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# METHOD OF CALCULATION FOR WALLS OF VERTICAL SQUARED TIMBER

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**Abstract**

**Introduction:** In recent years, houses out of vertical squared timber have become widespread. Vertical bars make it possible to use the effective wood behavior in compression and ensure maximum strength of the material along the fibers. Vertical bars are subject to compression with bending, which can result in loss of strength and buckling in building structures. In the available research papers and technical literature, the issue of the stress-strain state of such walls has not been analyzed. **The purpose of this study** was to formulate a calculation method for walls out of vertical squared timber, based on the available traditional approaches to wooden structures. We propose a calculation **method** for walls out of vertical squared timber as a set of elements resisting compression with bending, including a check for limiting slenderness. **Results:** Permissible heights of walls for buildings with bays of 10 and 12 m were obtained. The results can be used in the design of low-rise residential and public buildings, mansard superstructures of multi-story buildings.

**Keywords**

Vertical squared timber, stress-strain state, compression, bending.

## Introduction

Wood is becoming increasingly widespread in construction due to its positive mechanical and physical properties (Mayo, 2015; Zmijewki and Wojtowicz-Jankowska, 2017). They include low density, low thermal conductivity, low coefficient of linear expansion, and biological compatibility with humans. In addition, wooden structures are characterized by high acoustic performance and architectural expression. Nowadays, much attention is paid to resource-saving and environmentally friendly materials that have a minimal environmental impact. Whole-section timber meets these requirements in full (Müller et al., 2021; Skullestad et al., 2016). According to the results of studies on wood materials, solid wood has the least impact on the human habitat (Cabral and Blanchet, 2021; Dias et al., 2020). It is no doubt that wooden houses are energy-efficient. Wood, as a structural material, has been scrutinized by researchers, housebuilders, and building users.

Design concepts of wooden buildings and structures come in a great variety. Recent studies show that a significant share of wooden houses is built out of solid, whole-section timber (Cohen and Gaston, 2003; Janakieska et al., 2021). Comprehensive design systems for such houses are being developed (Chaggaris et al., 2021). They include tests for strength, serviceability, fire safety, and cost.

Modern researchers and practitioners discuss various options of wall structures made out of solid wood. The method of connection plays a significant role in the operation of wooden walls.

Resch (1999) as well as Piao and Shupe (2016) suggested using composite vertical elements out of small-diameter timber (3.6–12.8 cm). Each element consists of several bars joined with tenons and glue.

Tsai and Wonodihardjo (2018) described a method of house construction out of waste wood using nails and screws as connectors. Bedon and Fragiacomo (2019) conducted a numerical analysis of timber-to-timber joints with inclined self-tapping screws. The studies showed that the strength properties of walls made out of composite members with metal fittings are lower than those of walls made out of whole-section members.

Sandhaas (2016) developed wooden walls out of laminated elements consisting of lamellae arranged side-by-side and connected with dowels. The wall structure is built without the use of glue. Miyata (2020) noted sufficient stiffness characteristics of such walls. However, walls made out of laminated elements have shear strains exceeding those in walls made out of whole-section timber.

Schiro et al. (2018) conducted experimental studies on timber-to-timber screw-connections. Iraola et al. showed that, in connections of timber elements, made with metal fittings, the geometry of the contact area has a substantial significance.

The elements of wooden walls are connected not only with metal but also with wooden fasteners. Thermo-mechanically compressed wood dowels were suggested as a joint element as an alternative to glue and metal fasteners (El Houjeyri et al., 2021).

Structures out of solid wood with contact joints are of interest. Wooden wall elements with dovetail contact joints are manufactured by means of digital milling (Cokcan et al., 2016). Squared and round timber processed using CNC machines (Bucklin et al., 2021; Colella, 2020) are used for walls of arbitrary curvilinear shapes. Digitally produced mortise and tenon joints are currently under investigation (Gamerro et al., 2020). Such inventions are not yet widely used in wooden buildings due to the complexity of the manufacturing process and the low number of wooden buildings of curvilinear configurations.

The efficiency of mortise and tenon joints largely depends on the quality of squared timber milling. Violations of the manufacturing procedure lead to gaps and the weakening of structures (He et al., 2021). Theoretical and experimental studies on such joints were conducted (Feio et al., 2014; Yu et al., 2021). New timber processing techniques (Pinkowski et al., 2019) and milling methods (Starikov et al., 2020) were implemented.

