RIGA TECHNICAL UNIVERSITY
Building Faculty
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CREEP OF COMPOSITE WOODEN ELEMENTS SUBJECTED TO BENDING

Civil Engineering, structural engineering (P-06)

Summary of Doctoral Thesis

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CONFIRMATION

I confirm that I have elaborated this doctoral thesis, which is submitted for the obtaining a doctor's degree at Riga Technical University. This doctoral thesis is not submitted in any other university for receiving a scientific degree.

Andris Baikovs …………………………….(Signature)

Date: June 27, 2011

The doctoral thesis is written in Latvian, it includes introduction, 5 chapters, conclusions, bibliography list, 23 tables, 51 figures and photos, in total 110 pages. Bibliography contains 64 sources. This work has been partly supported by the European Social Fund within the National Programme „Support for the carrying out doctoral study programme's and post-doctoral researches" Project „Support for the development of doctoral studies at Riga Technical University".

GENERAL DESCRIPTION OF WORK

Topicality

Currently, boards made from wood slivers, wood fiber or wood chips are widely used in low-rise construction. In the manufacturing of such materials low-value wood and wood industry residues can be widely used, thus supporting a green or sustainable construction which is based on maximum possible nature-friendly living environment creation. One of the basic principles of green building is to use building materials derived from renewable resources such as timber, as well as re-processed non-renewable resources - plastics. Wood as a building material is an environmentally beneficial choice from life-cycle perspective, because ecologists believe that one of the greatest threats to modern society is climate change caused by gases such as carbon dioxide CO_2, which contribute the greenhouse effect; while the wood products and wood building stores a carbon dioxide in the long-term – by using the parts of pulled down wood building components for energy production, climate-affecting gas volume can be reduced significantly as it replaces fossil fuels such as oil exploitation.

Non-standard laminated convex-concave elements are being increasingly used during search process of constructively better material exploitation and aesthetically more attractive solutions for the construction of various structures. In some cases, it is rational to create the middle layer, which consists of glued wood chips or fibered wood industry residues, thus increasing the efficiency of timber weight when the design of various layered wood composite elements are made according to loads and operating conditions. Rational use of wood composite materials in structural elements makes it necessary to build the structure of these materials accordingly to mechanical, moisture and temperature influence, and both material manufacturing process and conditions during the operating period. Effectiveness of strengthening of glued timber construction elements, as well as the dangerous intersections of the advanced composites is based on a series of studies, but there are not enough results of such design element work in the case of long-term loading. This problem is particularly important for the structural elements from wood composites, because according to tests the leading is deformability not the strength - deformations of these elements from loading increases with time (creep).

Therefore, it is significant to qualitatively and quantitatively take into account the behaviour properties of material and its individual components under various pressures and exposure conditions. Unfortunately, the effect of long term loads for various wood composite materials is modeled differently, therefore, for analysis of behavior of the loaded wood composite elements (beams, plates, shells) in the long-term loading conditions, it is necessary to develop simplified prediction method for creep deformations of various composite materials.

Aim of the work

Develop a methodology for calculation of wood composite material deformations in bending, which estimates the effects of restrictive opportunities of deformations caused from moisture effect and long-term load effects, and compare the results with the experimentally obtained in long-term loading of elements subjected to bending.

Research tasks

- Develop a methodology for calculating the moisture-induced deformations and the radius of curvature of the concave-convex elements, which are reinforced with the fiberglass to reduce the moisture deformations.
- Develop a methodology for calculating the creep of composite wooden elements subjected to bending, by using a linear elastic-viscous material deformation law in differential equation form, which is supplemented with the creep curve shape factor α offered by Ogarkov (hereinafter referred to as "supplemented rheological equation")
- Compare the experimental results obtained during the long-term loading of wood beams, “double-T” section beams with a plywood wall, “double-T” section beams with chipboard walls and wood beams shelves, plywood board and particle board, with a constant load, with the analytical results calculated using the developed methodology of the calculation and the other most common linear viscous-elastic material deformation laws.
- Develop a model for the calculation of laminated convex-concave wood composite element deformations caused from moisture changes and taking into account the time factor.

Scientific novelty

- Developed calculation model for determination of curvature radius and longitudinal deformations under variable humidity conditions for initially convex-concave element which consists of orthotropic layers, if for the preservation of original form are used double-sided fiberglass reinforcement.
- Developed the methodology for calculating the actual performance of curved layered wood composite construction elements during the long-term loading under constant load (creep).
- Approbation of the developed creep deformation calculation methodology by comparing the calculated and experimental results of structural elements loaded in time with constant load.
- It is estimated that with the developed methodology can be calculated deformations at constant load for a variety of loaded wood composite elements - beams and plates.

- It is estimated that for entire group of wood material elements, the creep deformations in bending can be described the best by using the "supplemented rheological equation" for which the coefficients are determined by the "developed methodology."

