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Long-Term Strength Prediction of Wood Based Composites Using the Kinetic Equations

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Abstract. The existing behaviour models of the structures under constant load (creep) have a fairly wide forecast horizon and low accuracy. As a rule, they consider the transition from an undestroyed state of an element to a destroyed one, in one stage. The purpose of this study is to substantiate and develop a new approach to predicting long-term strength based on kinetic equations, which, in turn, should consider the multistage nature of the process of gradual destruction of structure elements. To achieve this purpose, the study solves the tasks of creating a multistage kinetic transition of individual structure elements from an initially elastic state to a viscoelastic state, and then to a fractured state. When describing this process, the authors employed the methods of formal kinetics and the theory of continuum damage mechanics, including the method of basic diagrams. Wood-based composites were used as the materials under study. Based on the results of the conducted full-scale and computational experiments, the study discovers that a mathematical model based on kinetic equations adequately describes the behaviour of the materials under study for long-term strength; the proposed two-stage model determines the forecast horizon much more accurately than the available one-stage models. The kinetic parameters that determine the rate of transition of a structural element from an elastic state to a viscoelastic state, and then to a destroyed state, were determined based on experimental base chart. The time to fracture was determined at three-point bending at a load equal to 70% of the flexural strength at temperatures of 20°C and 60°C, constant humidity RH 65% and moisture content MC 8%. When building control charts, the load increased by another 15%. The method allows narrowing the forecast horizon and determining the moment of transition of a structure from a stationary state to a blow-up regime with a higher accuracy

Keywords: models of fracture kinetics, fracture criteria, multistage fracture, creep, long-term strength

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INTRODUCTION

Fracture simulation of structured materials is critical for technical applications. This includes issues not only of the short-term strength of composite materials, but also of their long-term strength and creep. The theory of damage gives a phenomenological description of the evolution of scattered defects, pores, and microcracks, the number of which in any elementary volume is assumed to be extremely large. Initially, the concept of damage was associated with the proportion of voids appearing in the body section under the action of intense loads [1; 2]. In case of a multidimensional stress-strain state, this visual interpretation of damage encounters difficulties associated with the need to determine the fraction of voids in sections of a material element with different orientations of the normal. The study proposes various definitions of material damage, which are tensor quantities obtained by averaging the parameters of the microstructure [3]. However, the interpretation of damage based on microstructural concepts appears to be unnecessary.

Admittedly, at the phenomenological level, the presence of micropores and microcracks leads to two main effects: degradation of elastic moduli and residual deformations. In addition, in applied problems, as a rule, the issue of the preferred orientation of microdefects is not acute. This fact is conditioned upon the structure of the material, which is often known in advance. For example, a beam made of wood (this also applies to other composites) is predominantly destroyed by splitting along the fibres (delamination of the fibre from the binder matrix). In addition, the presence of planes of weakening (healed or open cracks and faults), which are oriented in a special way, considerably affects the result of technogenic impact on the wood-based composites (WBC).

The studies [4-6] discuss a model of an isotropic damaged body, wherein a scalar damage parameter is used, which is closely related to the energy spent on the appearance of new surfaces during cracking. At this stage, a model of the initially damaged isotropic material with strength anisotropy is constructed using the scalar damage parameter, which is considered to be related to the surface energy of microdefects. The type of anisotropy that a material acquires is determined by its structure. In this case, a medium composed of identical plane-parallel layers is considered to be "glued" to each other. The interlayer tensile and shear strength is considered lower than the strength of the material, which the layers themselves are composed of, thereby dictating the predominant orientation of microdamage. In this case, there is no need to introduce a tensor measurement of deformation, and the scalar measurement of damage becomes possible, while in the anisotropic case, the measurement can be interpreted in terms of the irreversible energy consumption for the appearance of new surfaces.

One of the first theories of strength was formulated by Griffith [7]. According to this theory, strength is defined as the stress under which the condition of equality of two energies is fulfilled: the energy expended on the formation of a new surface of a growing crack, and the elastic energy released during a crack growth. According to this theory, destruction is interpreted as a critical event, which follows a critical tension.

This interpretation is not confirmed by experience, because it is known that the accumulation of molecular and supramolecular defects occurs long before the moment of destruction. Therefore, destruction develops over time and does not constitute a critical event. The introduction of a temporary scale of the fracture process led to the creation of a kinetic theory of strength. Temporal dependencies were proposed by A. Aleksandrov [8] upon describing the relaxation properties of viscoelastic deformation of solids in the form of generalised Maxwell equations. The clearest physical interpretation and development of these ideas was provided by Professor S.M. Zhurkov, who is the founder of the kinetic theory of strength [9]. This theory considers destruction as a temporary accumulation of molecular and supramolecular defects. The durability of stressed bodies is defined as a fundamental parameter of strength and reflects the average rate of destruction at all structural levels: molecular, supramolecular, and macroscopic.