The tenon joint performance also depends on the wood species and strength. Lara-Bocanegra et al. (2020) pointed out that by choosing the material properly, it is possible to ensure the high strength of items with tenon joints.

Therefore, the subject of this paper, addressing walls out of solid wood, is highly relevant and under debate.

Based on the cited studies, it should be noted that shear strains of walls out of laminated and composite members with metal fittings exceed those of walls out of whole-section timber. Therefore, in a number of cases, composite timber members with metal fittings are characterized by lower strength than whole-section timber elements with timber-to-timber contact joints. Joints with metal fittings are less practical to manufacture than timber mortise and tenon joints. Therefore, based on the performed studies, it is possible to consider contact tenon joints of wooden members to be the most efficient. Besides, contact joints are less sensitive to changes in temperature and humidity in the room since they allow for some freedom of strains in wooden members. To be used in practice, items shall be easy to manufacture. Pavlenin and Shutova (2020) as well as other researchers noted that the Naturi technology meets the above parameters in many respects.

This paper addresses wall structures for low-rise houses, made out of vertical squared timber using the Naturi technology.

Houses built out of vertical squared timber using the Naturi technology are gaining popularity in modern low-rise construction since the technology provides positive structural and operational performance of walls. Such a solution makes it possible to use the type of wood compression along fibers advantageous for wood, and reduce settlement of walls while they are in use as compared to walls made out of horizontal squared timber. Walls are made out of whole-section timber without the use of metal fittings and glue. This simplifies the manufacturing process and makes it possible to avoid the influence of the ductility of joints. Besides, the use of whole-section timber rules out the delamination of items along the glue lines.

The history of construction out of vertical squared timber started as early as in the 20th century. We are aware of historic buildings where walls were made of squared and round timber installed vertically. However, such a structure has a disadvantage, which was noted by Russian architect Krasovsky (2002): gaps between the bars, occurring during operation.

Austrian researcher Georg Ganaus (2009) patented the Naturi technology for the construction of houses out of vertical squared timber. Based on this technology, squared timber is milled and drilled to make cutouts to connect the bars with each other. Thus, it is possible to avoid open gaps between the bars in the wall structure. Afterward, this technology was improved by Ganaus together with Russian experts Lazarev, Stepanishchev, and Yelchugin (Ganaus et al., 2018).

The growing interest in structures out of vertical squared timber results in the design of not only residential but also public buildings, including for rural infrastructure. Public buildings have increased bays and floor height in comparison to residential buildings. As a result, the load on the walls and their effective length increase. For practical design, data on strength and stability of walls out of vertical squared timber for various building bays as well as thermal characteristics are required.

To this date, a number of studies on such walls have been performed. Höckner (2019) specified their positive thermal properties.

Among studies on the stress-strain state of wooden walls and methods of their analysis, papers addressing wall panels out of solid wood can be distinguished. Researchers studied the static structural behavior of CLT (cross laminated timber) (Meloni et al., 2018) and DLT (dowel laminated timber) panels (Miyata, 2020). Meloni et al. (2018) used the finite element method to analyze the shear strains of CLT wall panels (Meloni et al., 2018). Thiel and Schickhofer (2010) described software to determine the bending stresses and deformations of CLT panels for two limit states and a number of design situations.

Miyata et al. (2018) considered a numerical analysis model of walls with pillars stacked with nails or screws. The strength of the walls was estimated by the performance of nail or screw joints.

Inayama et al. (2011) proposed a calculation method for rigidity and ultimate strength of inserted wooden siding walls.

Despite many studies, the issues of the stress-strain state of walls out of vertical squared timber with contact joints have not been covered in contemporary technical and academic literature.

The given finite-element models are a convenient tool for the analysis of wooden wall structures since they make it possible to determine a number of options with minimal labor input. It is needless to say that numerical methods are needed for practical calculations. However, there were cases when the elastic response of wood was overestimated in numerical calculations (Iraola et al., 2021). It is a good practice to compare a numerical method with an analytical model.