Practical value

Proposed method of shape preservation for convex-concave sheet by using reinforced plastic reinforcement, and for this purpose designed and experimentally verified easy in application long-term deformation prediction method for prediction of long-term creep deformations with constant load loaded convex-concave laminated sheets, beam and plate elements, taking into account rheological characteristics of each individual layer. Developed calculation model for determination of creep deformations for laminated elements, which allows with the FEM assistance operatively determine creep deformations.

Defended propositions

- Developed calculation model for determination of curvature radius for laminated convex-concave plate in variable humidity conditions, if for the preservation of original form the double-sided fiberglass reinforcement is used.
- Determination methodology of creep curve shape factor, relaxation time and long-term modulus for “supplemented rheological equation"
- It is estimated that by using the "developed methodology" for describing experimental results (obtained in long-term flexural loading with a constant load for a variety of wood structural elements - beams, particle board, plywood board, a composite profile double-T beams with chipboard walls and wood shelves, and composite double T-profile beam with plywood walls and wood shelves) the difference between the experimentally determined and calculated results using the “supplemented rheological equation”, for which the coefficients are determined by the “developed methodology”, in average is less than in the case of linear elastic-viscous material deformation law in differential equation form or “supplemented rheological equation”.
- Calculation model for the prediction of deformations caused by moisture changes taking into account the time factor for the convex-concave laminated wood composite element, if it is reinforced on one of the sides or both.

The scope of the scientific work

The thesis consists of an introduction, 5 main chapters, conclusions and a list of used literature. This work consists of 110 pages, 51 pictures, 23 tables, 64 list of references.

List of approbation and publications

The results of the thesis are reported and discussed in the following international conferences:

- 13th International Conference on "Mechanics of Composite Materials" (Jurmala, April 2004).
- RTU 45th International Scientific Conference (Riga, 2004. October).
- DAAAM 5th International Conference "Industrial engineering - adding innovation capacity of Labour Force and entrepreneurs" (Tallinn, Estonia in April 2006)
- 14. International Conference "Mechanics of Composite Materials" (Jurmala, June 2006).
- RTU 50. International Scientific Conference (Riga, 2009. Oct).
- International Conference "Stabilty and Ductility of Structures" (Vilnius, Lithuania 2009.september)

Main results are set out in 5 publications:

1. A. Baikovs, K. Rocēns. Behavior of the timber beams strengthened with carbon fiber strip. - Scientific Proceedings of RTU Collection Architecture and Civil Engineering. Series 2, Volume 5th Riga, 2004, pp.77.-88.
2. A. Baikovs, K. Rocēns. Stability of the shape of sheet anticlastic Composite Materials Under Variable Conditions moisture. - Proceedings of the 5th International Conference of DAAAM Baltic, INDUSTRIAL ENGINEERING - INNOVATION CAPACITY adding of Labour Force And Entrepreneurs. Tallinn University of Technology, 2006, pp.239-244th
3. A. Baikovs, K. Rocēns. Creep approximation method for bent wood material element. - Scientific Proceedings of RTU Collection Construction Science. Series 2, Volume ninth Riga, 2008, pp.6-15.
4. A. Baikovs, K. Rocēns. Prediction of the shape Change of hybrid laminated composite material sheet. - Scientific Proceedings of RTU Collection Construction Science. Series 2, Volume 10th Riga, 2009, pp.6-15.
5. A. Baikovs, K. Rocēns. Prediction of the shape anticlastic Change of hybrid composite material - the Journal of Civil Engineering and Management - Gediminas Technical University, Vilnius, Lithuania, 2010, pp.222-229

CONTENT OF WORK

The first chapter describes the current situation of composite wood material and element design issues, and mentions most often used calculation methods of creep deformations and listed their advantages and disadvantages. This chapter reviews the most important factors influencing the behavior of wood, laminate and wood particle boards - changes in moisture, warming, cooling, and mainly the influence of mechanical loads, which leads to changes of timber shape. The orientation of the wood components (boards, wood slivers, wood fiber or wood chips) in the element, dimension proportions, wood packing grade, moisture, glue bonding properties, bonding length, saturation of glue or other chemical substances and the time of loading should be taken into account to obtain valid calculation model of wood composite material elements, because the wood is the material with rheological characteristics, which depend not only from the time of loading, but also from loading speed. Relations between stresses and deformations, for the material with the rheological properties are determined by so-called rheological equations, which in most cases are described by using differential equations. First-order linear differential equations, known as linear elastic-viscous material deformation law in differential equation form [Ржаницин А. Р., 1958], which is the relationship between the short-term modulus E, the long-term modulus of elasticity H, relaxation time n, deformations ε and stresses σ, are often used to describe deformation characteristics of wood. However, this differential equation in a number of cases incompletely describes the experimental results. Whereas the creep stress state of real wood materials and elements are complicated, and the nature of the creep curves for different composite wood materials may vary, then more precisely it would be to clarify the shape of creep curve with reference to the experimental results that approximation shortcoming can be significantly reduced using the proposed by Ogarkov [Огарков Б.И., 1957] "updated rheological equation", which contains the creep curve shape factor α, with the help of which it is possible to significantly change the nature of the curve. In this case, we obtain the following differential equation:

