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LONG-TERM CREEP OF CHIPBOARDS

KOKSKAIDU PLĀTŅU ILGLAICĪGĀ ŠĻŪDE

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Key words: wooden composite, viscoelastic properties, anisotropy, long-term creep, multilayer system

1. Introduction

Products of widespread and growing popularity are wooden particleboards and oriented strand boards (OSB). These are engineered products made by processing trees into wooden chips or strands, which are bonded together under heat and pressure with waterproof resin. When appropriate particle geometry is used (long, thin flakes), board strength and stiffness can be made high enough to make the material suitable for structural applications. Relatively large quantity of particleboards and OSB now finds structural uses in housing and offers special economic advantages over other materials.

One area of uncertainty in regard to wooden composite boards used structurally lies in long-term loading and moisture effects. General investigation on durability and creep studies indicates that creep and moisture effects in particleboard are more severe than in plywood or lumber. However, past studies on creep have been only preliminary and have not provided information for use in practical long-time situations. Data on wooden composite mechanical behaviour, and the causes for such behaviour, are needed before their application to wide new uses can be assessed accurately.

Creep is defined as time-dependent deformation at constant load. In the case of bending when load is applied to a beam, an immediate deflection occurs. This deflection under load increases with time. Relative creep is deflection at a particular time divided by the immediate or initial deflection. For purposes of strain-analysis under long-term loading, wood may be considered as a linear viscoelastic material. Under sufficiently high levels of temperature, moisture content and stress, distinctly non-linear behaviour becomes evident (Schniewind, Barrett 1972). Orthotropic behaviour in creep and relaxation is a result of the structural symmetry of wood (Bodig, Jayne 1982; Kollmann, Côté 1968).

The difference in creep behaviour between wooden composite and solid wood could be attributed to the uniform orientation of the fibers in wood in comparison with probably random orientation of groups of fibers in wooden composite and mechanical weakening of the components in wooden composites during processing. Under certain conditions moisture content and sorption effects are more pronounced in particleboard than in whole wood. This suggests that resin bonds and modification of wood structure (Rocens 1979; Rocens 1983) under high temperature and pressing play an important role on the board performance (Bryan, Schniewind 1965).

Under conditions of steady moisture content, relative creep values of 2 to 3 for particleboards were obtained by several researchers (Gillwald, Luthardt 1966; Perkitny, Perkitny 1966). Under adsorption conditions relative creep is much higher – values of 3 to 6 have been reported (Bryan, Schniewind 1965). Relative creep values of 3 to 5 after 3 years loading in climate rooms, and values 7 to 15 after a similar period in the atmosphere were measured in (Kratz 1969). It is mentioned (Halligan, Schniewind 1972) that creep did not relate with particleboard mechanical properties or with resin type.

Mechano-sorptive (MS) creep is a deformation due to an interaction between stress and moisture content (MC) change. In many situations where wood or wooden composite is used as structural member, it undergoes MS deformation resulting from applied stress and MC change. Bending creep behaviour of particleboards was investigated under cyclic moisture changes (Zhou et al. 2000; Zhou et al. 2001). It was determined that relative deflection and compliance of the boards increased over the history of cyclic moisture changes, and their magnitudes varied with examples. Because MS creep may result in great deformation or early failure of material, this phenomenon is important not only for fundamental studies but also for practical application of wood.

In manufacturing process the properties of densified wood in comparison with the customary wood have been changed (Khuhrjanskii 1964; Ogarkov, Apostol 1981). It is showed (Berzon, Rocens 1976; Rocens 1983; Rocens 1979) that the relationships between modules of elasticity of solid wood and density by pressing in radial direction are non-linear and different in the longitudinal, tangential and radial direction. The density distribution has a significant effect on particleboard properties (Xu, Winistorfer 1995). It could be controlled to some extent by manipulating raw material variable and press cycle as well as alignment of layers.
In order to determine mechanical and hygromechanical behaviour of wooden composites, the multilayer model (Brauns, Rocens 2001; Smittakorn, Heyliger 2001; Tsai, Hahn 1980) and model based on the laminate analogy (Brauns, Rocens 1994; Brauns, Rocens 1997; Halpin et al. 1971) can be used.

