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Performance of TGk dowel connector plates in wooden structure joints under long-term load

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Keywords: dowel, TGk metal connector plates, dowel joint, test scheme, deformation diagram, short-term diagram, long-term tests, wood of the dowel hole, isochronous curves.

Abstract. The article is devoted to the study of the bearing capacity and deformation of connections of wooden structures using plates with cylindrical TGk dowels of 5 mm diameter under prolonged load action. The deformation properties of connections of wooden structures are studied to a lesser extent, including in the stage of nonlinear creep under long-term load. The purpose of the research is to confirm the operational strength and rigidity of the compounds under consideration. For the theoretical analysis of the work of connections using metal connector plates under prolonged loading, the provisions of the theory of aging of materials are used. For experimental analysis, long-term tests were carried out on samples of pine beams with dimensions of 80 x 80 x 300 mm. All samples were installed under a constant load with different loading levels. The exposure period of the samples was 730 days. As a result of the performed studies, a conclusion was made about a sufficient degree of strength and rigidity of the connections of wooden structures on the TGk metal connector plates. Isochronous curves of deformation of the wood of the dowel hole and the connections themselves for certain moments of time are obtained. A calculated diagram of the deformation of the wood of the dowel hole $\sigma - \delta$ and calculated diagram $T - \Delta$ connections under prolonged loading is constructed. The results obtained are necessary for practical calculations of composite wooden elements with this type of connections, taking into account the time of action of the load.

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1. *Introduction*

Wood belongs to the group of materials with rheonomic properties. The strength and deformation of both the wood itself and its connections depend on the loading rate and the load duration [1–5]. The creep that occurs in this case has a significant effect on the parameters of the stress-strain state of the connections of wooden structures under prolonged load action.

The work of wood under the action of long-term loads can be divided into two areas. The 1st area is characterized by constant attenuation of deformations over time. The 2nd region is characterized by an increase in deformations with increasing speed in time, followed by the destruction of the material. Experimental and theoretical studies of the connections, including composite ones, under the action of long-term loads are given in a number of publications [6–13]. Under prolonged load action on a dowel connection, there is an increase in deformations of the dowel hole wood in time due to wood creep, which leads to redistribution of stresses over time even under constant load on the connection.

When loading a composite element with dowel connections subject to deformation, along with an increase in the deformations of the connections, over time, the deformations of wood itself develop, which together represent the stress-strain state of the composite wooden element at a certain point in time. The most effective way to confirm the operational reliability of new structures during the standard service life is to conduct long-term tests with the study and confirmation of the operational strength and rigidity of the structure, which is reflected in studies of various wooden structural elements under the influence of long-term loading [14–21].

Vyatka State University developed dowel connectors, which are connecting elements for wooden structures containing a group of cylindrical dowels of increased diameter of 5...8 mm with a more saturated arrangement and fixed on a common base. Connectors of the basic type (Fig. 1), called TGk metal connector plates, were designed mainly for making composite wooden elements of enlarged cross-section from beams and logs. The base of such a connector plate is made from hard materials with a high modulus of elasticity (steel, rigid structural plastics), which is marked by the letter “T”. Depending on the end part of the dowel, the plates are divided into types, with “G” marking the dowels sharpened on both sides. Fastening the dowel on the base is performed by welding as marked by letter “k”. Therefore, this type of dowel connector plate has the marking of “TGk” [22].

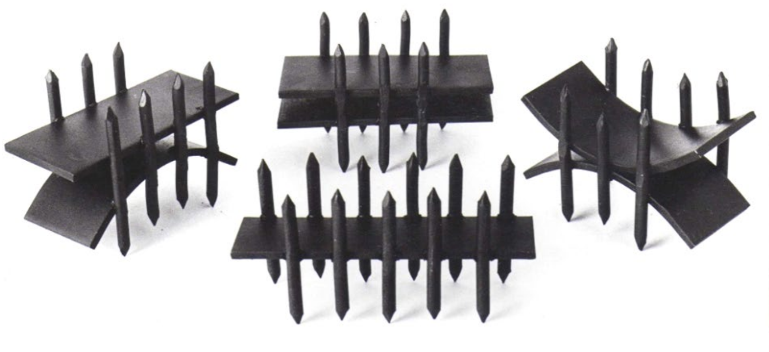

Figure 1. TGk metal connector plates of different types.

