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Prediction of the Building Materials Performance in Products and Structures

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Abstract

A technique for predicting the performance of wood composites in building products and structures is presented. It takes into account the action of environmental factors, such as freezing-thawing, climatic influences and temperature. The impact of external influences on the durability of wood composites and measuring techniques of their effect correction are described.

Keywords

Wood composites; strength; durability; performance.

In early works [1, 2], the problem of structural materials performance was considered from the perspective of the classical mechanics ideas of plastic deformations. Moreover, the destruction of solids was considered as a critical event that occurs when the stresses acting in the material reach a certain limiting value.

Subsequently, operability (durability) began to be considered as part of the general theory of reliability, and its calculations were carried out using the mathematical apparatus of probability theory, as well as the set theory. The complexity of this approach lies in the limited possibilities of obtaining sufficient statistical material [2, 3].

The next way to building a theory for predicting reliability and durability is based on the study of the physicochemical properties and parameters of objects, the processes occurring in them, the physical nature and mechanism of destruction. In this case equations which reflect physical laws are used [4, 5].

Currently, the following methods are used to calculate and predict the bearing capacity of building materials and structures that determine their durability:

1. *The phenomenological method* involves the theory of deformation and fracture of composite materials based on the mechanics of composites [6]. The purpose of the method is to relate the mechanical characteristics of the composite to the characteristics of the components, which will allow the mechanical properties of the components to predict the mechanical properties of the entire composite. Voigt proposed determining the elastic modulus of composites by the following dependence

$$E = \left[\psi' E' + \psi'' E'' + \ldots + \psi^n E^n\right], \qquad (1)$$

where ψ', E' are volume fractions and elastic modules of the components, respectively.

2. *Prediction of durability according to the kinetic laws of aging*. The change in swelling pressure directly reflects the loss or formation of intrastructural bonds in the material, which makes it possible to predict durability according to the kinetic laws of aging [7].

3. *Prediction of the composite materials' strength using polystructure theory*. The essence of the theory lies in the representation of the material as polystructural, i.e. in the allocation of many inter-dependent structures – from the atomic level to the coarse composite structures of solid building elements – sprouting one into another (composite in composite) in a single structure [8].

4. *Kinetic concept of strength*. According to the kinetic concept of strength, the destruction of a solid is considered not as a critical event, but as a gradual kinetic, thermoactivation process that develops in a mechanically stressed body in time from the moment of application of a certain load, including less than critical [9]. Reliability and guarantee against the occurrence of

limiting conditions of the construction are ensured by proper consideration of the most possible adverse characteristics of materials: overloads, the use of the most disadvantageous (but really possible) combination of loads and effects, the proper choice of design patterns and calculation prerequisites, taking into account, if necessary, the plastic and rheological properties of materials, as well as taking into account the conditions and features of the actual work of structures and foundations.

At present the most promising direction is the thermofluctuation concept of fracture and deformation of solids, which considers the durability of materials. The development of the kinetic concept is due primarily to the fundamental works of the S.N. Zhurkov school. In contrast to mechanical concepts, which take into account only the competition between the applied force and the forces of interatomic bonds, it considers the thermal motion of atoms as a decisive factor in the process of mechanical failure [10]. At first was established the universal nature of the durability time dependence (Fig. 1):

$$\sigma = \frac{2.3}{\beta} \lg\left(\frac{a}{\tau}\right); \qquad \tau = a \exp(-\beta\sigma), \tag{2}$$

where a and β are constant coefficients that determine the dependence of the durability on a stress at a constant test temperature.

The essence of this dependence is that the destruction of the material takes time during which processes occurring in the loaded body lead to its separation into fragments.

Over a wide range of loads, the dependence in the coordinates of $\lg\tau$–σ has a linear character. However, it is characterized by the presence of two bends. The first is in the region of low stress values (at $\sigma \to 0$), since this would mean that the decay of the body into parts occurs spontaneously in the absence of external stress.

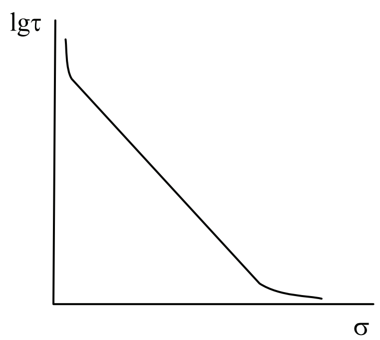


Fig. 1. A schematic view of the durability force dependence in a wide range of stress changes (temperature is constant)

The second bend appears in the high stresses region due to the limited propagation velocity of elastic waves in a solid.

Having experimentally studied the role of temperature, i.e. its influence on constants a and β, S.N. Zhurkov came to the formula of durability that bears his name:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{RT}\right), \tag{3}$$

where τ is the durability; τ_0 is the period of atomic vibrations in a solid; U_0 is the effective activation energy of destruction, kJ/mol; γ is the structurally sensitive constant, kJ/(mol·MPa); R is the universal gas constant, kJ/(mol·K); σ is the stress, MPa; T is the temperature, K [9, 10].

Such a formula was previously obtained by other authors, but the physical meaning of its constants was not revealed and no interpretation of the destruction mechanism was given.

The structure of the formula suggests that the contribution of the load to the breaking of bonds is reflected by the value $\gamma\sigma$ (work of the mechanical field), and the rest of the work is produced by thermal motion, the proportion of which is $U = U_0 - \gamma\sigma$. The fundamental interpretation was received for two constants τ_0 and U_0. It turned out that for different bodies $\tau_0 = 10^{-12} - 10^{-13}$ s, which is close to the period of atomic vibrations. U_0 coincides with the energy of evaporation (or sublimation) of metals, i.e. energy of breaking bonds of atoms. The mechanical destruction of polymers is thermochemical destruction, only accelerated by a mechanical field. Therefore, the value of U_0 will be equal to the activation energy of thermal destruction E_a and will differ for different carbochain polymers due to the difference in the kinetics of their destruction.

Mechanical destruction processes occur in the bodies at any temperature. This is a mechanothermal process that occurs in time and is realized through elementary acts of the interatomic (chemical) bonds breaking. Time itself does not play a role, it only increases the number of thermal fluctuations necessary for the implementation of those bond breaking processes that impede a critical event. The latency of a critical event is equal to $\tau_{cr} = \tau_\infty \exp\frac{U}{RT}$. However, this event may not occur, since due to thermal motion, broken bonds are re-combined.

In a mechanical field, the process of bond breaking is accelerated, so the role of the load is to reduce the bond energy (and, accordingly, the activation energy, which is proportional to it), to change the distance between kinetic units and also to fix their movements, in particular, in making difficult radical recombination. Over the entire range of applied loads, the product $\gamma\sigma$ turned out to be significantly less than U_0. Therefore, the main destructive factor is thermal fluctuations, i.e. the destruction energy of the body is drawn to a greater extent from the supply of thermal energy than from the work of external forces [9]. And the direction of the applied force ensures the irreversibility of the process due to the accumulation of these fractures.

Formula (3) implies the invariance of the state of the substance and the stability of the constants in the entire range of temperatures and loads. However, for each substance there is a limiting temperature, reaching of which results in body decomposition into fragments. This limiting temperature corresponds to the position of the pole. S.Ya. Frenkel in the preface to the monograph of G.M. Bartenev "Strength and fracture mechanism of polymers" substantiates that $1/T_m \neq 0$ and $\tau_m \neq 10^{-13}$ s. Since U is not the true activation energy, and γ is sensitive to the structure, the temperature dependence of both constants follows from the expansion of the function $U(T, \sigma)$ in a series. According to S.Ya. Frenkel, τ_m corresponds to vibrations of chemically unbound atoms or molecules in real lattices. However, the polymer structure is discrete, i.e. various relaxation processes, which are determined by the displacement or decay of structural elements of different quantities, and their vibration time significantly exceeds the atomic vibration time, therefore τ_m significantly exceeds 10^{-13} s [9].