This report covers some of the results concerning elastic and viscoelastic properties of wooden composite, with primary interest in long-term creep behaviour taking into account the effect of cyclic changes of relative humidity in room with and without heating during the test period. Structural wooden board has been modelled as a multilayer system consisting of thin layers. To determine the elastic and viscoelastic characteristics of material, a method for determination and analysis of the stress state in calculation element with flat orthotropic particle (fibre) taking into account rheological characteristics of the fibre and binder (matrix), the content of components and anisotropy of fibres is developed.

2. Materials and methods

Three-layer medium density particleboards (density: 710±10 kg/m^3, thickness: 16 mm) were obtained from manufacturer and used in this study. The urea-formaldehyde-bonded boards were with 9 percent resin in the core and 13 percent resin in the surface. The particleboards were made of leaf-bearing wooden chips and softwood chips (30±10%). Twenty specimens (450 mm × 75 mm × 16 mm) were cut from different boards. Five specimens were prepared for testing of elasticity modulus and rupture in three-point bending with the span 400 mm. Three specimens were prepared for initial compliance test, and twelve specimens for creep test. Before test, all specimens were stored in a laboratory room maintained at 18±2°C. The initial MC of specimens was 7%, but during the long-time creep test, it was 7±2%.

The room had a camera for twelve creep test frames. The specimens were simply supported on roller assemblies with loads (186,7N) centrally applied by lever system. The long lasting bending load was 30% based on the average fracture load of the tested specimens. A dial micrometer was mounted above each specimen and was in contact with the top of a specimen. The deflection of the centre of specimens was measured with an accuracy of 0.01 mm. Deflection measurements were taken immediately after loading of each specimen and continued periodically until it appeared that the stage of secondary creep had been reached. In the following test period, the readings were made rarely. The duration of long-time creep test was 15 years.

3. Model development

The primary calculation element of composite material consists of an orthotropic fibre with rectangular cross-section A_f, the dimensions of which are $b_f \times h_f$, the thickness of binder is h_m. Here and below, the index f refers to the fibre and index m to matrix (resin). In the case of spraying the binder does not completely fill the space between fibres. The complexity of the problem is magnified by the necessity of predicting the workability of the material with the time factor being taken into account (Brauns, Rocens 1993; Skudra et al. 1975).

In order to determine the strain characteristics of primary structural element, i.e., the compliance tensor S_{ijkl} and its variations with the passage of time t at a given load, certain assumptions were made. It is assumed that element is a macroscopically homogeneous orthotropic body, and there is a good coalescence at the sites of the fibre and sprayed binder. Additional stresses in the lateral direction x_2 and x_3, if stresses along the fibre (direction x_1) are applied, are small. During loading of the element in a lateral direction, the strains are proportional to the volume of the corresponding component of the material:

$$\varepsilon_{ij}(t) = \mu_f \varepsilon_{f\,ij}(t) + (1-\mu_f)\varepsilon_{m\,ij}(t) \quad (i,j=2,3), \tag{1}$$

where μ_f is volume fraction of fibre. It is determined as

$$\mu_f = \frac{A_f}{(b_f + 2h_m)(h_f + 2h_m)}. \tag{2}$$

As the physical dependences for matrix and fibre the dependence of the linear heredity theory of creep (the Bolzmann-Volterra theory), which were chosen in the form

$$\varepsilon_{m\,ij}(t) = S_{m\,ijkl}\sigma_{m\,kl}(t) + \widetilde{K}_{m\,ijkl}\sigma_{m\,kl}; \tag{3}$$

$$\varepsilon_{f\,ij}(t) = S_{f\,ijkl}\sigma_{f\,kl}(t) + \widetilde{K}_{f\,ijkl}\sigma_{f\,kl} \quad (i,j,k,l=1,2,3), \tag{4}$$

where $\widetilde{K}_{m\,ijkl}$ and $\widetilde{K}_{f\,ijkl}$ are integral operators of creep.