At the first stage of studies of compounds on TGk metal connector plates, short-term mechanical characteristics of the wood of the dowel hole and deformation characteristics of the dowel material were determined. The results of experimental and theoretical studies were obtained to determine the bearing capacity and deformability of connections under short-term loading.

The relevance of further studies of compounds is due to the need for experimental and theoretical analysis of the data obtained, taking into account the duration of the load. The purpose of the research is to confirm the operational strength and rigidity of the connections on the TGk metal connector plates, as well as to study the operation of the connections (primarily to obtain quantitative estimates of deformations at design stress levels) under long-term load, which is necessary for practical calculations of composite wooden elements.

To achieve this goal, the following tasks were set:

- to conduct experimental studies of wooden samples with a long-term permanent load;
- to construct isochronous curves of the dowel hole wood deformation and of connections the TGk metal connector plates for certain moments of time;
- to construct a calculated diagram of the dowel hole wood deformation $\sigma-\delta$ and $T-\Delta$ connections under prolonged loading.

2. Methods

To analyze the operation of connectors of wooden structures on TGk metal connector plates under long-term loading, we will use the provisions of the theory of aging of materials as the simplest apparatus for describing long-term processes [23, 24]. Based on this theory, there should be a relationship

$$F\left(\delta_0 \sigma_0 t T^0\right)=0, \tag{1}$$

δ_0, σ_0 are displacements and stresses under simple loading ; t, T^0 are time and temperature.

The complete displacement will be written as

$$\delta_0=\delta_{0el}+\delta_{0pl}+\delta_{0pl}+\alpha T^0, \tag{2}$$

δ_{0el}, δ_{0pl} are elastic and plastic displacements; δ_{0pl}, αT^0 are creep displacements and temperature displacements.

In case of non-uniform distribution of stresses, dependence (1) refers to the intensities of strains and stresses and can be written as

$$\delta_i = \delta_i\left(\sigma_i t T^0\right). \tag{3}$$

The main hypothesis of the theory of aging is that dependence (3) can be valid both in the stationary mode of loading (σ_0 = const, T^0 = const), for which it is easily determined from the experiment, and in the non-stationary mode (σ_0 = var, T^0 = var).

The calculation of the connections is based on the creep curves of the wood of the dowel hole, taking into account the fact that the properties of the dowel material (metal) do not change with time. Creep curves are built at different levels of applied stresses – a family of curves is obtained in the coordinates $\sigma - \delta$ (stress – strain). At the moment $\sigma = 0$, the initial displacement corresponds to the instantaneous displacement (elastic or elastic-plastic) as a result of the applied stress. At a certain point in time, for different curves of the family, we will have creep displacements corresponding to the acting stresses, which allows us to construct the dependence

$$\delta = \varphi\left(\sigma, t\right). \tag{4}$$

This dependence expresses an isochronous creep curve for a point in time. For the initial value of time t = 0, the isochronous curve coincides with the short-term deformation curve. Therefore, for fixed times, you can get a family of isochronous curves in the coordinates $\sigma - \delta$ for the deformation of the wood of the dowel hole, $T - \Delta$ (bearing capacity – deformation of the connection) for deformation of the connections and $M - f$ (bending moment – deflection of a beam of an entire section) for deformation of elements of a composite beam.

After finding isochronous creep curves, the problem is reduced to performing calculations at a certain point in time using known strain diagrams. For dowel connections, after the experimental determination of the family of curves $\sigma - \delta$, the calculation is performed according to the procedure [25]. For the initial time $t = 0$, the calculation completely coincides with the determination of the stress-strain state of dowel connections under short-term loading. For each moment of time, exactly the same calculation is carried out, but the isochronous creep curve for a specific time is taken as the deformation curve.

According to the performed calculations, it is possible to construct creep curves for connections and for deformation of elements of composite beams

$$\Delta = \varphi\left(T, t\right), \quad f = \varphi\left(M, t\right). \tag{5}$$

Creep curves obtained experimentally allow, in the calculations of a composite element, to correct the modulus of elasticity of wood in bending at a point in time. Using the obtained data, it is possible to perform the calculation of a composite wooden element on pliable bonds for any moment of time.

