Structural solutions of wood-concrete floors using shear-resistant joints

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Abstract. Currently, various composite structures made of wood, steel and concrete are used in construction. Some studies are aimed at developing the direction of wood-concrete slab-ribbed structures. Analyzing the methods of joining wood-concrete structures, it was found that the stiffness at the “edge-slab” border has a significant effect on the stress-strain state of the whole structure, and rigid joints allow using the positive properties of concrete and wood materials more rationally, taking into account structural, rheological and physical properties. To increase the shear resistance at the border of joining, a new combined joint based on the unilateral gear plate “Bulldog” and a screw nog is proposed. A numerical model has been made to calculate the joint deformation due to the action of a single shear force, which is based on the law of deformation of linearly elastic materials and the Winkler model. It describes the deformation of a nog lying on an elastically deformable base. Empirical formulae were used to take into account the nonlinearity of deformations during the long-term impact of force on the joint in conjunction with the anisotropy of wood. The dependence curves of the joint stiffness coefficient on the diameter of nog, gear plate and the restraint value of nog in the wood are constructed for dowel and combined joints. It was shown that reinforcement of the joints (up to 6-7 times) could be achieved by increasing the diameter of the nog, and combined compounds based on a gear plate allows to increase this indicator by 2...4 times. The use of screws is recommended as cross-links, the presence of concrete in the head and thread in the wood will reduce the negative effect of warping of wood during shrinkage on the operation of the proposed compounds.

1. Introduction
A composite structure is an element whose cross section consists of several separate layers that are heterogeneous in material. The individual layers having been rigidly connected along the entire length, the cross-section of the rod can be considered monolithic, but in most cases, it is not possible to rigidly connect the individual layers, so it is necessary to take into account the joint compliance effect. Such a group of elements is considered as compound rods.

Compound rods made of wood, metal, and reinforced concrete are widely used as building structures. The prerequisite for the distribution of compound rods is, as a rule, the limited range of wood and metal, causing the need for connecting several elements to obtain sections of the required size. Widespread in construction are wood-composite floor elements [1-4], steel reinforced concrete
floors including profiled steel flooring and combinations of elements from LVL and other materials [5].

The capabilities of the building complex during the reconstruction of buildings and structures have a sufficient palette of modern engineering technologies – these are fully prefabricated reinforced concrete floors, systems of metal beams and reinforced concrete prefabricated and monolithic slabs, solid monolithic flat and ribbed reinforced concrete floors and others.

A large number of studies were devoted to the study of the work of composite plates and floor beams.

The work [6] investigates the crack resistance of composite beams, consisting of a combination of two different layers: self-compacting concrete (SCC) and engineered cementitious composites (ECC). The article [7] explores demountable joints of prefabricated steel-reinforced concrete structures. Studies [8] are devoted to a method of improvement the blending of floors, consisting of steel U-shaped profiles and reinforced concrete slab by using angle connectors. Study [9] develops a new steel-concrete-steel (SCS) sandwich beam with hybrid shear connectors comprising both J-hooks and overlapped headed studs. The work [10] investigates a method of improvement the crack resistance of supporting sectors of steel-reinforced concrete floors under the influence of negative moments when the stretched zone is in a reinforced concrete slab. The article [11] explores the work of wood-concrete beams, where joints are performed due to the combined tongue-in-grooves and the setting of sheer studs that prevent transversal relative displacements of the layers. The work [12] investigates the possibility of strengthening gluelam beams of I-section due to reinforcement with polymer composites. The article [13] described the structural behaviour of aluminium-timber composite (ATC) beams. In the proposed ATC system, a timber slab was connected to aluminium girders by hexagon head wood screws. Study [14] presents the results of a numerical analysis of the vibrations of a multilayer composite beam LCB with transverse cracks under the dynamic buckling. The article [15] reviews aspects of frequency of curved cracked composite (CCC) beams. The work [16] analyzes the composite I-beam reinforced with PU foam with the addition of chopped glass fiber. Study [17]
develops the deformation and failure of hybrid composite sandwich beams with an aluminum foam core under quasi-static load and low-velocity impact are investigated. Research [18, 19] are devoted to the features of the calculation of the strength and deformability of composite beams.