A fundamental form of kinetic strength theory is the Zhurkov equation. Moreover, the Zhurkov equation, which is created to describe the mechanism of destruction at the molecular level, is automatically transferred to describe the mechanism of destruction of meso- and macro-levels, and does not take into account the way the relaxation processes occur at these levels. In addition, this equation assumes that the process passes within one stage. In particular, the connections between the elements are considered to be either not destroyed, and are under the action of thermo-force load or destroyed after a time determined by the Zhurkov formula.

The purpose of this study is to substantiate and develop a new approach to predicting long-term strength based on kinetic equations, which, in turn, should consider the multistage nature of gradual destruction of structure elements. To achieve this purpose, the study solves the tasks of creating a multistage kinetic transition of individual structure elements from an initially elastic state to a viscoelastic state, and then to a fractured state.

THEORETICAL OVERVIEW

To create a kinetic model of the relaxation behaviour of a polymer under the action of thermomechanical action, several different states of its individual structure element (SE) are to be considered. Individual elements of a structure are understood as local body volumes, whose local stresses differ. For a crystalline polymer

under load, these can be both crystalline and amorphous regions [10].

The initial (input) state of a structure element is a state wherein no external mechanical effect occurs. In this case, all the individual structure elements of the target are in thermodynamic equilibrium. Elastic steady state (E) of a structure element is a structure element that has been in an elastic state for a certain time. The viscoelastic steady state of a structure element (VE) is a structure element in a viscoelastic state, i.e., a state of relaxation of internal stresses. Destructed steady state of a structural element (D) is a destroyed structural element formed from a viscoelastic one, whose stresses at the time of destruction are redistributed between those structure elements that are in elastic and viscoelastic states at that moment [11; 12].

The authors consider a solid not in the form of an uninterrupted continuum, but in the form of a solid structure, comprising separate supporting structure elements, interconnected in a particular way. Then, due to internal heterogeneity, the action of external loading on the surface of the body causes its internal structure elements to experience internal stresses of various magnitude and vectors [13; 14]. Structure elements with stresses greater than the tensile strength will be immediately destroyed. After their destruction, external forces will be redistributed between the remaining undamaged structure elements so that each of them bears a new load on the part of neighbouring SE [15; 16]. The behaviour of polymers over time is usually described in the form of combinations of primary rheological bodies, such as the elastic body of Hook, the viscous body of Newton, or combinations thereof (Maxwell or Voigt bodies).

By combining these primary rheological bodies, one can create a certain rheological model, the behaviour of which in time (kinetics) would accurately describe the behaviour of the real body under the influence of external loads. It is generally recognised that during a period of constant creep, a solid body, under the action of external temperature-force loading, behaves as if it were consistently in an elastic, viscoelastic, or plastic state. Therewith, it is assumed that the total deformation of the body, as a rule, comprises three different parts: instantaneously reversible (elastic), highly elastic, reversible in time, i.e., relaxing in time (viscoelastic), and irreversible (plastic) [17; 18]. In this case, total deformation is understood as the total deformation of the entire body, and not of its individual parts or structure elements.

The main hypothesis of the deformation is formulated as follows: firstly, the body is deformed and destroyed into separate structure elements. In particular, only into those elements where the local stress first reaches the limits of proportionality, and then the limits of strength. In this case, the individual structure element is first elastically deformed, and then passes in series into a viscoelastic or plastic state, and then collapses. Secondly, a single destroyed structure element is surrounded for a certain time by non-destructive structure elements that are in an elastic or viscoelastic state. Thirdly, the body is considered destroyed if the number of destroyed structure elements exceeds certain predefined values.

Thus, the destruction kinetics of the body under the action of thermomechanical loading will comprise different variants of the transition sequence of the elastic structure elements (*E*) into the viscoelastic structure elements (*VE*), and then in the destroyed structure elements (*D*):

$$E \rightarrow VE \rightarrow D \qquad (1)$$

Thus, in the process of destruction, the number and, consequently, the concentration of structure elements in different rheological states are constantly changing. The concentration of changes of a particular structure element can be determined experimentally by measuring values that correlate with the fracture parameters of a particular type of body deformation.

In this case, according to the law of conservation of masses, the total number of structure elements in different states must remain constant at each moment. Consideration of the fracture process from the standpoint of combining cracks, for example, smaller ones into larger ones, does not change the number of structure elements, but only examines them in different states.