In order to determine the mechanical characteristics of the wood of the dowel hole and construct a long-term deformation diagram $\sigma_{cr} - \delta$, as well as to study the operation of wood connections on metal connecting plates TGk, experimental studies of samples with a long-term permanent load were carried out. All tests of samples were carried out in accordance with the requirements of recommendations for testing the connection of wood structures TsNIISK.

The whole complex of tests consists of the following stages:

1. preparation of samples, determination of the mechanical characteristics of wood;
2. short-term tests of the control series;
3. long-term testing.

At the first stage, samples were made from four pairs of pine beams with a cross section of 80×80 mm. Length 300 mm – from the condition of the placement of dowels and taking into account the possibility of determining the mechanical characteristics of the wood of the dowel hole. For the manufacture of samples, pairwise sawing of beams was used, so that each sample consists of the wood of two beams (for analogy with composite beams). Of the total number of samples, 50 % were intended for the control series – short-term tests. When sawing the beams in pairs, the alternate selection of samples was taken into account, so that each working sample subjected to a long-term load, in the accepted sample selection scheme, corresponded to two control samples adjacent in length bar. This makes it possible to evaluate the mechanical characteristics of the working sample by the average value of the characteristics of two control samples. The moisture content of wood for the period of sample preparation was 8...9 %. Samples-cubes 20×20×30 mm in size were sawn out of the working area of all samples, and the compressive strength along the wood fibers was determined in accordance with GOST 16483.10-1973. The average value of the short-term compressive strength of wood R_z = 46.8 MPa, which corresponds to the average quality of wood in terms of strength indicators.

At the second stage short-term tests of samples of the control series were carried out. The mechanical characteristics of the dowel hole were determined by testing the samples with a dowel stamp 5 mm in diameter according to the scheme described in [26]. Tests with a dowel stamp were performed on all samples of the control series and on samples of the working series. According to the strength and deformation characteristics, a conclusion was made about the identity of the wood selected for testing. The average value of the short-term strength of the wood of the dowel hole $R_{cr.n}$ = 36.0 MPa is taken as the base value for determining the levels of loading of the long-term load. Tests of specimens with TGk dowel plates with a dowel diameter of 5 mm and a length of 60 mm were performed according to symmetrical scheme 1 [27]. As a result the average value of the breaking force per one conditional slice for the given wood was T = 2.60 kN.

The third stage of testing is loading and holding samples under a long-term constant load. The test schemes both for determining the mechanical characteristics and for the connections correspond to the schemes for short-term tests of symmetrical connections with the only addition – all wooden elements are sealed in tightly fitting plastic bags in order to reduce the effect of fluctuations in the temperature and humidity conditions of the room on the deformation of the connections over time. A layer of 0.5 mm thick polyethylene film between the dowel plate and the wooden elements does not significantly affect the operation of the connections. The samples were loaded using disk lever installations with a gear ratio of efforts of 12.5. Before loading the samples, each setup was calibrated using a DOR-1 dynamometer of the Tokar system with a stepwise application of the load. All samples were installed under a constant load with different loading steps, shown in Fig. 2.

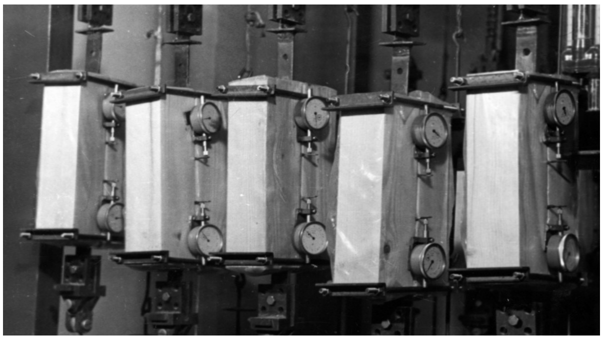

Figure 2. General view of samples during long-term testing.