$$nE\dot{\varepsilon} + \alpha H\varepsilon\left[\left(\frac{t}{n}\right)^{1-\alpha}\right]^{-1} = n\dot{\sigma} + \alpha\sigma\left[\left(\frac{t}{n}\right)^{1-\alpha}\right]^{-1} \tag{1.1}$$

Of the available literature concluded that the basis for the calculation of the laminated material properties have already been laid down in several models, also evaluation of the modified wood properties are described in several works, so these issues are not addressed in the work. But it was concluded that there is no universal method of calculating of the various types of curved wood composite material elements for predicting creep deformations. Therefore, the selected study areas are as follows:

- to develop a universal calculation method for prediction of the long-term deflections of different types of concave-convex elements - beams, plates and shells;

- to develop a calculation methodology, application of which would require experimental results of composite components only at a few time moments, for the prediction of deformations for the elements loaded with constant long-term load.

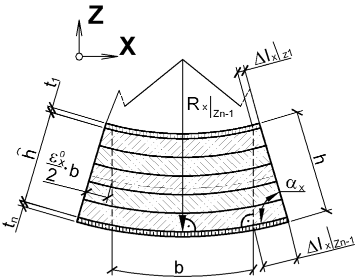
The second chapter is devoted to the development of the model for a concave-convex sheet element consisting of linearly elastic orthotropic layers, for the calculation of radius of curvature and longitudinal deformation changes, using the plane stress statements of laminated material mechanics in matrix form. With the developed calculation model can be determined the thickness of the glued fiberglass plastic, which restricts the deformations of convex-concave sheet deformations over time at changing humidity. Dealt the case where the moisture content for all layers of the element under any humidity changes is identical. Calculation of the shape invariability characteristics under variable moisture, for the element obtained by reinforcement of the *sheet* with reinforced plastics, is carried out in several stages. In the **first stage,** the appropriate moisture change $\Delta\widehat{\mathrm{W}}$ for straightening the concave-convex not strengthened composite material sheet is calculated. It is assumed that both curvature radiuses of the sheet become equal to ∞ almost at the same moment. Calculations are made by choosing the appropriate moisture change (reducing the moisture until the concave-convex composite material element straightens out), or using a definite moisture change, which has already provided the required curvature of the flat composite material sheet. The longitudinal deformations $\widehat{\varepsilon}$ caused by moisture changes $\Delta\widehat{\mathrm{W}}$ on the top and bottom surfaces of the sheet are determined in this stage.

To calculate the longitudinal deformations ε_n of the *element*, which occurs due to the moisture change $\mathbf{\Delta W = \Delta\widehat{W} - \Delta\widetilde{W}}$, in the **second stage** a reinforced sheet without any initial curvature subjected to moisture changes $\Delta\widetilde{W}$ is inspected conditionally and longitudinal deformations $\widetilde{\varepsilon}$ are calculated.

In the **third stage** the resultant longitudinal deformations ε_n of the concave-convex *element*, which has been subjected to the moisture action and changed moisture content by ΔW, are calculated using relevance:

$$\varepsilon_{n-1} = \widehat{\varepsilon}_{\widehat{n}} - \widetilde{\varepsilon}_{n-1} \qquad (2.1)$$

To define the bending radii on the top and bottom surfaces of the *element*, an equation system (2.2) is constructed based on the relationship between the angle and the sides of a right-angled triangle (shown in Fig.2.1). The system determines the bending radius $R_x\big|_{Zn-1}$ (2.2) of the bottom surface. The difference between the bending radiuses $R_x\big|_{Zn-1}$ and $\widehat{R}_x\big|_{Z\widehat{n}}$ characterizes the influence of the reinforcement at a definite moisture change. Analogical relevance's are used to calculate the bending radius $R_y\big|_{Zn-1}$.



$$R_x\big|_{Zn-1} = \frac{\hat{h} \cdot (\frac{b}{2} + \Delta l_x\big|_{Zn-1})}{\Delta l_x\big|_{Zn-1} - \Delta l_x\big|_{Z1}}$$, where (2.2)

$$\Delta l_x\big|_{Zn} = \varepsilon_x\big|_{Zn} \cdot \frac{b}{2} \qquad (2.3)$$

Fig 2.1. Calculation scheme of the bending radius in plane XZ for the strengthened element

