Notes for calculated resistance to tension for laminated wood

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Abstract. Wood as a material with sharply expressed anisotropic properties fully transfers them to glued wood. Depending on the force vector under tension along, across and at an angle to the fibers, it differ tenfold. The results of studies of laminated wood tensile at different angles to the orientation of the fibers are given. The results of calculations are determined with testing of standard samples for design strength according to the method of ALTI–CNISK. It is established that the angle between fiber orientation and vector of the applied force α influences a lot by the tensile strength and depends on the sort of wood. The value of tensile strength is decreased when the angle vary from 0 to 90°. Experimental values are compared with theoretical results which are given in current standards − Rules and Norms 64.13330.2017 “Wooden structures”. The difference between theoretical and standard results is 4 ... 70%. More accurate approximating expressions of experiments are presented, which can be used in practice instead of formula (6) from Rules and Norms.

1. Introduction
The existing base of construction and production of building structures in the Northern regions of Russia is still focused on the use or reinforced concrete, brick and steel structures, while at the same time huge reserves of forest resources underutilized. However, accumulated in 70 – 90 years foreign and domestic experience in the use of laminated wood structures lowed, that compared to traditional solutions they have significant advantages: metal consumption decreases by 3 times, the mass of buildings by 2...3 times, the installation labor intensity is up to 2,5 times [1]. Even more effective are the free-dimensional systems of laminated wooden constructions, which allow to block large spans without intermediate supports, revealing all the advantages of the material and structures, confirming the well–known motto of ancient Roman Architectural order – strength, benefit, beauty (Vitruvius). Self-renewability of forest recourses, environmental safety, high strength and rigidity, excellent technological and acoustic characteristics of wood, ideal aesthetic properties, light weight and processability, minimal energy consumption of the production of the construction products – this is the main list of convincing factors, confirming that wood is the leader of the big Three of global consumption of building materials and ranks first in the chain: wood – concrete – steel.
2. Relevance, scientific significance of the issue
The use of laminated wood as a structural material in construction requires on the one hand- the development of new forms of building structures, from the other hand—full knowledge of the properties of the material used – and his anisotropy

However in the norms [2] and another technical literature the data about anisotropic properties of laminated wood is not sufficiently presented, they are often identified with the characteristics of solid wood, which is not quite adequate. Studies of modern laminated wooden constructions have established, that it is advisable to calculate them by the main stresses. However, in the current standards not all the characteristics, a required for the calculations of structures, according to the First theory of strength are give.

3. Formulation of the problem
The task of the experimental – theoretical study was determination of the calculated strength characteristics of laminated wood under tension at various angles to the fibers. In solving this problem the specific orientation of the annual rings of wood wasn’t taken in to account, and the glued package was considered as a transversely – isotropic body with a cross plane of symmetry of the material properties. The hypothesis applied doesn’t contradict the accepted assumptions regarding this approach. Glue seams provide «solidity» of package of layers and it’s conditional homogeneity [3]. The hypotheses used do not contradict the accepted assumptions regarding this approach by various scientists [4-9].

At present it is recommended to determine calculated characteristics of structural materials, made of solid and laminated wood either according to tests of natural size elements, or on the bases of tests of small standard samples with their subsequent calculation according to the method of ALTI–CNIISK [10-12]. We have adopted the second method for determining for calculated resistance of laminated wood when stretching it at different angles to the direction of the fibers.

4. Theoretical part
According to current regulations [2] the calculated resistance of pine and spruce wood, sorted by varieties, is determined by the formula:

\[ R^p = R^A \times \Pi_{ml} \]  

(1)

where \( R^A \) – is the calculated resistance of wood, determined by the formula (2); \( m_l \) – is the coefficient of long – term strength, corresponding to the mode of modern duration; \( \Pi_{ml} \) – is the product of the coefficients of working conditions.

The calculated resistance of wood is determined by the formula:

\[ R^A = R^n / \gamma_m \]  

(2)

where \( R^n \) – is characteristic strength of wood determine with the security of 95%; \( \gamma_m \) – is the reliability coefficient for the material determind from the condition of transition from security of 0,95 to security of 0,99, using the formula:

\[ \gamma_m = \left( 1 - \eta_{II} \right) / \left( 1 - \eta_r \cdot \nu \right) \]  

(3)

where \( \eta_{II} \)–is the quintile in the assumed statistical distribution function with security of 0,95, \( \eta_{II} = 1,65 \); \( \eta_r \)– is the quintile in the assumed statistical distribution function with security of 0,99, \( \eta_r = 2,33 \); \( \nu \) – is the coefficient of variation.

