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VERIFICATION OF PHYSICAL RELATIONS FOR STRESSED WOOD AT VARIABLE HUMIDITY

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The scope of this paper was to adapt the proposed theoretical assumptions to the description of the results of experimental research carried out on samples of pine sapwood on which variety state of stress was exerted and which, at the same time, were changing their moisture content. The results indicate that the theory gives a good description of the radial deformation of wood subjected to compression. Greater differences appear between the theoretical description and the experiment concerning tangential deformation.

Key words: tension, compression, wetting of stressed wood, physical relations, pine sapwood

Notation

ε_R [1] swelling strain in the radial direction of the sample, compressed in radial direction
ε_T [1] swelling strain in the tangential direction of the sample, tension in tangential direction
$\dot{\varepsilon}_R$ [1] free swelling strain in the radial direction of the sample
$\dot{\varepsilon}_T$ [1] free swelling strain in the tangential direction of the sample
E_R [MPa] modulus of elasticity in the radial direction
E_T [MPa] modulus of elasticity in the tangential direction
β_R [MPa^{-1}] coefficient of the mechano-sorptive effect in radial direction
β_T [MPa^{-1}] coefficient of the mechano-sorptive effect in tangential direction
σR [MPa] compressive stress in the radial direction
σ_T [MPa] tensile stress in the tangential direction
θ [1] specific moisture content
$\nu_{TR,\ RT}$ [1] Poisson's ratio

INTRODUCTION

Mechanical and physical properties of wood are depending on many factors, first of all on the specific gravity, moisture, structural defects, origin of samples, percentage of late wood, method of applying a load on samples, temperature etc. These matters are dealt with by Leontiew (1952) and Kollmann (1967). The problem of the variation of elasticity constant in relation to the angles formed by the edges of rectangular samples and the main axes of elasticity are discussed by Hearmon (1948) and also Keylwerth (1951) and Grimsel (1994).

The greatest difficulty in the description and modelling of deformations of wetted wood is posed by the changes in mechanical properties of wood in the process of wetting.

At the beginning of the wetting, wood adsorbs moisture very quickly and at the end of the process, after the saturation point of the fibers has been reached, very slowly. Similar phenomenon can be observed during the process of compression. The change in the material cannot be described with one simple model. It embraces a range of subdisciplines of mechanics from the theory of elasticity or viscoelasticity to the theory of cracking. To work out a single model which would give a comprehensive description of deformation is a difficult task. Literature provides examples of this (Rybarczyk 1972, Ganowicz and Rybarczyk 1974 or Ranta-Maunus 1975). It appears that a more realistic approach is the application of few adequate models for a given process and interconnecting them in the transition phases. A proposal of such a description was made by Kowalski and Kowal (1998). The proposed physical relations describe compression of moistened wood on the basis of the mechanics of continuous media, to be more precise the theory of mixtures. The above mentioned paper presents an experimental verification of the proposed description for the following states of strain: tension in radial direction, compression in tangential direction and both of these states.

The scope of this paper was to adapt the above mentioned theory to the description of results of an experimental research conducted on samples of pine sapwood cut also crosswise to the fibers but loaded in a different way. The moisture content in the samples was changed from almost completely dry to the values exceeding the point of saturation of the fibers (above 30%). The process of wetting was conducted for three different states of stress:

– tension in tangential direction,
– compression in radial direction,
– both of the above states of stress occurring simultaneously.

The effect of the work was a comparison of the results of experimental and theoretical research and confirmation of the earlier proposed hypothesis (Kowal and Kowalski 1995) that the principle of superposition in a uniaxial and biaxial states of stress does not hold.

EXPERIMENTS

The research was carried out on pine sapwood. It was an object of numerous previously performed analyses both experimental and theoretical (Kowal 1989, Kowal et al. 1992, Kowal and Kowalski 1995, Kowal 1998). Continuation of examination of this type of wood is connected with the need of verification of the proposed theory (Kowalski and Kowal 1998). The samples which were prepared for the experiment were seasoned in laboratory conditions for a period six months. Forty samples without any visible defects were used in the experiment. On the examined surfaces measuring bases were marked with pins which constituted measuring points visible under microscope (Fig. 1).