Carried out the approbation of the developed method - calculated the orthotropic composite material element consisting of five layers glued together, whose longitudinal fibres are oriented at right angles towards the longitudinal fibres of adjacent layers (90˚/0˚/90˚/0˚/90˚). As the reinforcement is used glass fibre sheet with glass fibres oriented in two directions and epoxy resin adhesive (henceforth GFRP). The characteristic values of GFRP rigidity are found in [Kelly A., Cahn R.W., Bever M.B., 1995]. Radius of curvature values is calculated depending on the humidity changes when moisture content of the composite material layers decreases from 17% to 10%, and is compared with the results calculated with the finite element method using the software package ANSYS V.11 (henceforth FEM) (shown in Fig.2.2).

Using FEM and the developed calculation model, three cases were analytically approbated: the wood composite sheet consisting of five layers and curved by moisture were reinforced with the GFRP sheet with the thickness 3.15mm on the concaved surface, arched surface and on both sides. The usage of double-sided reinforcement with such thickness ensures the invariability of both bending radiuses of the sheet with the precision which does not exceed 5% admissible in engineering calculations (see Fig.2.2).

The longitudinal deformations of the element are calculated in the plane which corresponds to the middle plane of the composite sheet. The difference between the longitudinal deformations calculated using the developed calculation model and FEM in all listed cases does not exceed 3.3%.

In the **third chapter** is developed unambiguous method for the determination of rheological coefficients *n, H, α* for the "complemented rheological equation". Relevance's for determination of coefficients are acquired and checked for creep in case of constant stress, but as for foundation of produced method is taken the equation which can be used in solving of different rheological tasks for various materials, then the determined coefficients are applicable also in other rheological tasks, for example, in case of stress relaxation.

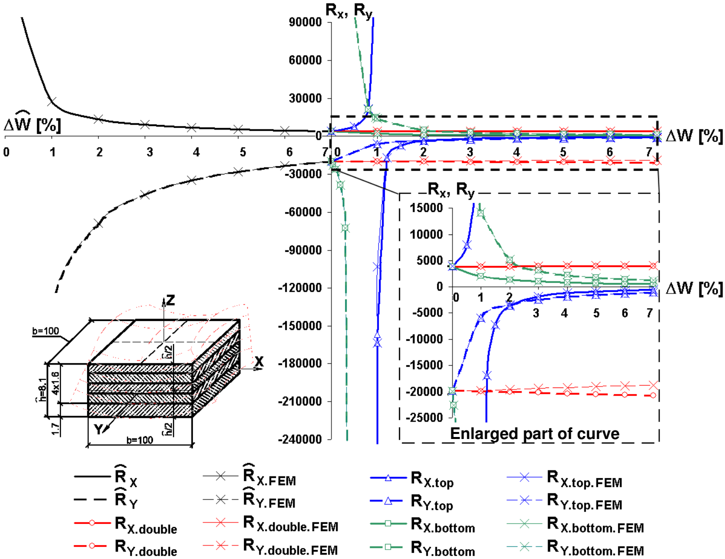


Fig 2.2. Change in bending radiuses R_x and R_y in dependence of the material moisture changes for the concave-convex sheet (on the left side of the graph) and for the strengthened elements (on the right side of the graph) if the thickness of the reinforcement is 3.15 mm.

For description of creep curves the dependence, which is obtained by integration of differential equation (1.1) in case of constant stress, is used.

$$\varepsilon = \frac{\sigma}{E} + \sigma\left(\frac{1}{H} - \frac{1}{E}\right)\left\{1 - e^{-\frac{H}{E}\left(\frac{t}{n}\right)^{\alpha}}\right\}, \qquad (3.1)$$

Creep curve shape coefficient α is obtained from the equation (3.1) by equalizing the long-term elastic modulus H to the experimentally obtained elastic modulus at the end of experiment E_B, and transforming the equation in a form

$$\frac{\varepsilon_B - \varepsilon}{\varepsilon_B - \varepsilon_0} = e^{-\frac{E_B}{E}\left(\frac{t}{n}\right)^{\alpha}}, \text{ where} \qquad (3.2)$$

$$E_B = \frac{\sigma}{\varepsilon_B}, \qquad (3.3)$$

and, ε_B - final experimentally obtained longitudinal deformation;

ε_0 - initial deformation of sample.

