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CALCULATION OF BENDING ELEMENTS OF WOOD AFTER THE ACTION OF LOW-CYCLE REPEATED LOADS ON THE CRITERION OF DEFORMATION DESTRUCTION

РОЗРАХУНОК ЗГИНАЛЬНИХ ЕЛЕМЕНТІВ З ДЕРЕВИНИ ПІСЛЯ ДІЇ МАЛОЦИКЛОВИХ ПОВТОРНИХ НАВАНТАЖЕНЬ ЗА КРИТЕРІЄМ ДЕФОРМАЦІЙНОГО РУЙНУВАННЯ

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В статті наведені рівняння рівноваги для розрахунку нормального перерізу згинального елемента з деревини після сприйняття ним повторних малоциклових навантажень. Запропоновано деформаційно-силову модель методики розрахунку дерев'яних балок прямокутного перерізу з цільної та клеєної деревини з врахуванням виникнення складок в стиснутій зоні.
Результати розробки дають змогу проектувати конструкції з цільної та клеєної деревини використовуючи більш повне врахування можливостей матеріалу та особливостей роботи елементу, а це дасть можливість більш економно підбирати поперечний переріз елементів будівельних конструкцій.

Existing norms of design for wooden constructions valid in different countries including Ukraine entirely disregard the effect of low-cycle repeated loadings during the operation of buildings and structures. The article deals with development of the bearing capacity computation of the bending elements manufactured from solid and glue-laminated wood exposed to repeated loadings in accordance with the deformation model.
Equilibrium equations for computing the bending element made of wood after being exposed to repeated loadings are presented in the article. The deformation method is proposed for the computation of the rectangular wooden beams manufactured from solid and glued laminated wood with allowance for the occurrence of folds in the compression zone.
The results of the research allow designing the solid and glue-laminated wooden constructions taking into consideration the possibilities of the

material and peculiar features of the performance of the element, which in turn will allow choosing the cross-section of the elements of building structures more economically.
On the basis of the study of the process of layer deformation by section height and the determination of the characteristics of the stress-strain state of these layers under the effect of repeated loading, it is possible to fulfill more accurate computation of the elements manufactured from wood at different stages of the stress-strain state through destruction.

Ключові слова. Деревина, несуча здатність, повторні навантаження, згинальний момент, деформації, напруження.

Introduction. Year by year the use of wood, especially glue-laminated wood, in the construction industry is increasing in almost all the industrialized countriesand this fact is indisputable. The durability of the wooden structures depends on the quality of the material and its manufacturing, the operational environment and the level of the stress-strain state. This is the only adequately strong construction material which is perpetually recovered in nature and causes almost no catastrophic ecological consequences at bulk utilization. Therefore, it can be named the material of the future in the construction of industrial, sporting, public and residential buildings and structures. The performance of the elements manufactured both fromsolid and glue-laminated wood under the conditions of the repeated bending is currently in sufficiently studied.

Existing norms [1, 2, 3, 4] do not take into consideration the behavior of the beams made of solid and glue-laminated wood in actual operating environment and under repeated non-cyclic loadings (Fig. 1), neither do they allow the determination of the following: the position of the neutral plane (neutral line) which separates the compression and tensile zones; the stage of the stress-strain state of the cross-section at various stages of loading the entire structure is exposed to.

In the computation model of the cross-section for determining the load bearing capacity of the constructions made of solid and glue-laminated wood a triangular distribution diagram of stresses is adopted in compression and tensile wood zones under the application of single loadings. At such distribution diagrams, the height of the compression zone of wood and the position of the neutral plane (neutral line) does not change as the loading increases. However, this fails to meet their actual position and prevents from considering and accurately determining the stress-stain state in the normal section of the element at different stages of its performance. At the same time, under the work in compression along the fibers the deformation diagram is known to have a curvilinear character with a clearly pronounced downward leg[5, 6, 7, 8, 9, 10]. However, all the currently existing computation methods do not take into consideration the yielding behavior of the