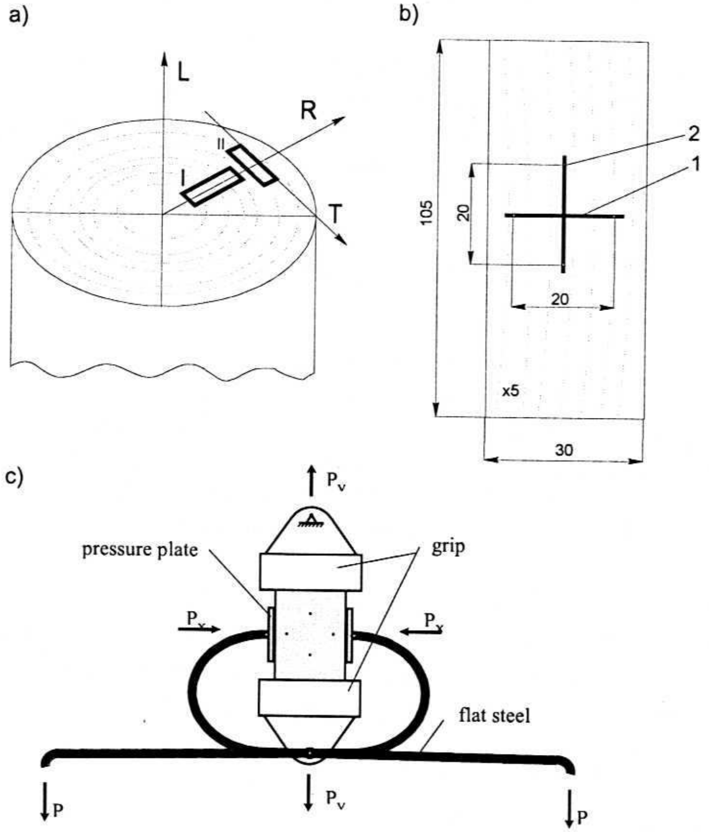

Fig. 1. a) Anatomic directions of wood (L – lengthwise, R – radial, T – tangential);
b) Wood sample (1 – gauge length, 2 – gilded pins)
c) Schematic diagram of executing plane state of stresses of the sample
Rys. 1. a) Kierunki anatomiczne drewna (L – wzdłuż włókien, R – promieniowy, T – styczny);
b) Próbka drewna (1 – baza pomiarowa, 2 – pozłacane szpilki)
c) Schemat wywoływania dwukierunkowego stanu naprężeń w próbce

The moistening was performed with distilled water of temperature 20°C. The process of wetting was treated as isothermal.

The samples of wood were examined as moistened free and in three states of stress, that is: tension in tangential direction, compression in radial direction and in both of the above states of stress occurring at the same time. The stress in the samples was 0.50 MPa. They were examined in three different cases of moisture content:

– constant moisture content $\theta \cong 1\%$ (dry samples),

– variable moisture content from 1 to 36%,

– constant moisture content $\theta \geq 36\%$.

In the second programme of moistening the samples were wetted in steps reaching in successive phases average values 1, 7, 14, 22, 29 and 36% of moisture content within 30 min. The pin marking the measuring basis shown on Fig. 1 was monitored every 1 minute.

Deformation of dry samples ($\theta \cong 1\%$) and wet samples ($\theta \geq 36\%$) was also observed for 30 minutes but the obtained deformations were also small.

A more precise description of the methodology of this type of research was presented in articles of Kowal (1989) and Kowal et al. (1992).

PHYSICAL RELATIONS

The relations between mechanical deformations and stress were determined on the basis of the dependence following from the Hooke's Law, which is called Neo-Hookean, in which material constants may depend on the moisture content and temperature in a wooden skeleton. The derivation procedure of the above physical relations was presented in article Kowalski and Kowal (1998). In the following way I shall quote only its selected elements indispensable for the understanding of the ensuing procedure.