Depending on the number of samples, the values of the multipliers were taken according to student table with a minimum security of 0,95 for the standard resistance, and 0,99 for calculated resistance.
Standard resistance of laminated wood was calculated by the formula, indirectly taken into account the influence of heterogeneity lumber by introducing the appropriate coefficients:

\[ R_0^n = R_0^n \cdot K_n \cdot K_m, \] (4)

where \( R_0^n \) – is the standard resistance of samples of laminated wood; \( K_n \) – is the coefficient of transition to the scale factor, into account the effect of defects on the strength of wood, \( K_n = 0.2 \ldots 0.6 \); \( K_m \) – is the transition coefficient, taken into account the influence of the dimensions of the working section on the strength of wood, \( K_m = 0.77 \ldots 0.9 \).

Standard resistance of laminated wood samples was determined by the formula:

\[ R_0^n = M \left( 1 - \eta_n v_n \right), \] (5)

where \( M \) – is the average value of the temporary resistance of small samples with standard tests.

The calculated resistance of wood to stretching at an angle to direction of the fibers is recommended to be determined by the formula:

\[ R_{\alpha}^4 = \frac{R_{\alpha}^4}{1 + \left( \frac{R_{\alpha}^4}{R_{00}^4} - 1 \right) \cdot \sin^3 \alpha}, \] (6)

where \( \alpha \) – is the angle between the direction of the fibers and the vector of the applied force.

In the scientific papers [3,13] the resistance of wood at an angle to the fibers is proposed to be determined by the formula:

\[ \sigma_{\alpha}^B = \frac{\sigma_0^B}{\cos^3 \alpha + b \cdot \sin^2 2\alpha + c \cdot \sin^4 \alpha}, \] (7)

where \( c = \sigma_0^B / \sigma_{90}^B \); \( b = \sigma_0^B / \sigma_{45}^B - (1 + c)/4 \); \( \sigma_{90}^B \) – the tensile strength of wood under tension in the radial direction; \( \sigma_{45}^B \) – the same, in the tangential direction; \( \sigma_{45}^B \) – the same, in the direction at an angle of 45 to the annual layers.

The spare of the samples of the laminated wood (figure 1) and the method of tensile testing along the fibers are taken according to [14], and when stretched across the fibers and at angle to them in the range of from 15 to 90° – refer to [15].

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The shape and dimension of the tensile test sample under different angles to fibers.

The samples of laminated woods were taken from laminated wooden constructions, manufactured under mass production «Krasniy Octyabr» factory in Archangelsk. The layer thickness was within 33±1 mm according to [16]; wood species – spruce; glue brand – "FRF50". The moisture content of the wood was within 7…8%. The average density is 0.43…0.46 g/cm³; the temperature in the
laboratory is 20...22 °C. Total tested 5 series of samples. The arrangement of layer fibers in relation to the direction of the tensile force in the respective series was taken as 0°, 15°, 30°, 45°, 60°, 75° and 90°. The results of statistical processing with the definition of the calculated resistance of laminated wood under tension at different angles using formulas (1)...(5) have been obtained. The processing the obtained results and the determination of the calculated resistances are performed according to a specially compiled computer program, they are presented in [1].

5. Practical significance
Table 1 shows the recommended values of the calculated resistance of laminated wood at the studied angles. This characteristics in comparison with standardized [2] are show in the form of graphs in figure 2.

