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PHYSICO-MATHEMATICAL MODEL OF WOOD DURABILITY UNDER CYCLIC ENVIRONMENTAL CHANGES IN TEMPERATURE AND HUMIDITY

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Abstract
Introduction. A significant drawback of composite materials is their tendency to degrade over time, eventually leading to complete failure. **Purpose of the study.** The objective of this research is to identify the physical principles and develop a theoretical framework to explain this degradation. Wood, as a natural composite, serves as a convenient object for such investigations. Many physical and theoretical aspects of its behavior remain insufficiently understood. In particular, the reduction in mechanical strength at the junctions (with nagels) of wooden components under cyclic variations in temperature and humidity requires further exploration. **Methods.** This paper presents a physico-mathematical model for assessing the mechanical strength of wood under such environmental influences. The model is based on the Arrhenius equation and current understanding of wood's cellular structure, whose key components are cellulose filaments (serving as the reinforcing framework) and lignin (the binding matrix). The model assumes that non-steady processes of heat and moisture transfer within the wood, driven by environmental conditions, gradually break the interatomic bonds within lignin compounds. **Results.** The study derives expressions to estimate the maximum number of wetting-drying cycles that wood can withstand, considering the material's temperature. It also provides an evaluation of its service life (resource) affected by these cyclic influences. The proposed theory is of universal relevance.

Keywords: composite; heat and moisture transfer; Arrhenius equation; cellular structure of wood; mathematical model; resource.

The paper is dedicated to the memory of the world-renowned scientist Svante August Arrhenius (1859–1927). In 2024, we commemorated the 165th anniversary of his birth.

Introduction

The aim of this work is to develop a physical and mathematical model for predicting the durability (resource) of wood under cyclic changes in environmental temperature and humidity. This model is essential for estimating the service life of wooden structures during their design and operation. In this context, wood is considered a natural composite material, many physical and theoretical aspects of which remain insufficiently explored.

Materials and Methods

Composite materials, both artificial and natural, have gained widespread use in the modern world due to their advantageous properties. However, a significant drawback of these materials is their tendency to lose mechanical strength over time, potentially leading to complete failure. Therefore, one of the current challenges in material science is to establish the physical basis and develop a theory to explain the gradual reduction in mechanical strength of such materials.

A key characteristic of most composite materials is the presence of at least two essential components: a binder (matrix) and a filler (reinforcement). Typically, the binder is the weakest component and is most susceptible to degradation. This degradation occurs due to the breaking of interatomic bonds within the compounds that form the binder, eventually resulting in the loss of the material's structural integrity. This phenomenon is particularly evident in wood, which

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has been the subject of extensive research by the authors.

Wood was chosen for this study due to its high demand and the fact that, as a natural composite, it provides a convenient model for identifying general degradation patterns and evaluating durability.

Wooden structures are extensively used in construction, although their application extends beyond this field. They are also found in shipbuilding, transportation devices, railways, electrical and power installations (e.g., wooden electrolysis baths, power line poles, substations), lifting mechanisms, and various industrial facilities. In most of these applications, wooden structural elements are joined using special metal fasteners known as dowels or dowel connections (Fig. 1) (Bazhenov, 1959; Mironov et al., 2000; Ugolev, 2005; USSR State Committee for Standards, 1985).

In recent years, a new type of dowel connection using metal toothed plates has become increasingly common due to its manufacturability, simplicity, strength, reliability, and durability (Fig. 1c).

The disadvantage of dowel joints is that, over time, these connections deteriorate — primarily due to the degradation of the wood. This degradation is driven by complex heat and mass (moisture) transfer processes occurring under cyclic environmental conditions, especially fluctuating temperature and humidity, combined with the constant stress-strain state of the material.

Wood typically consists of approximately 45–60 % cellulose, 15–35 % lignin, 15–25 % hemicellulose, and various extractives (Fig. 2) (Bazhenov, 1959; Ugolev, 2005).

Cellulose is a linear polysaccharide polymer and is the primary component that provides wood with elasticity and mechanical strength (Fig. 2) (Mironov et al., 2000; USSR State Committee for Standards, 1985). It is a highly resistant white substance, insoluble in water and common organic solvents (e.g., alcohol, ether, acetone). Bundles of cellulose macromolecules, known as microfibrils, form the cellulose framework of the cell wall and serve as reinforcement.

Hemicellulose, which is structurally similar to cellulose, acts as a reinforcement enhancer.

Lignin is an aromatic (polyphenolic) polymer with a complex structure, containing more carbon and less oxygen than cellulose. It is chemically unstable, easily oxidized, and reacts with chlorine. It dissolves when heated in alkalis or aqueous solutions of sulfurous acid and its salts (Demitrova and Chemodanov, 2016; Mironov et al., 2000). Lignin functions as a binder.