To eliminate these assumptions (inaccuracies) in the formula (3) S.B. Ratner and V.P. Yartsev entered and physically justified the fourth constant T_m. The presence of this constant does not affect either the interpretation of the role and contribution of thermal motion and the work of external forces, or the physical meaning of the remaining constants (U_0 and γ) [9]

$$\tau = \tau_m \exp\left[\frac{U_0 - \gamma\sigma}{R}\left(T^{-1} - T_m^{-1}\right)\right], \quad (4)$$

where τ_m, U_0, γ, and T_m are the physical constants of the material: τ_m is the minimum durability (the period of oscillation of kinetic units – atoms, groups of atoms, segments), s; U_0 is the maximum activation energy of destruction, kJ/mol; γ is the structural and mechanical constant, kJ/(mol·MPa); T_m is the limiting temperature of the existence of a solid (decomposition temperature), K; R is the universal gas constant, kJ/(mol·K); τ is the time to failure (durability), s; σ is the voltage, MPa; T is the temperature, K.

The structure of formula (4) implies that the countdown of the reciprocal temperature does not come from $1/T = 0$, but from $1/T_m$, i.e. there is a certain limiting temperature above which the material does not work, and its durability τ_m is minimal.

The physical meaning of the constants in equation (4):

– T_m is the limiting temperature of the polymer's existence, at which all chemical bonds break in one thermal vibration and the solid completely breaks up;

– τ_m is the minimum fracture time of a solid (at $T = T_m$), often much more than $\tau_0 = 10^{-13}$ s;

– U_0 is the maximum activation energy of the destruction process. It is determined by the energy of bonds, which prevent the loss of body integrity, and is close to the activation energy of the decay of interatomic bonds in solids: in metals – to the sublimation energy and in polymers – to the activation energy of the thermal destruction process;

– γ is a structural-mechanical constant characterizing the efficiency of a mechanical field under the action of a load. It is proportional to strength and has a volume dimension $\gamma = \chi\omega$ (ω is the fluctuation volume in which a burst of thermal energy occurs, sufficient to break the limiting bond; it corresponds to a chemical bond dimension of $\approx 10^{-23}$ cm; χ characterizes the concentration of overstresses on the broken bond). When treating γ as an overstress coefficient (the stronger the body, the lower the level of local overstresses in it, and therefore γ is less), it should be borne in mind that it does not remain constant during the entire duration of the test of this sample for durability, which is caused by a decrease in the number of bonds and crack growth. The state with the minimum value of γ is reached shortly after application of the load and for a long time remains constant, in the stage of a steady creep. By the end of the process, corresponding to the so-called third creep stage, the constant begins to increase again. Thus, the value of γ determined from the durability data is a certain integral, averaged value.

Formula (4) is often not justified. This is observed upon brittle fracture of filled polyamides and polyalkyleneterephthalates, i.e. polymers in which, along with chemical and intermolecular forces, there are also intermediate forces corresponding to hydrogen bonds or the action between π-electrons, as well as for some types of wood boards with small chips, in which 2 types of bonds are formed as a result of pressing (chemical and Van der Waltz). The result is a family of lines that do not converge to the pole in the coordinates $\lg\tau - \sigma$ and $\lg\tau - 1/T$ (Fig. 2*b*). In this case, the dependence is described by the formula

$$\tau = \tau_* \exp\frac{U}{RT}\exp(-\beta\sigma), \quad (5)$$

where τ_*, U are empirical constants; β – structural-mechanical coefficient, 1/MPa.

Cases of inversion of a pencil of lines are also observed (equation (6)). They converge at the pole not at an extremely high, but at an extremely low temperature. This type of dependence is characteristic of oriented materials, such as wood, fiberglass during tension of films, as well as fatigue abrasion [9]

$$\tau = \tau_m^* \exp\frac{U_0^* - \gamma^*\sigma}{RT}\left(\frac{T_m^*}{T} - 1\right), \quad (6)$$

where τ_m^*, U_0^*, γ^*, T_m^* are empirical constants.

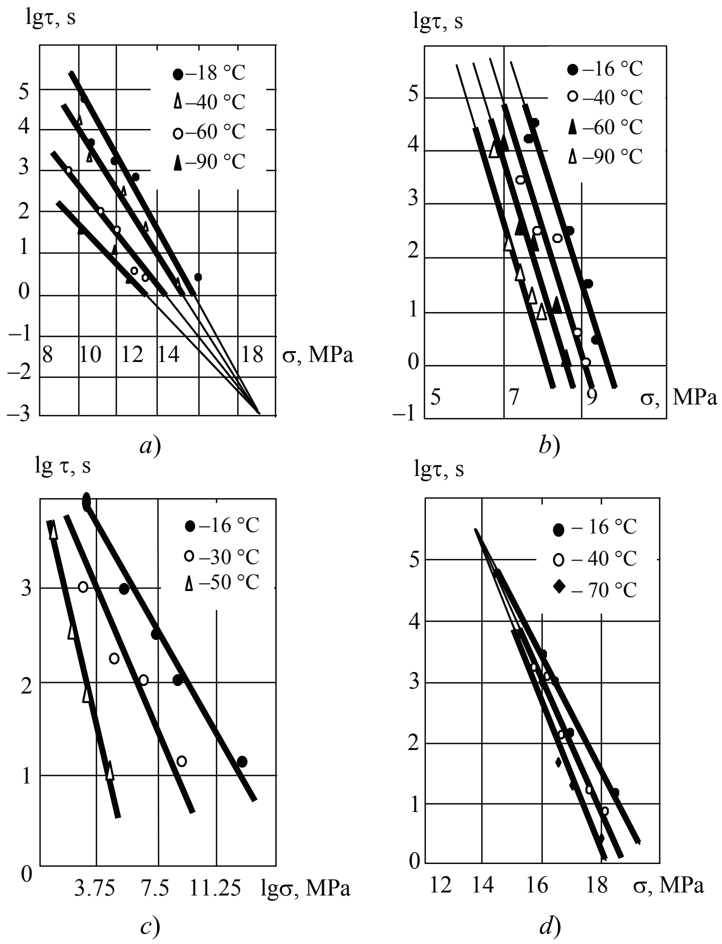


Fig. 2. The durability dependence on stress during transverse bending for wood boards with a density:
a – 700 (particleboard); *b* – 800 (chipboard with fine chips); *c* – the time to failure from the stress of bitumen BN 90/10 s 50 mass. % AFI in tension; *d* – 850 (fiberboard), kg/m^3

The kinetic concept works both with brittle and brittle-elastic and elastic behavior of polymers.

When loading the body, two processes arise in it simultaneously: deformation and fracture. They proceed at different speeds, and the process is disclosed that takes less time to implement. What is the difference between these processes? Deformation occurs through rearrangement, i.e. rupture and subsequent occurrence of intermolecular bonds. The destruction of the body (separation into parts) requires the breaking of chemical bonds in the main chain. Both processes have a thermofluctuation nature and are described by the same equation [9]:

– for the direct beam

$$\theta = \theta_m \exp\left[\frac{U_0 - \gamma\sigma}{RT}\left(1 - \frac{T}{T_m}\right)\right], \quad (7)$$

– for the return beam

$$\theta = \theta_m^* \exp\frac{U_0^* - \gamma^*\sigma}{RT}\left(\frac{T_m^*}{T} - 1\right), \quad (8)$$

where θ_m is the minimum durability (period of vibration of kinetic units: atoms, molecules, segments), s; U_0 is the maximum activation energy for moving a segment from one position to another, kJ/mol; γ is the structural-mechanical constant, reflecting the uneven load distribution along the polymer chains, kJ/(mol·MPa); T_m is the limiting softening temperature, K; R is the universal gas constant, kJ/(mol·K); θ is the time to achieve a given deformation (deformation durability), s; σ is the stress, MPa; T is the temperature, K; θ_m^*, U_0^*, γ^*, T_m^* are empirical constants.

The thermofluctuation concept of fracture and deformation can be used not only in predicting the health (durability) of composite materials (products and structures) in a wide range of operational parameters, but also in the design of building structures and products, selecting their sections taking into account the influence of external factors.