However, the “charters” for the conservation and restoration of architectural monuments and places of interest provide for the mandatory preservation of the authenticity of the original author’s decisions on parts and elements of buildings, in particular wooden beams of floors and attic floors. Many years of experience in the reconstruction of buildings and structures show that when examining floors on wooden load-bearing beams, the latter for the most part did not lose their bearing capacity, except for those that were in adverse temperature and humidity conditions [20].

Wood concrete, as a composite system, is a constructive combination of two materials with various physical and mechanical properties inherent in them. The most characteristic in this system are two varieties of structural elements (beams and slabs), which have received a single term “wood concrete” in the special technical literature. Monolithic concrete beams reinforced in the stretched zone with longitudinal wooden rods – by structural analogy with reinforced concrete beams. Compound composite elements: wooden beams in the lower branch (extended zone) and slabs in the upper branch (compressed zone) made of concrete, or reinforced concrete. Steel-ferroconcrete structures serve as an analogy for composite beams and slabs [21].

![Figure 2. The design of the experimental wood-concrete beam and calculation scheme of testing the beam [20]: a – in the research of I.A. Kiriyenko; b – in the research of M.A. Kienya; c – in the research of N.I. Petrov; d – in the research of G.S. Pushkin.](image)

The idea of joint use of wood and concrete in structures, where tension forces are perceived by wood and compressive forces are perceived by concrete, appeared at the end of the 19th century. The first patent for wood-concrete was obtained in Switzerland in 1896. Here the first case of the use of wood as reinforcement in concrete structures was recorded [22].

In 1912, at the Brington Institute of London, an engineer R. Kaise conducted experiments on wood-concrete beams, where wooden bars were used as reinforcement [22]. Engineers V. Ricardini and I. Viscardini carried out similar experiments in Italy. These experiments demonstrated the possibility of using wood in concrete as a reinforcement, since it adheres well to concrete and does not swell when applied in a moistened state. To avoid the appearance of cracks due to swelling of wood, it is recommended that reinforcing wooden rods be kept in an aqueous medium in order to maximize water saturation. Significant and detailed studies of wood-concrete were carried out in Russia by professor
I.A. Kiriyenko, engineer M.A. Kienya, professor N.I. Petrov and engineer G.S. Pushkin, assistant professor G.D. Tsiskrelli. They have the idea of reinforcing beams with wooden elements in the stretched zone. Despite a fairly large number of studies [20], these structures were not widely used due to a number of significant drawbacks:

- the complex rheological properties of wood, the heterogeneity of its structure do not allow us to consider the conditions of deformation of reinforcing wooden rods by analogy with steel reinforcement;
- the joint work of concrete and reinforcement made of wood is more determined by the moisture content of the wood itself, as well as the humidity of the environment;
- wood being hydroscopic with a fibrous - tubular structure, in a dry state absorbs moisture from concrete and swells, which leads to cracking in concrete. When using wet wood, the drying process violates the reliable adhesion of concrete to reinforcement;
- with equal bearing capacity, the volume and mass indicators of wood-concrete beams significantly exceed these characteristics of ferroconcrete beams.

Wood-ferroconcrete structures were further developed in France on the basis of new design principles. Engineer J. Chode connected a reinforced concrete slab with a wooden beam for the purpose of their joint work, using steel nails (nogs) hammered into a wooden beam, which serve as shear bonds. Tests of the proposed wood-ferroconcrete structure were carried out in 1924 with satisfactory results [23].