Mathematical model of deformation-destruction process. The main variables describing the state of the system, determine the substances Ai, that is in different rheological states. The number SE in different states shall be denoted as N_i; n is the vector of quantities components. The concentration is denoted as follows: $C_i \equiv N_i/V$. Each stage of the system is matched by its speed $W_s(C, T)$. The velocity of the stage is intense and is defined as a function of intense quantities – concentration and temperature.

The kinetics equations have the following in coordinate form:

$$\frac{dN_i}{dt} = V\sum_s \gamma_{si} W_s\left(C,T\right), \quad i = 1,\ldots,n \qquad (2)$$

Where γ_{si} is the stoichiometric vector with components $\gamma_{si}=\alpha_{si}-\beta_{si}$; s is the stage; are the non-negative integers and stoichiometric coefficients. In the absence of autocatalysis, as in this case, this vector completely determines the stoichiometric equations of the stage.

For each material, there are a priori restrictions on vectors linear conservation laws (balance ratios). If N_{si} is the number of structure elements that are in a certain rheological state and k is a species in the molar volume of a substance A_i, then for any s and k:

$$\sum_i \alpha_{si} N_{ki} = \sum_i \beta_{si} N_{ki} \quad \text{or} \quad \sum_i \gamma_{si} N_{ki} = 0 \qquad (3)$$

The balance relations (2) give rise to linear conservation laws for system (1), that is, for any k: $\sum_i \alpha_{ki} N_i = const$,

which means:

$$\frac{d}{dt}\sum_i \alpha_{ki} N_i = V \sum_{s,i} \alpha_{si}\gamma_{ki} W_s = 0 \quad (4)$$

Then the following kinetic model of the DD process will correspond to the transformation scheme (1):

$$\frac{dCA(t)}{dt} = -k_1 CA(t) \quad (5)$$

$$\frac{dCB(t)}{dt} = k_1 CA(t) - k_2 CB(t) \quad (6)$$

$$\frac{dCC(t)}{dt} = k_2 CB(t) \quad (7)$$

with initial conditions t=0; $CA(0)$=1; $CB(0)$=$CC(0)$=0, and boundary conditions $CA(t)$+$CB(t)$+$CC(t)$=1, where $CA(t)\in(1...0)$ is the current concentration of structure elements that are in an undamaged, elastic state at time t; $CB(t)\in(0...1)$ is the current concentration of structure elements that are in a non-destructive, i.e., viscoelastic state at time t; $CC(t)\in(0...1)$ is the current concentration of the structure elements that are in a destroyed state at time t; is the rate constant of the transition of structure elements from elastic state to viscoelastic, s^{-1}; k^2 is the rate constant of the transition of the structure elements from the viscoelastic state to the destroyed, s^{-1} [19].

MATERIALS AND METHODS

Materials. For the present study, Kronospan UA Ltd. provided three commercially produced structural particleboards bonded with urea formaldehyde resin (UF): melamine faced particleboard (MF PB) according to EN 14322; veneered by oak particleboard (VF PB) according to EN 316, EN 622-5, and particleboard P2 (P2 PB) according to EN 312, type P2; EN 13501-1: class D-s1, d0. For each type, two regular-size (2750 mm × 1830 mm) boards with thicknesses of 18 mm were cut into 450 mm (length) × 50 mm (width) pieces. Before cutting, boards were stored in a conditioning room maintained at 20°C and 65% RH. Static 3-point bending tests were performed in the special test machine with temperature-controlled chamber. Specimens were prepared and cut according to ASTM D 1037-99. Loading and deflection were measured, and MOR and MOE were calculated according to Section 9 in ASTM D 1037-99 [19]. The temperatures analysed were 20°C and 60°C.

Specimens were preheated in the chamber until they reached equilibrium with the target temperature. The preheating times were determined from preliminary experiments by an embedded thermocouple, and the prediction model was developed in a previous study [20]. Table 1 presents the results of tests performed on the samples to establish their mechanical properties in the chamber at the target temperature. 150 specimens were cut from each type of board. 10 specimens were prepared for testing modulus of elasticity (MOE) and rupture (MOR) before main testing. All specimens were conditioned at 20°C and 65% RH prior to use. The average densities of specimens were 757 kg/m^3, 792 kg/m^3, and 733 kg/m^3, respectively, in an air-dried condition moisture content of about 5%.