In the first case, the calculation of the durability of building composites is carried out in the following sequence [11 – 13]:

1) for a material in a particular product or design, the stress-strain state is determined;

2) the operating temperature is set;

3) the stresses arising in the cross section of the product (structure) are calculated;

4) the nature of the durability dependence on stress, the equation for durability and the constants included in this equation are established;

5) according to the selected equation, with the set parameters σ and T, the theoretical durability of the material is calculated (the time it takes to lose shape or break). To facilitate the calculations, diagrams of the durability dependence on stresses and temperatures were constructed. An example diagram is shown in Fig. 3;

6) external influences are established that affect the material performance (aggressive environments, climatic factors, the presence of aging factors, etc.);

7) the implementation of the Bailey principle under various influences is verified. If this principle is satisfied, then the action of external factors can be taken into account with the help of amendments. Otherwise, full-scale testing is necessary. In [14], it was found that for all wood composites it is performed under the action of loads, liquid aggressive media (water), and partially under the action of elevated temperatures;

8) using amendments (Δ), the actual durability of the product or structure is determined, i.e. durability, taking into account the external environment impact on the material. Corrections were given in [14];

9) durability spread value is taken into account.

We explain some of the provisions that are presented in the methodology for predicting the durability of building materials, products and structures.

Implementation of the Bailey principle

The Bailey principle or the rule of additivity states that the time of the "life" of a solid does not depend on interruptions ("rest") when it is loaded. During the entire loading time, irreversible changes accumulate in the material, leading to the separation of the body into parts [9]. The principle is described by the formula:

$$\int_0^{t^1} \frac{dt}{\tau[\sigma(t)]} = 1, \qquad (9)$$

where τ is the durability, s; σ is the long-term strength, MPa; t is the load action time, s.

It follows from the equation that during the life of the material (from the beginning of loading to when the sum of the consumed fractions of the durability resource becomes equal to units), the partial destruction of the solid occurs. This principle is valid not only in destruction, but also in deformation.

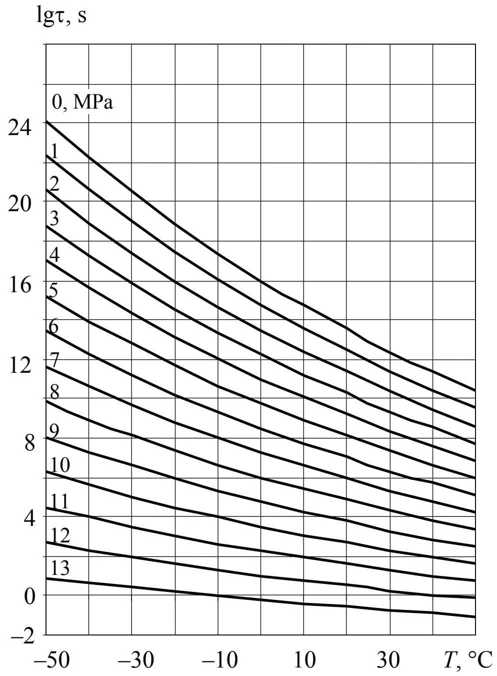


Fig. 3. An example of a diagram for determining the transverse bending performance of chipboard with a density of 650 kg/m^3

However, the Bailey principle is not always true. If the relaxation time is of the same order as the period of the loading cycle, then the principle of additivity of loading times is violated. This is explained by the weakening of solids occurring in the unloading half-phase, which arise from disorientation of the material structure in combination with hysteresis heating. If the relaxation time is much longer than the cycle period, then it does not affect the durability and its summation. With multiple loading, the bearing capacity (Miner criterion) is significantly lost, and the Bailey principle also fails [9]

In the course of the research, the implementation of the Bailey principle was checked at elevated temperature, humidity, with a change in the stress value. The results are shown in Table 1, from which it can be seen that in both cases, the chipboard, fiberboard and laminate have the same durability and strain. Therefore, for these materials, the Bailey principle is valid both in fracture and in deformation, and does not depend on their macrostructure.

For wood-based products, one of the most dangerous is the effect of moisture, which is explained by their structure. Soaking negatively affects the strength and deformation characteristics and is present at almost all stages of the material. In addition, during operation, composite materials operate in variable temperature mode. Therefore, the implementation of the Bailey principle was verified on the example of chipboards operating in the mode of cyclic changes in temperature and moisture.

From Table 1 it becomes obvious that under the discrete action of the load and temperature, the durability of the chipboard decreases (by 1.5 orders of magnitude), i.e. under these conditions, the Bailey principle is not satisfied. Since chipboards are resistant to thermal aging [14], the decrease in durability is associated with bond stress resulting from a sharp change in temperature, which leads to an increase in atomic vibrations with a constant change in bond length (bonds stretch or shrink).

The results are presented in Table 2. It shows that the durability of fiberboard and particleboard coincides both with continuous and discrete action of aggressive media.

Therefore, for wood fiber composites, the Bailey principle is satisfied not only from the action of the load, but also after exposure to a liquid aggressive environment [15].

It should be said about how the relaxation (rest) time affects the durability of the material. The relaxation time does not have a significant effect. Only the time of the factor's action makes a tangible contribution, which is evident when studying the implementation of the Bailey principle under the combined action of load and water Table 3 [15]. However, one should not forget that with too long rest (several days) not only capillary, but also hygroscopic moisture will evaporate. This will lead to a partial restoration of strength, and, consequently, to an increase in durability.

Thus, the factors acting on the material can be divided into two large groups. One of them will be factors which discrete action on the material can be taken into account by simple summation. Another group will include impacts which influence on the material cannot be taken into account using the Bailey principle. Both that and others, with the corresponding possible combinations, are drawn together in Table 4.

Table 1

Effect of temperature and load on the durability of wood-based panels

Type of material	Type of a test	External impact	Impact of external factors	Stress σ, MPa	Durability lgτ, s	Deformation, mm
Chipboard	Destruction	Load	Continuous	7.6	3.600	–
			Discrete	7.6	3.600	
		Temperature and load	Continuous	13.5	2.931	
			Discrete	13.5	1.168	
	Deformation	Load	Continuous	15.0	–	0.0152
			Discrete	15.0		0.0152
Fiberboard	Destruction		Continuous	28.5	4.132	–
			Discrete	28.5	4.007	
Laminate			Continuous	29.0	3.068	
			Discrete	29.0	2.980	

Table 2

The influence of external factors on the durability of wood boards

Series	Factors	Factors' impact	Cycle time, min	Stress σ, MPa	Durability lgτ, s
		Fiberboard			
1	Load, water	Continuous	–	22	3.227
2		Discrete	30		3.345
		Chipboard			
1	Load, water	Continuous	–	9	3.102
2		Discrete effect of a load and water	10		2.884
3		Discrete effect of water			2.810

Table 3

The effect of the rest duration on the durability of wood-fiber boards

Test	Factors	Factor's impact	Rest duration, min	Stress σ, MPa	Durability lgτ, units
1	Load, water	Discrete	15	22	3.345
2			60		3.218
3			1440		3.391

Table 4

The Bailey principle implementation for various factors in the wood plastics destruction and deformation

Impact type	The Bailey principle implementation	
	Under destruction	Under deformation
Load	Implemented	Implemented
Load, temperature	Does not implemented	–
Load, water	Implemented	
Load		
Load, water		
Load		

Durability variation

The durability variation depends on the material structure and is taken into account as follows. Constant values do not change under constant conditions, and the very fluctuation in the durability and strength of wood composites is caused by the unevenness of their structure and the presence of defects in the material. Then the durability calculation, taking into account the magnitude of the spread, will take the following form:

$$\lg \tau_{actual} = \lg \tau \pm k_{long} \varepsilon_{\lg \tau}, \tag{10}$$

where lgτ is the durability determined by equations (2) – (4), as amended; k_{long} – coefficient taking into account the duration of the tests (presented in Table 5); $\varepsilon_{\lg \tau}$ – the deviation value.