In 1930, according to this principle, on one of the buildings in Moscow, V.I. Ratner made several ribbed slabs and conducted experimental research. Two series of slabs were made. Regardless of the type of slab, steel nails with a length of 100 mm to a depth of 60 mm were driven along the axis of the upper edge of the bars, tilted in both directions to the supports at an angle of 45 ° at a distance of 50 ... 100 mm, at a distance of 250 mm from the support, nails were hammered and in the side faces of the bars. A 50 mm thick ferroconcrete slab reinforced with a reinforcing mesh of ordinary reinforcement wire with a diameter of 3 mm was installed on the upper edge of the wooden bars (figure 3, a). The experimental wood-ferroconcrete ribbed slabs collapsed along the load-bearing wooden beams at bending moment values of approximately M = 100 kN·m after the limit for resistance of wood to tension has been reached [24].

![Figure 3. Designs of experimental wood-concrete slabs [20]: a – series I and II in the research of V.I. Ratner; b – in the research of University of Illinois.](image-url)
To determine the most rational type of connection of concrete with wood, the optimal ratio of the geometric and strength parameters of the constituent layers, extensive laboratory studies were conducted in the laboratories of the University of Illinois from 1935 to 1942 [25]. Wood concrete beams consisted of concrete slabs laid on a solid row of wooden planks put very close to each other. The total height of the beams was 305 mm, 290 mm, 366 mm. The number of boards set the width of the beams in the wooden base. The wooden base of the beams consisted of: four boards with a section of 41.4 × 200 mm and three boards with a section of 41.4x140 mm. 16 series of beams with various nog types of joints (nails, bolts, studs, crutches) of concrete and a wooden base were tested. Studies have established that it is important to ensure joint work of the concrete slabs and wooden beams (figure 3, b).

These compounds must meet a number of requirements:
- to provide the perception of shear efforts along the entire length of the seam of joint of slab and beam and breaking efforts near supports;
- to provide the necessary rigidity and strength of the connection at all the stages of the beam’s work;
- not to be the cause of the destruction of the combined section of the beam;
- to be simple in design and production;
- to be economically feasible;
- must ensure the durability of the structure.

Theoretical and experimental researches of elements of the bonds of wood-concrete elements in the second half of the 20th century carried out by V.A. Glotov, V.I. Kulish, I.Yu. Belutski, Yu.S. Gribovski, A.V. Schumacher, et al. For wood concrete floors, these scientists considered different solutions for combining wooden beams with reinforced concrete slab [26], which are represented on figure 4.

**Figure 4.** Types of joints of reinforced concrete slab with wood-glued beam [26]: a– wood-glued beam; b – reinforced concrete slab; c – steel nog; d – steel rod stop; e – connecting support; f – single steel anchor; g – loop steel anchor; h – pre-stressed bolts; i – hole; j – glue seam.
Figure 4 shows the solutions associated with increasing the rigidity of the joints, which are either low-tech (a, b, d, g, j) or uneconomical in terms of steel spread (h, i). As for the classical method of joint with cylindrical noggs, it is characterized by significant compliance due to the bending of the axis of nog and the crushing of wood in the hole.

Based on the analysis, we can formulate the main goal of the study: numerical studies of a slab-ribbed wood-concrete floor structure with connectors of steel-toothed washers and nails.

The object of study is a slab-ribbed wood-concrete floor structure using a combination of steel gear connectors and pins. Subject of research – numerical studies of wood-concrete floor construction using shear-resistant joints.

To achieve the goal, the following tasks can be defined:
1. Investigation of the wood-concrete floor structure taking into account differences in the structural, rheological and physical properties of wood and concrete.
2. The choice of the optimal way to increase the strength and reliability of wood-concrete floor structures.
3. Determination of the effect of the combined connection of nails and gear plates on the stress-strain state of the structure under study as a result of shear forces.
4. The study of the effect of the diameter of the nails on the reinforcement of joints in wood-concrete floor structures.
5. Consideration of the possibility of using screws as pins in the joints of the structures under study.

2. Methods
In connection with disadvantages of the above types of joints, it is advisable to develop and use a new type of joint, which is characterized by the ease of production, as well as combination of the advantages of traditional joints of composite flexural wooden elements. For connection of the reinforced concrete slab and wooden ribs, it is proposed to use combined joints based on a single-sided gear washer (figure 5).