The purpose of this paper was to formulate an analytical calculation method for walls out of vertical squared timber, made using the Naturi technology based on the available traditional common methods for the analysis of wooden structures. To achieve the purpose, we needed to address the following tasks: to study the wall behavior in compression with bending under the action of the wind load along and across the building; to study the wall buckling strain.

## Methods

According to the Naturi technology, a wall of a building is made out of vertical milled bars. Such connections do not ensure a monolithic structure but develop composite action due to contact tenon joints. This paper proposes a calculation method for a wall made out of vertical squared timber as a set of conventional posts with wooden joints (hereinafter — conventional posts). Each conventional post consists of two bars connected with mortise and tenon joints and using wooden dowels. A diagram of the post section is given in Fig. 1.

In a general case, vertical and horizontal loads act on a building. Horizontal loads include the action of wind. We evaluated the static structural behavior of conventional posts for two design cases: under the action of wind along and across the building. In terms of the stress-strain state, we analyzed the behavior of conventional posts in compression with bending and buckling strain.

*Calculation for compression with bending*

*Design case: under the action of the wind load across the building*

We considered a wooden wall of a building, made out of vertical squared timber and represented as a set of conventional posts consisting of two bars (Fig. 1). It is accepted that the wind load across the building is distributed between individual conventional posts of the longitudinal wall, as shown in Fig. 2a. The calculation for a wall under the action of the wind load across the building comes down to the calculation for a conventional post in compression with bending.

The calculation was based on a deformation scheme for the combined action of three factors: the longitudinal force of vertical loads, the bending moment from the wind load, and the additional moment from the longitudinal force applied to the deformed post bent due to the moment.

The edge compressive stresses were checked and compared to the design compressive strength of wood along the fibers by Eq. (1).

$$\frac{N}{F_{calc}} + \frac{M_d}{W_{calc}} < R_c, \tag{1}$$

where $N$ — the longitudinal force;

$M_d$ — the bending moment determined using the deformation scheme;

$R_c$ — the design compressive strength of wood along the fibers.

$$M_d = \frac{M}{\xi}, \tag{2}$$

where $\xi$ — the coefficient that takes into account the action of the longitudinal force applied to the deformed element.

$$\xi = 1 - \frac{N}{\phi\, R_c F_{gross}}, \tag{3}$$

where $\varphi$ — the buckling coefficient.

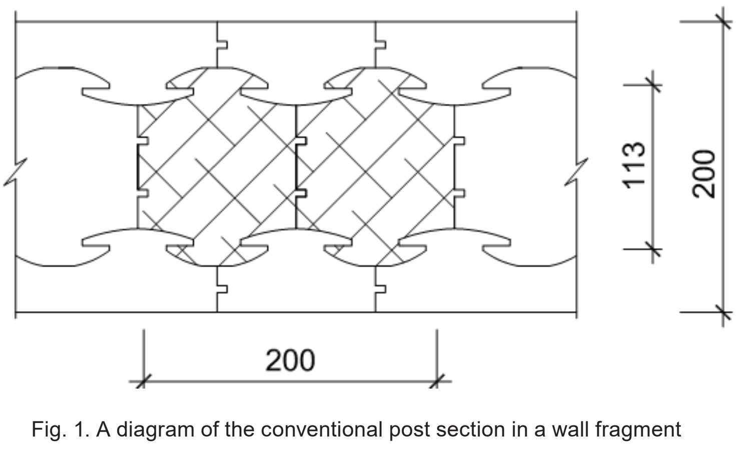
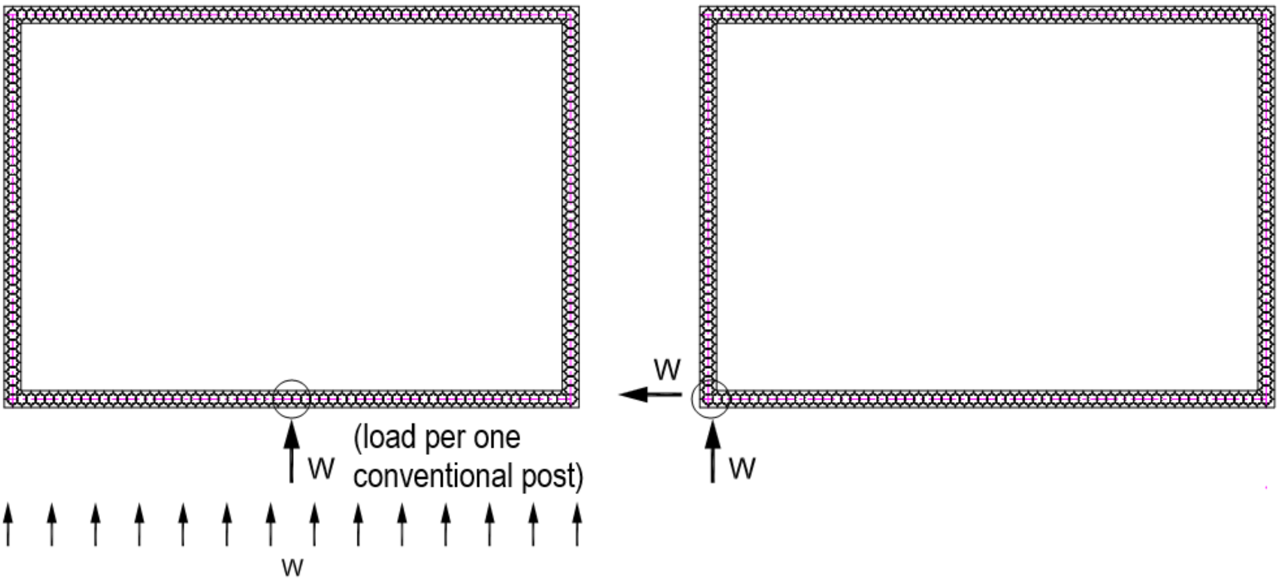