Table 1. *Properties of particleboard used in study*

Board type	Density[d], kg/m^3	Number of samples	Thickness[d], mm	MOR[d], MPa	MOE[d], MPa
MF PB[a]	757±7	10	18.1±0.1	17.1±1.1	2 110±29
VF PB[b]	792±8	10	18.5±0.1	20.5±1.9	2 520±15
P2 PB[c]	733±6	10	18.1±0.1	16.2±0.6	2 020±22

Notes: *[a]MF PB – Melamine Faced Particleboard; [b]VF PB – Veneered Faced Particleboard; [c]P2 PB – Particleboard according to EN 312, type P2; [d] Thickness, density, MOR and MOE was measured after specimens reached equilibrium at 65% RH, temperature 20°C and moisture content 5%*

Tests were performed according to the scheme of three-point bending per ASTM D 1037-99 loads equal to 75% of the maximum allowable. The nature of the behaviour of the system under the action of constant load was described by the movement of the midpoint in time until rupture.

Methods. Considering the curve of long load, it can be established that its initial section contains structure elements only in the elastic state, which return to the undeformed state after the load is removed. During this period of elastic deformation, there is no transition of structure elements to a viscoelastic state. Therefore, the beginning of the kinetics of the DD is taken to be the end time of the elastic deformation and the beginning of the site of viscoelastic deformation, i.e., the time of the beginning of the process first unsteady and then steady creep. Throughout the process of creep, there is a decrease in the number of non-destructive structure elements, i.e., those in elastic or viscoelastic states and an increase in structure elements in the destroyed state.

To describe the kinetics of deformation, it is possible to compare the change in the concentration of SE in the elastic state and the destroyed state with the change in the magnitude of the deformation over time. In this case, the rate of change of the concentration over time of elastic SE will be proportional to the change in the rate of deformation due to the transition of elastic SE in viscoelastic, and the decrease in the concentration

of elastic SE will be proportional to the increase in the absolute deformation of the DD process, that is, $CA(t) \propto \varepsilon(t)$.

Since the change in the SE concentrations in a certain state can be given as a first-order kinetic dependence [21], the following equation can be written:

$$\frac{dCA(t)}{dt} = -k_1 \cdot CA(t)$$

$$\frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -k_1 t, \int_{\varepsilon_1}^{\varepsilon_2} \frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -\int_{t_1}^{t_2} k_1 dt, \quad \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right) = -k_1(t_2 - t_1), \quad k_1 = -\frac{1}{(t_2 - t_1)} \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right) \tag{9}$$

Evidently, when the deformation changes ε_1 and ε_2 the same number of times, the value k_1 does not change. This allows creating a kinetic model of deformation-destruction to replace concentrations proportional to their values – deformations, stresses, acoustic, or electromagnetic emission pulses, quantities of matter, etc. [19].

The magnitude inverse of the first order reaction rate constant, $\tau_e = 1/k_1$, is a temporal measurement describing the average life expectancy of SE that are in an elastic state before their transition to a viscoelastic state. Similarly, the inverse of the rate constant of the transition of the viscoelastic state of the SE to the destroyed determines the average life expectancy of the structure elements in the viscoelastic state: $\tau_{ve} = 1/k_2$.

Since time is included in Eq. (9) as a difference rather than a relation to a deformation, a dimensionless time is introduced to eliminate the dimension factor: $\tau_i = t_i/t_{cr}$. Therewith, total creep deformation can be represented as the sum of total elastic and viscoelastic deformations, i.e., deformations due to the destruction of elastic and viscoelastic SE:

$$\varepsilon_e + \varepsilon_{ve} = \varepsilon_{cr} \tag{10}$$

$$t_e + t_{ve} = t_{cr} \tag{11}$$

Because according to Eqs (8), (10):

$$\frac{1}{k_1}\dot{\varepsilon}_e + \frac{1}{k_2}\dot{\varepsilon}_{ve} = \varepsilon_{cr},$$

then

$$\frac{1}{k_1} + \frac{1}{k_2} = \frac{\sum_{t_1}^{t_{cr}} t_{e_i} + \sum_{t_1}^{t_{cr}} t_{ve_i}}{t_{cr}} = 1 \tag{12}$$

The expression for k_2 is obtained by solving the system of two Eqs (13), (16) as follows:

$$k_2 = \frac{ln\left(\frac{\varepsilon_2}{\varepsilon_1}\right)}{t_1 - t_2 - t_{cr} * ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)} \tag{13}$$

The solution of the system of differential equations (5), (6), (7), for example, by the operating method, allows obtaining the values of current concentrations of SE, which are in elastic, viscoelastic, and destroyed states:

or, having undergone a proportional deformation:

$$\frac{d\varepsilon_e(t)}{dt} = -k_1 \cdot \varepsilon_e(t) \tag{8}$$

The equation (12) is integrated after the separation of variables (time, deformation) (9):

$$CA(t) = CA(0)e^{-k_1 t} \tag{14}$$

$$CB(t) = CA(0)\left(\frac{k_1}{k_1 - k_2}e^{-k_2 t} - \frac{k_1}{k_1 - k_2}e^{-k_1 t}\right) \tag{15}$$

$$CC(t) = CA(0)\left(1 - \frac{k_1}{k_1 - k_2}e^{-k_2 t} + \frac{k_2}{k_1 - k_2}e^{-k_1 t}\right) \tag{16}$$

