

CREEP LIFE PREDICTION BY THE BASIC MODELS OF DEFORMATION-DESTRUCTION KINETICS OF WOOD-BASED COMPOSITES

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ABSTRACT

Existing models of kinetics of deformation-destruction are related mainly to the description of the transition from the undamaged state of the material into a destroyed stage. The purpose of this study was to create the basic model of deformation-destruction kinetics describing this process in the form of several successive transitions of separate structural elements (SE), in a material that deforms from one rheological state to another one in time. A formal kinetics apparatus is involved to describe this process, which allows, knowing the speed of the transition of the SE from one rheological state to another one, to predict the time to reach the critical concentration of destroyed SE. It is established that the process of deformation-destruction can be considered a process of gradual transition of the SE, first an elastic state into viscoelastic and then destroyed. The change in the concentration of one or another SE can be determined experimentally by measuring the quantities that correlate with the parameters of deformation-destruction. For the first time, a two-stage nonlinear kinetic model of resource loss with the creep of composite materials based on wood was proposed. The application of the method of basic deformation diagrams in conjunction with the two-stage description of the process of accumulation of damage can increase the accuracy of the prediction of allowable time for different load patterns during creep.

Key words: particleboard, model of kinetics, kinetics of deformation, criteria of destruction, two-stage model of deformation-destruction.

INTRODUCTION

One of the first theories of strength was formulated by GRIFFITH (1921). According to this energy theory, strength was 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 growth of crack. 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 is not 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 ALEKSANDROV (1941) who describes the relaxation properties of viscoelastic deformation of solids, in the form of generalized 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 (REGEL *et al.* 1974). In this, the theory destruction is considered as a temporary process of accumulation of molecular and supramolecular defects. The durability of a 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 mezzo and macro-levels, and does not take into account how the relaxation processes occur at these levels. In addition, this equation assumes that the process passes in only one stage. Namely, 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 initial state of a structure element is a state in which there is no external mechanical effect. In this case, all the individual elements of the structure of the target are in thermodynamic equilibrium. Elastic steady state (E) of a structure element is a state, where structure element is in an elastic state for some time. The viscoelastic steady state (VE) of a structure element is a state, where structure element is in a viscoelastic state, that is, a state of relaxation of internal stresses. Destroyed steady state (D) of a structural element is a state, where destroyed structural element is formed from a viscoelastic, whose stresses at the time of destruction are redistributed between those elements of the structure that are presently in elastic and viscoelastic states.

We shall consider a solid body not in the form of a continuous continuum, but in the form of a solid structure, consisting of separate supporting elements of the structure, interconnected in a certain way. Then the action of external loading on the surface of the body will cause its internal elements of the structure, due to internal heterogeneity, to experience different in magnitude and direction of internal stresses (KULMAN and BOIKO 2015). Elements of structure whose stresses are greater than the tensile strength will be immediately destroyed. After their destruction, external efforts will be redistributed between the remaining undamaged elements of the structure so that each of them will bear a new load on the part of neighbouring SE.

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 in one way or another create a rheological model, whose behaviour in time (kinetics) will accurately describe the behaviour of the real body under the influence of external loads. It is generally recognized that during a period of constant creep, a solid body, under the action of external temperature-force loading, behaves as consistent in an elastic, viscoelastic or plastic state. At the same time, it is assumed that the total deformation of the body consists of three different parts by nature: instantaneously reversible (elastic), highly elastic, reversible in time, i.e., relaxing in time (viscoelastic) and irreversible (plastic) (REGEL 1964). In this case, total deformation is understood as the total deformation of the whole body, and not its individual parts or elements of structure (AKYÜZ *et al.* 2019, YAPICI *et al.* 2016).

We take as the main hypothesis of the deformation that: first, the body is deformed and destroyed individually in separate elements of the structure. Namely, only in those elements in which the local stress first reaches the limits of proportionality, and then the limits of strength. In this case, the individual element of the structure is first elastically deformed, and then passes in series in a viscoelastic or plastic state, and then collapses. Secondly, a single destroyed element of the structure is surrounded for some time by non-

destructive elements of the structure that are in an elastic or viscoelastic state. In-third, the body will be considered destroyed if the number of destroyed elements of the structure exceeds certain predefined values (POŠTA *et al.* 2016).

Thus, the kinetics of the destruction of the body under the action of thermomechanical loading will consist of different variants of the sequence of transition of the elastic elements of the structure (E) into the viscoelastic elements of the structure (VE), and then in the destroyed elements of the structure (D): $E \rightarrow VE \rightarrow D$. Within the process of destruction, the number and, consequently, the concentration of elements of the structure that are in different rheological states are constantly changing. The changes concentration of a particular element of the structure can be determined experimentally by measuring values that correlate with the fracture parameters of a particular type of body deformation.