From (3.2) expressing the deformations at time moments $t_1 = t_2 / 2$ and $t_2 = t_B / 2$, is drawn up the equation system, resolution of which is the relevance for determination of creep curve shape coefficient α**,** characterized with four experimentally obtained values of longitudinal deformations in different time moments:

$$\alpha = \frac{1}{2}\left(\frac{\ln\left(\frac{\varepsilon_B - \varepsilon_2}{\varepsilon_B - \varepsilon_0} \right)}{\ln\left(\frac{\varepsilon_B - \varepsilon_1}{\varepsilon_B - \varepsilon_0} \right)} \right) \qquad (3.4)$$

Relaxation time *n* is determined from the equation (3.1) by equalizing the power function of exponent to one, and replacing time *t* with time t_k

$$n = \frac{t_k}{\left(\frac{E}{H} \right)^{\frac{1}{\alpha}}}, \qquad (3.5)$$

where t_k - time moment, when the experimental longitudinal deformation has reached the value ε_k, according to [Rocēns K.A., Markovs A.P., Daube J.J., 1989]

$$\varepsilon_k = \varepsilon_0 + (\varepsilon_B - \varepsilon_0) \cdot (1 - e^{-1}) \cdot \qquad (3.6)$$

Relaxation time, calculated using the equation (3.5) henceforth will be called as "conditional relaxation time".

Long-term elastic modulus *H* is determined in several stages. Initially its value is assumed equal with experimentally obtained elastic modulus in the end of experiment E_B. Afterwards, a value is gradually changed with the purpose to bring the calculated deformation in the end of creep curve nearer to the experimentally obtained until they match. Conditional relaxation time n_j at each selected value of elastic module E_{Bj} is determined from dependence

$$n_j = \frac{t_k}{\left(\frac{E}{E_{Bj}} \right)^{\frac{1}{\alpha}}} . \qquad (3.7)$$

The last determined value of elastic module E_{Bj}, using which the calculated end point of creep curve matches with the experimentally obtained, is the long-term elastic modulus *H* of material. Developed method for determination of rheological coefficients will be henceforth called as "developed methodology".

In the **fourth chapter** the advantages of "developed methodology" are analysed for experimentally obtained creep curves of five different wood material elements in bending - Douglas-fir beam [Gerhards C.C, 1999], three-layer medium density particleboard plate, 3-ply plywood plate [Tankut A., Denzizli-Tankut N., Gibson H., Eckelman C., 2003], composite hardboard-webbed I-beam with Douglass-fir flanges (hereafter abbreviated called for "I-beam-1") and composite plywood webbed I-beam with Douglass-fir flanges [McNatt J.D., Superfesky M.J., 1983] (hereafter abbreviated called for "I-beam-2"). All of creep experiments took place in uncontrolled interior environments, except for an experiment with plywood plate, when the temperature in the time of loading was constantly 21.1ºC.

Creep curve calculated using "complemented rheological equation" are graphically compared with creep curves obtained using:

1. equation for typical viscous-elastic body [Ржаницин А. Р., 1958],
2. "complemented rheological equation", with rheological coefficients α and n calculated using method of Rocēns K.A., Markovs A.P., Daube J.J., [1989] and long-term elastic modulus H is equalized to E_B (hereafter abbreviated called for "complemented rheological equation with coefficients α, n, $H=E_B$");
3. "complemented rheological equation", with creep curve shape coefficients α and n calculated using method of Rocēns K.A., Markovs A.P., Daube J.J., [1989], and long-term elastic modulus H is gradually approximated to its true value so that the end point of calculated creep curve matches with the experimentally obtained (hereafter abbreviated called for "complemented rheological equation with coefficients α, $n_j=f(H)$, $H=E_{Bj}$"). The long-term elastic modulus can be approximated in the case of every rheological equation, therefore to objectively compare existing method for determination of coefficients α and n with the "developed method", the approximation of long-term elastic modulus with "complemented rheological equation" was performed;
4. "complemented rheological equation", with creep curve shape coefficients α and n calculated using formulas (3.4) and (3.7) of developed method, and long-term elastic modulus H equalized to E_B (hereafter abbreviated called for "complemented rheological equation with coefficients α, $n_j=f(\alpha, H)$, $H=E_B$"). This curve is constructed in a compare intention with the "complemented rheological equation", which is taken for foundation of developed method, and where gradual approximation of long-term elastic modulus is not applied too. In the calculations of load bearing constructions determinant is the resulting deformations, not the deformations in the process of creep, therefore in the calculations of building constructions approximation is obligatory.

Creep curves calculated using the rheological equation of typical viscous-elastic body, "complemented rheological equation" and "developed method" were compared with the experimentally obtained creep curves. In all the cases maximal difference from the experimentally obtained deformations, is the smallest one in the case of "developed method" (see Figs.4.1 to 4.5).