Moreover, given the initial conditions $t=0$; $CA(0)=1$; $CB(0)=CC(0)=0$, and boundary conditions $t \in (0...1)$: $CA(t)+CB(t)+CC(t)=1$ in the coordinates of dimensionless time, one can obtain as follows:

$$\int_0^1 CA(t)dt + \int_0^1 CB(t)dt + \int_0^1 CC(t)dt = 1 \tag{17}$$

therefore, $k_1^{-1}+k_2^{-1} = 1$. Thus, in real time coordinates $k_1^{-1}+k_2^{-1}=t_{cr}$.

The method involves determining the damage characteristics and predicting the time of reaching the critical mark of the measure of damage. While as a scalar value ψ is a preventive comparison of the degree of damage equal to the ratio of the current concentration of destroyed structure elements to the current concentration of non-destructive structure elements. The resource is considered to be exhaustive value describing the extent of damage exceeding [22]:

$$\psi = \frac{CC(t)}{CA(t) + CB(t)} \geq \psi_f = 1 \tag{18}$$

where ψ_{fis} the measure of permissible damage; $CA(t)$, $CB(t)$, $CC(t)$ are determined by formulas (14), (15), (16), respectively; $k_1 = \frac{1}{t_1 - t_2}\ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)$ is the rate constant of transition of structure elements from elastic state to viscoelastic creep diagram, s^{-1}; t_1 is the time of the end of the section of elastic deformation and the beginning of the section of viscoelastic deformation, s; t_2 is the time of measurement of deformation at the site of constant creep; ε_1 is the deformation at time t_1; ε_2 is the deformation at time t_2; $k_2 = \alpha^{-1} k_1$ is the rate constant of the transition of the structure elements from the viscoelastic state to the destroyed, s^{-1}; α is the parameter describing the rheological properties (features) of the material, the degree of its inelasticity.

In this case, the rate constants of the transition of local structure elements from one state to another, depending on the load and temperature, are determined according to the long-term strength chart, which establishes the dependence of the change in the rate of deformation in time.

The method is implemented as follows. A basic deformation diagram is constructed at isothermal creep of a part under constant load at a fixed temperature in the coordinates: ε is the absolute deformation, μm; t is the time, *s*. In this case, the time to fracture and the maximum deformation at the time of fracture are determined. The moment of time of the end of elastic deformation is fixed, as well as the magnitude of the deformation at this moment t. After the base diagram is constructed, the moment is selected $t_2 = t_{cr}/2.5$ and at this point the deflection value is determined. Further, formulas (9) and (1) determine the value k_1 and k_2, as well as the value:

$$\alpha = k_1/k_2 \quad (19)$$

By measuring the change in the deformation of a part over time, a control chart of deformation is constructed. The moment of time t_{2k} is chosen at the point of constant creep and absolute deformation ε_{2k} at that moment is recorded. Eq. (16) allows obtaining a value k_{1k}, and Eq. (19) – $k_{2k} = k_{1k}/\alpha$.

Eqs (13), (14), (15) are used to determine the change in the current concentrations of SE, which are in elastic, viscoelastic, and fractured states. Based on Eq. (18), the estimated time t_ψ is determined reaching the limit value of the damage parameter ψ.

RESULTS AND DISCUSSION

The experimental factors levels and test results of studies long-term strength PB at constant load are presented in Table 2.

Table 2. *Experimental factors levels and test results for particleboards*

Test conditions				Test results[a]									
				Displacement, mm					Time displacement, h				
Board type	Number of samples	Stress level (MPa)	Temperature (°C)	In all ε_{cr}	Visco elastic ε_{ve}	%	Elastic ε_e	%	In all t_{cr}	Visco elastic t_{ve}	%	Elastic t_e	%
MF PB	20	12.8	20	2.46	0.79	32.1	1.67	67.9	127.1	98.4	77.4	28.7	22.6
	20		60	3.95	1.33	33.7	2.62	66.3	84	73.3	87.3	10.7	12.7
VF PB	20	15.4	20	1.5	0.59	39.3	0.91	60.7	477.82	380.9	79.7	96.92	20.3
	20		60	1.77	0.54	30.5	1.23	69.5	190.71	140	73.4	50.74	26.6
P2 PB	20	12.15	20	4.91	1.63	33.2	3.28	66.8	78.77	69.6	88.4	9.17	11.6
	20		60	1.57	0.51	32.1	1.07	67.9	35.75	24.2	67.8	11.51	32.2

Notes: [a]*The average test values for each group of 20 samples are presented*

Experimental studies of the long-term strength curve of PB have found that the material behaves in a complex viscoelastic manner during the creep. And the curve of its deformation contains the recurring sections, inherent in the curves of elastic and viscoelastic deformation (Fig. 1).