The loading steps are chosen on the basis of 0.25; 0.5; 0.50; 0.75 of the breaking force for mechanical characteristics and connections, which is 0.67, 1.0; 1.2; 2.0 in fractions of the calculated bearing capacity for the nominal shear of the dowel. For each level of loading, 2 samples are installed, which makes it possible to obtain 4 results. Readings on deformations indicators ICH-10 were taken immediately after loading, then after 1, 3, 12, 24 hours, and subsequently after three, and then seven days. Along with deformation measurements, the temperature and humidity of the air in the laboratory were constantly recorded, as well as the humidity of control samples from wood of the same quality using an electronic moisture meter.

3. Results and Discussion

1. The process of deformation in time of the wood of the dowel hole and connections is shown in Fig. 3. The exposure period of the samples was 730 days. During this period, the deformations of the wood of the dowel hole increased by 5.1...7.7 times, and the deformations of the connections were increased by 2.4...4.8 times, depending on the steps of loading. At the load step T = 1.0 kN, the deformations of the connections increased by a factor of 3.5 and amounted to 0.45 mm for two

shear specimens. According to the form of creep curves, one can note an uneven growth of deformations; there are periods of more intense growth of deformations, attenuation, and growth again, especially at higher loading levels. This process can be explained by a change in the relative humidity of the air in the room from 25 to 40 % in winter to 70 to 80 % in summer, although measures were taken to reduce this effect on deformations.

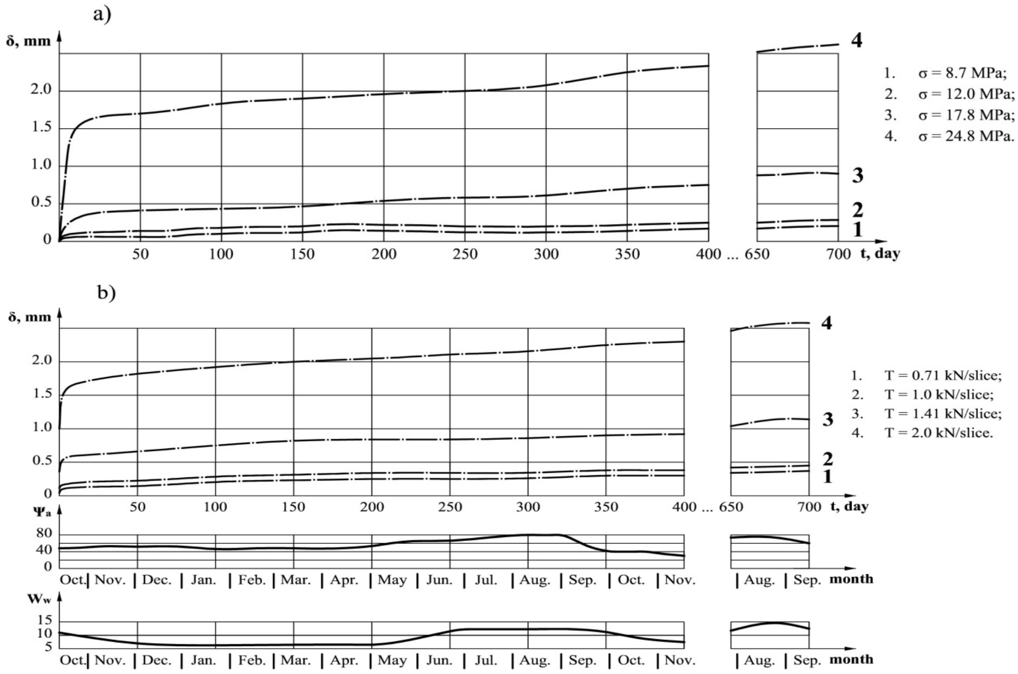

Figure 3. Creep curves a) wood of the dowel hole; b) connections on TGk metal connector plates.

In general, the process of deformation in time of both mechanical characteristics and connections at loading stages up to half the breaking load is damped, regular, and predictable. At higher loading stages, a gradual, undamped process of strain growth is observed, although failure did not occur on any of the specimens.

Prediction of deformations in time can be carried out by applying the well-known Maxwell-Thomson rheological equation [28]

$$\sigma + n\sigma' = E\varepsilon + nH\varepsilon' \tag{6}$$

its solution can be written as

$$\varepsilon(t) = \frac{\sigma}{H}\left(1 + \frac{H-E}{H}e^{-\frac{Et}{Hn}}\right), \tag{7}$$

σ is the magnitude of the voltage (load); H, E, n are rheological coefficients; H is instantaneous elasticity coefficient; E is long-term elasticity coefficient; n is relaxation time factor.