The samples used in the research were 5 mm thick fibrewise. The strains ε_L in this direction for the above mentioned states of stress were slight. Therefore, in all experimental tests $\sigma_L = 0$, $\sigma_{RL} = 0$, $\sigma_{TL} = 0$, plane state of stress was examined and physical relations for such a state reduced to the following equations:

$$\varepsilon_R(\Theta) = \overset{\circ}{\varepsilon}_R(\Theta) + \frac{1}{E_R(\Theta)}\sigma_R - \frac{\nu_{TR}}{E_T(\Theta)}\sigma_T \tag{1}$$

$$\varepsilon_T(\Theta) = \overset{\circ}{\varepsilon}_T(\Theta) - \frac{\nu_{TR}}{E_R(\Theta)}\sigma_R + \frac{1}{E_T(\Theta)}\sigma_T \tag{2}$$

$$\varepsilon_R(\Theta) = \frac{1}{2G_{RT}(\Theta)}\sigma_{RT} \tag{3}$$

the proposed system of equations can be used in practice if the coefficients called the material constants are known. The next step should be to determine these coefficients. The method of determination of values of these coefficients was presented in article Kowalski and Kowal (1998). In this paper they will only be quoted.

The final form of physical relations for stressed wood in which the moisture content is changing is the following:

$$\varepsilon_R(x) = \overset{\circ}{\varepsilon}_R(\Theta_o) + \left[\overset{\circ}{\varepsilon}_R(\Theta_n) - \overset{\circ}{\varepsilon}_R(\Theta_0)\right]\left(2x - x^2\right) + \left[\frac{1}{E_R(\Theta_o)} + \beta_R(\Theta_0)\cdot x\right]\sigma_R - \\ -\nu_{TR}\left[\frac{\sigma_T}{E_T(\Theta_0)} + \beta_T(\Theta_o)\cdot x\right]\sigma_T \tag{4}$$

$$\varepsilon_T(x) = \overset{\circ}{\varepsilon}_T(\Theta_o) + \left[\overset{\circ}{\varepsilon}_T(\Theta_n) - \overset{\circ}{\varepsilon}_T(\Theta_0)\right]\left(3x^2 - 2x^3\right) + \nu_{RT}\left[\frac{1}{E_R(\Theta_o)} + \beta_R(\Theta_0)\cdot x\right]\sigma_R - \\ -\left[\frac{1}{E_T(\Theta_0)} + \beta_T(\Theta_o)\cdot x\right]\sigma_T \tag{5}$$

$$2\varepsilon_{RT}(x) = \left[\frac{1}{G_{RT}(\Theta_o)} + \beta_{RT}(\Theta_0)\cdot x\right]\sigma_{RT} \tag{6}$$

where:

$$x = \frac{(\Theta - \Theta_o)}{(\Theta_n - \Theta_o)}, \quad 0 \le x \le 1$$

Equations (4) and (5) describe deformation of wood in radial and tangential directions respectively. Equation (6) describes of wood non-dilatational strain.

RESULTS

The results of the experimental research obtained in this work are presented in the form of four tests.

Test I. Free deformations of wet wood – were observed in the range of moisture states from dry to exceeding the fibers saturation point. The results are presented in Fig. 2 and 3.

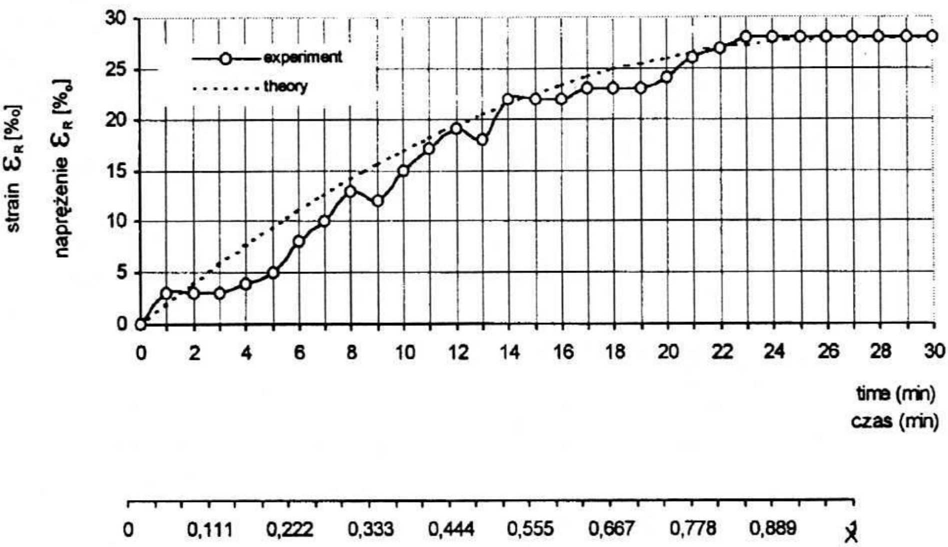

Fig. 2. Swelling strains of the unstressed wood in radial direction, $\dot{\varepsilon}_R$ [‰]
Rys. 2. Swobodne odkształcenia wilgotnościowe w kierunku promieniowym, $\dot{\varepsilon}_R$ [‰]