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

The purpose of this study is to create basic model of kinetics of the process of scattered fracture based on a multistage transition of structural elements from one rheological state to another by successive or more complex transformations. 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) was taken into consideration. Individual elements of a structure are understood to mean local body volumes, whose local stresses are different. For a crystalline polymer under load, these can be regions both crystalline and amorphous.

MATERIAL AND METHODS

Materials

Three commercially produced structural particleboards bonded with urea formaldehyde resin (UF) provided by Kronospan UA Ltd. were used for this study: melamine faced particleboard (MF PB) according to EN 14322; veneered faced particleboard by oak (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) of boards with thicknesses of 18 mm were cut into 450 mm × 50 mm pieces. Panels before cutting and all specimens were conditioned at 20 °C and 65% RH, to the moisture content of about 5%.

Static 3-point bending tests were carried out in the special test machine with temperature-controlled chamber (BOIKO *et al.* 2013). Specimens were prepared and cut according to ASTM D 1037-12. Loading force and deflection were measured, and MOR and MOE were calculated according to Section 9 in ASTM D 1037-12. Investigated temperatures 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 (KULMAN and BOIKO 2016). The mechanical properties of reference samples were tested in the chamber at the target temperature, results are shown in Table 1. One hundred fifty specimens were cut from each type of board. Ten test pieces were prepared for determination the modulus of elasticity (MOE) and modulus of rupture (MOR) before main testing.

Tab. 1 Standard properties of particleboard.

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

^aMF PB – Melamine Faced Particleboard.

^bVF PB – Veneered Faced Particleboard.

^cP2 PB – Particleboard according to EN 312, type P2.

Tests according to the scheme of three-point bending according to ASTM D 1037-12 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.

Model hypothesis and rationale

The option of sequential destruction in two elementary stages, which occur simultaneously in the body for its deformation-destruction (DD) is considered. The scheme of transformation of structural elements in the process is given in the following form: E→VE→D. The rate of destruction is defined as the change in the number of destroyed structural elements N per unit time, attributed to the unit volume of the body.

We first assume that destruction can occur in any body volume (homogeneous destruction). Unlike heterogeneous destruction, when it can occur at the boundaries of phase distribution. The rate of destruction is written:

$$r = \pm dN/Vdt \text{ (for homogeneous destruction),}$$

$$r = \pm dN/Sdt \text{ (for heterogeneous destruction).}$$

Derivative sign means, spent or accumulated (formed) or a certain amount of SE in different states in the process of destruction. If, during homogeneous destruction, the volume of the system remains constant (closed system), then: $dN/V = dC$. Hence, the rate of destruction is related to the concentration of elements of the structure in time: $r = \pm dC/dt$.

We apply the stoichiometric law of equivalents to the kinetics of DD, which states that the ratio the number of SE, that change their state, is equal to or a multiple of the molar quantities equivalents. In our case, the equivalent is some part of the volume of the body, which, when destroyed, becomes one of the destroyed structural elements. That is, this element is formed only as a result of DD.

We also apply the law of multiple relations to the quantitative description of the DD process. According to the law of multiple relations, in the event of destruction, the mass of one type of SE is the mass of another type of SE, which are referred to as small integers. The law of multiple relations is confirmed by the discreteness of the process of destruction, as well as by the fact that all destroyed elements of one homogeneous substance have the same concentration and a strictly defined specific mass (volume).

In our description of the DD process, we will rely on two concepts: first, the law of mass action as the law of a simple process (its elementary stage); secondly, the complexity of the mechanism of the DD process, consisting of one or another set of successive or parallel elementary stages.

The law of the active masses has been applied far beyond chemical kinetics in so-called "models of development" and has been widely used in biology and ecology, economics, neurophysiology and genetics. The fundamental concept of chemical kinetics is the mechanism of reaction. In a broad sense, it is the interpretation of experienced data about the complex process. Such a mechanism should identify the individual stages and stages of the process, describe the characteristics of the intermediate products, certain energy levels

of the process, etc. A narrow understanding of the mechanism as a set of stages can also be applied. If the stages are assumed to be simple, then they consist of elementary reactions as a kinetic law, which is accepted as the law of mass action or the law of acting surfaces - for catalytic reactions. This is the concept of mechanism that operates in formal kinetics, which studies kinetic models – systems of differential and algebraic equations corresponding to the mechanism of the process.