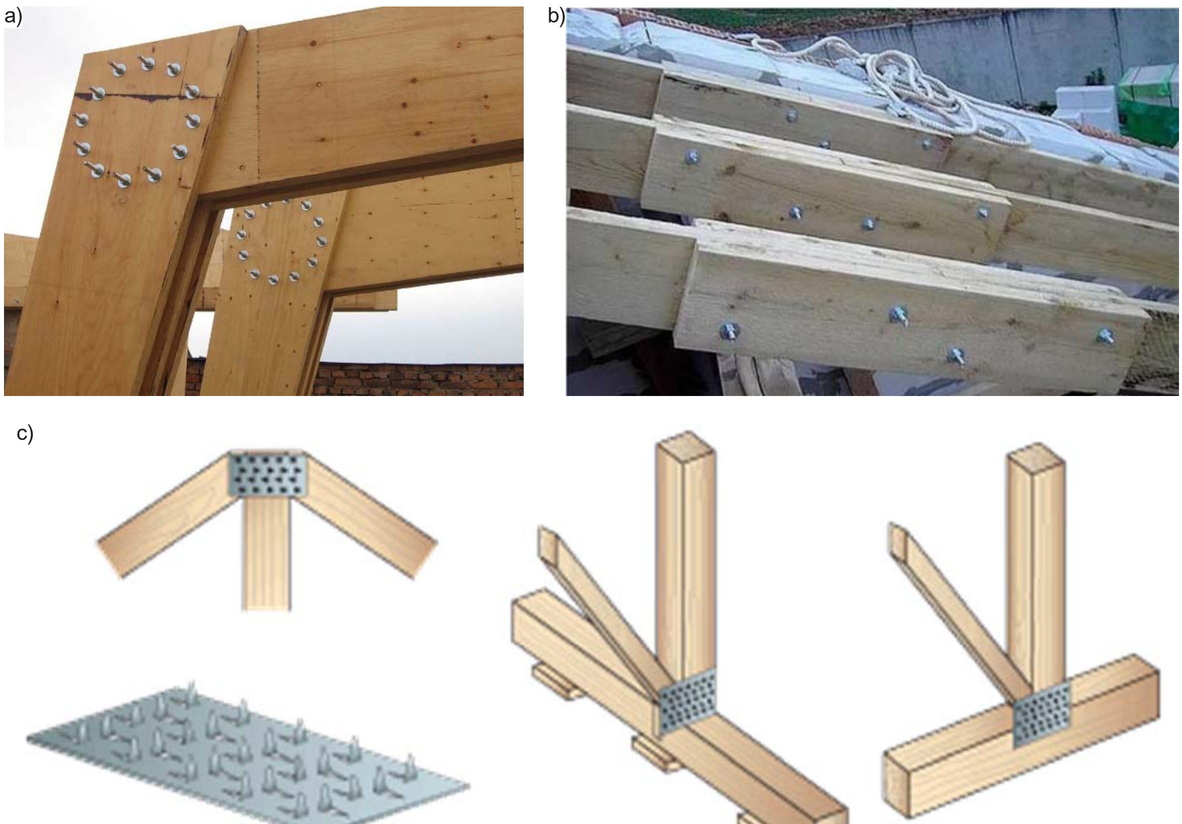

Fig.1. Examples of dowel joints: bolted (a, b) and with metal toothed plates (c); (https://maxshops.ru/wp-content/uploads/f/a/9/fa9960e35d70c139fcf63a9b261a892f.jpeg; https://kak-sdelano.ru/assets/uploads/2016/06/odnoskatnaja-krisha-26.jpg)

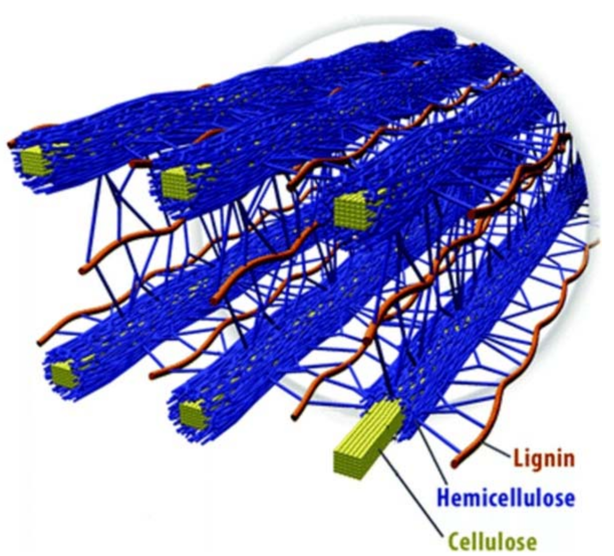

Fig. 2. Structure of wood cell walls: https://sun9-45.userapi.com/impf/04602ID4Wjx_xYvWMyxhDLm_RFVV74Arytebmw/EdDc-je9-Zh0.jpg?size=604x548&quality=96&sign=23a84978b2b1b-8275d4c3d11d3f529af&type=album