Analysing these results observed greater deformation of wood in the tangential than in the radial direction which is bound with the anisotropic properties of wood.

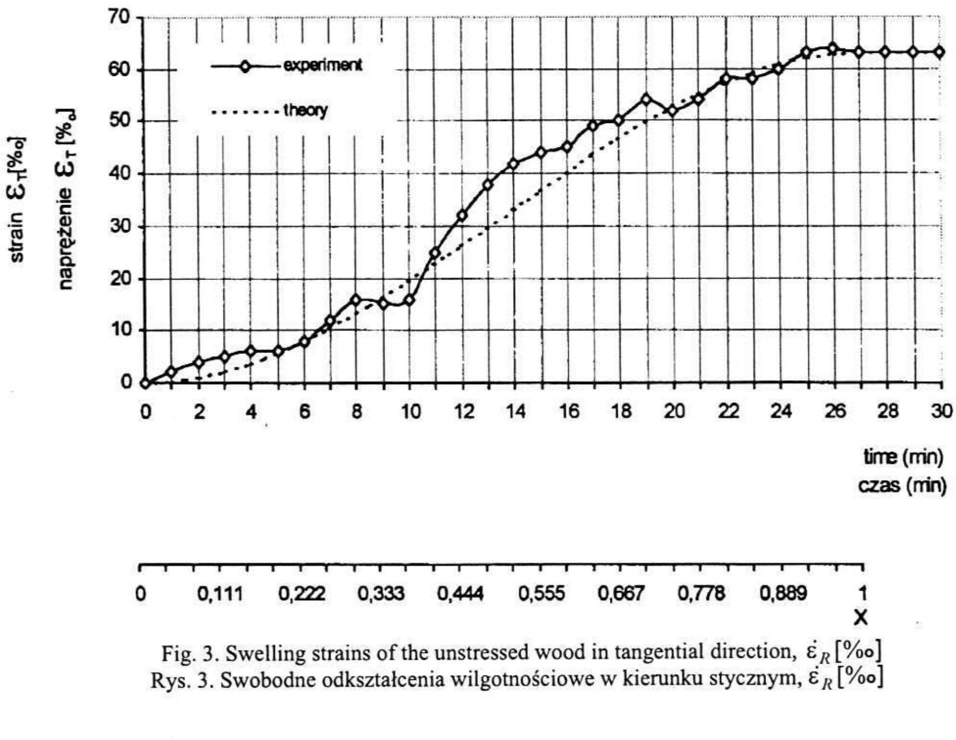

Fig. 3. Swelling strains of the unstressed wood in tangential direction, $\dot{\varepsilon}_R$ [‰]
Rys. 3. Swobodne odkształcenia wilgotnościowe w kierunku stycznym, $\dot{\varepsilon}_R$ [‰]

It was observed, that the moisture deformations reach maximum values for the fibers saturation point and additionally the function for the tangential direction has inflexion points. To description those strains followed equations, which were educed in article of Kowalski and Kowal (1998):

$$\overset{\circ}{\varepsilon}_R(x) = \overset{\circ}{\varepsilon}_R(\Theta_o) + \left[\overset{\circ}{\varepsilon}_R(\Theta_n) - \overset{\circ}{\varepsilon}_R(\Theta_0)\right]\left(2x - x^2\right) \tag{7}$$

$$\overset{\circ}{\varepsilon}_T(x) = \overset{\circ}{\varepsilon}_T(\Theta_o) + \left[\overset{\circ}{\varepsilon}_T(\Theta_n) - \overset{\circ}{\varepsilon}_T(\Theta_0)\right]\left(3x^2 - 2x^3\right) \tag{8}$$

It was estimated that the experimental curves and their theoretical interpretations are differing from one to ten percent.