Rheological coefficients); H, E, n are determined from experimental creep curves using the technique [29]. The coefficient of instantaneous elasticity H is found from the instantaneous deformation formed immediately after the application of the load

$$H = \frac{\sigma}{\varepsilon_0}. \tag{8}$$

The coefficient of long-term elasticity is determined by the formula

$$E = \frac{\sigma}{\varepsilon_\infty} = \sigma\left(\frac{2\varepsilon_1 - (\varepsilon_0 + \varepsilon_2)}{\varepsilon_1^2 - \varepsilon_0\varepsilon_2}\right), \tag{9}$$

ε_i is deformations at a certain time of observation.

The relaxation time coefficient is determined from the expression

$$\varepsilon(t)=\varepsilon\left(\frac{nH}{E}\right)=\varepsilon_{\infty}-\sigma\left(\frac{H-E}{HE}\right)e^{-1}. \tag{10}$$

The process of predicting deformations in time according to the described method is carried out in the following sequence. Two timings are elected from the condition $t_2=2t,$ determined by the creep curves of the deformation ε_1 and $\varepsilon_2,$ then the rheological coefficients are determined by formulas (8...10). Substituting them into formula (7) and setting a certain value of time, we obtain the necessary deformations at any point.

2. Based on the obtained data on the mechanical characteristics of the wood of the dowel hole under a long-term load, the calculations of the connections were performed according to the method [25] for a certain point in time in order to compare the results with experimental data.

To do this, using formula (4), isochronous curves of the deformation of the wood of the dowel hole were constructed for time points 0; 0.8; 24; 73; 200; 411; and 730 days, which are shown in Fig. 4.

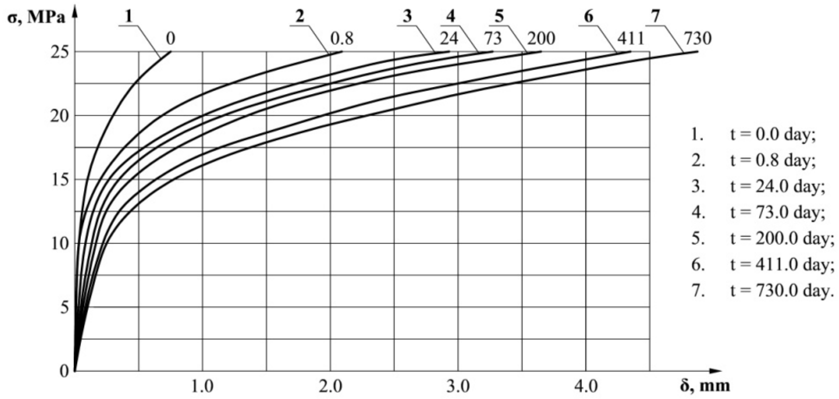

Figure 4. Isochronous curves of deformation of the wood of the dowel hole.

To calculate the connections, we used the previously obtained [26] dowel deformation diagram $M-\chi$ for symmetrical loading. The results of calculations and experimental values of deformations of connections of long-term tests (minimum and maximum values of the four results at individual loading stages) are shown in Table 1.

Table 1. Comparison of calculated and experimental values of connections deformations under long-term loading.

Time, day	Deformations of connections δ (mm) at loading levels T (kN per slice)					
	T = 0.71		T = 1.00		T = 1.41	
	Calculation	Experiment	Calculation	Experiment	Calculation	Experiment
0	0.078	0.062 ... 0.770	0.151	0.112 ... 0.237	0.315	0.267 ... 0.457
24	0.112	0.115 ... 0.137	0.220	0.147 ... 0.292	0.530	0.505 ... 0.865
200	0.181	0.213 ... 0.298	0.315	0.350 ... 0.395	0.768	0.675 ... 1.070
730	0.237	0.258 ... 0.446	0.406	0.420 ... 0.495	1.247	0.800 ... 1.373

The data in the table indicate a good enough convergence of the calculated and experimental results. In most cases, the calculated values of deformations fit into the range of experimental data scatter. The maximum discrepancy from the boundaries of the interval is 8 %.