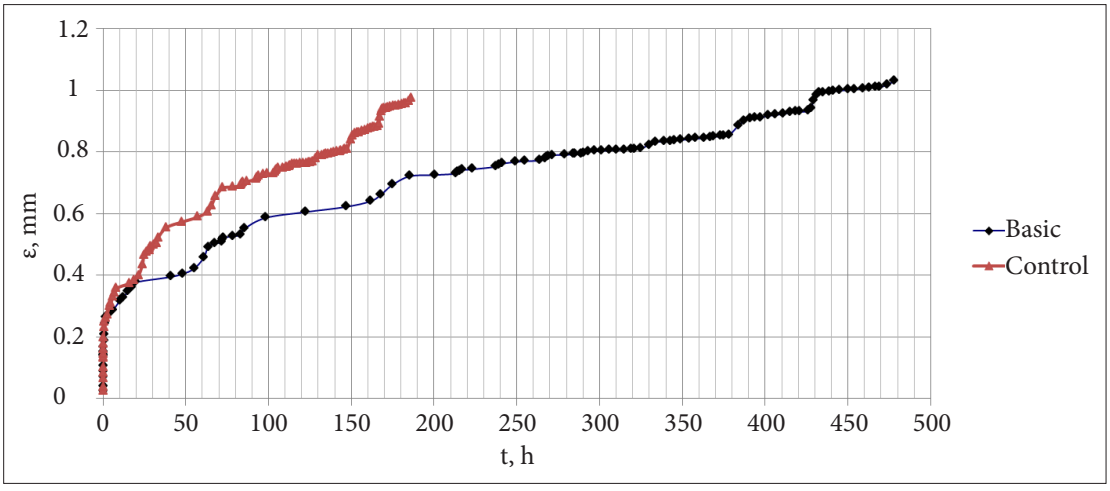

Figure 1. *Basic and control creep diagrams. Dependences of the average absolute deformation for one group of the samples VF PB by stress level SL = 15.4 MPa and temperature T = 20°C for basic diagram, and by stress level SL=17.7 MPa and temperature T = 20°C for control (predicted) diagram*

The nature of the deformation-destruction curves over time (Fig. 1) indicates that the process is non-stationary. The deformation process at all its stages, both at the subcritical (stationary creep process) and at the closed (active fracture process) behaves nonlinearly and has a stepped character. In Figure 1 it is shown that the general curve of dependence of deformation in time, consists of separate sections, which have different repetitive strain rates. Table 1 shows that the amount of viscoelastic deformation is on average 33% of the total amount of deformation. In this case, the time of viscoelastic deformation (behaviour) PB occupies about 80% of the total deformation time. And the value of both the magnitude of viscoelastic deformation and its time is in a very narrow range, which indicates the similarity of the deformation process and the destruction of PB under different conditions of its loading.

Analysing the deformation curves over time, it can be stated that the general deformation curve up to fracture periodically repeats cycles of elastic and viscoelastic behaviour. This confirms the assumption that the process is multi-stage.

According to the graph of the basic deformation diagram (basic long-term strength curve Fig. 1), the following quantities are defined: t_1=0.003*3600=10.8 [s], ε_1=80 [μm], t_2=200*3600=7.2*10^5 [s], ε_2=730 [μm], t_{cr}=477*3600=1,717*10^6 [s]. Eqs (9), (13), (19) yield the following results: k_1=0,307*10^{-5} s^{-1}, k_2=0.719*10^{-6} s^{-1}; α=4.273.

Figure 2 demonstrates a basic model diagram, constructed in the coordinates of the "concentrations of SE in different states – time" [19].