Fig. 1. A diagram of the conventional post section in a wall fragment



a) b)

Fig. 2. A diagram of the wind load across the building: a) acting on a conventional post in a row; b) acting on a conventional post in a corner

$$\phi = \frac{3000}{\lambda^2}, \tag{4}$$

where $\lambda$ — the element slenderness.

The plane strain buckling, if necessary, can be checked using Eq. (5).

$$\frac{N}{\phi R_c F_{gross}} + \left(\frac{M_d}{\phi_f R_b W_{gross}}\right)^n < 1, \tag{5}$$

where $\varphi_f$ — the buckling stability coefficient;

$n$ — the power exponent characterizing the restraint of the strained edge of the element out of the strain plane;

$R_b$ — the design bending strength.

As an example, we performed calculations for a wall out of vertical squared timber. The wall thickness was 20.0 cm with account for the finishing layer of wood. The calculations were performed for a wall element — a conventional post with a design section of 20.0 x 11.3 cm (*h*) shown in Fig. 1. Weakening in the design section was taken into account approximately with the 0.8 coefficient to the sectional area and the section modulus. In the calculations, we used permanent and temporary loads from two stories and roofing as well as the wind load across the building for the first wind area, as shown in Fig. 2a. The section slenderness of the post out of the longitudinal wall plane was adopted equal to the slenderness of an individual branch, i.e., an individual bar. Table 1 shows the obtained indicators for the behavior of a conventional post. The plane strain buckling was not checked due to low values of normal stresses.

Table 1. Geometric parameters, forces, and stresses in conventional posts under the action of wind across the building

| **Wall height, m** | **Building bay, m** | **Slenderness of a conventional post (branch)** | **Buckling coefficient** | **Bending moment (Eq. (2)), kN·m** | **Longitudinal force, kN** | **Normal stresses check, (Eq. (1)), kN/cm$^2$** |
|---|---|---|---|---|---|---|
| 3 | 10 | 91.55 < 120* | 0.358 | 0.37 | 11.59 | 0.18 < 1.38** |
| | 12 | 91.55 < 120* | 0.358 | 0.38 | 13.85 | 0.19 < 1.38** |
| 3.5 | 10 | 106.8 < 120* | 0.26 | 0.53 | 11.65 | 0.22 < 1.38** |
| | 12 | 106.8 < 120* | 0.26 | 0.56 | 13.91 | 0.24 < 1.38** |
| 4 | 10 | 122 > 120* | 0.2 | 0.72 | 11.72 | 0.26 < 1.38** |
| | 12 | 122 > 120* | 0.2 | 0.8 | 13.98 | 0.31 < 1.38** |

120* — limiting slenderness (Regulations SP 64 13330.2017 “Timber structures”)

1.38** — the design compressive strength of second-grade wood along the fibers (Regulations SP 64 13330.2017 “Timber structures”)

Therefore, based on Table 1, we obtain satisfactory results concerning the strength and limiting slenderness of a conventional post at a floor height of up to 3.5 m and building bays of 10 and 12 m. The slenderness of a conventional post with a height of 4 m with the same bays exceeds the limiting one.