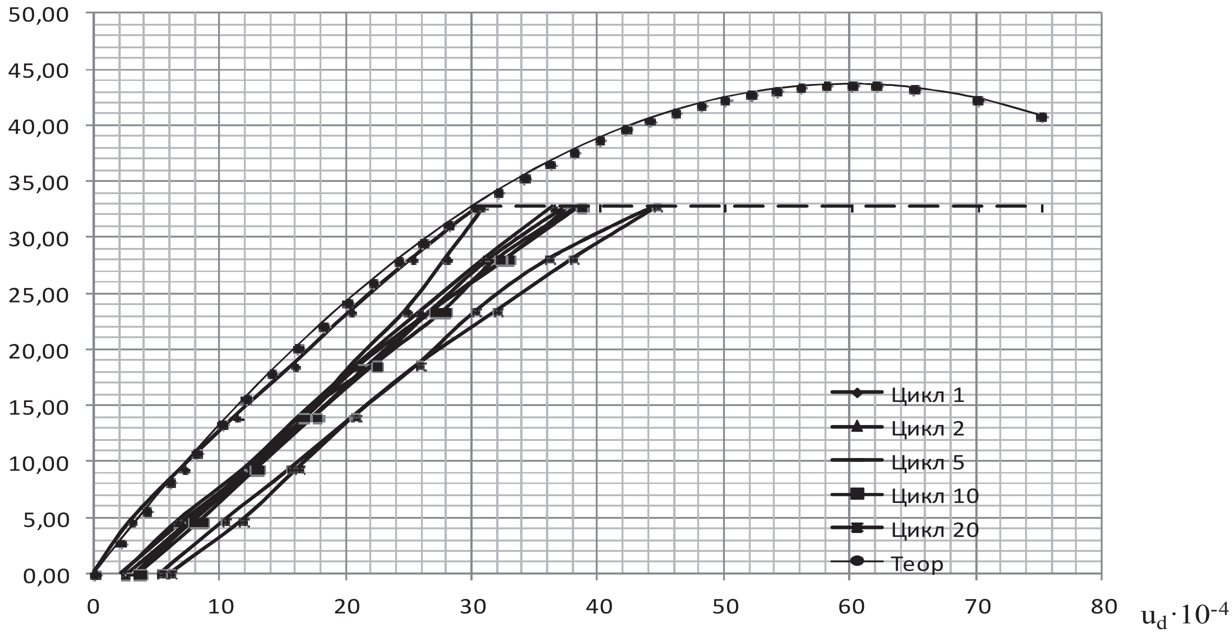

Fig.1 Wood deformation diagram “$\sigma_d - u_d$”of the performance of wood (pine) along the fibers exposed to the low-cycle loading with stress levels of (0 - 0.75) $f_{c,o,T}$

material as well as the presence of a downward leg under the compression strain of wood, which is a certain important backup in the behavior of the structure. It is definitely counter-productive to use the behavior of the wood throughout the length of the downward legunder the effect of significant deformations while a limited part of the backupis needed to be used.

Thus, it is possible to avoid these disadvantages by adopting a curvilinear distribution diagram of stresses in the wood of the compression zone [11, 12, 13, 14], which to a greater extent complies with the actual performance of the cross-sections of the bending elements manufactured from wood.

State-of-the-art summary. The most important trend of the scientific-and-technological advance is to ensure the reliability of building structures. One of the means of fulfilling this task is the study of the behavior of the structures manufactured from wood under the conditions which are as close to real as possible. In this regard, the issues on improving computations and design of building structures have become increasingly important. Closer definition of the strength and deformation characteristics of the elements manufactured from wood underlow-cycle loadings are of great importance, since a large number of structures under exploitation performunder such conditions.

As a rule, technological exploitation levels of low-cycle loadings (for the covering of industrial, public and residential buildings as well as multiple purpose constructions) do not exceed the estimated marginal levels, and in many cases, operational levels. The application of such loadings allows the performance of the material of the structure elements at low and medium stress levels. This creates favorable conditions for the redistribution of stresses with gradual relaxation and the subsequent elimination of the stress concentrators within the defects of the material, resulting in densification and suspension in the growth of deformations. This process is characterized as low-cycle strengthening, and the phenomenon of suspension in the growth of deformations is defined as low-cycle adaptability.

On the basis of the study of the process of layer deformation by section height and the determination of the characteristics of the stress-strain state of these layers under the effect of repeated loading, it is possible to fulfill more accurate computation of the elements manufactured from wood at different stages of the stress-strain state[15, 16] through destruction.

The currently exiting methods for predicting the strength and durability of anisotropic material [17, 18] are based on a built-up mathematical model of durability, which takes into consideration the level of prolonged loadings, humidity and ambient temperature of the operation environment, but does not consider the loading variations.

The purpose of this study is to produce the computation of bending elements manufactured from solid and glue-laminated wood after the application of repeated non-cyclic loadings according to the deformation criterion at various stages of the element's performance [15].