In Eqs (3) and (4), the value of S_{ijkl} is determined by using technical constants of the densified wooden flakes and binder. The influence of the fibre length l_f and discrete bonding along the fibre is taken into account in finding the calculated value of the longitudinal modulus and the corresponding coefficients of the lateral strain ν_{fi1} ($i = 2, 3$). Here the reduction factor ψ is used, which is obtained from the dependence

$$\psi = \frac{\int\limits_{l_{f\min}}^{l_{f\max}} \left[\frac{\tilde{\sigma}_{f1\max}}{\sigma_{f1\max}}(l_f) - \frac{\mathrm{th}(Dl_f/4)}{Dl_f/2} \right] Z(l_f) dl_f}{\int\limits_{l_{f\min}}^{l_{f\max}} Z(l_f) dl_f} . \tag{5}$$

The factor ψ takes into account variable length of fibre l_f, statistical distribution of fibres with respect to length $Z(l_f)$ and incomplete bonding between fibres. The fibre stress $\tilde{\sigma}_{f1}$ arises in the case of alternating regions with and without an ideal bond, σ_{f1} – in the case of an ideal bond. The value of coefficient D is found according to the developed applied method (Brauns, Rocens 1991). The effective values of modules in transversal directions E_{f2} and E_{f3} as well as Poisson's ratio ν_{f32} were determined according to the assumption of uniformity of the field of stresses and taking into account the binder volume.

The compliance tensor components $S_{iijj}(t)$ and stresses in material constituents are determined by solving a system of three linear equations, which in matrix form is written as

$$\mathbf{AX}(t) = \mathbf{B}(t) . \tag{6}$$

The vector of unknown components is the compliances and stresses, i.e.,

$$\mathbf{X}(t) = \left[S_{iijj}(t), \sigma_{m11}(t), \sigma_{f11}(t) \right]^{\mathrm{T}} \quad (i, j = 1,2,3) . \tag{7}$$

The index "T" denotes transposition.

For the compliance $S_{1111}(t)$ the matrix of the system $\mathbf{A}$ and vector $\mathbf{B}(t)$ are determined on the basis of physical equations and equilibrium equation during the action of $\sigma_{11} = 1$. They have the following form

$$\mathbf{A} = \begin{bmatrix} 1 & -1/E_m & 0 \\ 1 & 0 & -1/E_{f1} \\ 0 & 1-\mu_f & \mu_f \end{bmatrix} ; \tag{8}$$

$$\mathbf{B}(t) = \left[\tilde{K}_{m1111}\sigma_{m11}, \tilde{K}_{f1111}\sigma_{f11}, 1 \right]^{\mathrm{T}} . \tag{9}$$

When determining the compliance $S_{1122}(t)$, the deformation of a structural element by the action of stresses $\sigma_{22} = 1$ was considered. In this case, the matrices $\mathbf{A}$ and $\mathbf{B}(t)$ are determined by using physical equations for the main strains, main lateral strains, and the additional lateral strains of the binder and fibre. In order to solve the problem, the equations for the simultaneity of strains for complete lateral strains, and equilibrium equation for additional stresses were taken into account. The form of matrix $\mathbf{A}$ coincides with (8), while vector $\mathbf{B}(t)$ is written as

$$\mathbf{B}(t)=\begin{bmatrix} -\dfrac{\nu_m(t)}{E_m}-\nu_m(t)\tilde{K}_{m2222}\cdot 1+\tilde{K}_{m1111}\sigma_{m11} \\ -\dfrac{\nu_{f12}(t)}{E_{f2}}-\nu_{f12}(t)\tilde{K}_{f2222}\cdot 1+\tilde{K}_{f1111}\sigma_{f11} \\ 0 \end{bmatrix}. \tag{10}$$