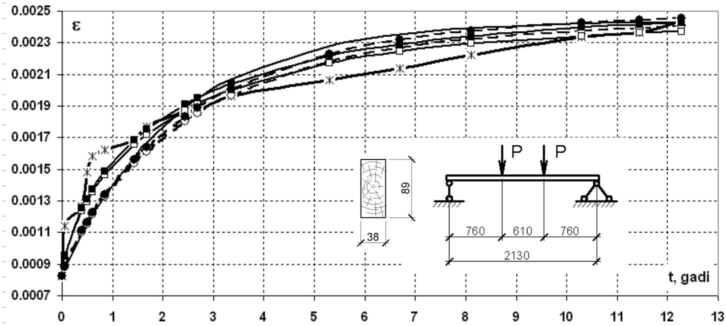


Fig 4.1. Loading scheme, cross-section and creep curves of Douglas-fir beam, if load P=0.526 kN. Patterns applied in graphic:

—✳— Experimental results;
——— Calculation using rheological equation for typical viscous-elastic body;
– ○ – used "complemented rheological equation with coefficients α , n, $H=E_B$";
– ● – used "complemented rheological equation with coefficients α , $n_j=f(H)$, $H=E_{Bj}$";
—◇— used "complemented rheological equation with coefficients α , $n_j=f(\alpha$, H), $H=E_B$";
– ◆ – used "gradual approximation method".

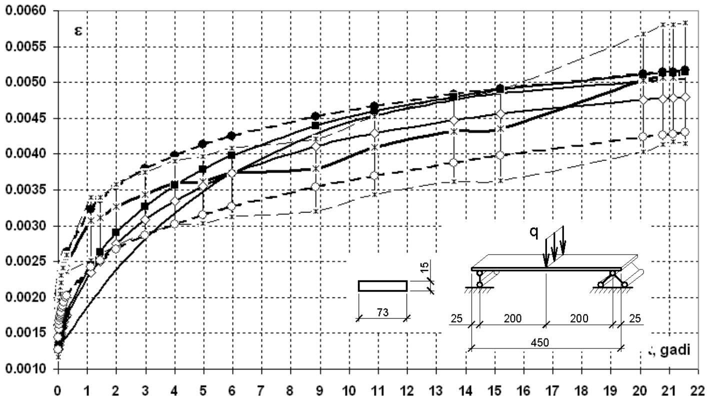


Fig 4.2. Loading scheme, cross-section and creep curves of particleboard plate, if load q=2.562 kN·m. Patterns applied in graphic:

—✳— *Dispersion borders of the experimental results;*

decoding of patterns —✳— , ——— , – ○ – , —□— , —■— , – ● – *see in fig.4.1.*

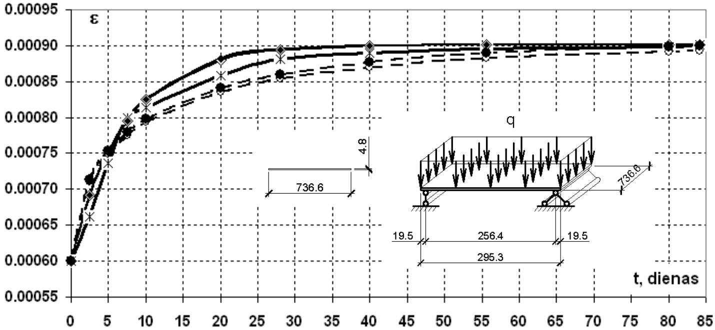


Fig 4.3. Loading scheme, cross-section and creep curves of plywood plate, if load q=4.323kN/cm^2. Decoding of patterns see in fig.4.2.

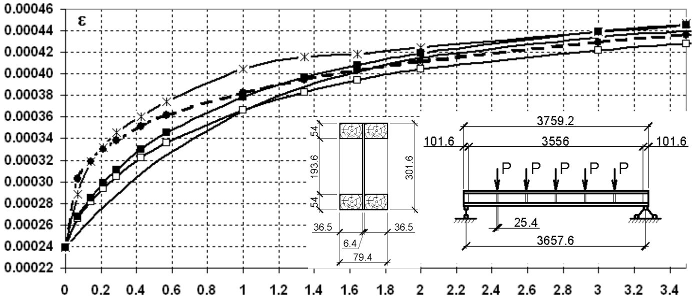


Fig.4.4. Loading scheme, cross-section and creep curves of composite wood I-beam-1, if load P=1.089 kN. Decoding of patterns see in fig.4.1.

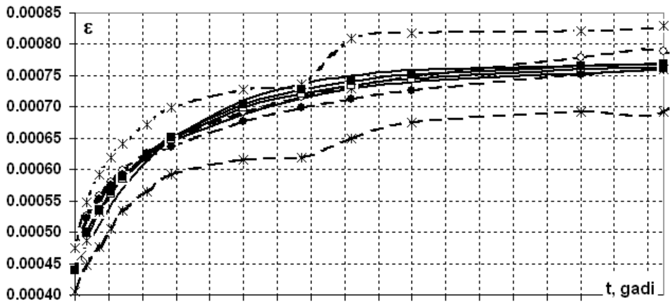


Fig 4.5. Creep curves of composite wood I-beam-2. Decoding of patterns see in fig 4.2. Loading scheme, cross-section and value of applied load are analogous to those show in the fig 4.4.