The two concepts outlined above define the development of two lines that should complement each other. Namely, it is a study of the kinetic regularities of the elementary act of fracture and the design of the theory of kinetics of complex joint deformations.

Mathematical model of deformation-destruction process

Let us write down the process of the DD of a body in the form of a change in the number of structural elements that are in different states during the whole time before destruction. The exponential dependence of the change in the concentration of submicrocracks, microcracks and macrocracks on creep gives reason to consider the process of delocalized destruction as a kinetic analogue of the first order process (REGEL *et al.* 1974, PETROV *et al.* 1993, YAPICI *et al.* 2016).

The main variables that characterize the state of the system, determine the substances A_i , that is in different rheological states. Denote the number SE in different states as N_i ; n – is the vector of quantities components. Denote the concentration: $C_i \equiv N_i/V$.

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:

$$\frac{dN_i}{dt} = V \sum_s \gamma_{si} W_s(C, T), \quad i = 1, \dots, n \quad (1)$$

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

For each material, there are a priori restrictions on vectors γ_{si} – linear conservation laws (balance ratios). If N_{si} – the number of structural 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 :

$$\sum_i \alpha_{si} N_{ki} = \sum_i \beta_{si} N_{ki} \text{ or } \sum_i \gamma_{si} N_{ki} = 0 \quad (2)$$

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

$$\frac{d}{dt} \sum_i \alpha_{ki} N_i = V \sum_{s,i} \alpha_{si} \gamma_{ki} W_s = 0 \quad (3)$$

Record the speed of each stage of the deformation-destruction process using the law of mass action. At the same time, the general scheme of phenomenological kinetics was used, which consists in recording the equations of the dynamics of state change, based on the general concepts and dependence of the processes of formation and consumption of an individual SE system:

$$W_s(C, T) = W_s^+(C, T) - W_s^-(C, T) \quad (4)$$

$$W_s^+(C, T) = k_s^+(T) \prod_i C_i^{\alpha_{si}} \quad (5)$$

$$W_s^-(C, T) = k_s^-(T) \prod_i C_i^{\beta_{si}} \quad (6)$$

$W_s^+(C, T)$ – function of appearance a structural element in a state C_i (E, VE or D);

$W_s^-(C, T)$ – the function of disappearance a structural element in a state C_i (E, VE or D);

$k_s^{+/-}(T)$ – rate constants of the transition of the SE from one rheological state to another in the s -stage.

From the law of conservation of masses follows, that changes in the concentrations of quantities, characterizing the properties of the material, or their changes during DD, satisfy the ordinary differential equations system (ODE) of the n^{th} order of the form:

$$\frac{dC_i}{dt} = \sum_s \gamma_{si} W_s(C, T), \quad i = 1, \dots, n \quad (7)$$

System (7) is defined in some bounded region of the phase space S : ($0 \leq C_i \leq b_i$, $i = 1, \dots, n$) – simplex process area. The boundaries are determined from the balance of the number of elements of the structure that are in different rheological states.

To create a DD model, first of all, we will compile a list of objects that are involved in this process. Objects by analogy with the study of DD processes can be taken as a state of a separate structural element of the material, which largely determines its behaviour over time: elastic, viscoelastic, destroyed. Thus, the state of the material at certain points in time will be determined by the number of structural elements that are in a particular rheological state.

Denote the objects that enter the material at a certain point in time after its loading, A_1, \dots, A_n . Let us assume for the kinetic model the mechanism of the DD process in the form of a list of its elementary stages. Each stage is determined by its stoichiometric equation:



where s – stage; α_{si}, β_{si} – non-negative integers are stoichiometric coefficients.

The mechanism of DD is interpreted as follows. Each stage corresponds to one elementary transition, each elementary transition goes to one clock cycle, in which only those SE are involved and in the quantities specified in the stoichiometric equation. The elementary act time is much less time between them.

We will consider loading material as a structure consisting of a set of separate structural elements that are under constant external loading. Then the state of its individual structural element at different points in time can be described as follows:

$A_1 \equiv A$ – the elastic state of the structural element (E);

$A_2 \equiv B$ – viscoelastic state (VE);

$A_3 \equiv C$ – destroyed state (D).