In the case of the action of stresses $\sigma_{22} = 1$, the component $S_{2222}(t)$ was also found. The matrices **A** and $\mathbf{B}(t)$ are formed using the dependence (1) for the main strains of the components of the material, the physical equations for the main strains, the complete main strains and lateral strains of the composite, and also the equation for simultaneity of strains in the lateral direction. The vector of the free terms has the form

$$\mathbf{B}(t)=\begin{bmatrix} \dfrac{\mu_f}{E_{f2}}+\dfrac{1-\mu_f}{E_m}+\mu_f\tilde{K}_{f2222}\cdot 1+(1-\mu_f)\tilde{K}_{m2222}\cdot 1- \\ -\nu_m(t)(1-\mu_f)\tilde{K}_{m1111}\sigma_{m11}-\nu_{f21}(t)\mu_f\tilde{K}_{f1111}\sigma_{f11} \\ \\ -\dfrac{\nu_{f12}(t)}{E_{f2}}+\dfrac{\nu_m(t)}{E_m}-\nu_{f12}(t)\tilde{K}_{f2222}\cdot 1+\nu_m(t)\tilde{K}_{m2222}\cdot 1- \\ -\tilde{K}_{m1111}\sigma_{m11}+\tilde{K}_{f1111}\sigma_{f11} \\ \\ 0 \end{bmatrix}, \tag{11}$$

but the system matrix can be given as

$$\mathbf{A}=\begin{bmatrix} 1 & (1-\mu_f)\dfrac{\nu_m}{E_m} & \mu_f\dfrac{\nu_{f21}}{E_{f1}} \\ 0 & 1/E_m & -1/E_{f1} \\ 0 & 1-\mu_f & \mu_f \end{bmatrix}. \tag{12}$$

In a similar way the remaining compliances of this group were determined, and because of their size are not given here.

The compliance in shear was estimated from the dependence of the change in the longitudinal force $F(x_1)$ in the fibre of finite length during shear loading. By numerical differentiation of function $F(x_1)$, the dependence of the change in the shear stresses for discrete bonding $\tau_m(x_1)$ and the length-averaged value of these stresses has to be found. In the case of short fibers and incomplete bonding the reduction factor χ for shear compliance was determined by the dependence

$$\chi = \frac{1}{\langle \tau_m \rangle^*} \frac{\int\limits_{l_{f\,\min}}^{l_{f\,\max}} \langle \tau_m \rangle (l_f) Z(l_f) dl_f}{\int\limits_{l_{f\,\min}}^{l_{f\,\max}} Z(l_f) dl_f} . \qquad (13)$$

Here the value $<\tau_m>^*$ expresses the conditional level of the mean shear stress, if the fibre length is large and the bonding is ideal. During the action of shearing stresses $\sigma_{ij} = 1$ ($i \neq j$; $i, j = 1,2,3$), the components of the compliance tensor can be written as

$$S_{ijij}(t) = \mu_f S_{f\,ijij}(t) + (1-\mu_f) S_{m\,ijij}(t)\chi . \qquad (14)$$

The averaging of the compliances according to Voigt and Reuss (Christensen, 1979; Lagzdins et al. 1992) in effect makes it possible to determine the lower and upper bonds of elastic and viscoelastic characteristics of composite material with anisotropic reinforcement.

4. Numerical results and discussion

Numerical analysis was performed based on wooden composite consisting of finite-length elements (flakes, chips) (Brauns, Rocens 1991) and glue. The properties of elements were determined taking into account the pressing during the material fabrication and considering the statistical length distribution and incomplete fibre bonding (Brauns, Rocens 1993). The averaged technical characteristics of densified wooden fibres used in numerical analysis were: modules of elasticity – E_1 = 16500, E_2 = 700 (MPa); shear modules – G_{12} = 900, G_{13} = 1500, G_{23} = 300 (MPa); Poisson's coefficients – ν_{21} = 0.45, ν_{31} = 0.34, ν_{32} = 0.30. As correction factors with respect to the moisture change for elasticity modules and shear modules have been taken: $E_1 - \alpha_1$ = 250, $E_2 - \alpha_2$ = 25, $G_{12} - \alpha_{12}$ = 25, $G_{13} - \alpha_{13}$ = 30, $G_{23} - \alpha_{23}$ = 20 (MPa). Mechanical characteristics of urea-formaldehyde resin used in calculations were: E = 2300, G = 840 (MPa), ν = 0.37.