*Calculation for compression with bending*

*Design case: under the action of the wind load along the building*

In case of the wind load along the building, there are two options. As for the first option, the wind load is distributed among individual conventional posts of a side wall. This option is similar to the case of the wind load across the building described above. As for the second option, the wind load along the building can be taken up by the entire side wall and distributed equally between the longitudinal walls (Fig. 3a).

Since a longitudinal wall is not monolithic, this load will mostly be received by the outermost conventional posts of the longitudinal walls. The posts will undergo compression with bending in the wall plane according to the same scheme as in the case of the action of the wind load across the building. If the outermost posts cannot take up vertical loads and the wind action from the building side wall, they will affect the neighboring ones. This may cause a deflection in the wall, instability of its geometrical shape. The second option of load distribution is described in the following example.

We performed calculations for a wall out of vertical squared timber with a thickness of 20.0 cm with the finishing layer of wood. The calculations were carried out using Eqs. (1)–(5) for a wall element — a conventional post with a design section of 11.3 x 20.0 cm (*h*) described above (Fig. 1). Fig. 3a shows a diagram for the distribution of the wind load along the building. To take into account the ductility of the post joints in the wall plane, the section slenderness was adopted equal to the slenderness of an individual branch, i.e., an individual bar. Table 2 shows the specified geometric parameters of the conventional posts as well as the obtained forces and stresses in the posts.

In addition, it should be noted that the wall, floor slabs, and roofing form the longitudinal frame of the building and develop composite action to take up the loads along the building. Due to pivot joints and possible shrinkage of wood during operation, the behavior of the floor slabs and roofing is not included in the calculations as some strength margin.

Table 2. Geometric parameters, forces, and stresses in conventional posts under the action of the wind along the building

| **Wall height, m** | **Building bay, m** | **Slenderness of a conventional post (branch)** | **Buckling coefficient** | **Bending moment (Eq. (2)), kN·m** | **Longitudinal force, kN** | **Normal stresses check, (Eq. (1)), kN/cm²** | **Buckling check (Eq. (5))** |
|---|---|---|---|---|---|---|---|
| 3 | 10 | 91.6 < 120* | 0.358 | 7.83 | 11.59 | 1.36 < 1.38** | 0.41 < 1 |
| | 12 | 91.6 < 120* | 0.358 | 9.74 | 13.85 | 1.69 > 1.38** | 0.5 < 1 |
| 3.5 | 10 | 106.8 < 120* | 0.26 | 11.56 | 11.65 | 1.98 > 1.38** | 0.65 < 1 |
| | 12 | 106.8 < 120* | 0.26 | 14.76 | 13.91 | 2.52 > 1.38** | 0.83 < 1 |
| 4 | 10 | 122 > 120* | 0.2 | 16.7 | 11.72 | 2.64 > 1.38** | 1.03 ~ 1 |
| | 12 | 122 > 120* | 0.2 | 22.0 | 13.98 | 3.7 > 1.48** | 1.32 > 1 |

120* — limiting slenderness (Regulations SP 64 13330.2017 “Timber structures”)

1.38** — the design compressive strength of second-grade wood along the fibers (Regulations SP 64 13330.2017 “Timber structures”)