The operation of dowel joints involves complex heat and moisture transfer processes, including phase transitions (“ice–water–steam”), often under harsh conditions. These processes are influenced by environmental variations in temperature and humidity over daily and seasonal cycles. Extensive experience with wooden structures has shown that these processes adversely affect both the reliability of dowel joints and the overall structural integrity (Erofeev et al., 2008; Fedosov and Kotlov, 2014; Fedosov et al., 2015, 2017a). It is also important to consider that wood can be destroyed by biological factors such as bacterial and fungal decay, and by corrosion of the metal components (Erofeev et al., 2008; Ugolev, 2005; USSR State Committee for Standards, 1985). However, with proper maintenance, the impact of these factors can be minimized.

The mathematical models of heat and moisture transfer proposed in earlier studies (Fedosov and Kotlov, 2014, 2019; Fedosov et al., 2015, 2016c, 2017a) allow for a detailed analysis of the cyclic wetting and drying of wood in dowel joints under fluctuating temperatures. However, these models alone do not yet provide a definitive answer regarding the condition and resource (service life) of wood in dowel connections. Addressing this gap requires the development of a methodology for estimating the material’s remaining resource.

This methodology should be grounded in established knowledge about wood’s internal structure and the role of its organic components in providing mechanical strength (Fig. 2). From this perspective, cellulose and lignin are the most critical compounds. Cellulose fibers form a spatial framework that perceives loads, while lignin acts as a binder that holds the cellulose structure together. These two components are primarily responsible for the material’s mechanical properties (Bazhenov, 1959; Borovikov and Ugolev, 1989; Demitrova and Chemodanov, 2016; Grunin et al., 2017; Ugolev, 2005; USSR State Committee for Standards, 1985; Vanin, 1949.

Lignin is particularly prone to decomposition when exposed to external factors such as elevated temperatures and moisture, which can ultimately lead to failure of the dowel connection. It is reasonable to assume that the degradation of lignin results from the breaking of atomic bonds within its molecular structure, i.e., it is a physicochemical process. To account for the influence of temperature on the breakdown of lignin molecules, it is convenient to use the Arrhenius equation. This fundamental law is applicable to both the formation and destruction of chemical bonds under the influence of physical factors (Fedosov et al., 2016a; Knunyants, 1988).

Theory

Based on the above (Section 1.2), it can be assumed that the mechanical strength of wood is proportional to the number of lignin chemical bonds N remaining intact during their gradual degradation under the influence of the aforementioned factors. Therefore, the following relation can be written:

$$R = R_0 \frac{N}{N_0}, \tag{1}$$

where R_0 and $R \le R_0$ are the initial and current values of the mechanical strength of wood, respectively; N_0 is the initial number of chemical bonds; N is the current number of chemical bonds.

The number of destroyed chemical bonds can be determined as the product of the number of wetting and drying cycles n_c and the number of bonds destroyed per cycle N_{Dc}:

$$N_D = n_c N_{Dc} = N_0 - N. \tag{2}$$

To determine N, it is advisable to use the Arrhenius law, which describes the rate constant of chemical transformations (Knunyants, 1988):

$$K = A \cdot \exp\left(-\frac{E}{kT}\right), \tag{3}$$

where K is the rate constant of the chemical reaction, 1/s; A is a constant coefficient (number of chemical interactions per unit time), 1/ s; E is the activation energy of the reaction, J; T is the absolute temperature, K; k = 1.38·10^{-23} J /K, the Boltzmann constant.

Given the rate constant K, the reaction rate over time, in units of 1 /(s·m^3), can be determined as follows (Fedosov et al., 2016a; Knunyants, 1988):

$$\frac{dN}{dt} = -K \cdot N = -A \cdot N \cdot \exp\left(-\frac{E}{k \cdot T}\right), \tag{4}$$

where N is the current number of chemical bonds, 1/m^3, remaining intact at an arbitrary time t (assuming a first-order reaction).

