooth, determined by the thickness of the steel plate (workpiece); b_{eq} – equivalent width.

According to [4] the solution of equation (4) $EI(x)$ = const is the following:

$$y(x) = e^{\frac{Px}{\sqrt{2}}}\left(C_1\cos\frac{Px}{\sqrt{2}} + C_2\sin\frac{Px}{\sqrt{2}}\right) + e^{\frac{-Px}{\sqrt{2}}}\left(C_3\cos\frac{Px}{\sqrt{2}} + C_4\sin\frac{Px}{\sqrt{2}}\right), \tag{5}$$

where C_1, C_2, C_3, C_4 – integration constants determined from the boundary conditions; P – expression replacement for convenience of calculation, $P = \sqrt[4]{C/EI}$.

When a claw is operating in the elastic stage (before the formation of a plastic hinge), the boundary conditions can be written as:

$$\begin{cases} x = 0 \to \frac{dy}{dx} = 0 \text{ и } \frac{d^3y}{dx^3} = -\frac{N}{EI}; \\ x = h_{tooth} \to \frac{d^2y}{dx^2} = 0 \text{ и } \frac{d^3y}{dx^3} = 0, \end{cases} \tag{6}$$

where h_{tooth} – tooth height, mm.

With the following subscription $P/\sqrt{2} = A$, arbitrary integration constants can be found as follows:

$$\begin{gathered} C_1 = \frac{N}{8EI{\cdot}A^3}; \\ C_2 = \frac{Ne^{Ah}\sin Ah - 2Ne^{-Ah}\cos Ah + Ne^{-Ah}\sin Ah}{8A^3EIe^{Ah}\cos Ah(e^{Ah}+e^{-Ah})}; \\ C_3 = -C_1; \\ C_4 = -\frac{Ne^{Ah}\cos Ah + Ne^{-Ah}\sin Ah + Ne^{-Ah}\sin Ah}{8A^3EIe^{Ah}\cos Ah(e^{Ah}+e^{-Ah})}, \end{gathered} \tag{7}$$

where N – load applied to the washer tooth, kN.

In order to describe the process of wood deformation in a dowel socket of the contact zone, we use the well-known expression:

$$y(x) = \frac{q(x)}{C}. \quad (8)$$

The total deformation of the socket wood Δ_t in the tooth base ($x = 0$) is determined by the expression:

$$\Delta_t = \int_0^h \frac{q(x)}{C} = \frac{-Q(0)}{C} = \frac{N}{C}. \quad (9)$$

When a claw is located at an angle to the vector of the applied load N (0°<α<90°), proper allowance must be made for the stress components of N applied through the length and breadth of the claw plane.

We used generally accepted formula [5, 9, 19] in this study, taking into account the wood anisotropy in order to express the bedding values when bearing stress at any angle to the wood fibers γ:

$$C_\gamma^{temp} = \frac{C_0}{1+\left(\frac{C_0}{C_{90}}-1\right)\sin^3\gamma}, \quad (10)$$

where C_γ^{temp} – short-term coefficient of wood thickness when crushed at the γ angle to the fibers; C_0, C_{90} – bedding values when wood bearing at an angle of γ = 0° and γ = 90° respectively, determined depending on the following dependeces [12]:

$$C_0^{temp} = (-0.14b_{cr} + 2.289)R_c;$$
$$C_{90}^{temp} = (-0.094b_{cr} + 0.826)R_c, \quad (11)$$

where C_0^{temp} and C_{90}^{temp}– short-term bed coefficients of wood when crushed at angles of 0° and 90°, kN/m^3; b_{cr} – width of the creasing side of the tooth, m; R_c – calculated resistance of wood to compression along the fibers, kPa.

The calculation is made for each washer tooth of all presented options. The criterion of strength of each tooth is the force causing the ultimate deformation of a tooth Δ_{ult} = 2 mm.

Results and discussion

Consider a single-section connection operating at longitudinal shear (Fig. 4). Conditionally, we believe that the resulting spreader impacts on a bolt, the work of which on shear along with the claw washer is not conditionally taken into account.