Then the following kinetic model of the DD process will correspond to the transformation scheme (3):

$$\frac{dCA(t)}{dt} = -k_1 CA(t) \quad (9)$$

$$\frac{dCB(t)}{dt} = k_1 CA(t) - k_2 CB(t) \quad (10)$$

$$\frac{dCC(t)}{dt} = k_2 CB(t) \quad (11)$$

with initial conditions, $t = 0$: $CA(0) = 1$; $CB(0) = CC(0) = 0$, and boundary conditions: $CA(t) + CB(t) + CC(t) = 1$, where $CA(t) \in (1 \dots 0)$ – the current concentration of structural elements that are in an undamaged, elastic state at time t ; $CB(t) \in (0 \dots 1)$ – the current concentration

of structural elements that are in a non-destructive, i.e. viscoelastic state at time t ; $CC(t) \in (0 \dots 1)$ – the current concentration of the structural elements that are in a destroyed state at time t ; k_1 – the rate constant of the transition of structure elements from elastic state to viscoelastic, s^{-1} ; k_2 – the rate constant of the transition of the elements of the structure from the viscoelastic state to the destroyed, s^{-1} ;

Considering the curve of long load, it can be determined that its initial section contains elements of the structure only in the elastic state, which after removal of the load return to the non-deformed state. During this period of elastic deformation, there is no transition of structural 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 structural elements, i.e., those in elastic or viscoelastic states and an increase in structural 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, i.e.: $CA(t) \propto \varepsilon(t)$.

Since the change in the SE concentrations in one state or another can be given as a first order kinetic dependence (REGEL *et al.* 1974, PETROV *et al.* 1993), we can write:

$$\begin{aligned} \frac{dCA(t)}{dt} &= -k_1 \cdot CA(t) \text{ or, having gone to proportional deformation:} \\ \frac{d\varepsilon_e(t)}{dt} &= -k_1 \cdot \varepsilon_e(t) \end{aligned} \quad (12)$$

We integrate (12) after separation of variables (time, deformation):

$$\frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -k_1 \cdot t, \quad \int_{\varepsilon_1}^{\varepsilon_2} \frac{d\varepsilon_e(t)}{\varepsilon_e(t)} = -\int_{t_1}^{t_2} k_1 dt, \quad \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right) = -k_1(t_2 - t_1), \quad k_1 = -\frac{1}{(t_2 - t_1)} \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right). \quad (13)$$

As we can see, when the deformation changes ε_1 and ε_2 by the same number of times the value of k_1 does not change. This allows for the creation of a kinetic model of deformation-destruction to replace concentrations proportional to their values – deformations, stresses, acoustic or electromagnetic emission pulses, quantities of matter, etc.

The magnitude inverse of the first order reaction rate constant, $\tau_e = 1/k_1$, has a dimension of time and characterizes with creep the average life expectancy of SE, which 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 structural elements that are in the viscoelastic state: $\tau_{ve} = 1/k_2$.

Since time is included in Eq. (13) as a difference rather than a relation as a deformation, we introduce a dimensionless time to eliminate the dimension factor: $\tau_i = t_i / t_{cr}$. At the same time, 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:

$$\varepsilon_e + \varepsilon_{ve} = \varepsilon_{cr} \quad (14)$$

$$t_e + t_{ve} = t_{cr} \quad (15)$$

Because according to Eqs. (12), (14):

$$\frac{1}{k_1} \dot{\varepsilon}_e + \frac{1}{k_2} \dot{\varepsilon}_{ve} = \varepsilon_{cr}, \text{ then } \frac{1}{k_1} + \frac{1}{k_2} = \frac{\sum_{t_1}^{t_{cr}} t_{e_i} + \sum_{t_1}^{t_{cr}} t_{ve_i}}{t_{cr}} = 1 \quad (16)$$

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

$$k_2 = \frac{\ln\left(\frac{\varepsilon_2}{\varepsilon_1}\right)}{t_1 - t_2 - t_{cr} * \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)} \quad (17)$$

The solution of the system of differential equations (9), (10), (11), for example by the operating method, allows to obtain values of current concentrations of SE, which are in elastic, viscoelastic and destroyed states:

$$CA(t) = CA(0) e^{-k_1 t} \quad (18)$$

$$CB(t) = CA(0) \left(\frac{k_1}{k_1 - k_2} e^{-k_2 t} - \frac{k_1}{k_1 - k_2} e^{-k_1 t} \right) \quad (19)$$

$$CC(t) = CA(0) \left(1 - \frac{k_1}{k_1 - k_2} e^{-k_2 t} + \frac{k_2}{k_1 - k_2} e^{-k_1 t} \right) \quad (20)$$