The solution of Eq. (4) can be obtained by separating the variables and integrating both sides over the time interval of the first cycle of wetting and drying of the wood in the dowel joint:

$$\int_{N_0}^{N_1} \frac{dN}{N} = -A \cdot \int_{t_0=0}^{t_1} \exp\left(-\frac{E}{k \cdot T_1}\right) dt. \quad (5)$$

This yields an expression for determining the number of remaining chemical bonds $N_1 \leq N_0$ at time t_1, marking the end of the first cycle of wetting and drying:

$$N_1 = N_0 \cdot e^{-\Delta t_1 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_1}\right)}, \quad (6)$$

where N_0 corresponds to the initial time $t_0 = 0$; T_1 is the temperature during this cycle; and $\Delta t_1 = t_1 - t_0$ is the duration of the cycle.

For the second cycle of wetting and drying of wood, expression (5) can be written as follows

$$\int_{N_1}^{N_2} \frac{dN}{N} = -A \cdot \int_{t_1}^{t_2} \exp\left(-\frac{E}{k \cdot T_2}\right) dt, \quad (7)$$

where $N_2 \leq N_1$ is the number of chemical bonds remaining in operation at time $t_2 \geq t_1$, marking the end of the second cycle; T_2 is the temperature at which this cycle occurred.

By analogy with (6), and taking into account (7), we can write:

$$N_2 = N_1 \cdot e^{-\Delta t_2 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_2}\right)} = N_0 \cdot e^{-\Delta t_1 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_1}\right)} \cdot e^{-\Delta t_2 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_2}\right)}, \quad (8)$$

where $\Delta t_2 = t_2 - t_1$ is the duration of the second cycle.

If we repeat the calculations from (5) to (8), then to determine the number of chemical bonds remaining in operation at time $t_3 \geq t_2$, marking the end of the third cycle of wetting and drying, we can write the following formula:

$$N_3 = N_2 \cdot e^{-\Delta t_3 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_3}\right)} = N_0 \cdot e^{-\Delta t_1 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_1}\right)} \cdot e^{-\Delta t_2 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_2}\right)} \times e^{-\Delta t_3 \cdot A \cdot \exp\left(-\frac{E}{k \cdot T_3}\right)}, \quad (9)$$

where $\Delta t_3 = t_3 - t_2$ is the duration of the third cycle; T_3 is the temperature at which this cycle took place.

Expression (9) can be written in a more compact form:

$$N_3 = N_0 \cdot e^{-A \cdot \sum_{i=1}^{i=3} \Delta t_i \cdot \exp\left(-\frac{E}{k \cdot T_i}\right)}. \quad (10)$$

By extending the above reasoning, it is straightforward to derive a formula similar to (10) for determining the number of chemical bonds remaining in operation after an arbitrary number of n_c successive cycles of wetting and drying of the wood in dowel joints:

$$N = N_0 \cdot e^{-A \cdot \sum_{i=1}^{n_c} \Delta t_i \cdot \exp\left(-\frac{E}{k \cdot T_i}\right)}, \quad (11)$$

where Δt_i is the duration of the i-th cycle, and T_i is the temperature at which this cycle occurred.

By substituting (11) to (1), we obtain the formula for determining the current value of the mechanical strength of wood:

$$R = R_0 \cdot e^{-A \cdot \sum_{i=1}^{n_c} \Delta t_i \cdot \exp\left(-\frac{E}{k \cdot T_i}\right)}. \quad (12)$$

Analysis of the obtained expression (12) leads to the conclusion that the mechanical strength of wood is influenced by three major operational factors: the number of wetting and drying cycles, the duration of these cycles, and the temperature. Moreover, an increase in any of these parameters results in a decrease in mechanical strength.

Expression (12) is significantly simplified if the successive wetting and drying processes have the same duration $\Delta t_i = \Delta t$ = const, and occur at the same temperature $T_i = T$ = const. In this case, the summation in the formula can be replaced by multiplication:

$$R = R_0 \cdot e^{-A \cdot n_c \cdot \Delta t \cdot \exp\left(-\frac{E}{k \cdot T}\right)}. \quad (13)$$

The resulting expression (13) allows us to determine the limit number of wetting and drying cycles. As known, the ratio of the strength limit to the allowable stress is called the safety factor (Fridman, 2007; Ministry of Construction, Housing and Utilities of the Russian Federation, 2017):

$$K_S = \frac{R_0}{R_D}. \quad (14)$$

The safety factor for wood is set higher than for other materials (e.g., metals). Depending on the nature of the applied force, safety factors can vary considerably: from K_S = 3÷5 for compression and shear, to K_S = 8÷10 for tension along the fibers (Fridman, 2007; Ministry of Construction, Housing and Utilities of the Russian Federation, 2017; Konev, 2024). Based on Eq. (14), it is possible to determine the permissible level of mechanical impact on wood:

$$R_D = \frac{R_0}{K_S}. \quad (15)$$

The practical significance of this parameter lies in the fact that during the operation of the nagel connection, the mechanical strength of the wood decreases over time due to the cyclic processes of wetting and drying, until it reaches the maximum permissible value. At that point, the destruction of the wood — i.e. the failure of the dowel connection —

occurs. The number of wetting and drying cycles that precede this failure should also be considered the limit value of this parameter, and its knowledge is of practical importance.