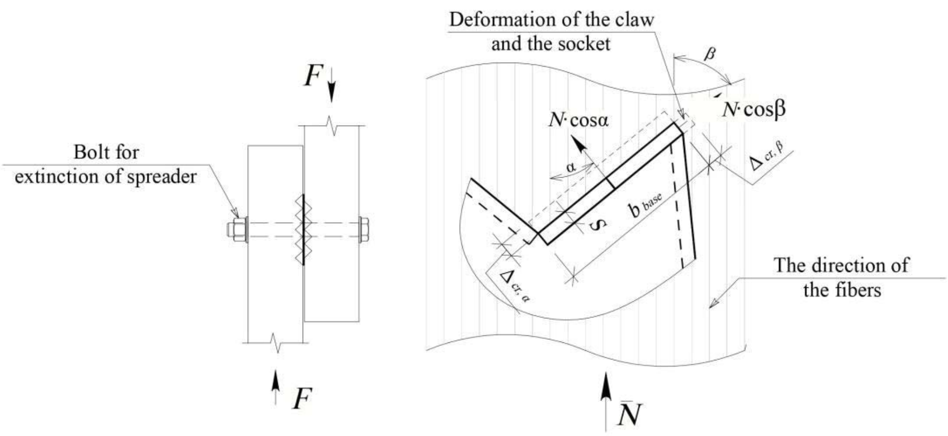

Fig. 4. Scheme of a single-section connection at longitudinal shear (on the left) and the structural design of a washer claw (on the right)

The bearing capacity of the washer is determined in the following sequence:

1. It is assumed that a single force $\overline{N} = 1$ acts on each washer claw parallel to the direction of the wood fibers.

2. The force is decomposed into components normal to the frontal and lateral surfaces of the claw, which form the angles α and β with the direction of the force $\overline{N}$ and the direction of the fibers.

3. While solving the equations (4) and (9), determine the moving direction of the claw according to the force component vector $\overline{N}$ ($\Delta_{cr,\alpha}$ and $\Delta_{cr,\beta}$ in the normal direction of the front and lateral surfaces of the claw, respectively).

4. Determine the ultimate force, taken by the claw, according to the equation:

$$N_{ult,c} = \left(\Delta_{ult}/\Delta_{cr,\alpha}\right)\cos\alpha + \left(\Delta_{ult}/\Delta_{cr,\beta}\right)\cos\beta, \tag{12}$$

where Δ_{ult} − maximum allowable displacement, Δ_{ult} = 2 mm.

5. Bearing capacity of a double-sided claw washer $N_{c.w}$ is determined as the sum of the supporting abilities of all claws based on the maximum strain of the joint:

$$N_{ult,w} = 0.5\sum N_{ult,c}, \tag{13}$$

where 0.5 − coefficient that takes into account the bearing of wood on both sides of the washer.

The calculation results are summarized in Table 2. The dependence of the bearing capacity of the washers on the thickness is shown in Fig. 5.

Table 2

The bearing capacity of the claw washers depending on the cutting pattern and the workpiece thickness

Washer cutting pattern (by the number of teeth on one side, pcs)	Bearing capacity of the washer $N_{ult,w}$, kN, depending on the thickness of a workpiece, mm					
	1.0	1.1	1.2	1.3	1.4	1.5
n = 8	3.06	3.33	3.54	3.73	3.88	4.01
n = 9	3.45	3.67	3.86	4.02	4.16	4.27
n = 10	3.72	3.93	4.10	4.24	4.36	4.47
n = 11	3.81	3.99	4.16	4.31	4.43	4.54
n = 12	4.22	4.38	4.52	4.64	4.74	4.83

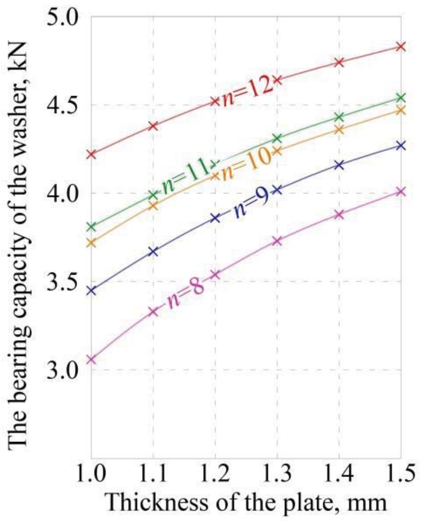

Fig. 5. Dependence of bearing capacity ($N_{ult,w}$) on thickness of the plate (t)

The bearing capacity of a claw washer $N_{ult,w}$ stamped from a plate of the same diameter can vary significantly (up to 54 %). When varying the thickness of the plate-workpiece within 1–1.5 mm, an increase of $N_{ult,w}$ varies within the limits of 15–31 %; with an increase in the total number of teeth the influence of thickness decreases.