Test II. Tension wood in the tangential direction – the research was conducted for the stress $\sigma_T = \sigma = 0.50$ MPa, the other stress 0. The measurements regarded deformations in tangential and radial directions. To theoretical description were called from article of Kowalski and Kowal (1998) the values material constants moisture content – dependents: the modulus of elasticity in tangential direction $E_T(\theta_o) \cong 562$ MPa; the coefficient of the mechano-sorptive effect $\beta_T(\theta_o) \cong 0.030$ MPa^{-1} and Poisson's ratio, $\nu_{TR} = 0.25$ which does not depend on moisture content.

The values of moisture deformations in the tangential directions such stress of wood both theoretically and experimentally obtained are shown in Fig. 4.

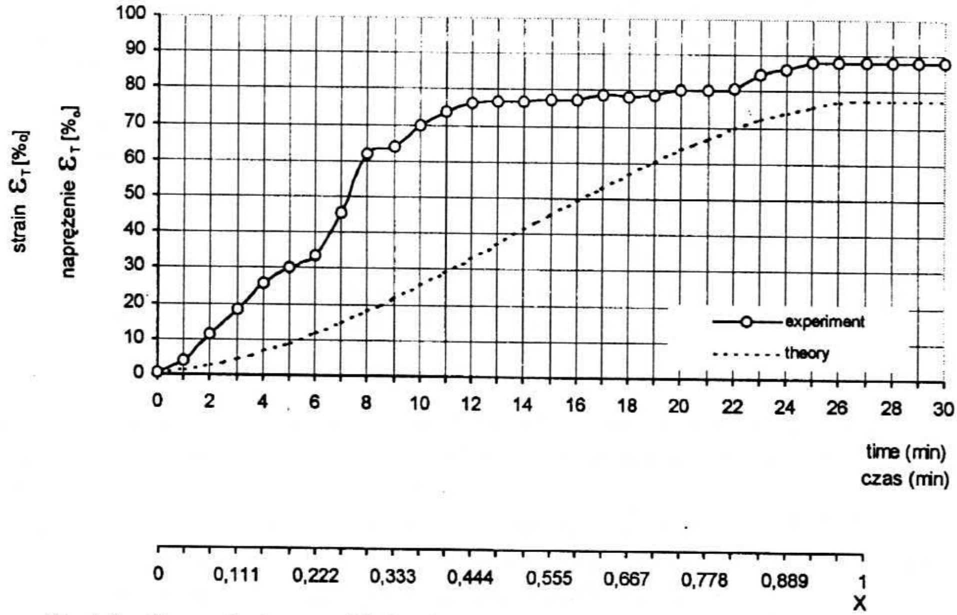

Fig. 4. Swelling strains in tangential direction, ε_T of the sample, tension in tangential direction
Rys. 4. Odkształcenia wilgotnościowe w kierunku stycznym, ε_T próbek rozciąganych w kierunku stycznym

The results of experimental and theoretical research differ in the case of tension. The reason for these differences may be the curvatures of annual growths, which could not be eliminated during the process of sample cutting in this direction.

Test III. Wood compression in the radial direction – was performed with the stress $\sigma_R = \sigma = 0.50$MPa, the other stress 0. The test measured deformations in radial and tangential directions. To description theoretical called from article of Kowalski and Kowal (1998) the values material constants moisture content-dependents: the modulus of elasticity in radial direction $E_R(\theta_o) \cong 715$MPa; and coefficient of the mechano-sorptive effect $\beta_R(\theta_o) \cong 0.008$MPa^{-1} and Poisson's ratio, $\nu_{RT} = 0.31$, which does not depend on moisture content

The values of moisture deformations for this direction obtained which were presented in Fig. 5.