It is quite clear that if we set $R = R_D$ in the left-hand side of Eq. (13), we must assume that the number of cycles on the right-hand side corresponds to the limit value: $n_c = n_d$.

Then this equation, taking into account Eq. (15), can be written in the following form:

$$\frac{1}{K_S} = e^{-A \cdot n_d \cdot \Delta t \cdot \exp\left(-\frac{E}{k \cdot T}\right)}. \quad (16)$$

As a result of solving this equation with respect to n_d , the following expression is obtained to determine the limit number of wetting and drying cycles for the wood of the dowel joint:

$$n_d = \frac{\ln K_S}{A \cdot \Delta t} \exp\left(\frac{E}{k \cdot T}\right). \quad (17)$$

Analysis of expression (17) shows that an increase in the duration of the wetting and drying cycles, as well as in temperature, leads to a decrease in the permissible number of such cycles — i.e., a reduction in the service life of the nagel. However, by increasing the safety factor, this service life can be extended.

To use Eqs. (12), (13) and (17), it is necessary to know two constants included in them — *A* and *E*. However, currently there is no available information about these parameters, and their values can only be estimated through experiments. Furthermore, these equations allow for the determination of the limit number of wetting and drying cycles only at a constant temperature. At the same time, it is well known that the temperature conditions during the operation of nagel can vary significantly, even within a single cycle of wood wetting and drying (Fedosov and Kotlov, 2019; Fedosov et al., 2015, 2016c).

To obtain an expression that allows the determination of the limit number of wetting and drying cycles for the wood of the dowel joint in the general case, it is necessary to refer again to expression (12). Using expression (15) and the specified expression by analogy with (16), we can write the following:

$$\frac{1}{K_S} = e^{-A \cdot \sum_{i=1}^{n_d} \Delta t_i \cdot \exp\left(-\frac{E}{k \cdot T_i}\right)}, \quad (18)$$

or, in a more convenient form:

$$\ln K_S = A \cdot \sum_{i=1}^{n_d} \Delta t_i \cdot \exp\left(-\frac{E}{k \cdot T_i}\right). \quad (19)$$

From the analysis of expression (19), it is clear that in this case it is impossible to express n_d explicitly, and the equation can only be solved for n_d through iterative calculations.

Despite the lack of information about the values of the constant parameters included in formulas (17) and (19) — which, as noted earlier, can only be determined experimentally — expression (17) can still be used for some quantitative estimates. To do this, it is necessary to adopt some standard conditions as a baseline, such as temperature *T* = 293 K (20 °C), which is often used for reference, and Δ*t* = 24 h. Under these conditions, expression (17) takes the following form:

$$n_d^b = \frac{\ln K_S}{A \cdot 24} \exp\left(\frac{E}{k \cdot 293}\right). \quad (20)$$

By dividing the left and right sides of formula (17) by the corresponding sides of formula (20), an expression can be obtained for determining the limit number of cycles in relative terms with respect to the baseline conditions:

$$n_d^* = \frac{n_d}{n_d^b} = \frac{24}{\Delta t} \exp\left[\frac{E}{k}\left(\frac{1}{T} - \frac{1}{293}\right)\right]. \quad (21)$$

The resulting expression (21) eliminates the unknown parameter *A* and allows for the assessment of the influence of two key factors — ambient temperature *T* and cycle duration Δ*t* — on the permissible number of wetting and drying cycles. The only limitation of this formula is the lack of information regarding the value of the chemical bond energy *E*. However, for preliminary estimates, existing data on this parameter for compounds found in lignin can be used. According to some sources (Demitrova and Chemodanov, 2016; Grunin et al., 2017; Knunyants, 1988; Ministry of Construction, Housing and Utilities of the Russian Federation, 2017; Vanin, 1949; Volkov and Zharsky, 2005), the value of this parameter varies widely: *E* = 0.2÷10 eV ($0.32 \cdot 10^{-19} \div 10^{-18}$ J). It can be reasonably assumed that, under the relatively weak effects being considered, the chemical bonds most likely to break are those with energies near the lower end of this range. Therefore, for the purposes of calculation, it is advisable to use a conservative estimate: $E = 0.5 \cdot 10^{-19}$ J.