The deviation value can be determined by the formulas:

– for direct beam

$$\varepsilon_{\lg \tau} = -\frac{\gamma}{2.3\,RT}\left(1 - \frac{T}{T_m}\right)(\sigma - \sigma_c), \tag{11}$$

– for return beam

$$\varepsilon_{\lg \tau} = \frac{\gamma'}{2.3\,RT}\left(\frac{T'_m}{T} - 1\right)(\sigma - \sigma_c), \tag{12}$$

– for parallel lines

$$\varepsilon_{\lg \tau} = -\beta(\sigma - \sigma_c), \tag{13}$$

where σ is stress corresponding to the peak in the spread curves, MPa; σ_c is security stress 0.93, MPa; γ, T_m, γ', T'_m, β are material constants; R is universal gas constant, kJ/(mol·K).

The coefficients k_{long} were determined experimentally. As follows from the Table 5 with increasing durability, the coefficient decreases. This suggests that at low stress the probability of hazardous defects occurrence also decreases.

Table 5

Coefficient taking into account the test duration

Material	Test duration, range for lgτ				
	0–1	1–2	2–3	3–4	> 4
Chipboard	1.000	0.580	0.580	0.290	0.2200
Laminate Kronospan 31’	0.930	0.440	0.040	0.040	0.0400
Laminate Kronostar 31’	0.870	0.620	0.380	0.140	0.1400
Laminate Tarkett 32’	0.966	0.682	0.398	0.114	0.0114
MDF (Kostroma)	0.980	0.720	0.450	0.190	0.1900
MDF (Voronezh)	0.970	0.680	0.400	0.110	0.1100

Table 6

Determination of the deviation value

Material	Constant values				σ, MPa	σ_c, MPa	$\varepsilon_{\lg\tau}$
	τ_m (τ'_m), s	T_m (T'_m), K	U_0 (U'_0), kJ/mol	γ (γ′), kJ/(MPa·mol)			
Wood	10^7	160	–131	–1,70	90.00	50.0	0.8664
Solid fiberboard	$10^{5.85}$	182	–115	–9,16	41.50	33.5	0.6848
Laminate Kronospan 31’	$10^{-1.35}$	651	232	6,23	35.75	32.0	0.4376
Laminate Kronostar 31’	10^{-2}	552	299	7,17	39.30	32.3	0.6797
Laminate Tarkett 32’	$10^{-4.38}$	451	404	6,90	45.80	41.0	0.1924
MDF (Kostroma)	$10^{5.7}$	280	–478	–21,20	44.40	35.4	0.5413

Methods for amendments calculation

In the process of operation, building materials operate in a constant temperature mode. Therefore, there is a need to study the effect of temperature and humidity fluctuations in real operating conditions on the durability of the material.

Examples of experimental results in the lgτ – σ coordinates are presented in Fig. 4 [16–18]. It can be seen from them that when tested in natural conditions for wood boards and plywood, the dependences of the durability logarithm on strength are linear. The obtained lines were plotted on the graphs of the dependence of durability on voltage for constant temperatures, which are described by equations (4) – (6).

It should be noted that plywood is characterized by a complex mechanism of work. At high stresses during the destruction of plywood, the properties of the resin (binder) are decisive, and the secondary properties of wood veneer, i.e. cellulose [19, 20]. The strength dependence on the logarithm of durability obtained in natural conditions for this composite can be divided into two straight sections.

The effect of temperature changes most often leads to a significant decrease in the durability of the material. Of the materials studied, plywood [17] is less affected by temperature and humidity fluctuations.

To predict the durability in the variable temperature mode, the corrections were determined [17, 18]. They are presented in Table 7. Under the action of constant stresses, the durability of chipboards and laminate is described by equation (4). The action of alternating stresses can be taken into account using the

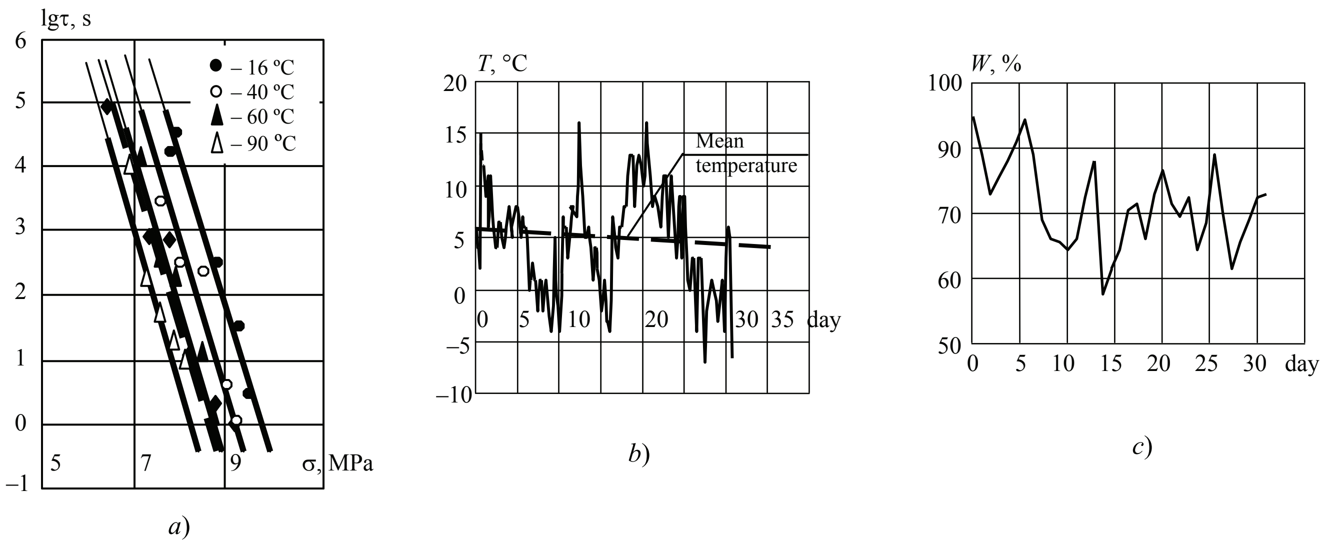


Fig. 4. The effect of climatic factors:
a – the dependence of durability on stress during transverse bending for chipboards with a density of 800 kg / m3 in the temperature range from plus 13 to minus 7 ° C (——— under constant temperature; – – – – under temperature fluctuations);
b, *c* – daily fluctuation graphsof temperature and humidity, respectively

correction (Table 8). The amendments are defined as follows. For the given stresses and temperatures, the theoretical values of durability are found by formula (4), and the experimental values are obtained from the graphs (Fig. 4). Then, for each point, the difference between the durability values is calculated ($\Delta\tau = \tau_{theor} - \tau_{exp}$). The magnitude of the correction is a functional dependence on stress [14].

The influence of aggressive media can also be taken into account using functional dependencies [21]

$$\sigma = \frac{1}{\gamma}\left(U_0 - \frac{2.3RT}{1 - T/T_m}\lg\frac{\tau}{\tau_m}\right)\frac{f(t)}{100}$$

or

$$\sigma = \frac{1}{\beta}\left(\frac{U}{2.3RT} - \lg\frac{\tau}{\tau_*}\right)\frac{f(t)}{100}.$$

The calculated values of the main operating parameters are presented in Table 9.

Table 7

Values of amendments taking into account the effect of temperature fluctuations

Type of material	Temperature range	Stress range, MPa	Amendment, $\Delta\tau_{mean}$
Wood	From +12 to –27 °C	–	$-10^{0.107\sigma - 7.41}$
Plywood FC	From +16 to –4 °C	More than 135	$-10^{0.6}$
		Less than 135	$-10^{0.1145\sigma - 12.64}$
Chipboard with a density of 800 kg/m^3	From +13 to –7 °C	–	$-10^{2.56}$
	From +5 to –25 °C		$-10^{2.58}$

Table 8

Definition of amendments for the transition from constant to variable loads

Material	Stress, MPa	Durability, lgτ: Under constant load, $\lg\tau_1$	Durability, lgτ: Under variable load, $\lg\tau_2$	$\Delta = \lg\tau_2 - \lg\tau_1$	Amendment value Δ
Solid chipboard	13.00	5.75	2.35	–3.40	0.375 σ – 8.3
	14.00	4.80	1.75	–3.05	
	15.00	3.85	1.20	–2.65	
Laminate Kronospan	30.25	2.80	2.80	0.00	0.38σ – 11.44
	29.00	3.60	3.20	–0.40	
	28.00	4.20	3.40	–0.80	
	27.00	4.80	3.70	–1.10	

Note: For laminate, the correction is valid at stresses less than 30 MPa, and for chipboard it is less than 14 MPa.