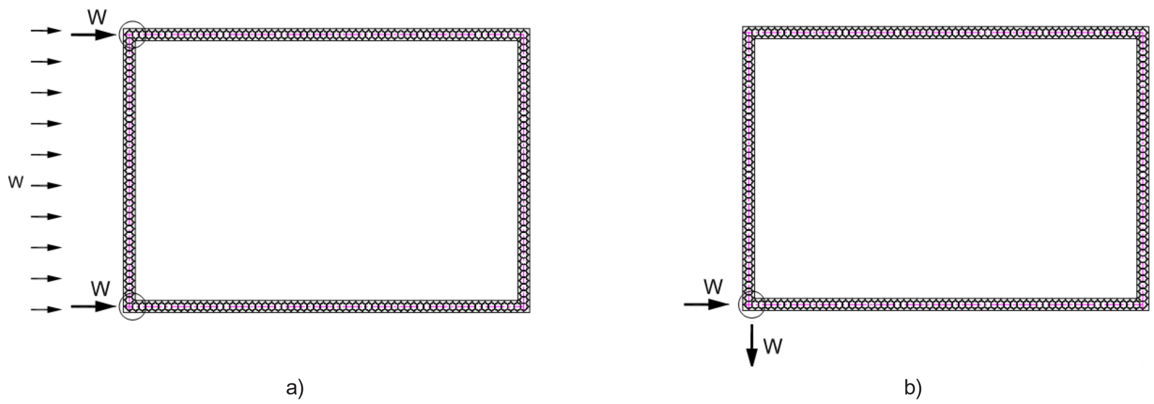


Fig. 3. A diagram of the wind load along the building: a) redistribution of the wind load from the side wall to the conventional posts in the corners; b) positive and negative wind pressure on the post in the corner

Thus, we considered two options for the distribution of the wind load along the building. The first option implies the uniform distribution of the wind load among the conventional posts of the side wall similar to the case of the wind load across the building described above. The second option implies the transfer of the wind load by the side wall to the longitudinal walls through the conventional posts in the corners. Table 2 shows the calculated data for the second case. As shown in the table, the conventional post with a height of 3 m and a building bay of 10 m demonstrates satisfactory performance in terms of strength, plane strain buckling, and limiting slenderness. The conventional post with a height of 3 m and a building bay of 12 m, the posts with a height of 3.5 m and bays of 10 and 12 m demonstrate satisfactory performance in terms of limiting slenderness and plane strain buckling but have high normal stresses exceeding the design wood resistance. The conventional post with a height of 4 m does not demonstrate satisfactory performance in terms of strength, plane strain buckling, and limiting slenderness.

*Calculation for buckling*

If in Eq. (1), the bending stress component is less than 10% of the compression stress component, the design section of the wall (conventional post) is calculated for buckling.

According to the proposed method, a check of wall stability comes down to a check of a conventional post in the plane and out of the plane of the wall depending on the direction of the horizontal wind load causing the bending moment.

The stability of a conventional post is checked based on the following condition:

$$\frac{N}{\phi F_{calc}} < R_c. \qquad (6)$$

The slenderness of a conventional post is adopted equal to the slenderness of an individual bar. The buckling coefficient is calculated in the same manner as for axially loaded elements depending on the value of the post slenderness. The design length of a post is adopted equal to the floor height.

**Results and discussion**

A wall out of vertical squared timber is represented by a set of conventional posts, each consisting of two bars. A check of a wall for strength and limiting slenderness comes down to a check of a conventional post. Table 3 summarizes the results of calculations for conventional posts. The following conclusions can be drawn:

At wind loads across the building, a conventional post resists compression with bending out of the longitudinal wall plane. The calculations for the action of specified vertical loads and horizontal wind loads across the building show that the conventional post under consideration has sufficient strength and slenderness not exceeding the limiting one, at a height of up to 3.5 m and bays of 10 and 12 m.

At wind loads along the building, an outermost conventional post resists compression with bending in the longitudinal wall plane. The calculations for the action of specified vertical loads and horizontal wind loads along the building show that, when the wind loads are transferred from the side wall to the longitudinal walls, the outermost conventional posts of the section under consideration can take up wind pressure at a height of max. 3.5 m and bay of max. 10 m.

The buckling strain of conventional posts is taken into account if stresses from the moment are less than 10% of the compression stresses.

The outermost conventional posts are actually corner posts. The corner posts are characterized by a combined stress state under the action of the wind load both along and across the building. In both cases, the posts are exposed to positive and negative wind pressure, as shown in Figs. 2b and 3b. This leads to the bending and torsional buckling mode.