3. For practical calculations of connections on TGk metal connector plates, a design diagram of the deformation of the wood of the dowel hole is required, taking into account the duration of loading and the design resistance to crushing wood crushing of the wood of the dowel hole $R_{cr.n}$.

To construct this diagram, we will use the short-term diagram of the deformation of the wood of the dowel hole with the boundaries of the data scatter, obtained earlier [26], and the isochronous curve in Fig. 3 with a maximum exposure time of 730 days.

After performing calculations on the average values of σ_{cr} with the upper and lower boundaries of the interval with a confidence level of α = 0.95, we obtain the calculated long-term diagram of the deformation of the wood of the dowel hole diameter of 5 mm, the values of which are given in Table 2.

Table 2. Estimated diagram of the deformation of the wood of the dowel hole considering the duration of loading.

Value (mm)	Deformations δ (mm) at the level of load σ (MPa)									
	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
δ_{av}	0.08	0.15	0.23	0.38	0.57	0.90	1.45	2.27	3.50	5.30
δ_{min}	0.03	0.07	0.13	0.20	0.30	0.43	0.63	0.93	1.40	2.10
δ_{max}	0.12	0.02	0.35	0.56	0.90	1.50	2.43	3.83	6.80	30.0

Let us determine the calculated resistance of the collapse of the wood of the dowel hole

$$R_{cr.n} = R^n_{cr.n} K_{hom} \frac{m_d}{\gamma_m}, \tag{11}$$

$R^n_{cr.n}$ is normative resistance to crushing of the wood of the dowel hole; K_{hom} is coefficient of wood homogeneity; m_d is coefficient taking into account the duration of the load application; γ_m is coefficient of transition from the confidence level α = 0.95 to α = 0.99 for the design resistance, γ_m = 1.09 according to the γ is distribution.

The duration coefficient is determined by the method recommendations for testing wood structures TsNIISK.

$$m_d = \left(B - Clg\, t\right)^{-1}; \tag{12}$$

$$B = \frac{17.1}{17.1 - \lg T}, \quad C = \frac{B-1}{\lg T}, \tag{13}$$

t is time for short-term tests $\rightarrow t = t'/38.2$; T is service life of the structure.

For dowels with a diameter of 5 mm installed in solid wood, we have the standard resistance to crushing of the wood of the dowel hole $R^n_{cr.n}$ = 28.75 MPa. t' = 1667 sec at F_{pcs} = 2.8 cm^2. $\sigma_{\max}$ = 49.5 MPa at a load of 0.5 kN per minute – m_d = 0.54, which does not contradict long-term tests of the wood of the dowel hole. As a result of calculations according to (11), we obtain the calculated resistance to crushing of the wood of the dowel hole $R^n_{cr.n}$ = 13.5 MPa.

According to the previously obtained [26] dependences $\sigma - \delta$ and $M - \chi$, the calculation of connections on TGk plates with a dowel diameter of 5 mm and 60 mm long was performed to determine the calculated bearing capacity Tn. The calculation results for some load levels are shown in Table 3.

Table 3. Parameters of the stress-strain state of connections under long-term load.

Load, kN	Deformations, mm		Bending moment, kN/cm		Bearing stress, MPa	
	$\dot{X}$	X_{min} ... X_{max}	$\dot{X}$	X_{min} ... X_{max}	$\dot{X}$	X_{min} ... X_{max}
0.50	0.139	0.079 ... 0.181	0.396	0.317 ... 0.440	7.094	6.536 ... 7.859
1.00	0.365	0.247 ... 0.469	0.892	0.759 ... 0.984	12.41	11.41... 13.67
1.50	1.095	0.583 ... 1.774	1.283	1.202 ... 1.296	18.38	18.24 ... 19.42
2.00	4.929	2.179 ... 8.465	1.360	1.308 ... 1.426	26.98	25.35 ... 27.69

The design bearing capacity of the dowel is determined in accordance with the method of limit states from the condition of fulfillment of the inequalities

$$\sigma_{cr.n} \le R_{cr.n}, \quad M_{n.\max} \le M_t, \quad \delta_n < \delta_{per}. \tag{14}$$

The design resistance to crushing of the wood of the dowel hole is determined by (6) and the design bending moment is determined by the formula

$$M_t = W_y R_n K_c, \tag{15}$$

W_y is moment of resistance of circular section; R_n is design bending resistance of the dowel; K_c is coefficient taking into account the increase in the yield strength due to the constraint of deformations during bending. K_c = 1.25, which corresponds to the onset of plastic deformations during tension and bending of class A 240 reinforcing wire.