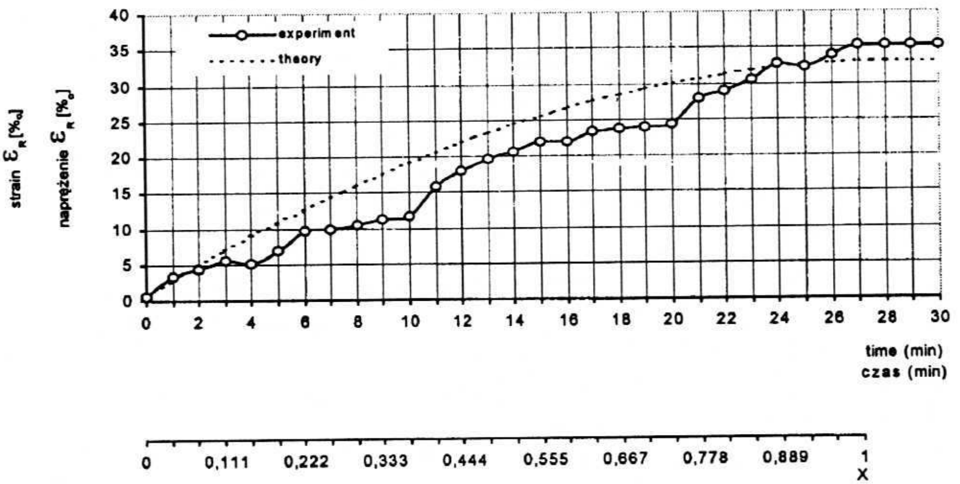

Fig. 5. Swelling strains in the radial direction, ε_R of the sample, compressed in radial direction
Rys. 5. Odkształcenia wilgotnościowe w kierunku promieniowym, ε_R of the sample, ściskanych w kierunku promieniowym

The results of experimental and theoretical research in the case of compressing stress in the radial direction differ to a smaller degree. They can be considered as satisfactory.

Test IV. The plane state of stress in wood was obtained by a simultaneous application of stresses described in tests II and III. The research was conducted for the stress $\sigma_R = -\sigma$, $\sigma_T = \sigma$, $\sigma = 0.50$MPa. The measurements regarded deformations in radial and tangential directions.The results were presented in Fig. 6 and 7.

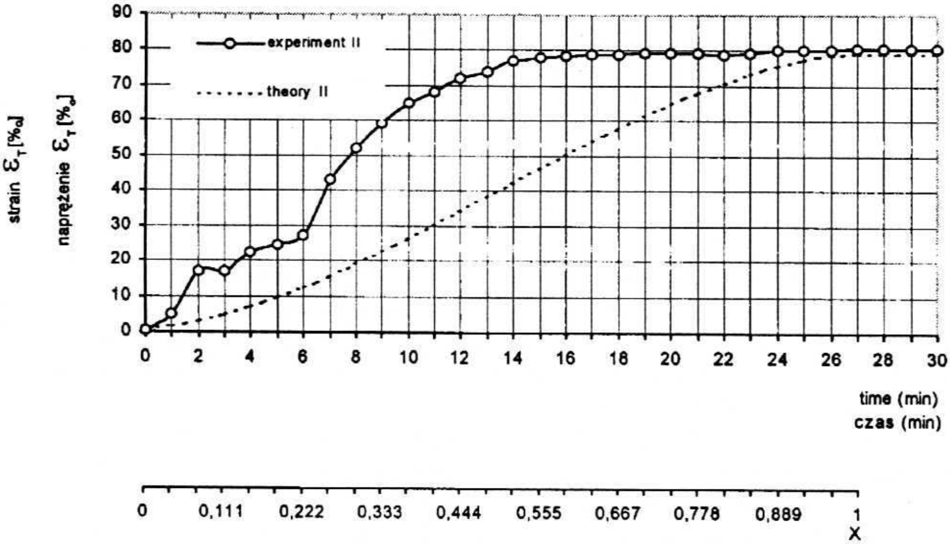

Fig.6. Swelling strains in the tangential direction, ε_T of the sample, both tensed in tangential direction and compressed in radial direction

Rys. 6. Odkształcenia wilgotnościowe w kierunku stycznym, ε_T próbek równocześnie rozciąganych w kierunku stycznym i ściskanych w kierunku promieniowym