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 we get:

$$\int_0^1 CA(t) dt + \int_0^1 CB(t) dt + \int_0^1 CC(t) dt = 1 \quad (21)$$

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

The method involves determining the characteristic parameters of the damage and predicting the time of reaching the critical mark of the measure of damage. While as a preventive comparison of the degree of damage is a scalar value ψ which is equal to the ratio of the current concentration of destroyed elements of the structure to the current concentration of non-destructive elements of the structure. The resource is considered to be exhaustive value the extent of damage exceeding (KULMAN 2020):

$$\psi = \frac{CC(t)}{CA(t) + CB(t)} \geq \psi_f = 1 \quad (22)$$

where ψ_f – a measure of permissible damage; $CA(t)$, $CB(t)$, $CC(t)$ – are determined by formulas (18), (19), (20), respectively; $k_1 = \frac{1}{t_1 - t_2} \ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)$ – rate constant of transition of

structure elements from elastic state to viscoelastic creep diagram, s^{-1} ; t_1 – the time of the end of the section of elastic deformation and the beginning of the section of viscoelastic deformation, with; t_2 – the time of measurement of deformation at the site of constant creep; ε_1 – deformation at time t_1 ; ε_2 – deformation at time t_2 ; $k_2 = \alpha^{-1} k_1$ – the rate constant of the transition of the elements of the structure from the viscoelastic state to the destroyed, s^{-1} ; α – parameter characterizing 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 by 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 - absolute deformation, μm ; t - 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 the section 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 $t_2 = t_{cr} / (2 \dots 3)$ and at this point the deflection value is determined. Further, formulas (13) and (17) determine the value k_1 and k_2 , as well as the value α :

$$\alpha = k_1/k_2 \quad (23)$$

By measuring the change in the deformation of a part over time, a control chart of deformation is constructed. The moment of time is chosen t_{2k} at the site of constant creep and absolute deformation at that moment is recorded ε_{2k} . From Eq. (16), there is a value k_{1k} , and the Eq. (23) $k_{2k} = k_{1k}/\alpha$.

Using Eqs. (17), (18), (19), it is determined the change in the current concentrations of SE, which are in elastic, viscoelastic and fractured states. And on the basis of Eq. (22) the estimated time is determined t_ψ reaching the limit value of the damage parameter ψ .

RESULTS AND DISCUSSION

The experimental factor levels and test results of studies of the long-term strength particleboard at constant load are shown in Table 2.

Tab. 2 Experimental factors levels and test results for particleboards.

Board type	Test conditions		Test results ^a									
	Stress level (MPa)	Temperature (°C)	Displacement, mm					Time displacement, h				
			In all ε_{cr}	visco elastic ε_{ve}	%	elastic ε_e	%	In all t_{cr}	visco elastic t_{ve}	%	elastic t_e	%
MF PB	12.8	20	2.46	0.79	32.1	1.67	67.9	127.1	98.4	77.4	28.70	22.6
		60	3.95	1.33	33.7	2.62	66.3	84.00	73.3	87.3	10.70	12.7
VF PB	15.4	20	1.50	0.59	39.3	0.91	60.7	477.82	380.9	79.7	96.92	20.3
		60	1.77	0.54	30.5	1.23	69.5	190.71	140.0	73.4	50.74	26.6
P2 PB	12.15	20	4.91	1.63	33.2	3.28	66.8	78.77	69.6	88.4	9.17	11.6
		60	1.57	0.51	32.1	1.07	67.9	35.75	24.2	67.8	11.51	32.2

^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, characteristic for the curves of elastic and viscoelastic deformation (Fig. 1).