Calculation

Fig. 3 shows the dependence of the relative value of the limit number of wetting and drying cycles, obtained using formula (21), which highlights the significant influence of both Δ*t* and especially *T*. For example, calculations show that at Δ*t* = 20 hours, a decrease in ambient temperature from 60 °C to 10 °C leads to a 6.9-fold increase in n_d.

Undoubtedly, the parameter n_d is of great practical importance. However, a more convenient indicator is the service life of wooden elements, t_r. It can be assumed that this consists of two main components: the service time due to cyclic changes in temperature and humidity conditions, t_c, and the operating time under stationary conditions — i.e., when the influence

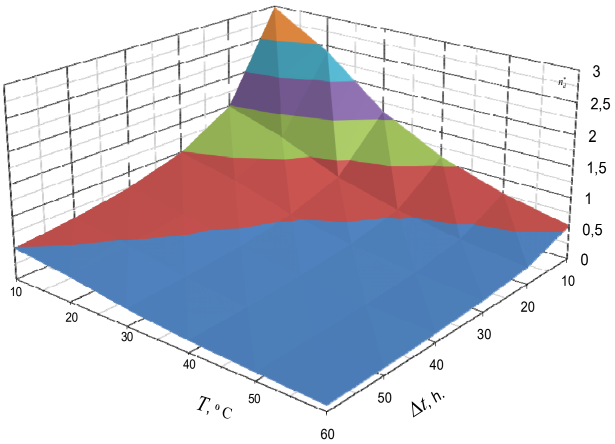

Fig. 3. Dependence of the relative value of the allowable number of wetting and drying cycles (from formula 21) on the duration of such cycles and ambient temperature

of non-stationary heat and moisture transfer in wood can be neglected — denoted as t_{st}:

$$t_r = t_{st} + t_c. \tag{22}$$

As for the parameter t_{st}, its reliable assessment is currently complicated since it requires taking into account the influence of various factors, including biological ones (e.g., rotting and fungal exposure) (Borovikov and Ugolev, 1989; Erofeev et al., 2008; Ugolev, 2005; Vanin, 1949). To determine the second component, t_c, the theoretical developments presented above can be used. Indeed, if the limit number of wetting and drying cycles is known for a given cycle duration Δt, then the desired value can be found as follows:

$$t_c = n_d \Delta t = \frac{\ln K_S}{A} \exp\left(\frac{E}{k \cdot T}\right). \tag{23}$$

The ratio in Eq. (23) allows us to conclude that the portion of the service life determined by cyclically varying temperature and humidity operating conditions depends only on two factors: the safety factor of mechanical strength margin K_S and the ambient temperature T.

To analyze the influence of these factors, it is advisable to use the approach described above — deriving an expression in relative terms. If we take the baseline conditions as $K_S = 3$ and $T = 293$ K, then expression (23) will take the following form:

$$t_c^B = \frac{\ln 3}{A} \exp\left(\frac{E}{k \cdot 293}\right). \tag{24}$$

By dividing both the left and right sides of formula (23) by the corresponding sides of formula (24), the required expression can be obtained:

$$t_c^* = \frac{t_c}{t_c^B} = \frac{\ln K_S}{\ln 3} \exp\left[\frac{E}{k}\left(\frac{1}{T} - \frac{1}{293}\right)\right], \tag{25}$$

where $K_S \geq 3$.

Using expression (25), the dependence shown in Fig. 4 was obtained, which also demonstrates a strong influence of temperature on the service life of wood. For example, a decrease in temperature from 40 °C to 0 °C at $K_S = 3$ leads to an increase in the wood's service life by approximately 5 times. This temperature effect is consistent across other values of K_S.

On the other hand, the influence of K_S is noticeably weaker. For example, at a temperature of 20 °C, increasing this parameter from $K_S = 3$ to $K_S = 10$ — more than threefold — results in only about a twofold increase in the service life component t_c (Fig. 4). Nevertheless, this factor can still be used in practice to extend the service life of wooden structures.

Results

To determine the actual values of the n_d and t_c parameters, an experiment was conducted using a sample of a bolted nagel joint, as shown in Fig. 5a (Fedosov et al., 2016b, 2017b; Kotlov et al., 2017). The sample was placed in a climate chamber, where it was subjected to periodic wetting and drying at a constant temperature. Simultaneously, a mechanical load corresponding to $K_S = 3$ was applied to the sample. The cyclic wetting and drying of the wood continued until structural failure occurred (Fig. 5b). The moisture content of the wood was monitored during the experiment using a Hydromette HT 85 T device and ranged from 8–12 % to 28–32 %, corresponding to the typical extremes encountered in actual operating conditions. The test results are presented in Table.

The data in Table allow us to use expressions (17) and (23) to determine the limit number of wetting and drying cycles n_d and the service life due to cyclic temperature and humidity changes t_c in actual values.