As a result of calculations according to (15), we have M_t = 1.0 kN/cm, at which the diagram of the deformation of the dowel during bending in all cases has a linear character.

Analysis of Table 3 makes it possible, based on the above, to determine the design bearing capacity of the dowel T_n = 1.0 kN, at which $M_{\max}$ = 0.984 $< M_t$ = 1.0 kN/cm; and $\sigma_{\text{cr.max}}$ = 13.67; $R_{cr.n}$ = 13.56 MPa. The obtained value is in good agreement with the results of calculations according to the recommendations for the design and manufacture of wood structures with connections on plates with cylindrical nagels of the TsNIISK-KirPI system.

4. To perform calculations of composite beams for a long-acting load, we construct isochronous curves of connections $T-\Delta$ for time points of 0, 24, 200 and 730 days. The construction of curves is based on the calculation of compounds using isochronous curves $\sigma-\delta$ Fig. 3. Isochronous curves of connections at the level of αt are shown in Fig. 5.

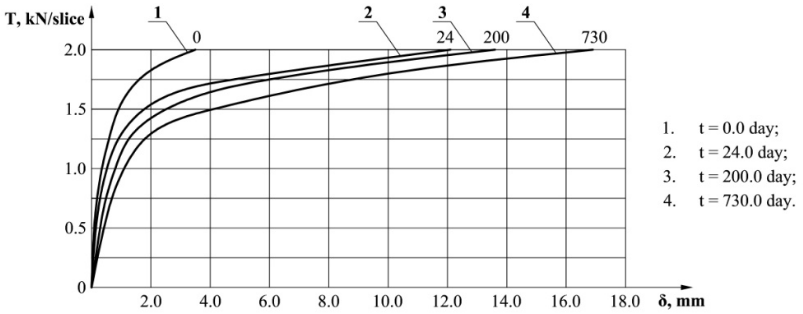

Figure 5. Isochronous deformation curves of *connections* $T-\Delta$.

In conclusion, in Table 4, we present the calculated deformation diagram $T-\Delta$ for non-symmetrical joints (shear bonds in constituent elements) on TGk metal connector plates with dowels of 5 mm diameter and 60 mm long. The calculated diagram is constructed similarly to the short-term diagram when performing calculations using the dependencies $\sigma-\delta$ according to Fig. 4 and $M-\chi$ (according to the symmetrical and non-symmetrical scheme), as well as taking into account the technological coefficients m_c and m_t [26].

Table 4. Calculation diagram of the deformation of connection under long loading.

Value	Deformations (mm) at the level. T (kN per slice)						
	0.25	0.50	0.75	1.00	1.25	1.50	1.75
δ_{av}	0.22	0.52	0.92	1.48	2.37	4.04	7.38
δ_{min}	0.11	0.31	0.60	0.98	1.49	2.34	3.84
δ_{max}	0.31	0.69	1.20	1.93	3.19	5.87	11.9

4. Conclusion

Based on the results of the research, the following main conclusions can be drawn regarding the long-term strength and rigidity for connections of wooden structures on TGk plates with cylindrical dowels.

1. As a result of the tests carried out, a sufficient degree of long-term strength and rigidity of the joints of wooden structures using the TGk metal connector plates was proved.

2. The isochronous curves of the dowel hole wood deformation and of the connections for certain points in time were obtained.
3. When calculating connections using TGk metal connector plates in the range of calculated loads, it is possible to use the predicted creep curves characterizing the base of the dowel hole at any time with rheological coefficients H = 2700 MPa, E = 500 MPa, n = 35.
4. A calculated diagram of the deformation of the wood of the dowel hole $\sigma - \delta$ and connections $T - \Delta$ under long-term load was constructed.
5. The data obtained make it possible to perform calculations of composite wooden elements on this type of connections, considering the duration of the load.

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