Presentation of the core material. As a rule, in the computations of wooden structures and in the current norms [3], a cross-section of dense, homogeneous, solid wood is considered to be an estimated cross-section. This approach to determining the estimated cross-section of wooden structures has a number of drawbacks.

What should be read as the term “estimated cross-section” for a wooden element? In building mechanics this term is associated with the equilibrium conditions of the cut-off section of the element, the assumptions about the distribution of deformations and stresses in this section and the criterion of the exhaustion of bearing capacity.

The most accurate evaluation of the behavior of the bending element made of wood, which at the border stage of performance [15] operates with a fold in the compression zone, can be obtained if we consider, as adopted in building mechanics, the estimated cross-section passing through the fold [19, 20], which is often difficult to spot in a wooden elementin a pre-destruction state due to the instant destruction of the structure.

The accepted “estimated cross-section” provides an opportunity to make assumptions about the shape of the stress diagram and its maximum ordinate in the adopted cross-section with a fold in the compression zone of an element made of wood. However, it should be noted that we are considering elastoplastic material with limited deformability.

For the estimated cross-section with a fold in a compression zone of an element made of wood one can use the common laws of deformation distribution by section height, both in compression and tensile zones. In fact, in this case one can use the apparatus of infinitesimal quantities. Such an apparatus is used under the condition of continuity of the function around the point of the cross-section being considered.

The use of such an apparatus in the mechanics ofrigidbodiesis determined by the hypothesis of continuity and homogeneity of the material [21]. In the section with a fold in the compression zone of the wooden element these conditions are practically fulfilled. Consequently, the estimated cross-section is a model that reflects the patterns of deformation and destruction of an element made of wood.

It should be noted here that according to the author's suggestions the characteristics such as the strength of the solid and glue-laminated wood ($f_{c,0,d}$, $f_{t,0,d}$) and the average value of the elasticity modulus (E_{mean}), which are based on current norms [1, 3], are to be determined through testing the samples with the structural dimensions and according to a certain specified methodology. Therefore, the approach adopted does not contradict the accumulated rich material on strength, bearing capacity and deflections of the elements made of solid or glue-laminated wood, performing on a transverse symmetrical or unsymmetrical bending.

For the construction of this model, data on the shape of the deformation and stress diagrams as well as the relation between deformations and stresses are obtained theoretically.

The adoption of the concept of “an estimated cross-section” allows using the law of distribution of deformations bisection height and the layered connection between deformations and stresses performing in the cross-section.

Wood when it performs in the structure manufactured from wood and undergoes a heterogeneous stress-strain state leads to a redistribution of stresses in the pre-boundary and boundary states. Such a redistribution of stresses is characterized by their decrease within the most deformed areas of the compression zone with the increase in deformations and stresses in less deformed areas with the formation of folds. In addition, the existing model of the stress-strain state does not take into consideration the downward leg of the deformation of wood and generally suggests a linear dependence between stresses and deformations.

The destruction of an element made of wood at the moment when the deformations at the point which is the most remote from the neutral line of the tensile zone reach the boundary values proposed to be considered a criterion of destruction in a transverse normal section. This is a deformation criterion and it is as follows:

$$u_{c,fin,d} = u_{c,fin,d,u}, \qquad (1)$$

where $u_{c,fin,d}$ is the value of the total relative deformations of the most tensile layers of wood; $u_{c,fin,d,u}$ is the limit value of the total relative deformations of wood in tension.

Let us consider the stress-strain behavior of the bending element made of wood. Fig. 2.

The basis of the computation method is as follows:

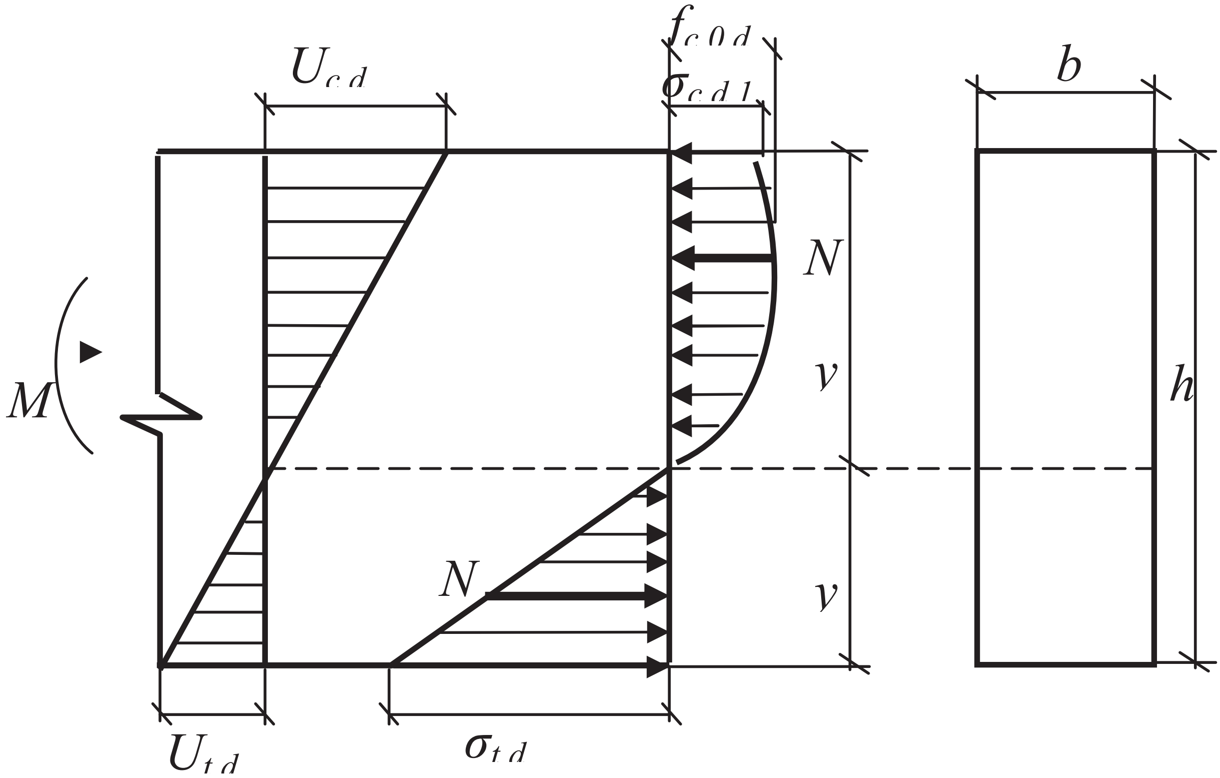

Fig.2 Relative deformations and internal flexure forces in the rectangular cross-section of the bending element made of wood after the effect of repeated loadings

a) the estimated section is a normal cross-section to the longitudinal axis of the element in which a fold is formed in the compression zone;

b) the hypothesis about the linear distribution of deformations is true with regard to the height of the estimated cross-section for the mean deformations;

c) the relation between stresses and deformations of the tensile wood is accepted as linear dependence;

d) the relation between the stresses and deformations of the compressed wood is accepted as a transformed diagram, which is depicted in Fig. 2 and is described by a polynomial of the second degree [6,7].

e) the wooden elements, in which force factors should be applied without causing torsion, are considered;

f) the peculiar values of the resistance of wood in a wooden element are accepted as estimated values.

The criteria of loss of bearing capacity of the cross-section are as follows:

a) the destruction of the tensile wood at achieving the limit values of deformation by the most tensile layer;

b) the extreme criterion is the loss of equilibrium between internal and external efforts;

c) the computation is completed according to the deformation model taking into consideration the growth of deformations in the estimated cross-section;

d) for the compression of wood a positive sign is accepted and for tension - a negative sign.

Based on the relative deformations $u_{c,d,cyc,n}$ which occurred in the normal cross-section of the bending element made of wood after the effects of repeated loadings [22] on the n-th cycle, we can describe the stresses at fixed values of the height of the compression zone of wood $y_1 = y_c$ and deformations of the border compressed wood fibber at $u_{c,d} = u_{c,d,cyc,n,1}$ and the deformations of the extreme tensile wood layer $u_{t,d} = u_{t,d,1}$. Considering the accumulation of residual deformations, the equation of equilibrium of external and internal forces in the normal cross-section are as follows:

$$\sum M_{и,л,cyc,n} = 0 \; ; \; M_{cyc,n} = M_{c,d,cyc,n} + M_{t,d,cyc,n}; \tag{2}$$

$$\sum N_{cyc,n} = 0 \; ; \; N_{c,d,cyc,n} = N_{t,d,cyc,n} \, , \tag{3}$$

where $M_{cyc,n}$; $M_{c,d,cyc,n}$ and $M_{t,d,cyc,n}$ are the bending moments in relation to external loading, stresses in the compressed and tensile wood at the n-th loading cycle; $N_{c,d,cyc,n}$ and $N_{t,d,cyc,n}$ are equals to the internal forces in the compressed and tensile wood of the normal cross-section of the bending element made of wood at the n-th cycle.