Table 1. Recommended calculated resistance of laminated wood under tension at different values of the α angles to the layers of laminated wooden constructions.

| Grade | 0°    | 15°   | 30°   | 45°   | 60°   | 75°   | 90° |
|-------|-------|-------|-------|-------|-------|-------|-----|
|       | R(α)  |       |       |       |       |       |     |
| I     | 19,74 | 7,39  | 3,00  | 1,55  | 0,68  | 0,58  | 0,5 |
|       | (18,0)*| (0,81)| (−0,25) | (0,37) | (−15,15) | (−5,14) | (0,23) |
|       | {19,74} | {11,6} | {3,96} | {1,55} | {0,82} | {0,56} | {0,5} |
|       | 14,41 | 5,95  | 2,53  | 1,41  | 0,64  | 0,57  | 0,5 |
| II    | 14,41  | 5,95  | 2,53  | 1,41  | 0,64  | 0,57  | 0,5 |
|       | (13,5) | (0,53) | (−0,16) | (0,24) | (−8,88) | (−3,22) | (0,15) |
|       | {14,41} | {8,52} | {3,25} | {1,41} | {0,79} | {0,56} | {0,5} |
|       | 10,67 | 4,33  | 1,86  | 1,03  | 0,48  | 0,43  | 0,38 |
| III   | 10,67  | 6,03  | 2,3   | 1,03  | 0,59  | 0,42  | 0,38 |
|       | (−)   | (−)   | (−)   | (−)   | (−)   | (−)   | (0,12) |
|       | {10,67} | {6,03} | {2,3} | {1,03} | {0,59} | {0,42} | {0,38} |

*Note: in ( ) parentheses are given for comparison the values of calculated resistances according to the formula number 6 of Rules and Norms [2], in {} parentheses – values of calculated resistances according to the formula (7) and departure values of this paper.

Figure 2. Dependence of the calculated resistance of laminated wood under tension at different α angles to fibers.
From the obtained results it follows that the calculated resistances laminated wooden constructions a long and across the fibers tilt angles $\alpha=0^\circ$ and $\alpha=15^\circ$ are close to those values giver in Rules and Norms and our results are slightly higher (up to 11%). For other tilt angles the differences are even greater, and make up 43...70%. For III grade wood the calculated resistance in the Norms and Rules are absent.

The definition of the calculated resistance according to the formula (7) at the intermediate angles gives significant differences when $\alpha=15^\circ$ and $30^\circ$ (24 ... 57%), and less noticeable at $\alpha = 15^\circ$ and $30^\circ$ (2 ... 23%).

The grade of wood affects the resistance to stretching. For I grade wood the differences is up to 37%; II grade is 32...85% (experimental values). More over with an increase of angle this difference decreases, which is due the fact that when stretch across the fibers the effect of the main defects in the form of curly grain, knots etc. in our opinion will decrease.

According to the results of experimental studies we obtained polynomials in the form of power series, allowing us to determine the strength of laminated wood for any $\alpha$ values (error to 1%).

- for I grade wood at $\alpha = 0...45^\circ$:
  \[ R_a^d = -0.0002x^3 + 0.029x^2 - 1.2x + 19.74 \]
- for I grade wood at $\alpha = 45...90^\circ$:
  \[ R_a^d = 0.0084x^2 - 0.629x + 16.28 \]
- for II grade wood at $\alpha = 0...45^\circ$:
  \[ R_a^d = -0.0001x^3 + 0.0173x^2 - 0.793x + 14.41 \]
- for II grade wood at $\alpha = 45...90^\circ$:
  \[ R_a^d = 0.0078x^2 - 0.5802x + 14.92 \]
- for III grade wood at $\alpha = 0...45^\circ$:
  \[ R_a^d = -0.0001x^3 + 0.014x^2 - 0.6x + 10.67 \]
- for III grade wood at $\alpha = 45...90^\circ$:
  \[ R_a^d = 0.0056x^2 - 0.41x + 10.68 \]

6. Conclusions
1. The values of the calculated resistance of laminated wooden constructions under tension depend more on the angle between the direction of fibers and the vector of the applied $\alpha$ force, and to lesser extent on the type of wood.
2. Experimental values differs significantly from theoretical, calculated by formula (6) from Rules and Norms 64.13330.2017 (up to 70%) and formula (7) from scientific researches [3, 13] (up to 57%).
3. To determine the calculated resistance at intermediate tilt angles we recommend using the polynomial functions (8)...(13) with an error up to 1%.
4. The obtained results and the calculated resistances can be used in the new addition of the Rules and Norms, as well as when calculating the main stresses of massive laminated wooden constructions in order to more fully realize the strength potential of laminated wood, as an anisotropic material.
5. It is recommended to conduct similar studies on other species of coniferous wood.
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