With a total number of teeth in the range of 8–12 pcs, the increase in bearing capacity is 20–38 %, the largest difference is common for the washers stamped out of a plate 1 mm thickness.

Cutting pattern of a double-sided claw washer with 12 teeth on each side was found to be the most effective option. Considering small height of teeth (h_{tooth} = = 4.9 mm) of the washers of this configuration, they can be recommended for use only with pre-dried timber, since the extraction of teeth from the sockets when shrinkage will adversely affect the operation of the claw connection. In wet timber, the most rational option is the claw washer with 9 tooth and 6.7 mm height.

Conclusions

1. The presented calculation procedure allows theoretical determining the bearing capacity of the connections of elements of wooden structures on the claw washers under the short-term loading, as well as determining the rational cutting parameters for one-sided and two-sided washers of arbitrary diameter.
2. The most effective cutting parameters for a double-sided claw washer made of 1–1.5 mm thick steel plate are determined according to the condition of ultimate deformation in the connection of wood elements during longitudinal shearing.
3. The effect of the diameter of a steel workpiece, the loading duration, and the species composition of the core elements of wooden structures on the bearing capacity of the washers requires additional studies.

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КОНТАКТНОЕ ВЗАИМОДЕЙСТВИЕ КОГТЕВОЙ ШАЙБЫ С ДРЕВЕСИНОЙ ОТ ПРЕДЕЛЬНОГО СДВИГА

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При проектировании, изготовлении и эксплуатации изделий из древесины и элементов деревянных конструкций необходимо решение проблемы обеспечения расчетной прочности, жесткости и их несущей способности, что актуально при реконструкции и в новом деревянном домостроении, так как от правильного выбора вида соединения зависит техническая возможность использования древесины в элементах конструкций. Для этого применяют различные типы специальных соединителей в виде когтевых шайб, кольцевых шпонок, нагельных групп и др. Существующий сортамент когтевых шайб подразумевает различные диаметры, толщины и конфигурацию когтей в зависимости от требуемой несущей способности и размеров сечений пиломатериалов. Принятая модель древесины − транстропное тело. Усилия, передающиеся в соединениях элементов деревянных конструкций, воспринимаются суммарной контактной поверхностью сопряженных элементов. Однако работа отдельных зубьев когтевых шайб изучена недостаточно: отсутствуют исследования влияния геометрических характеристик зуба на несущую способность коннектора, не оценивается изменение толщины соединителя и др. В качестве объекта исследования принят прототип − двухсторонняя когтевая шайба типа «Bulldog» диаметром 50 мм. Рассмотрены различные схемы раскроя шайбы, в которой предопределены размеры (ширина и высота) зуба треугольной формы. Оценивается влияние на несущую способность толщины шайбы (заготовки) в пределах 1,0…1,5 мм. Основным критерием выбранных схем раскроя является возможность изготовления шайб одноударной штамповкой без дополнительной подрезки. Исследовано 5 вариантов двухсторонних когтевых шайб с количеством зубьев 8–12 шт. с каждой стороны. В качестве математической модели работы зуба принято дифференциальное уравнение 4-го порядка, описывающее поведение нагеля на упругом основании с постоянным значением изгибной жесткости *EI*, переход к которому осуществлялся от переменного значения *EI* = *f*(*x*) путем поиска эквивалентной ширины сечения из условия изгиба элемента треугольного сечения при помощи переменной, направленной нормально к фронтальной поверхности, и постоянной, направленной нормально к боковой поверхности.

Для цитирования: Popov E.V., Ruslanova A.V., Sopilov V.V., Zdralovic N., Mamedov S.M., Labudin B.V. Contact Interaction of a Claw Washer with Wood at Limiting Shear // Изв. вузов. Лесн. журн. 2020. № 4. С. 178–189. DOI: 10.37482/0536-1036-2020-4-178-189

Ключевые слова: древесина, деревянные конструкции, анизотропия древесины, прочность, деформативность, когтевые шайбы, зубчатые шпонки.

Поступила 15.11.19 / Received on November 15, 2019