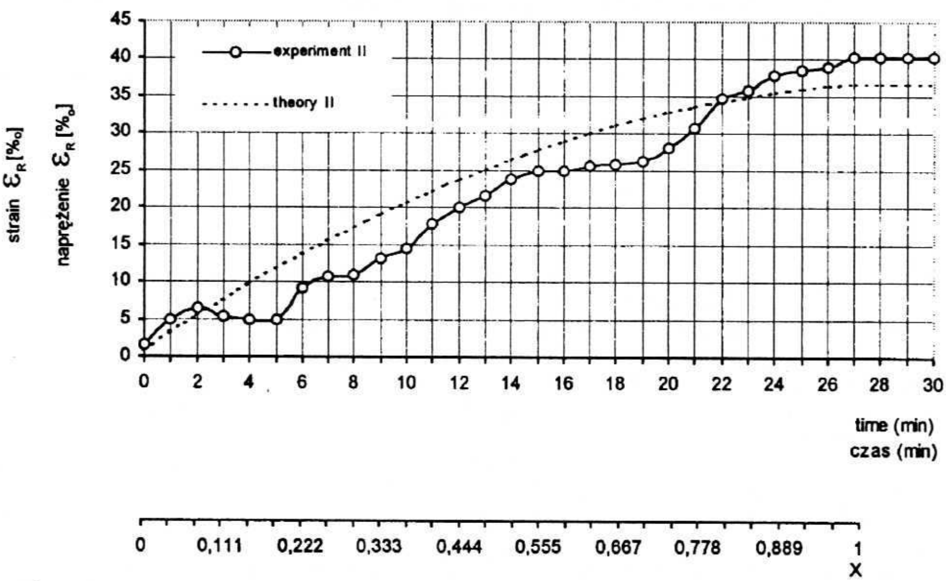

Fig. 7. Swelling strains in the radial direction, ε_R of the sample, both tensed in tangential direction and compressed in radial direction

Rys. 7. Odkształcenia wilgotnościowe w kierunku promieniowym, ε_R próbek równocześnie rozciąganych w kierunku stycznym i ściskanych w kierunku promieniowym

The results of experimental and theoretical research in the case of tension stress in the tangential direction differ to a high degree.

The results of experimental and theoretical research in the case of compressing stress in the radial direction are differing in a smaller degree.

RECAPITULATIONS

The aim of the work was to verify the theoretical predictions regarding to the description of wood wetting under stress. The experimental research concerned uniaxial states of stresses and complex states of stress of wetting wood. Obtaining samples of wood allowing for tangential tension was quite difficult. The curvature of annual growths was not entirely eliminated.

During tension in tangential direction it could have had an influence on the values of deformations which, are bigger than by theoretical description. It refers both to uniaxial and biaxial states of stresses.

The deformation in radial direction can be described with the proposed model with an adequate accuracy.

Comparing the obtained results in tangential and radial directions for uniaxial states of stress and complex states of stress, the previously proposed hypothesis is confirmed that the principle of superposition in case of deformation of wood which changes its moisture and is submitted to stresses does not hold.

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WERYFIKACJA ZWIĄZKÓW FIZYCZNYCH DLA NAPRĘŻONEGO DREWNA PRZY ZMNIENIAJĄCEJ SIĘ WILGOTNOŚCI

Streszczenie

Założenia teoretyczne zwane związkami fizycznymi zostały opracowane w oparciu o wyniki badań eksperymentalnych zachowania się drewna bielu sosnowego, w którym wywoływane były następujące stany naprężeń przy zmieniającej się jego wilgotności: rozciąganie w kierunku promieniowym, ściskanie w kierunku stycznym, obydwa wyżej wymienione stany naprężeń występujące równocześnie, a także swobodne pęcznienie.

Celem pracy było sprawdzenie przydatności poczynionych założeń teoretycznych do opisu wyników badań doświadczalnych przeprowadzonych na próbkach drewna bielu sosnowego.

Otrzymane wyniki pozwalają stwierdzić, że zaproponowane rozważania teoretyczne dosyć dobrze opisują odkształcanie się drewna w kierunku promieniowym zarówno rozciąganego jak i ściskanego. Większe różnice pomiędzy opisem teoretycznym a wartościami odkształceń będących wynikami przeprowadzonego eksperymentu zaobserwowano w kierunku stycznym. Przyczyną tych różnic mogą być krzywizny przyrostów rocznych, których nie udało się wyeliminować podczas przygotowywania próbek. Występujące różnice wymagają dalszych badań zarówno eksperymentalnych jak i teoretycznych.

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