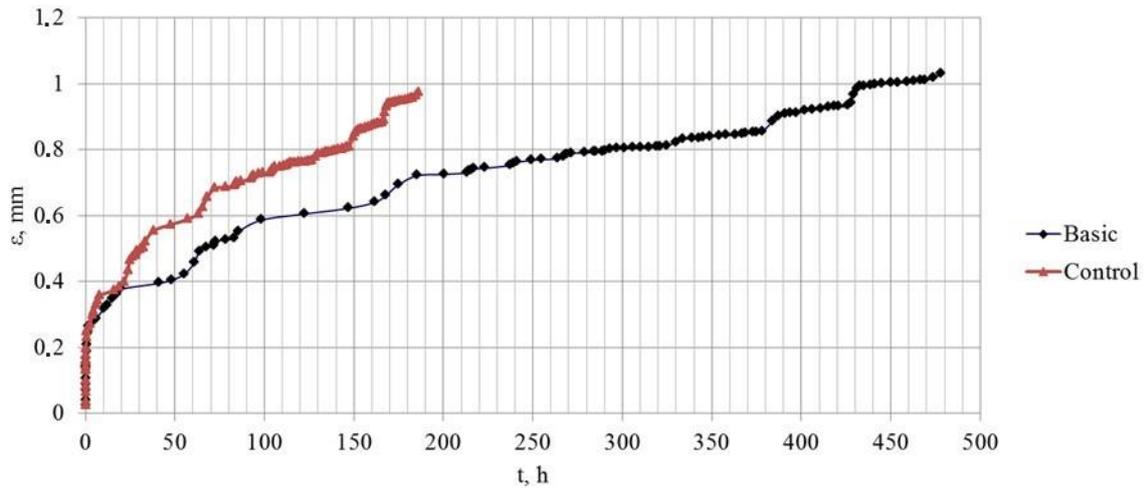
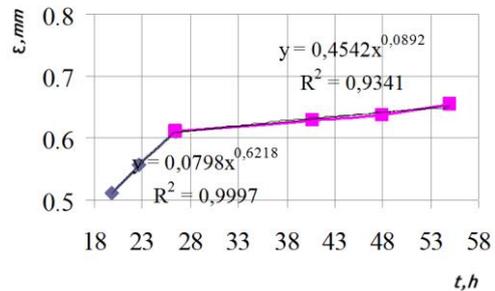
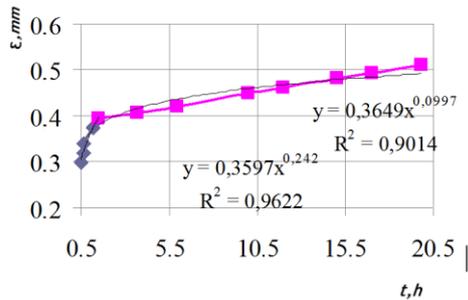
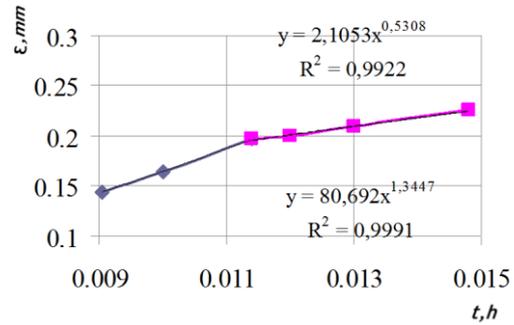
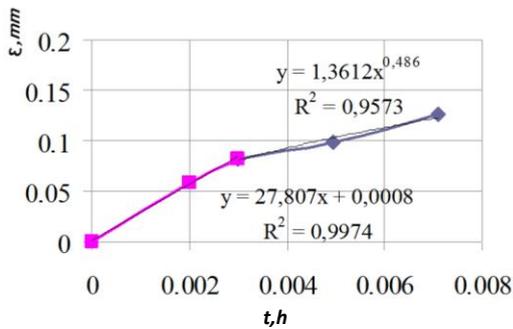


Fig. 1 Basic and control creep diagrams. Dependences of the average absolute deformation for one group of the samples VF PB by stress level $SL = 15.4$ MPa and temperature $T = 20$ °C for basic diagram, and by stress level $SL = 17.7$ MPa and temperature $T = 20$ °C for control (predicted) diagram.

The nature of the deformation-destruction curves over time (Fig. 1 and 2) 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 Fig. 2, there is shown that the general curve of dependence of deformation in time, consists of separate sections, which have different repetitive strain rates.