Table 3. Results of the calculations for a conventional post under the action of the wind load along and across the building

| **Wall height, m** | **Building bay, m** | **Wind load direction** | **Condition of strength at normal compression and bending stresses (Eq. (1)), kN/m$^2$** | **Condition of limiting slenderness** | **Condition of stability (Eq. (5))** |
|---|---|---|---|---|---|
| 3 | 10 | Across the building | 0.18 < 1.48** | 91.55 < 120* | |
| | | Along the building | 1.36 < 1.48** | | 0.41 < 1 |
| | 12 | Across the building | 0.19 < 1.48** | | |
| | | Along the building | 1.69 > 1.48** | | 0.5 < 1 |

| | | | | | |
|---|---|---|---|---|---|
| 3.5 | 10 | Across the building | 0.22 < 1.48** | 106.8 < 120* | |
| | | Along the building | 1.98 > 1.48** | | 0.65 < 1 |
| | 12 | Across the building | 0.24 < 1.48** | | |
| | | Along the building | 2.52 > 1.48** | | 0.83 < 1 |
| 4 | 10 | Across the building | 0.26 < 1.48** | 122 > 120* | |
| | | Along the building | 2.64 > 1.48** | | 1.03 ~ 1 |
| | 12 | Across the building | 0.31 < 1.48** | | |
| | | Along the building | 3.7 > 1.48** | | 1.32 > 1 |

120* — limiting slenderness (Regulations SP 64 13330.2017 “Timber structures”)

1.48** — the design compressive strength of second-grade wood along the fibers (Regulations SP 64 13330.2017 “Timber structures”)

Based on the above, the following recommendations can be formulated. The conventional posts to be placed in the corners shall be manufactured out of whole-section rectangular timber in order to rule out the impact of ductility from the contact joints of the bars. Besides, options with a laminated section or a section made by means of a special welding technique are possible (Župčić et al., 2021). To improve the strength characteristics of corner conventional posts, laminated veneer lumber (LVL) can be used with account for the relevant restrictions on the size of sections according to State Standard GOST 33124 “Laminated veneer lumber. Specifications”. Compressed wood is distinguished by its good mechanical properties and the possibility to obtain any size of section (Namari et al., 2021). Such type of wood can be used to manufacture corner conventional posts. The strength of walls out of vertical squared timber depends on the quality of bar joints. Their high quality can be achieved by improving milling methods. Automatic robotic assembly of wooden members is also promising (Leung et al., 2021).

## Conclusion

We formulated an analytical calculation method for walls out of vertical squared timber, made using the Naturi technology. According to the proposed method, a wall is considered a set of conventional posts with contact joints. The stress-strain state of conventional posts is considered under the action of vertical and horizontal loads directed along and across the building. Each conventional post is checked for strength and stability in compression with bending or buckling as well as for limiting slenderness. The method is based on the existing traditional provisions for calculations concerning wooden structures.

Several examples of wall element calculations were provided. Permissible heights of walls for buildings with bays of 10 and 12 m were obtained.

Recommendations on the structure of corner wall sections were provided based on the calculation esults.

These results can be used in the construction of residential and public buildings given the corresponding justification of structure fire resistance.

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# МЕТОД РАСЧЕТА СТЕНЫ ИЗ ДЕРЕВЯННОГО ВЕРТИКАЛЬНОГО БРУСА

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**Аннотация**

В последние годы получили распространение дома из деревянного профилированного бруса, установленного вертикально. Такое расположение стенового бруса позволяет использовать эффективный вид работы древесины на сжатие и реализовать максимальную прочность материала вдоль волокон. Вместе с тем брус, установленный в вертикальном положении, работает в условиях сжатия с изгибом, что может привести к потере прочности и устойчивости конструкций здания. В существующих научных публикациях и технической литературе не анализировался вопрос напряженно-деформированного состояния таких стен. **Целью данного исследования** является формулировка метода расчета стен из вертикального бруса на основе известных традиционных подходов к деревянным конструкциям. Предложен **метод** расчета стены из вертикального бруса как совокупности элементов, работающих на сжатие с изгибом, включающий проверку по предельной гибкости. **Результаты:** Получены допускаемые высоты стены при пролетах здания 10м и 12м. Результаты могут быть использованы при проектировании малоэтажных зданий жилого и общественного назначения, мансардных надстроек многоэтажных зданий.

**Ключевые слова**

Деревянный профилированный вертикальный брус, напряженно-деформированное состояние, сжатие, изгиб.