More precise creep curve is obtained when for the calculation of creep curve is used the "complemented rheological equation with coefficients α, $n_j=f(H)$, $H=E_{Bj}$" not the "developed method". However, the advantage of "developed method" is in the determination of coefficient α, which is determined from four experimentally obtained longitudinal deformations at time moments t_0, $t_B/4$, $t_B/2$ and t_B. Only three longitudinal deformations are used when calculating coefficient α using method of Rocēns K.A., Markovs A.P., Daube J.J., [1989], but two from them must be found with single condition - one of longitudinal deformations must be several times larger than other. That is why using coefficient α calculated with previously developed dependence [Rocēns K.A., Markovs A.P., Daube J.J., 1989] there is a need for complete experimentally obtained creep curve.

Particleboard sample has the highest mismatch of experimentally determined and analytically calculated results; because factors such as properties of pressed wood particles and their heterogeneous compression degree through the thickness of the particleboard was not taken into account. Therefore, in the chapter analyzed the experimental results of particleboard creep, in an attempt to justify the reasons for the differences between the experimental and analytically calculated results. Laboratory was carried out long-term deformation tests of the composite three-layer medium density (710±10 kg/m^3) urea-formaldehyde wood particleboards. At the premises of the Riga Technical University 12 samples with dimensions 450×75×15mm were cut out from different boards and carried out the tests in bending, with a concentrated load P_{creep}=186,7N in the middle of the span. Applied long-term bending load is 30% of the total fracture load for tested samples. Experimental results are recorded since April 11, 1986, and the behavior of the samples is still observed.

Carried out a calculation of tested samples by using a combination of "developed methodology" and the methodology for calculating deformations of particleboards using the rheological coefficients of components and their volume ratio [Rocēns K.A., Markovs A.P., Daube J.J., 1989]. Unlike the previous analyses, the particle board is calculated as the quasi-homogeneous material (see Fig 4.2.) and creep curve is calculated on the basis of two independent creep experiments - fenolformaldehyde adhesive in compression [А.М.Скудра, Ф.Я.Булавс, К.А.Роценс, 1971] and wooden beam subjected to bending [Gerhards C.C, 1999]. It is assumed that the rheological coefficients of adhesive will be the same in compression, tension and bending, and in the "contact point" between the adhesive and wood particles is the complete cohesion. Additional stresses, which occur in transverse direction to the longitudinal axis of the element, are small and are not taken into account.

Creep curves calculated using the rheological equation of typical viscous-elastic body, "complemented rheological equation with the coefficients α, $n_j=f(\alpha, H)$, $H=E_B$" and "developed method" were compared with the experimentally obtained creep curves (see Fig 4.6). Smallest difference between the maximal difference in component and maximal difference in composite is 0,81% for “complemented rheological equation” with the coefficients α , n_j=f(α , H), H=E_B”, but for „developed method” it is 3.31%, while for the rheological equation of typical viscous-elastic body the difference is 7.51%. So assuming the case when the components of the creep curve is described by a smaller difference from the "developed method", then the difference between the calculated and experimentally obtained creep curves of composite particleboard would also reduce. Secondly, if the calculated rheological coefficients of the components would be calculated from creep curves of components obtained at a stress rates with the sloping asymptote, as it is for the particleboard creep curve, then the difference between the calculated and experimentally obtained creep curves would be smaller.

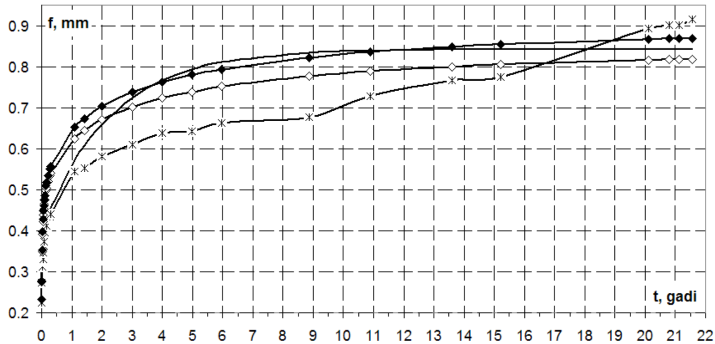


Fig 4.6. Creep curves of particleboard plate subjected to bending calculated as for composite material using the rheological properties of components. Patterns applied in graphic:

–◆– *Results calculated using rheological coefficients form “developed method”;*

decoding of patterns —✳— , ——— , —◇— *see in fig.4.1.*

In the **fifth chapter** is developed model of calculation creep deformations based on the assumptions used and calculation models developed in the previous chapters for laminated convex-concave element.