Table 9

Predicted durability of wood composites

Construction type	Load type	Material type (density, kg/m^3)	Material structure	σ, MPa	T, ºC	Predicted durablity τ, years: I	II	III	IV
1	2	3	4	5	6	7	8	9	10
Building material	Transverse bend	Chipboard (650)	*	Without load	+30 ÷ –30	–	–	50 ± 8	–
		Chipboard (700)	**					51 ± 8	48 ± 7
		Chipboard (800)	***				68 ± 12	50 ± 8	45 ± 7

Continuation of Table 9

1	2	3	4	5	6	7	8	9	10
Building material	Transverse bend	Chipboard (850)	*	Without load	+30 ÷ –30	–	50 ± 8	51 ± 8	51 ± 15
		Chipboard (850)	–				> 50	2 ± 3 mns	
		Chipboard (950)				50 ± 15	9 ± 3	39 ± 12	
	Compression	Chipboard (700)	**			> 50			
		Chipboard (800)	***			2 mns ± ± 15 days	–	–	–
		Chipboard (850)	*			> 50			
Solid flooring	Compression	Laminate	–	0,002		> 100			
Floring on lags	Transverse bend	Chipboard (650)	*	3.5	+ 20	> 50		2 days	
		Chipboard (800)	***			> 50	25 ±4	3 min	
		Chipboard (850)	*			54 ± 8	20 ± 3	20 ± 3	
		Wood	–	15		> 100	–	–	
		Laminate	–	3.5					
Formwork «Velox»	Transverse bend	Chipboard (700)	**	3.89 ÷0.17		–	–	15 ± 2	12 ± 2
		Chipboard (800)	***				45 ± 7	Destr.	103 ± 18 days
Formwork from chipboard		Chipboard (800)	***	1.36 ÷ 0.17	+30 ÷ –25	–	50 ± 8	15 ± 2	15 ± 2
		Chipboard (850)	*				48 ± 7	25 ± 3	22 ± 3
Cover panel: top siding	Transverse bend	Chipboard (850)	–	4			50 ± 8	2 ± 3 mns	–
		Chipboard (950)					9 ± 1.5	40 ± 7	
		Plywood FC				> 100	–		
Bottom siding	Transverse bend	Chipboard (850)		2,24	+ 20	–	60 ± 10	–	
		Plywood FC K				> 100			
Rib roof shields	Transverse bend	Wood		60	+35 ÷ –20	50,3	–		

Notes: * – high dispersion heterogeneous chips; ** – high fineness uniform chips; *** – homogeneous low dispersion chips; I) – without external factors; II) – under the influence of a stress concentrator (holes with a diameter of 5 mm); III) – with cyclic (20 cycles) action of water; IV) – taking into account climatic factors (variable temperatures and humidity; repeated freezing-thawing).

During operation, wood composites can work both under constant and variable loads (for example, wall panels, floors, etc.). Therefore, there was a need to study the effect of loading variability on the material durability.

For this purpose, lengthy tests were carried out on samples of wood chipboards and laminate with transverse bending (at +18 ÷ 20 °C). The initial stresses were taken, corresponding to 55–82 % of the breaking load for chipboard and 84–92 % for the laminate (initial level *1*, Fig. 5). Stress fluctuations were taken similar to the change in wind load for the city of Tambov, which was taken into account only for the northern wind directions in January and July [15].

The results obtained were plotted on the durability dependence on constant stresses ($\lg\tau - \sigma$), presented in Figs. 5 and 6. They make obvious that, at variable loads, the dependences are linear in nature, and with a decrease in stress, the decrease in durability becomes more significant [15].

For a laminate, durability lines showing variable and constant loading converge at a point corresponding to a stress of 30.25 MPa and a durability of 10.5 minutes. At higher stresses, the loading variability will not affect the durability of the composite, since the selected cycle is 20 minutes.

Chipboards are much more sensitive to load variability than laminate. Under the influence of the factor, the drop in the chipboard durability is two orders of magnitude greater than that of a laminate. This fact is associated with the structure of materials: a more homogeneous structure, due to less defectiveness, allows the laminate to better resist changes in the level of bond tension, and a lower porosity determines a lower probability of cracking per unit of the material volume.

Earlier, the influence of temperature fluctuations (positive and negative) on the chipboard durability was studied. In this case, the correction is 10 – 2.56, s [14]. From the results obtained, it can be seen that for chipboards with stresses above 12 MPa, temperature fluctuations are more dangerous than loads (at a voltage of 14 MPa $\Delta = 10^{-1.98}$, s) [15].

We use the example of a laminate to consider the correction selection method that takes into account the aging factor effects. Rectilinear dependences of the longevity (lgτ) of the Kronospan 31' laminate on stresses (σ) were constructed (Fig. 7). The comparison of dependences of lgτ – σ obtained without exposure and after aging makes it possible to find functional dependencies taking into account the factors' influence on the laminate durability:

– for UV exposure (within 200 hours)

$$\Delta = 0.025\sigma + 0.45, \quad (14)$$

– for thermal aging (within 250 hours)

$$\Delta = 0.0325\sigma - 0.205. \quad (15)$$

However, these dependencies do not take into account the duration of the aging factor. To this end, we build the dependence of changes in short-term strength on the duration of the aging factor. From Fig. 7 it can be seen that after the effects, the straight lines are almost parallel. For other wood composites (chipboard), after aging, the dependences lgτ (σ, *T*) and dilatometric curves were constructed. Their type was preserved [15]. Preservation of the form of the dependence lgτ (σ, *T*) and dilatometric curves before and after exposure to heat aging and UV exposure, suggests that there is no change in the structure of wood composites. From the equality of all temperatures, it follows that the most likely parallel

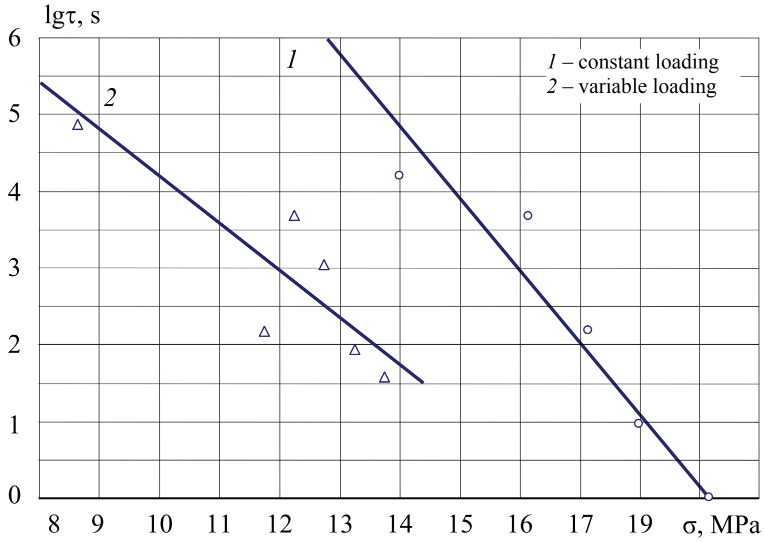


Fig. 5. **The dependence of the chipboard durability from constant and variable stresses (with a transverse bend and a temperature of 18 °C)**