In the normal cross-section of the bending element, stress is described by different functions in three different areas of the cross-section height. The first area is the tension area which begins from the bottom of the element to the neutral line; the second area is the compression area from the neutral line to the maximum value of the compression stresses; the third area is the compression stress from the end of the second area to the top of the bending element.

The "strain-strain "dependence $\sigma - u$ for the middle of the wooden bending element in the normal cross-section at the n-th cycle is expressed by two functions in different areas:

the first linear function helps to determine the stress in the tensile zone of the normal section in the middle of the span of the wooden element and it is valid in the range from 0 to y_t ;

$$\sigma_{t,d,cyc,n} = f_1(u) = E \cdot u_{t,d,cyc,n} = E(\frac{1}{\rho_{cyc}}) y_{t,cyc,n} \, ,, \tag{4}$$

where E is the elasticity modulus of wood under tension; $u_{t,d,cyc,n}$ are relative deformations of wood under tension the n-th cycle of the load application;

the second function describes the stresses occurring in two areas of the compression zone of the normal cross-section of the wooden element in the range from 0 to y_c ;

$$\sigma_{c,d,cyc,n} = f_2(u) = k_1 u_{c,d,cyc,n} + k_c u^2_{c,d,cyc,n} = k_1 \frac{1}{\rho_{cyc}} y_{c,cyc,n} + k_2 (\frac{1}{\rho_{cyc}})^2 y_{c,cyc,n}, \quad (5)$$

where k_1, k_c are the coefficients of the polynomial which are to be determined by the expressions:

$$k_1 = \frac{2 f_{c,o,d}}{u_{c,fin,d}}; \; k_c = -\frac{f_{c,o,d}}{u^2_{c,fin,d}}, \quad (6)$$

where $f_{c,0,d}$ is the estimated value of the compression along the fibers; $u_{c,fin,d}$ are relative full deformations under the compression of wood;

$$u_{c,cyc,n} = y_c \frac{1}{\rho_{cyc}}; \; u_{t,d,cyc,n} = y_t \frac{1}{\rho_{cyc}}, \quad (7)$$

where $\frac{1}{\rho_{cyc}}$ – element curve on the n-th cycle of repeated loads.

The tensile force in this cross-section will be equal to:

$$N_{t,cyc,n} = b \int_0^{y_{t,cyc,n}} f_1(u) dy = b \int_0^{u_{t,cyc,n}} E \frac{1}{\rho_{cyc}} y_{t,d,cyc,n} dy = \frac{1}{\rho_{cyc}} bE \frac{y^2_{t,cyc,n}}{2}, \quad (8)$$

where $dy = \frac{y_{t,cyc,n}}{u_{t,d,cyc,n}} du$

The compression forces in this cross-section will be equal to:

$$N_{c,cyc,n} = b \int_0^{y_{c,cyc,n}} f_2(u) dy = b \int_0^{u_{c,cyc,n}} \left(k_1 \frac{1}{\rho_{cyc}} y_{c,cyc,n} + k_c (\frac{1}{\rho_{cyc}})^2 y^2_{c,cyc,n} \right) dy =$$

$$= b \left(k_1 \frac{1}{\rho_{cyc}} \cdot \frac{y^2_{c,cyc,n}}{2} + k_c (\frac{1}{\rho_{cyc}})^2 \frac{y^3_{c,cyc,n}}{3} \right), \quad (9)$$

where $dy = \frac{y_{c,cyc,n}}{u_{c,d,cyc,n}} du \cdot$

The bending moment from the neutral line for the tensile zone in this cross-section will be equal to:

$$M_{t,cyc,n} = \int_0^{y_{t,cyc,n}} b y_{t,cyc,n} \cdot f_1(u) dy = \int_0^{u_{t,cyc,n}} bE y^2_{t,cyc,n} \frac{1}{\rho_{cyc}} dy = bE \frac{1}{\rho_{cyc}} \cdot \frac{y^3_{t,cyc,n}}{3}, \quad (10)$$

where $dy = \frac{y_{t,cyc,n}}{u_{t,d,cyc,n}} du$; $y_t = \frac{y_{t,cyc,n}}{u_{t,d,,cyc,n}} u_{c,d,cyc,n}$.