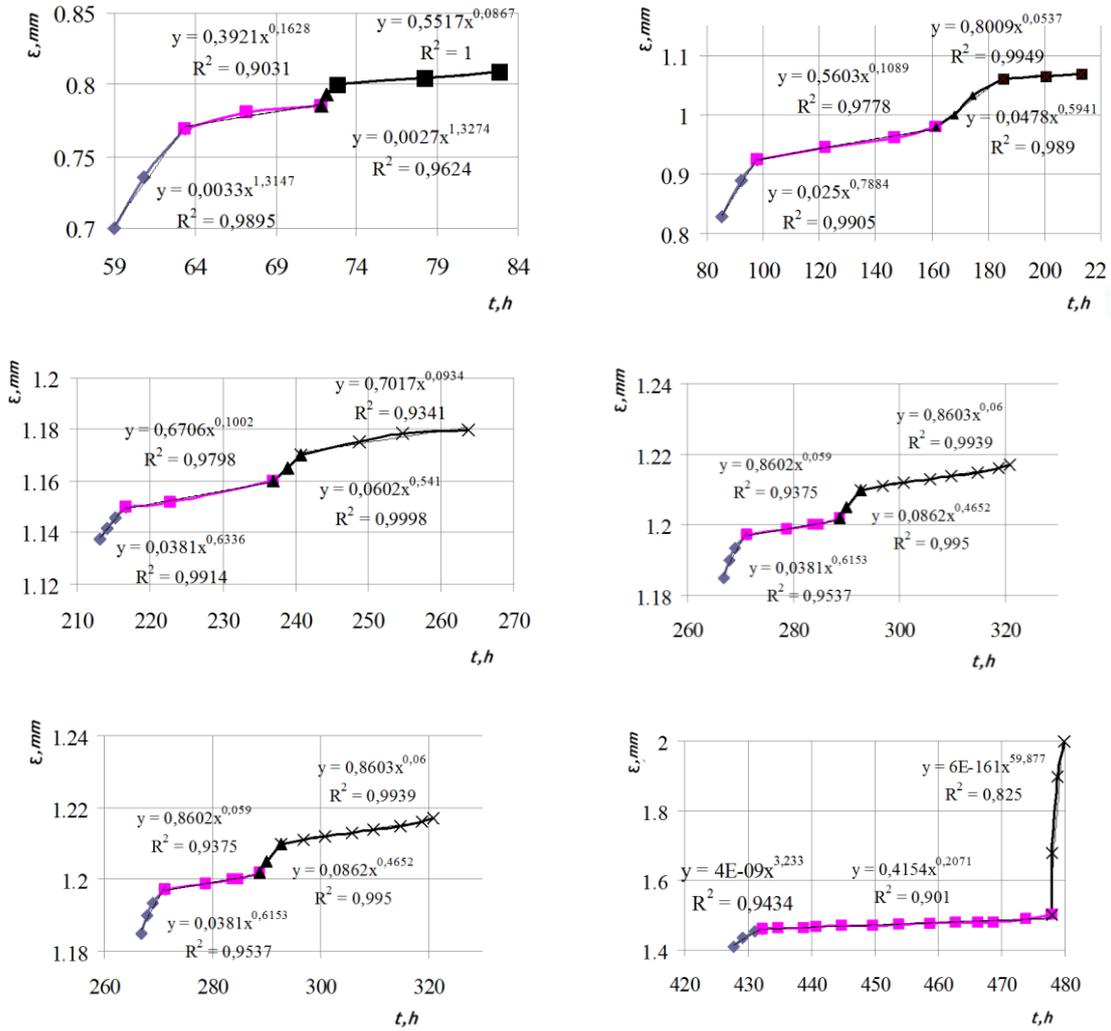


Fig. 2 Fragments by different time periods in creep curve for one of the sample VF PB by stress level $SL = 15.4$ MPa and temperature $T = 20$ °C.

Table 2 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, we can say that the general deformation curves up to fracture periodically repeats cycles of elastic and viscoelastic behaviour. This confirms our assumption that the process is multi-stage (GÜNTEKIN and AYDIN 2016, VAN BLOKLAND *et al.* 2019, SHARAPOV *et al.* 2019).

According to the graph of the basic deformation diagram (basic long-term strength curve) Fig. 1 we define such quantities: $t_1 = 0.003 \times 3600 = 10.8$ [s], $\epsilon_1 = 80$ [μm], $t_2 = 200 \times 3600 = 7.2 \times 10^5$ [s], $\epsilon_2 = 730$ [μm], $t_{cr} = 477 \times 3600 = 1.717 \times 10^6$ [s].

By Eqs. (13), (17), (23) we define: $k_1 = 0.307 \times 10^{-5} \text{ s}^{-1}$, $k_2 = 0.719 \times 10^{-6} \text{ s}^{-1}$; $\alpha = 4.273$.

A basic model diagram is shown in Fig. 3, constructed in the coordinates of the “concentrations of SE in different states – time”.