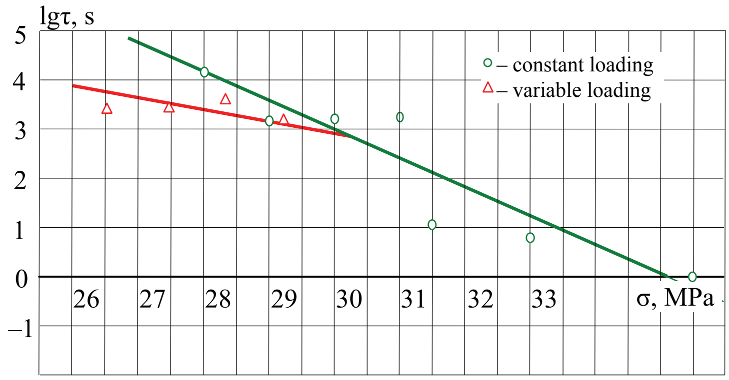


Fig. 6. The dependence of laminate durability on constant and variable stresses (with transverse bending) at a temperature of 20 °C

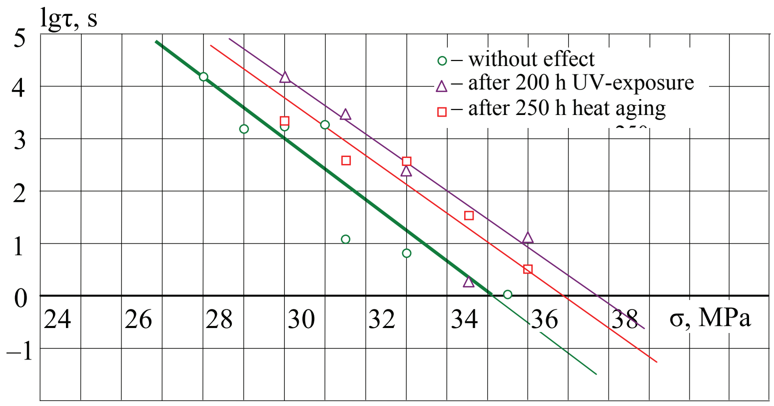


Fig. 7. The durability dependence on bending stresses for laminate Kronospan 31' after heat and photo aging

movement of the entire beam, and not just its one straight line. In this regard, the three constants U_0, τ_m and T_m retain their values, and only γ changes. Then, the change in durability is explained by the formation or destruction of bonds in the material, which will also affect the strength.

According to the thermofluctuation concept, the efficiency of the mechanical field impact on the material reflects the value γσ. Since γ is a constant for the material, at constant temperature and humidity, the durability will be proportional to the change in stresses: $\lg\tau \sim \sigma$.

The long-term strength of the material can be derived from the durability equation:

$$\sigma = \frac{1}{\gamma}\left(U_0 - \frac{2{,}3RT}{1 - T/T_m}\lg\frac{\tau}{\tau_m} \right).$$

At $\tau \to \tau_m$ (minimum durability), the strength does not depend on other constants and corresponds to the value U_0/γ. A change in the constant γ is responsible for a durability change, and this is established empirically by changing the strength of the material.

Suppose that the structural-mechanical constant does not undergo changes under the influence of heat aging and UV exposure. Then the magnitude of the durability correction can be determined by reducing the strength:

$$\Delta_i^k = \lg\tau_0 - \lg\tau_i = -\frac{\gamma}{RT}\left(1 - \frac{T}{T_m}\right)(\sigma_0 - \sigma_i),$$

where i is the factor duration, h; σ_0, σ_i – material strength (respectively, the initial and after exposure), MPa.

A slight change in constants can be taken into account using the conversion factor. Its values are determined by the ratio of durability amendments. At the same time, corrections of 200 and 250 hours were chosen as the main ones, since for these exposure durations of aging factors, the dependences $\lg\tau - \sigma$ were determined experimentally:

$$k_i^{\mathrm{UV}} = \frac{\Delta_{i\,i}^k}{\Delta_{200}^k}, \quad k_i^{\mathrm{therm}} = \frac{\Delta_i^k}{\Delta_{250}^k},$$

where i is the duration of the factor, h; Δ_i^k is constant γ correction value, s.

Then, amendments to the durability of the laminate, taking into account the duration of the factor, will take the following form:

$$\Delta_i^{\mathrm{UV}} = k_i\,(0.025\sigma + 0.45);$$

$$\Delta_i^{\mathrm{therm}} = k_i\,(0.0325\sigma - 0.205), \qquad (16)$$

where i is the duration of the factor, h; k is the conversion factor (Table 10); σ is the stress, MPa.

Table 10

Values of conversion factors for amendments

Effect type	Number of cycles	σ_0, MPa	σ_i, MPa	Constant γ correction value Δ_i^k, s	Conversion factor k_i
Thermal aging	10	35.75	37.47	1.052258	1.720000
	50		36.86	0.679073	1.110000
	100		36.73	0.599542	0.980000
	150		36.60	0.520011	0.850000
	200		36.70	0.581189	0.950000
	250		36.75	0.611778	1.000000
	300		36.13	0.232476	0.380000
UV exposure	10		35.85	0.061178	0.022472
	50		36.60	0.520011	0.191011
	100		37.80	1.254144	0.460674
	150		39.00	1.988277	0.730337
	200		40.20	2.722411	1.000000
	250		40.70	3.028299	1.112360
	300		41.15	3.303599	1.213483

In addition to durability, the remaining two parameters of the composite performance of (strength and heat resistance) can be predicted. To do this, we use diagrams (see Fig. 3) or equations for strength and heat resistance calculation, which can be derived from equations (4) – (6).

The selection of the product or design cross section is carried out in the following sequence [11, 14]:

1) the durability of the product (structure) is defined according the normative life of the product and the operating temperature (based on the technological mode or purpose of the building);

2) the stress-strain state of the material is determined;

3) the collection of loads on this design (product) is done and the maximum load arising in its cross section is calculated;

4) external influences affecting the performance of the material are established (stress concentrators, aggressive environments, climatic factors, etc.);

5) using corrections Δ, the true durability of the product or structure is determined, i.e. durability, taking into account the impact of external environment on the material;

6) the nature of the dependences of fracture (or deformation) and the equations describing them, as well as the constants included in these equations, are determined;

7) according to equations (4) – (6), the value of the long-term strength of the material is calculated. Its value can also be determined from the diagrams (see Fig. 3);

8) further calculation (selection of the cross section of the product or structural element) is performed according to the first group of limit states, by combining the method of limit states and the thermofluctuation concept. We combine both methods, replacing the temporary resistance with the value of long-term strength;

9) knowing the value of W, the necessary parameter is determined (for example, the thickness of the product), while the remaining two parameters of the product are set: width and length.

What is the essence of the limit state method? The stresses arising in the elements under the action of design forces should not exceed the design resistance of materials $\sigma = \frac{N}{F}\left(\frac{M}{W}\right) \le R$. In order to save materials, one should strive to bring them closer to the calculated resistance, i.e. σ = R [21].

When calculating by the second limit state, the following condition must be satisfied – deformations or displacements determined from standard loads (since design loads are rare and the risk of structural failure due to deformations exceeding their limit values is small) under the assumption of elastic work material, should not exceed the deformations established by the norms: $f = k\frac{q_n l^4}{EI} \le [f]$, where k is a coefficient depending on the type of structure, q_n is the standard load, l is the span, E is the elastic modulus, I is the moment of inertia [21].

The data obtained make it possible to predict the durability of building materials not only in a wide range of positive temperatures, but also after exposure to various external factors.

Here are examples of using the methodology for calculating building structures.

Calculation of dome elements

As an example, we consider the calculation of the edges of the roofing shields of the dome (Fig. 8) [22, 23]. We design them triangular with sides equal to half the length of the glued rods of the dome equal to 4.9 m.