The bending moment from the neutral line for the compression zone in this cross-section will be determined by:

$$M_{c,cyc,n} = b \int_0^{y_{c,cyc,n}} y_c \cdot f_2(u) dy =$$

$$= b \int_0^{u_{c,cyc,n}} \left(k_1 (\frac{1}{\rho_{cyc}}) y_{c,cyc,n}^2 + k_c (\frac{1}{\rho_{cyc}}) y_{c,cyc,n}^3 \right) dy = b \left(k_1 (\frac{1}{\rho_{cyc}}) \cdot \frac{y_{c,cyc,n}^3}{3} + k_c (\frac{1}{\rho_{cyc}})^2 \cdot \frac{y_{c,cyc,n}^4}{4} \right), \quad (11)$$

where $dy = \frac{y_{c,cyc,n}}{u_{c,d,cyc,n}} du$, $y_c = \frac{y_{c,cyc,n}}{u_{c,d,1}} u_{c,d,cyc,n}$.

It is possible to determine the number of cycles (low-cycle endurance), which a constructive bending element made of solid or glue-laminated wood can withstand without breaking, by the fact that the low-cycle endurance of wood in compression is determined by the proposition [22, 23] according to the formula

$$n_{cyc} = \sqrt[-0,0562]{\frac{\eta_{в,cyc}}{0,9909}}, \quad (12)$$

where $\eta_{в,cyc}$ is the upper level of the low-cycle load application at the performance of the wood in compression along the fibers.

Thus the number of cycles of repeated loadings onto the wooden element, which meets the effect of the cross bending, will be determined within the established upper level of the moment of action

$$n_{cyc} = \sqrt[-0,0562]{\frac{k_{cyc}\eta_{в,cyc,M}}{0,9909}}. \quad (13)$$

Herein $\eta_{\text{в,cyc,M}}$ is the upper level of the moment of the beam performance under repeated loadings at average stresses of the layers of the compression zone of the cross-section. It is
possible to establish this level of stresses for the bending element through the level of loadings, that is, through the upper level of the bending moment application

$$\eta_{в,cyc,M} = \frac{M_{cyc}}{M_{руйн}}, \quad (14)$$

where M_{cyc} – is the value of the upper level of the cycle loading;

$M_{руйн}$ – is the value of the crippling loading.

For the transition from the level of loadings to the average level of stresses, it is necessary to take into consideration the uneven distribution of stresses in the layers of the compressed wood zone and the mutual influence of the more stressed layers of wood on the less stressed and vice versa (the mutually supportive performance of the compatible layers of wood) under the application of repeated loadings. In the center of the weight of the compression zone the stress level exceeds the loading level by 10-20% at different load application levels. The correlation between the level of loadings and the level of stresses is expressed through the following coefficient k_{cyc}

$$\eta_{в,cyc,\sigma} = k_{cyc}\eta_{в,cyc,M}. \tag{15}$$

The coefficient k_{cyc}, taking into consideration the excess of stresses over loadings and the supporting effect of the internally adjacent fibers of wood, is recommended to accept $k_{cyc} = 1{,}1$.

Conclusions. 1. The proposed method enables to compute the stress state at all the stages of the performance of the elements manufactured from solid and glue-laminated wood through destruction as well as allows to consider the pre-history of their performance and to assess the impact of various modes of low-cycle loading.

2. The notion of the estimated cross-section with a fold in the compression zone of the wood has been formulated for the pre-destruction stage and the destruction stage, both under the effects of single loading and under the effect of repeated high-level loadings.

3. The improved method for determining the stress-strain state of cross-sections with the use of complete diagrams of wood deformation in compression allows to solve the tasks on the computation of elements made of wood under the effect of any type of compression or bending, not only at the boundary but also at intermediate stages, at the performance mode under single static and low-cycle variable loadings.

4. It is necessary to consider two forms of determining the bearing capacity of an element made of wood when constructing the analytical apparatus of the criteria for the exhaustion of the bearing capacity:

- destruction of an element due to the exhaustion of material strength under the effect of single or repeated loadings;
- destruction due to the loss of stability of the deformation of an element as a result of disbalance between the internal and external forces.

The second criterion was not considered in the study.

5. It is recommended to take into consideration the effect of the low-cycle load application on the subsequent performance of the elements made of solid and glue-laminated wood exposed to the cross bending due to the coefficient of low-cycle durability to ensure further faultless operation.

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