Figure 5. Combined joints for wood-concrete structures based on a screw and a gear washer: a - diagram of joints installation on a wooden rib; b - wood-concrete slab; c - diagram of joints with gear plates of a circular shape “C2” type and of an oblong shape “C3” type or “C4”; d - gear plates with one-sided arrangement of teeth.
The joints are performed in the following sequence:
1) After the installation of wooden ribs of floor, installation of the formwork is carried out and marking the installation sites of the combined joints.
2) The gear plates are installed and pressed, the hole in the plate is used as a marking for tightening screws. The diameter of the hole should be equal to the diameter of the screw. The diameter of the drill for making holes in the wood is taken equal to 0.6 ... 0.8 of the diameter of the uncut part.
3) The plates having been installed, the screws are screwed, the position of the head is determined by the thickness of the slab and the thickness of the protective concrete layer (5 ... 10 mm).
4) Reinforcing meshes of ferroconcrete slab are laid and concreting is performed.
5) The strength class of concrete is taken not lower than B15...B20.

Wood-reinforced concrete elements belong to composite rods, where two or more straight-line rods are interconnected along throughout the length by yielding bracing or rigid joints. Parameter \( \xi \), characterizing per unit stiffness at border of connecting is determined by the formula:

\[
\xi = \frac{c_j}{S_j},
\]

where \( c_j \) – shear stiffness of one joint; \( S_j \) – the step of arranging joint along the length of the ribs.

Shear bond stiffness is characterized by the ratio of the load to the magnitude of the mutual displacement of the connected elements caused by this load. For a nog joint, the shear stiffness of one joint in a wood-concrete structure will be determined by the magnitude of the deflection of the nog in the wood and concrete, as well as by the crushing of the wood of the nest. For a gear washer, the amount of displacement will depend on the deflection of the teeth and the crushing of the wood by the teeth.

![Diagram of the deformation of the nog in a wood-concrete element at longitudinal shear](image)

**Figure 6.** Diagram of the deformation of the nog in a wood-concrete element at longitudinal shear: \( \Delta \) is the magnitude of the shear of the layers of wood-ferroconcrete beam relative to each other; \( \delta_c \) - deformation of the nog in concrete; \( \delta_w \) - deformation of the nog in a wooden rib.

The calculation of the nog is performed according to V.N. Shaposhnikov's method as a beam on an elastically deformable base of Winkler. The differential equation of the elastic line under short-term load:

\[
EI(x) \cdot y''(x) + k \cdot y(x) = 0,
\]

where \( k \) is the short-term coefficient of the bed of unit of the length of the base for wood \( (k_w) \) or concrete \( (k_c) \), \( k = k_0 \cdot b_{cr} \).

The solution of equation (2) is:
\[ y(x) = e^{Ax} \cdot (C_1 \cos Ax + C_2 \sin Ax) + e^{-Ax} \cdot (C_3 \cos Ax + C_4 \sin Ax) \]  

where \( C_1, C_2, C_3, C_4 \) are integration constants determined from the boundary conditions;

\[ A = \frac{\sqrt{k_0 / (E_a I_a)}}{\sqrt{2}}. \]

To determine the amount of crushing of the nog socket, the expression 4 is used:

\[ y(x) = \frac{q(x)}{k}, \]  

where \( q(x) \) is active load distribution function.

Short-term to the coefficient of the bed of wood during crushing along the fibers adopted according to research [27] and is 100 N/cm\(^3\). However, creep has a significant effect on the deformation of joints of wooden structures. In his monograph, B.V. Labudin [28] summarizes the results of numerous studies of the effect of wood creep on the deformability of various types of compounds, and on the basis of regression analysis it was found that, with constant loading over time, the deformation process obeys regularities (5).

\[ \delta(t) = \delta_1[1 + \varphi(t)], \]

where \( \delta_1 \) is deformation of the joint at the initial moment of loading; \( \varphi(t) \) is creep characteristic of a compound, representing the ratio of creep to \( \delta_1 \).