They are set by durability (100 years, logτ = 9.5) and maximum temperatures for the summer (T = 35 °C) and winter (T = –20 °C). The stresses at which failure will occur under these conditions are determined by the equation:

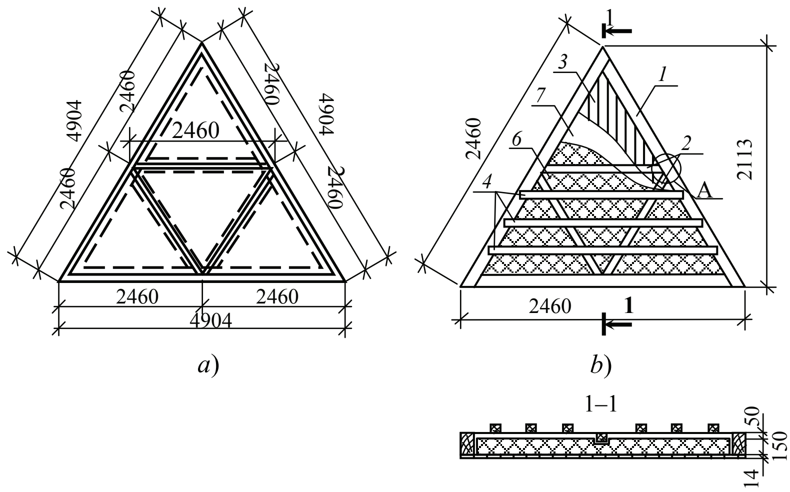
$$\sigma_{\text{long 1}} = \frac{1}{\gamma^*}\left(U_0^* - \frac{RT}{\frac{T_m^*}{T} - 1}\lg\frac{\tau}{\tau_m^*} \right) =$$

$$\frac{1}{-1{,}7}\left(-131 - \frac{4.6\cdot 4.2\cdot 0.308}{\frac{0.160}{0.308} - 1}\lg\frac{10^{9.5}}{10^7} \right) = 58.8 \text{ MPa},$$

$$\sigma_{\text{long 2}} = \frac{1}{-1.7}\left(-131 - \frac{4.6\cdot 4.2\cdot 0.253}{\frac{0.160}{0.253} - 1}\lg\frac{10^{9.5}}{10^7} \right) = 57.5 \text{ MPa},$$

then σ_{long} = 58.2 MPa.

Since stresses make up only 50 % of the destructive stress, the limit of long-term resistance has been successively achieved and durability is significantly increased (a bend appears on the line in the coordinates lgτ – σ).



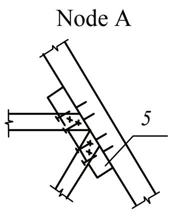


Fig. 8. The geometric diagram of the panels (*a*) and pre-nail nail roofing shield (*b*):
1 – contour ribs 50×150 mm; *2* – stiffeners 50×60 mm; *3* – lower skin (boards 14×70 mm); *4* – flooring 32×150 mm; *5* – pressure bars 60×60 mm; *6* – insulation from mineral wool plates; *7* – vapor barrier (roofing)

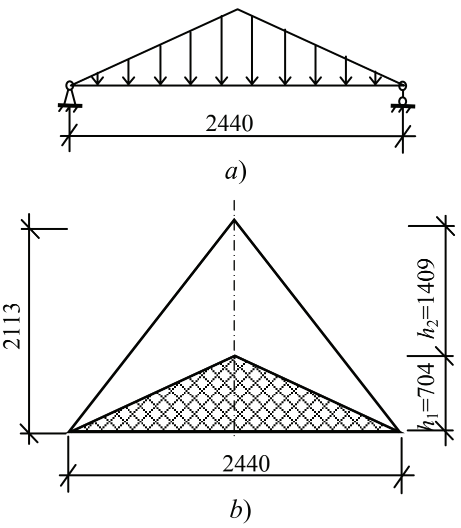


Fig. 9. Estimated rib design (*a*) and estimated area (*b*)

The load [21] acting on the edges of the flooring is approximately considered distributed according to the triangle law (Fig. 9). It is equal to $q_c^r = q_c h_1 = = 2.9257 \cdot 0.704 = 2.856$ kN/m, then the bending moment will be equal $M = q_c^r \ l^2 / 12 = = \dfrac{2.856 \cdot 2.44^2}{12} = 1.417$ kN/m.

The height of the ribs cross section is determined if their width is 50 mm $\sigma = M/W = 6M / bh^2 \le \sigma_{\text{long}}$, then $h = \sqrt{\dfrac{6 \cdot 1.417}{58.2 \cdot 10^3 \cdot 0.05}} = 0.054$ m. Accepted rib thickness 60 mm.

Then we carry out a check of the rigidity of the ribs of the flooring shields

$$\frac{f}{l} = \frac{1}{120}\frac{q_n^r \ l^3}{EI} = \frac{1}{120} \cdot \frac{1.91 \cdot 10^{-3} \cdot 2.44^3 \cdot 12}{10^4 \cdot 0.05 \cdot 0.06^3} =$$

$$= 0.026 > [f/l] = 1/200 = 0.005,$$

where $q_n^r = q_n \ h_1 = 2.0062 \cdot 0.704 = 1.91$ kN/m, Cross section of ribs increases to 100×60 mm, then $f/l = 0.0042 < [f/l] = 0.005$.

Based on the above examples, depending on various operating conditions, the potential service life (durability) of wood composites was determined (see Table 9).

An example of calculating the partition

As in the case of the coating panel, in the design of the partition there is no need for joining the individual laminate strips [15]. The connection of the lining of the laminated panels with a wooden frame can be carried out on an adhesive basis or with screws. Then, having decided on the dimensions of the partition (taking into account the size of the room), you need to choose the pitch of the frame ribs and the thickness of the laminate sheathing. We take the step of the wooden blocks in multiples of the 0.30 m module: let $b = 0.6$ m, which is also recommended in [24]. We collect the load on the partition. To do this, let us select a horizontal strip of 1 m wide.

The load from the dead weight of the panel sheathing:

$$q = \rho \, V / l = \rho \, h \, \delta \, l / l = \rho \, h \, \delta,$$

where ρ is the density of the laminate, kg/m^3; V is the volume of the casing enclosed between two edges of the frame, m^3; l is the distance between two edges of the frame, m; δ is the thickness of the laminate lining, m; h – height of the partition (sheathing), m.

We take the height of the room (partition) 2.8 m, then $q = 700 \cdot 2.8 \cdot 0.008 = 15.68$ kg/m (0.1568 kN/m).

Load from dead weight in one span equals to: $Q = q \cdot l = 0.1568 \cdot 0.6 = 0.09408$ kN.

Table 11

Local loads on the partition

Load	Standard value	Reliability factor for load	Rated load value
Horizontal evenly distributed along the length of the panel (from equipment, furniture, etc.)	0.50 kN/m		0.60 kN/m
The same concentrated	0.50 kN	1.2	0.60 kN
Vertical concentrated from hanging objects, acting in the plane of the panel sheathing	0.20 kN		0.24 kN
Concentrated moment load from vertically acting force	0.25 kN·m		0.30 kN·m