Calculation of the shape invariability characteristics under creep for the laminated element is carried out in several steps. In the first step are calculated rheological parameters for individual layers of element (short-term modulus of elasticity *E* and *G*, coefficient α, relaxation time *n* and long-term modulus of elasticity *H*) from the experimentally determined creep curves for each material using the "developed method" (see chapter 3).

In the second step, using the calculated rheological characteristics of individual layers at a time moments *t* with a certain interval are calculated deformative characteristics (modulus of elasticity and shear modulus). Using the relationships between the elastic constants of orthotropic material also are calculated the Poisson coefficients needed for the compilation of the layers reduced stiffness matrix at time moment t.

In the third step, is calculated the creep deformations of the whole convex-concaved element, using the deformative characteristics of the layers calculated at definite time moment using the FEM in the second step. The calculation is carried out separately for each time moment, taking into account the effects of deformations.

With the two analytical examples are shown a practical application of the proposed calculation model. In the first example is determined the part of creep deformations of reinforced convex-concave sheets discussed in the chapter 2, if taking into account the changes of the properties in time for both the wood chips and reinforced plastic. Determined the values of bending radiuses of convex-concave sheet, if the sheet is reinforced either at both or top or bottom surfaces, and calculated the part of creep deformations, which occurs from the change of material elastic characteristics over time, assuming by reference the deformed state of the sheet at the last moment discussed in an analytical example of Chapter 2. In FEM-step calculation when changing characteristics of deformative characteristics were not defined that the stress values will not change over time, this is why when the modulus of elasticity decreases smoothly, also changes the stress values. Stress value σ_x for the case of both sided reinforcement at average will decrease from 1.5 times to 2.3 times. This is explained by the fact that the decrease of elasticity module changes also the initial value of deformations caused by moisture, resulting in a decrease of stress values in the layers. In the case of the creep, due to the changes of deformative characteristics of layers from different materials with different relaxation time, occurs the stress redistribution between the layers of the sheet Values of curvature will change less than for 3.8% for the convex-concave sheet previously exposed to curving by elastic characteristic change caused by moisture changes and to reinforcing with 3.15 mm thick fibreglass. So by using the developed calculation model it is possible to calculate the thickness of the fiberglass reinforcement which provides desired range of the deformation changes of the sheet curved by changes of humidity.

In the second example are calculated the creep deformations of cylindrical shell, loaded with a uniformly distributed load. Inspected the element from orthotropic material, which consists of five glued together wooden chip layers. Viewed the case of linear creep - the stress value in the layers in any of time moments, at no point does not exceed 0,442 kN/cm^2. Obtained ratio of the creep and elastic deflection is 3.03. For the shell the long-term deflection is three times greater than the instantaneous also for the case with no additional moisture influence, so evaluation of the creep deformations is obligatory in case of thin walled curved sheets.

CONCLUSIONS

1. Developed calculation model for determination of curvature radius for laminated convex-concave plates in variable humidity conditions, if for the preservation of original form the fiberglass reinforcement is used.

2. Established that the effect of the thickness of fiberglass reinforcement on the convex-concave laminated composite material sheet curvature changes if the humidity changes from 10% to 17%. For example, showed the possibility to provide the initial form of a convex-concave laminated composite sheet at 5%, if reinforcing its both sides with two-way reinforced fiberglass.

3. Developed determination methodology of creep curve shape factor, relaxation time and long-term modulus ("the developed methodology") for a linear elastic-viscous material deformation law in differential equation form, which is supplemented with the creep curve shape factor α ("supplemented rheological equation"), for calculation of coefficients using the experimentally the biggest creep deformation t_{max} and deformations at time moments t_0, $t_{max}/2$ and $t_{max}/4$.

4. Established that the experimental results, obtained in long-term flexural loading under constant load in bending for a variety of wood structural elements (wood beams, particle board, plywood board, a composite profile double-T beams with chipboard walls and wood shelves and a composite double T-profile beam with plywood walls and wood shelves), can be described with "developed methodology".

5. Established that the difference between the experimentally determined and calculated results, for various elements from wood materials when using the "supplemented rheological equation", with coefficients calculated by the "developed methodology" on average is less than 3% if comparing with the case of linear elastic-viscous material deformation law in differential equation form or linear elastic-viscous material deformation law in differential equation form, which is supplemented with the creep curve shape factor, which is calculated using proposed methodology of Ogarkov.

6. Presented how the developed methodology for determining the rheological coefficients can be used to predict creep of wood composite materials by taking into account the relative volume of components and their rheological properties.

7. Developed calculation model for the prediction of deformations caused by moisture changes by taking into account the time factor for the convex-concave laminated wood composite element, if it is reinforced on one of the sides or both, and stated that in all the cases the curve change over 60 years does not exceed 5%.