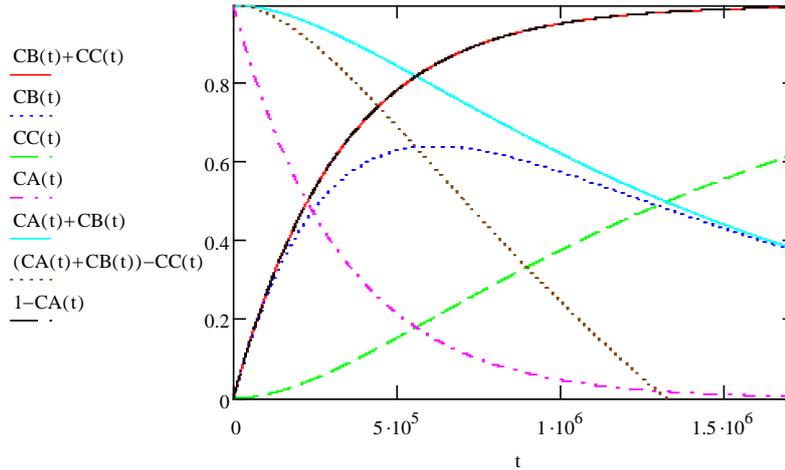


Fig. 3. Basic model diagram of long-term strength (creep): change concentrations of SE in the states: elastic – CA (t), viscoelastic – CB (t), destroyed – CC (t) in time for the basic deformation diagram.

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: $t_{2k} = 100 \times 3600 = 360000$ s, $\varepsilon_{2k} = 730$ [μm].

Using Eqs. (13), (23), the values of the rate constants k_{1k} , k_{2k} control deformation chart were determined:

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

The critical amount of damage will be reached at the moment when, based on the condition (22):

$$CA(t_\psi) + CB(t_\psi) - CC(t_\psi) = 0 \quad (24)$$

Solving together equations (18), (19), (20) and (24), we find the time to the predicted destruction: $t_{predict \psi} = 6.6 \times 10^5$ s.

The actual time to destruction of the control sample is $t_{fact \psi} = 6.7 \times 10^5$ s.

Fig. 4 shows a control model diagram, constructed in the coordinates of “concentrations of SE, which are in different states – time”, which clearly shows the process of loss of bearing capacity of the part in time during creep.

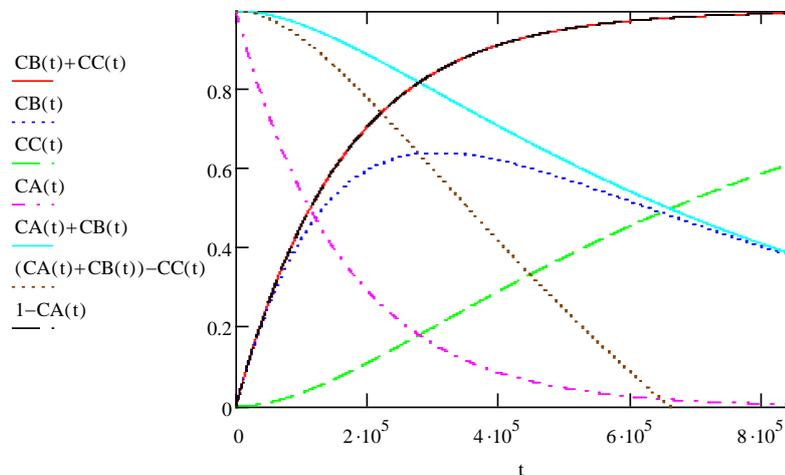


Fig. 4 Control (predicted) creep model diagram: change concentrations of SE in the states: elastic - CA (t), viscoelastic - CB (t), destroyed - CC (t) in time for the deformation control chart.

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.

Tab. 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	12.1	20	283572 ± 850	1.88E-05	4.34E-06	4.331
		60	128700 ± 780	4.53E-05	9.38E-06	4.831

^aThe 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.

Tab. 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	14.7	20	1.43E-05	3.30E-06	338933 ± 7500 ^a	372827 ^b
		60	1.82E-05	4.27E-06	262957 ± 5600	289252
VF PB	17.7	20	7.99E-06	1.87E-06	670000 ± 9800	660000
		60	1.19E-05	2.67E-06	504821 ± 5500	458928
P2 PB	13.9	20	2.50E-05	5.78E-06	234357 ± 6200	213052
		60	5.95E-05	1.23E-05	99000 ± 860	98000

^aThe confidence interval is indicated at $p = 0.05$ level.

^bPrediction results based on average kinetic coefficients.

A multi-stage description of the kinetics of deformation-fracture allows us to take into account the change in the rheological state of the material during its deformation. 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. (22)) with the actual time before the destruction of the control samples (Tab. 4. Creep life control diagram), we can conclude that it is quite high convergence of these quantities. 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 (MELZEROVÁ *et al.* 2016).

CONCLUSIONS

Based on the analysis of the results of theoretical and experimental studies of the process of deformation-destruction of wood composites, we can draw the following conclusions:

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

2. The use of formal kinetics methods for modelling the physicochemical processes that occur during deformation-destruction allows to design 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 to increase the accuracy of the prediction of allowable time under different load schemes during creep.

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