Because there is no data about long-term deformation under action of different loads on wood used in wooden composites, the extrapolation of creep curves given in literature was performed. The values of integral terms used in calculations were determined by using finite sum method.
Based on the above-discussed model, calculations of the compliances of layered material made of wood shavings were performed. For this purpose the structure of the wooden plastic is modelled by symmetrically distributed layers, the longitudinal axes of which are oriented in different directions in the plane with spacing of $\pi/6$. For the compliance $S_{1111}(t = 0)$ the following values were obtained: on averaging to Voigt – 2.20×10^{-4}, according to Reuss – 6.25×10^{-4} MPa^{-1}. The variation of compliance components and corresponding stresses are shown in Fig. 1.

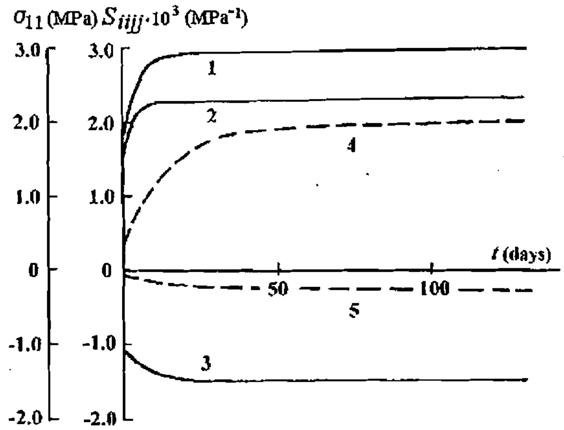

Fig. 1. Variation of the compliance and additional stresses as a function of time: S_{2222} (1), S_{3333} (2), S_{3322} (3), $\sigma_{m\,11}$ (4), $\sigma_{f\,11}$ (5)

Maximum relative deflection of wooden composite beams as a function of time at a constant load were approximated by the dependence

$$f_{\max}(t) = \frac{F}{b\xi}\left[0.25 S_{1111}(t) + 1.2\xi^2 S_{1313}(t)\right], \tag{15}$$

where F is the load; b is the width of the beams; $\xi = h/l$ (thickness to span ratio).

Figure 2 shows the bending creep data. As may be seen there is a reasonably good agreement between experimental data points and curve based on averaged compliances determined according to hypothesis of uniform strain field into material components. Initial values of relative deflection are about what would be expected in elastic state. Theoretical values of viscoelastic deflections are 10-15% less in comparison with experimental ones except initial period. The reason is high values of predicted stiffness.

The end of the creep process of three layer particleboards loaded for 15 years is not to be perceived. Variation in the deflection appears when room relative humidity changes. Note that some increases in experimental deflections were determined after 10 years (Fig. 2). It could be explained by fact that there were heating and ventilation problems in the laboratory room.