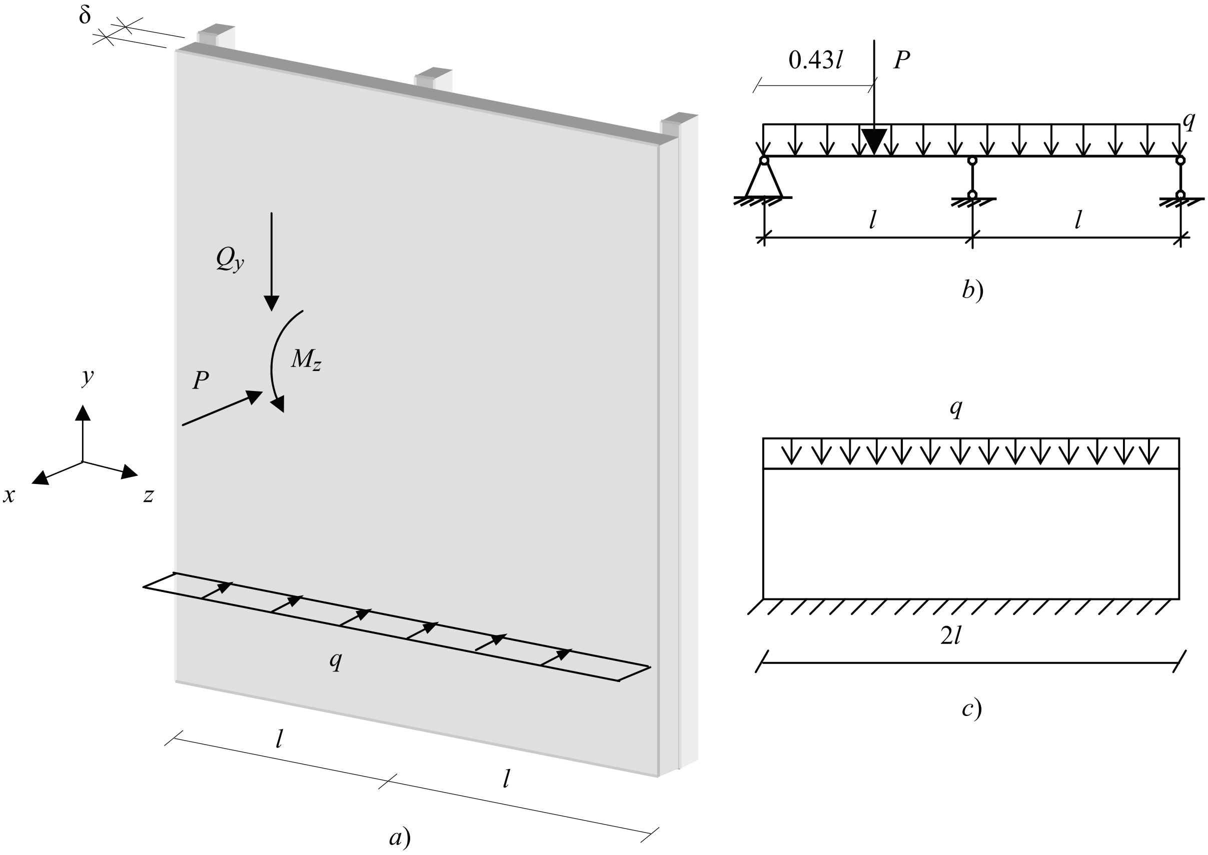


Fig. 10. The design scheme of the sheathing of the partition:
a – general view of the partition design; *b* – in the horizontal plane; *c* – in a vertical plane

The stress state of the partition (Fig. 10) will develop under the influence of constant vertical loads (from the dead weight of the structure and from hanging objects) and temporary horizontal (from equipment, furniture, etc.):

$$\sigma = \sqrt{\sigma_x^{\,2} + \sigma_y^{\,2}},$$

where $\sigma_x = M_x / W_x$ are horizontal stresses; $M_x = 0.07 q\, l^2 + 0.21\, P\, l$ is the moment of external forces in a horizontal plane, kN·m; $W_x = b\,\delta^2/6$ is sheathing resistance moment, m^3; b is conditionally allocated strip 1 m wide; δ – thickness of the laminate sheathing, m; $\sigma_y = Q_y/(\varphi\, A) + M_z/W_z$ are vertical stresses; q is horizontal evenly distributed load, kN/m; l is the span (in our case, the distance between the edges of the frame), m; P – horizontal concentrated load, kN; Q_y – total vertical load from the dead weight of the structure and hanging objects, kN; $A = l\,\delta$ is cross-sectional area of the panel skin, m^2; φ is the coefficient of longitudinal bending; M_z is the moment from the hung objects, kN·m; $W_z = l\,\delta^2/6$ is partition sheathing resistance moment, m^3.

We will take the skin thickness of 8 mm. From the value of the loads acting on the sheathing of the partition, we determine the stresses acting in it:

$$M_x = 0.07 \cdot 0.6 \cdot 0.6^2 + 0.21 \cdot 0.6 \cdot 0.6 =$$
$$= 0.01512 + 0.0756 = 0.09072 \text{ kN·m};$$

$$\sigma_x = \frac{6 \cdot 0.09072}{1 \cdot 0.008^2} = 8505 \text{ kPa};$$

$$\sigma_y = \frac{Q_y}{\varphi\, l\, \delta} + \frac{6\, M_z}{l\, \delta^2} = \frac{0.24 + 0.09408}{0.6 \cdot 0.008} + \frac{6 \cdot 0.3}{0.6 \cdot 0.008^2} =$$
$$= 69.6 + 46875 = 46945 \text{ kPa};$$

$$\sigma = \sqrt{8505^2 + 46945^2} = \sqrt{72\,335\,025 + 2\,203\,833\,025} =$$
$$= 47\ 709 \text{ kPa}.$$

The resulting stress exceeds the short-term strength of the Kronospan 31 ’laminate.

We increase the sheathing thickness to 12 mm:

$$Q = \rho\, V = \rho\, h\, \delta\, l = 700 \cdot 2.8 \cdot 0.012 \cdot 0.6 =$$
$$=14.112 \text{ kg } (0.14112 \text{ kN});$$

$$\sigma_x = \frac{6 \cdot 0.09072}{1 \cdot 0.012^2} = 3780 \text{ kPa};$$

$$\sigma_y = \frac{Q_y}{\varphi\, l\, \delta} + \frac{6\, M_z}{l\, \delta^2} = \frac{0.24 + 0.14112}{0.6 \cdot 0.012} + \frac{6 \cdot 0.3}{0.6 \cdot 0.012^2} =$$
$$= 52.93 + 20\,833 = 20\,886 \text{ kPa};$$

$$\sigma = \sqrt{3780^2 + 20886^2} = \sqrt{14\ 288\ 400 + 436\ 224\ 996} =$$
$$= 21\ 225 \text{ kPa}.$$

At an average indoor temperature + 20 °C and stress of 21.2 MPa, we determine the theoretical longevity of the partition according to the diagram [17] logτ = 8.447, which is about 8.87 years. Replacing the partition every 9 years is obviously impractical; therefore, the estimated term of its operation should be at least 50 years.

Let us increase the sheathing thickness to 16 mm:

$$Q = \rho\, V = \rho\, h\, \delta\, l = 700 \cdot 2.8 \cdot 0.016 \cdot 0.6 =$$
$$=18.816 \text{ kg } (0.18816 \text{ kN});$$

$$\sigma_x = \frac{6 \cdot 0.09072}{1 \cdot 0.016^2} = 2126 \text{ kPa};$$

$$\sigma_y = \frac{Q_y}{\varphi\, l\, \delta} + \frac{6\, M_z}{l\, \delta^2} = \frac{0.24 + 0.18816}{0.6 \cdot 0.016} + \frac{6 \cdot 0.3}{0.6 \cdot 0.016^2} =$$
$$= 44.6 + 11718.75 = 11\,763 \text{ kPa};$$

$$\sigma = \sqrt{2126^2 + 11763^2} = \sqrt{4\ 519\ 876 + 138\ 368\ 169} =$$
$$=11\ 954 \text{ kPa}.$$

According to the diagram, we determine that the theoretical partition service life is logτ = 14.119, i.e. more than 100 years. Taking into account the introduced amendments from the action of environmental factors, the real life of the sheathing:

$$\lg \tau_{\text{exp}} = \lg \tau_{\text{theor}} + \Sigma_i\ \Delta^i,$$

where Δ – corrections to durability taking into account the action of environmental factors.

The probability of water entering the thickness of the sheathing of the partition is negligible. This can happen in an emergency, for example when soaking from a room located on the floor above. Consider the effect of water for 7 hours: $\Delta^{\text{water}} = 0.214\,\sigma - 8.089 = = 0.214 \cdot 11.954 - 8.089 = -5.532$ (determined by interpolation);

Since the partition is indoors, and it will possibly be located opposite the window on the sunny side of the building, we take into account the effect of ultraviolet radiation:

$$\Delta^{\text{UV}} = 0.4607(0.025\sigma + 0.45) =$$
$$= 0.4607(0.025 \cdot 11.954 + 0.45) = 0.345$$

– correction from the impact of ultraviolet radiation for 100 hours;

$$\Delta^{\text{therm}} = 1.11(0.325\sigma - 0.205) =$$
$$= 1.11(0.325 \cdot 11.954 - 0.205) = 0.408$$

– correction from the impact of ultraviolet radiation for 100 hours.

Then the operational life of the laminate is:

$$\lg \tau_{\text{exp}} = 14.119 - 5.532 + 0.345 + 0.408 = 9.34$$

which corresponds to 69.42 years.

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