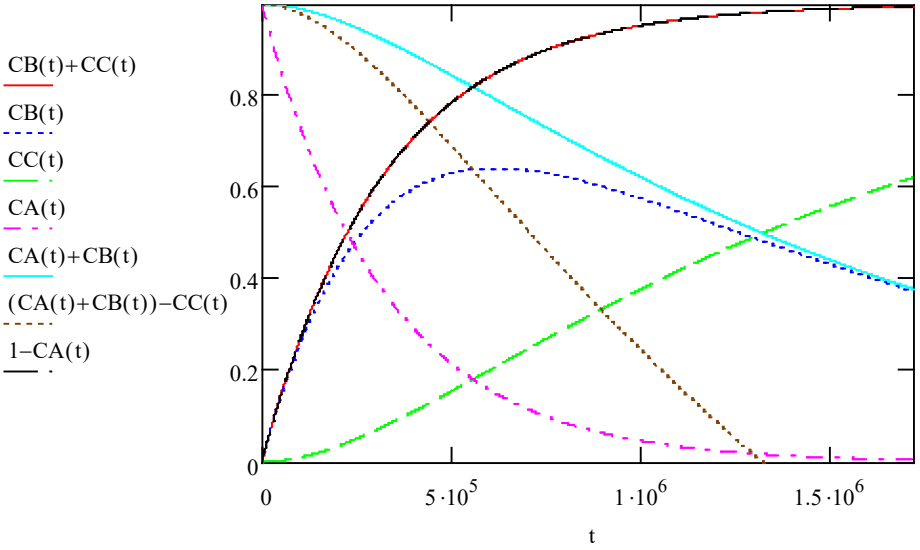

***Figure 2**. Basic model diagram of long-term strength (creep): change concentrations of SE in the states: elastic – CA(t), viscoelastic – CB(t), destroyed – CC(t) in time for the basic deformation diagram*

The deformation control chart was investigated for a similar part load exceeding the baseline by 15%. According to the control chart of deformation at the site of permanent creep at time – t_{2k}=100*3600=360000 [s], ε_{2k}=730 [μm].

The value of the rate constants k_{1k}, k_{2k} according to the control deformation chart are determined using Eqs (9), (19):

$$k_{1k} = -\frac{1}{(t_{2k} - t_1)} \ln\left(\frac{\varepsilon_1}{\varepsilon_{2k}}\right) = 0.614*10^{-5}\ \text{s}^{-1};\ k_{2k} = \alpha^{-1} * k_{1k} = 0.144*10^{-5}\ \text{s}^{-1}$$

The critical amount of damage will be reached at the moment when, based on the condition (18):

$$CA(t_\psi) + CB(t_\psi) - CC(t_\psi) = 0 \qquad (20)$$

Solving together equations (14), (15), (16), and (20) yields the time to the predicted destruction: $t_{\text{predict }\psi}$ = = 6.6*10^5 s. The factual time to destruction of the control sample is $t_{\text{fact }\psi}$=6.7*10^5 s.

Figure 3 demonstrates a control model diagram, constructed in the coordinates of "concentrations of SE, which are in different states – time", which clearly indicates the process of loss of bearing capacity of the part in time during creep.

The results of basic tests of six groups of samples, as well as the results of calculations of the kinetic basic parameters are presented in Table 3.

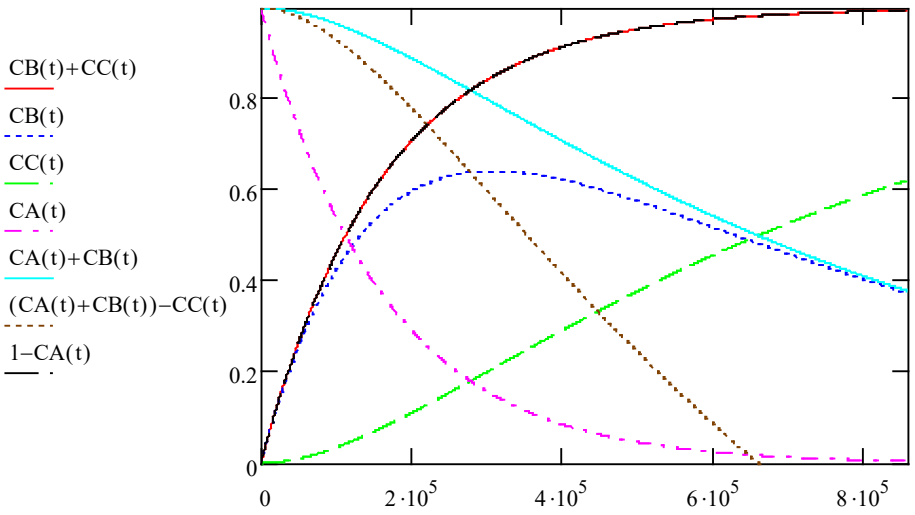

Figure 3. *Control (predicted) creep model diagram: change concentrations of SE in the states: elastic – CA(t), viscoelastic – CB(t), destroyed – CC(t) in time for the deformation control chart*

Table 3. *Basic test results and calculated basic kinetic parameters*

Board type	Test conditions		Test results			
	Stress level (MPa)	Temperature (°C)	Creep life t_{cr} (s)	k_1 (s^{-1})	k_2 (s^{-1})	α
MF PB	12.8	20	457560±7250[a]	1.16E-05	2.69E-06	4.325
		60	302400±3500	1.74E-05	4.08E-06	4.261
VF PB	15.4	20	1717000±9500	3.07E-06	7.19E-07	4.273
		60	686556±5600	7.94E-06	1.78E-06	4.453
P2 PB	12.15	20	283572±850	1.88E-05	4.34E-06	4.331
		60	128700±780	4.53E-05	9.38E-06	4.831

Notes: [a]*The confidence interval is indicated at p=0.05 level*

The results of control tests of six groups of samples, as well as the results of calculations of the control kinetic parameters are presented in Table 4.