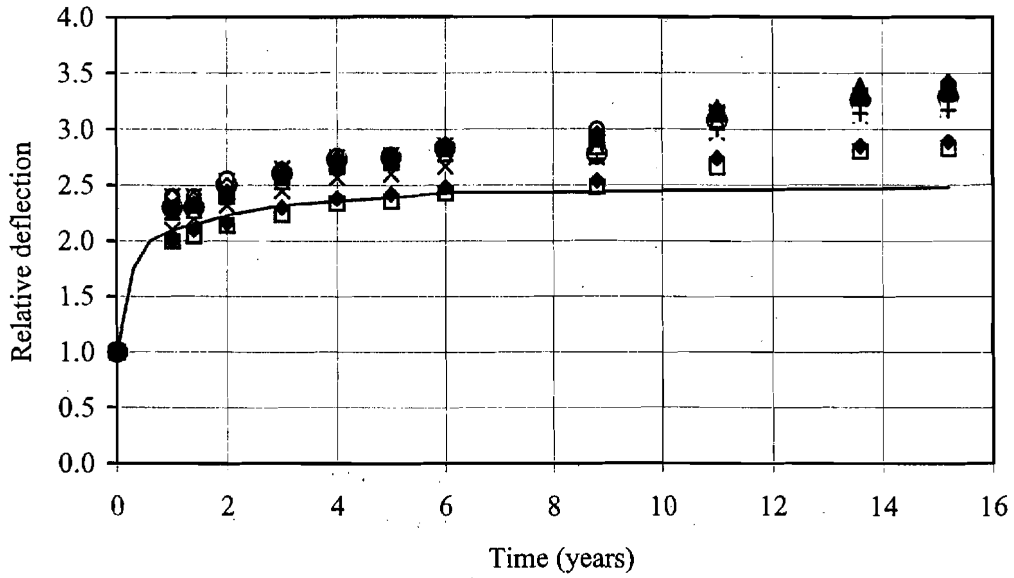

Fig. 2. Relative deflections of chipboard specimens vs. time; solid line – analytical prediction.

Conclusions

Comparison of experimental results determined in the test performed during 15 years with analytical prediction shows a reasonably good agreement. The method developed for determination of the compliance and stress state in calculation element of the material consisting of flat orthotropic viscoelastic chips and binder allows to predict realistic behaviour of wooden board. Because compliances were determined according to hypothesis of uniform strain field into material components, the theoretical values of viscoelastic deflections are 10-15% less in comparison with experimental ones. The reason is that the actual values of the strain characteristics of wooden composite lie between the upper and lower limits, and in predicting the characteristics of a material, the dimensions and the boundary conditions that determine the stress state of the designed element must be taken into account.

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Brauns J., Rocēns K., Pakrastiņš L. Kokskaidu plātņu ilglaicīgā šļūde.
Darba mērķis - pētīt elastīgās un viskozi elastīgās koksnes kompozīta īpašības detalizētāk aplūkojot vidēji blīvu trīsslāņu kokskaidu plātņu ilglaicīgo šļūdi liecē. Izveidots strukturāls modelis elastīgo un viskozi elastīgo raksturotājlielumu un spriegumstāvokļa noteikšanai kompozītam, kurš sastāv no plakanām ortotropām viskozi elastīgām skaidām un saistvielas. Analītiskie rezultāti salīdzināti ar eksperimentāliem, kas iegūti slogojot kokskaidu paraugus liecē 15 gadus ar nemainīgu slodzi.

Brauns J., Rocens K., Pakrastins L. Long-term creep of chipboards.
The results concerning elastic and viscoelastic properties of wooden composite, with primary interest in long-term creep behaviour of three-layer medium density chipboard in bending have been discussed. The experimental results determined in the test performed during 15 years are compared with analytical prediction. To determine the elastic and viscoelastic characteristics of the layer, a method for determination and analysis of the compliance and stress state in calculation element of the material consisting of a flat orthotropic viscoelastic chip (platelet) and binder is developed. A reasonably good agreement between data points of experimental displacement and curve based on averaged compliances determined according to the hypothesis of a uniform strain field is fixed.

Браунс Я., Роценс К., Пакрастиньш Л. Длительная ползучесть древесностружечных плит.
Исследованы упругие и вязкоупругие свойства древесных композитов, в частности длительная ползучесть трехслойных древесностружечных плит средней плотности при изгибе. Аналитические результаты сравниваются с экспериментальными, которые получены при помощи испытания на изгиб образцов древесностружечных плит в течение 15 лет под постоянной нагрузкой. Создана структурная модель для определения упругих и вязкоупругих характеристик, а также напряженного состояния композита, состоящего из плоских ортотропных вязкоупругих стружек и связующего.