The value is \( \varphi(t) \) determined by the expression (6).

\[ \varphi(t) = \varphi_c[1 - e^{-\gamma t}], \]

where \( \varphi_c \) is ultimate creep characteristic of the compound at the moment of stabilization of its deformation; \( \gamma \) is a coefficient characterizing the rate of development of creep deformation over time \( t \) (time is measured in days).

Given the expressions (5) and (6) are taken into account, the expression for the coefficient of the bed of wood is

\[ k_w = \frac{k_{w0} \cdot d_n}{[1 + \varphi_c(1 - e^{-\gamma t})]}. \]

For concrete, the coefficient of bed was taken according to [26] \( k_0 = 340 \text{ N/cm}^3 \).

To assess the proportion of increase in the stiffness coefficient of the combined joint, it is necessary to determine the shear stiffness of the gear washer. Diagram of single-sided toothed washer with diameter of 50, 75 and 90 mm are represented in figure 7.

**Figure 7.** Schemes of gear washers type C2 and design of a single tooth.
Table 1. Parameters of gear washers with a diameter of 50, 75 and 95 mm.

| Diameter, mm | Number of teeth | Plate thickness, $t$, mm | Tooth height, $h_{tooth}$, mm | Width of tooth base, $b_{tooth}$, mm | Equivalent width, $b_{eq}$, mm |
|--------------|-----------------|--------------------------|-------------------------------|-------------------------------------|---------------------|
| 50           | 12              | 1.0                      | 6.6                           | 14.5                                | 0.011               |
| 75           | 12              | 1.25                     | 10.4                          | 21.8                                | 0.017               |
| 95           | 12              | 1.35                     | 12.7                          | 27.6                                | 0.022               |

To determine the deformation of the tooth, the differential equation is used (2), an equivalent constant value of the bending stiffness $EI(x)=\text{const}$ is introduced into the calculation from the condition that the tip displacement is equal when the transverse load acts on the claw. This makes it possible to use the analytical solution of the equation, as for a dowel constant in height section.

Equivalent bending stiffness of the tooth $EI$ is determined by the formulas (8) when bending from a plane and in a plane, respectively:

$$EI_0 = \frac{E_{st} \cdot S \cdot b_{eq}}{12}; \quad EI_{90} = \frac{E_{st} \cdot S \cdot b_{eq}^3}{12}$$

(8)

where $E_{st}$ is the modulus of elasticity of steel ($E_{st} = 2 \times 10^8$ kPa); $b_{eq}$ is the equivalent tooth width; $S$ is the thickness of the plate from which the washer is stamped.

To express the bed coefficients when crushing at an arbitrary angle $\gamma$ to the wood fibers, we used the generally accepted dependence:

$$k_{\gamma,w}^{\text{temp}} = \frac{k_{\gamma,w}}{1 + \left(\frac{k_{90,w}}{k_{0,w}} - 1\right) \sin^3 \gamma}$$

(9)

where $k_{0,w}$; $k_{90,w}$ are coefficients when crumpled wood rectangular stamp at an angle $\gamma = 0^\circ$ and $\gamma = 90^\circ$, which values were obtained from approximate expressions obtained [29] when crushing wood with rectangular stamps:

$$k_{0,w}^{\text{temp}} = (-0.14 \cdot b_{cr} + 2.289) R_c; \quad k_{90,w}^{\text{temp}} = (-0.094 \cdot b_{cr} + 0.826) R_c,$$

(10)

where $b_{cr}$ is the width of the creasing surface; $R_c$ is temporary resistance of pure wood to compression along the fibers.

The duration of the load is taken into account in the same way as calculating the bed coefficient for a nog joint.

Shear stiffness of the claw in the direction of the force $\vec{T}$ is determined by the formula:

$$C_{tooth} = \frac{\vec{T} \cdot \cos \alpha}{\Delta \alpha} + \frac{\vec{T} \cdot \cos \beta}{\Delta \beta}.$$  

(11)

In this way, the shear stiffness of the gear washer is defined as the sum of the stiffnesses of all the teeth.