Comparing the results of the model time before the destruction of the control samples in each test group (Tab. 4. Creep life predict by Eq. (18)) with the actual time before the destruction of the control samples (Tab. 4. Creep life control diagram), it can be concluded that the convergence of these quantities is quite high. This suggests that the proposed method for predicting long-term creep strength can be used to improve the accuracy of predicting the performance of controlled mechanical systems.

Table 4. *Control test results, calculated control kinetic parameters and predicted time to failure*

Board type	Test conditions		Test results			
	Stress level (MPa)	Temperature (°C)	k_{1k} (s^{-1})	k_{2k} (s^{-1})	Creep life t_{cr} (s)	
					Control diagram	Predict by Eq. (22)
MF PB	14.72	20	1.43E-05	3.30E-06	338933±7500[a]	372827[b]
		60	1.82E-05	4.27E-06	262957±5600	289252
VF PB	17.71	20	7.99E-06	1.87E-06	670000±9800	660000
		60	1.19E-05	2.67E-06	504821±5500	458928
P2 PB	13.97	20	2.50E-05	5.78E-06	234357±6200	213052
		60	5.95E-05	1.23E-05	99000±860	98000

Notes: [a]*The confidence interval is indicated at p=0.05 level;* [b]*Prediction results based on average kinetic coefficients*

A multi-stage description of the kinetics of deformation-fracture allows considering the change in the rheological state of the material during its deformation. Therewith, it becomes possible to mathematically describe not only the process of its destruction, but also the healing process that goes along with it. However, this issue requires separate consideration and will be the subject of further research.

CONCLUSIONS

Based on the analysis of the results of theoretical and experimental studies of the process of deformation-destruction of wood composite materials, the following conclusions can be drawn:

1. For the first time, a two-stage nonlinear kinetic model of resource loss due to the creep of wood-based composites is proposed.

2. The use of formal kinetics methods for modelling the physicochemical processes that occur during deformation-destruction allows designing the multi-stage kinetic models.

3. The use of the method of basic deformation diagrams in combination with the two-stage description of the process of accumulation of damage, allows increasing the accuracy of the prediction of allowable time under different load schemes during creep.

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Прогнозування тривалої міцності деревних композитів з використанням кінетичних рівнянь

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Анотація. Існуючі моделі поведінки конструкцій при постійному навантаженні (повзучості) мають досить широкий горизонт прогнозування і низьку точність. Як правило, вони враховують перехід від неруйнованого стану елемента до зруйнованого за одну стадію. Метою цього дослідження було обґрунтування та розробка нового підходу до прогнозування довгострокової міцності на основі кінетичних рівнянь, який, у свою чергу, повинен враховувати багатоступеневий характер процесу поступового руйнування елементів конструкції. Для досягнення цієї мети були вирішені завдання створення багатоступінчастого кінетичного переходу окремих структурних елементів із спочатку пружного стану у в'язкопружний, а потім у тріщинований. Описуючи цей процес, автори статті використовували методи формальної кінетики та теорії механіки пошкоджень континууму, а також метод базових діаграм. В якості матеріалів, що вивчаються, були використані композити на основі деревини. За результатами проведених повномасштабних та обчислювальних експериментів було визначено: математична модель на основі кінетичних рівнянь адекватно описує поведінку досліджуваних матеріалів для довгострокової міцності; запропонована двоетапна модель визначає горизонт прогнозу набагато точніше, ніж існуючі одноетапні моделі. Кінетичні параметри, що визначають швидкість переходу структурного елемента з пружного стану у в'язкопружний, а потім у руйнований, були визначені на основі експериментальних базових діаграм. Час до руйнування визначали при триточковому вигині за навантаження, що дорівнює 70 % міцності на вигин при температурах 20 °C і 60 °C, постійній вологості RH 65 % та вологості MC 8 %. При побудові контрольних карт навантаження збільшилося ще на 15 %. Метод дозволяє звузити горизонт прогнозу та з більшою точністю визначити момент переходу споруди зі стаціонарного стану в режим із загостренням

Ключові слова: кінетична теорія, механіка пошкодження континууму, повзучість, довготривала міцність, параметри пошкоджень, критерій руйнування