Fig. 6 shows the results of calculations using these formulas for $K_S = 3$ and Δt = 24 h.

The authors plan to prepare and publish a series of research papers following the completion of the patenting process. These papers will focus on the design of the experimental setup and the results of the

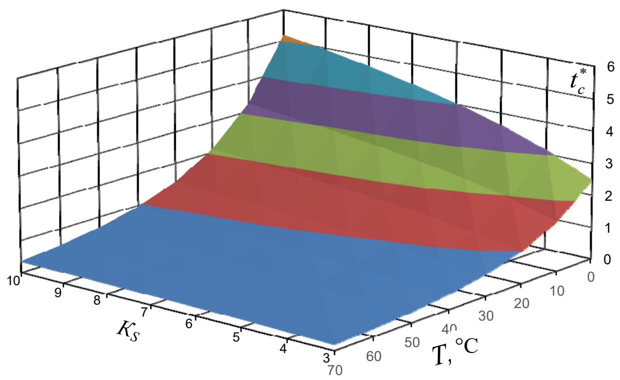

Fig. 4. Dependence of the relative service time of wood, due to the cyclic effects of wetting and drying processes, on temperature and safety factor for mechanical strength

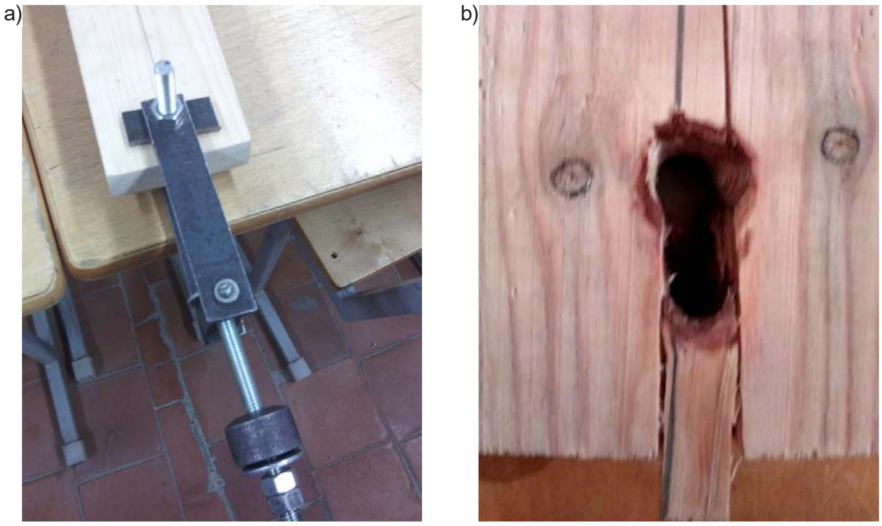

Fig. 5. Appearance of the bolted joint sample (nagel) in assembled form before installation in the climate chamber (a) and the nature of the failure after testing (b)

Failure characteristics of the bolted dowel joint sample

Temperature, T	Limit number of cycles, n_d	Sample lifetime, t_c	Duration of the wetting-drying cycle, Δt	Number of chemical interactions, A
ºC	units	h	h	1/s
40	5	103	20.6	0.31