The stiffness of the combined joint, consisting of a dowel and a gear washer, is determined by the formula:

$$C_{c.j} = \frac{1}{1/c_{n.c} + 1/(c_{n,w} + c_{t,w})}$$

(12)

where $1/c_{n,c}$ is displacement of the nog in the concrete by the action of shearing force $T = 1$ kN, $1/(c_{n,w} + c_{t,w})$ is displacement of the nog and the tooth washer in the wood by the action of $T = 1$ kN.

3. Results and Discussion

We considered the influence of some parameters on the stiffness coefficient of nog joint of wood-ferroconcrete structure. The diameter of the nog and the depth of embedment of the nog into the wood $l_w$ were adopted as varying parameters. The depth of embedment in concrete of the nog $l_c$ was adopted as a constant value equal to 70 mm, when the thickness of the ferroconcrete slabs was 80 mm.
In figure 8,a there is a graph of dependence of stiffness of nog joint on the diameter and size of embedding into the wood.

![Figure 8(a)](image)

**Figure 8.** Dependence of the stiffness coefficient of the nog joint: a - on the diameter of the nog and the value of embedding into wood; b - shear stiffness of joint $c_s$, kN/m with diameters of toothed washers 50, 75 and 95 mm.

The diameter of the nog varied within 6...20 mm, the value of embedding into wood [30, 31] - 50...150 mm. From the graphs, it is seen that an increase in the diameter of the nog gives a significantly greater effect of an increase in the stiffness of the joint (up to 670%). Increasing the length of embedding allows us to increase this indicator by 12 ... 27%. The effect of increasing the length of embedding of the nog increases with increasing its diameter, as the length of the zone of active deformation of the nog increases.

In figure 8,b there is a graph of the change in the rigidity of the nog joint at a value of embedment of the nog into the wood [32-34] $l = 50, 100$ and 150 mm, as well as the considered diameters of the gear washers 50, 75 and 95 mm. The lower curves correspond to the stiffness of the joint with a single nog, without a gear plate.

It is established that the use of gear connectors allows you to increase the rigidity of the joints 2.5 ... 3.3 times when using connectors with a diameter of 50 mm; 1.8 ... 3.8 times - with a diameter of 75 mm; 2.1 ... 4.2 times with a connector diameter of 95 mm. Obviously, with an increase in the diameter of the nog, the efficiency of using combined joints decreases, thus the most rational is the use of the proposed combined joints with 10 ... 14 nogs, which does not require making large diameter holes in the ribs. It is recommended to use screws as nogs, due to the presence of a thread and a head, it will be possible to ensure durable joint of the composite structure layers, which will prevent transverse mutual deformations of the plate and rib due to drying and warping of the wood [35]. The use of joint screws will ensure reliable and full-fledged operation in the joint of gear connectors.

### 4. Conclusions

As a result of a numerical study of wood-concrete floor structures, the team of authors formulated the following scientific and practical conclusions:

1. Due to differences in structural, rheological and physical properties of wood and concrete, the research of wood-concrete structures using wood as internal reinforcement is not of practical value.
2. The most optimal way to increase the strength and reliability of wood-concrete structures is to increase the shear stability of joints at the rib-slab border.

3. The main reasons for the flexibility of the joints at the border of the slab and the wooden rib are bending of the nails and crushing of the wood, the use of combined joints based on gear plates allows minimizing the influence of these factors on the stress-strain state of structure due to a significant increase in the shear resistance of the joint.

4. Reinforcement of the joints (up to 6, 7 times) can be achieved by increasing the diameter of the nog. Combined compounds based on a gear plate allows to increase this indicator by 2 ... 4 times.

5. The use of screws is recommended as cross-links, the presence of concrete in the head and thread in the wood will reduce the negative effect of warping of wood during shrinkage on the operation of the proposed compounds.

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