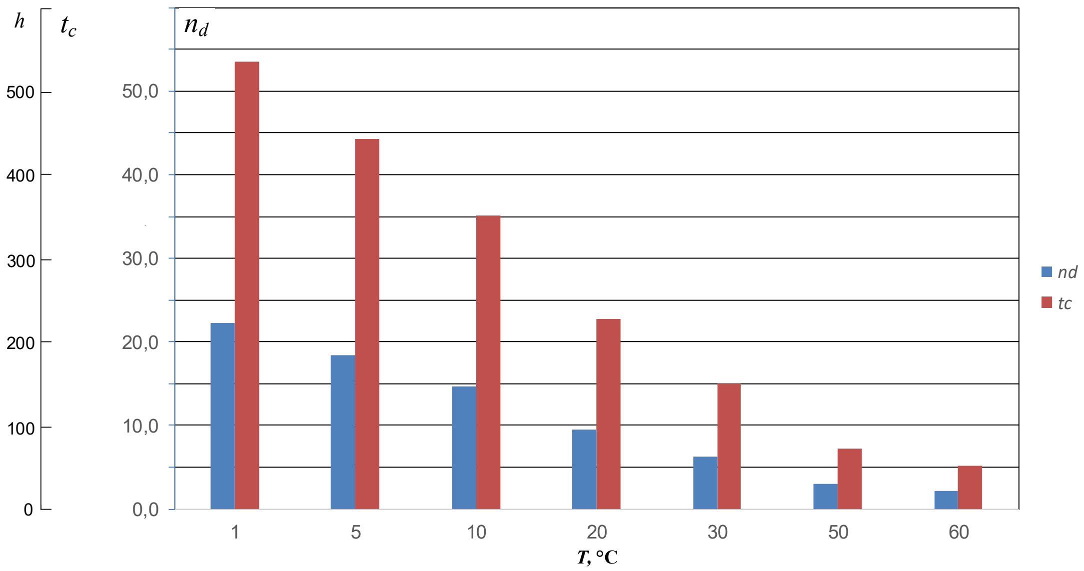

Fig. 6. Dependence of the allowable number of wetting and drying cycles n_d and the service life t_c of the nagel joint wood, in actual values, on temperature at K_S = 3 and Δt = 24 h

conducted experiments, confirming and expanding upon the theoretical findings presented in this paper.

Discussion

The information presented in Fig. 6 clearly indicates a significant influence of temperature on the durability of wood. For example, when the temperature varies from 1 °C to 50 °C — which is typical for the operating conditions of wooden structures in the middle zone of Russia and other regions with similar climatic conditions — the limit number of cycles n_d and the service life parameter t_c decrease by an order of magnitude. At first glance, these parameters may seem relatively low. However, they correspond to extreme fluctuations in the moisture content of wood and the duration of wetting and drying cycles. In reality, such extreme conditions occur quite rarely, and accounting for this factor remains a task for further research (Fedosov and

Kotlov, 2019; Fedosov et al., 2015, 2016c; Fedosov et al., 2017a).

The results presented in this paper regarding the influence of temperature on the service life of wood align well with the well-known fact that wooden architectural structures have survived to this day in the northern regions of Russia and other countries with cool climates.

Conclusions

1. The theoretical developments presented in this paper represent a further advancement and extension of previously developed mathematical models of heat and mass transfer processes in the wood of nagels, which occur under cyclically changing operating conditions. These developments enable the determination of the life cycle limits of wooden structure joints.

2. A convenient indicator for assessing the durability of the natural composite — wood — is the limit number of wetting and drying cycles. Knowing this parameter also allows for the estimation of the material's service life. The expressions obtained show that this parameter depends on three main factors: the safety factor, the duration of wetting and drying cycles, and the ambient temperature.

3. Since the quantitative estimates made in this paper are approximate, further theoretical development and experimental studies are necessary to refine the values of the constant parameters in the expressions and to reliably determine the service life of wooden structures.

4. The results presented in this paper have universal significance, as they form the basis for developing physical and mathematical models of destruction and durability for other types of composite materials, such as concrete with various fillers used under different conditions, fiberglass exposed to strong electric fields in high-voltage installations, and others.

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ФИЗИКО-МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ДОЛГОВЕЧНОСТИ ДРЕВЕСИНЫ ПРИ ЦИКЛИЧЕСКИХ ИЗМЕНЕНИЯХ ТЕМПЕРАТУРЫ И ВЛАЖНОСТИ В ОКРУЖАЮЩЕЙ СРЕДЕ

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Статья посвящена памяти
всемирно известного ученого
Сванте Августа Аррениуса (1859–1927).
В 2024 году отмечается
165-летие со дня его рождения.

Аннотация
Введение. Существенным недостатком композитных материалов является их склонность к постепенному ухудшению свойств с течением времени, что в конечном итоге приводит к полному разрушению. **Цель исследования.** Целью настоящей работы является выявление физических принципов и разработка теоретической базы для объяснения этого процесса. В качестве объекта исследования выбран природный композит — древесина. Многие физические и теоретические аспекты ее поведения остаются недостаточно изученными. В частности, требует дополнительного изучения снижение механической прочности в узлах соединения деревянных элементов (нагелями) при циклических изменениях температуры и влажности. **Методы.** В статье представлен физико-математический подход к оценке механической прочности древесины под воздействием таких факторов окружающей среды. Модель основана на уравнении Аррениуса и современных представлениях о клеточной структуре древесины, ключевыми компонентами которой являются целлюлозные волокна (армирующий каркас) и лигнин (связующая матрица). Предполагается, что нестационарные процессы тепло- и влагопереноса, обусловленные воздействием внешних условий, постепенно разрушают межатомные связи в соединениях лигнина. **Результаты.** Получены выражения для оценки максимально допустимого количества циклов увлажнения-сушки, которые древесина может выдержать при заданной температуре, а также оценки ее ресурса (срока службы) под влиянием этих циклических процессов. Предложенная теория имеет универсальное значение.

Ключевые слова: композит; тепло- и влагоперенос; уравнение Аррениуса; клеточная структура древесины; математическая модель; ресурс.