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EFFECT OF BENDING STRESSES ON THE WOOD CREEP IN CONDITIONS OF ASYMMETRIC CHANGES IN MOISTURE CONTENT

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SYNOPSIS. The impact of bending stresses on the pine wood creep in conditions of cyclic changes in the moisture content of its different stress zones was studied. Experiments were conducted at bending stresses amounting to 0.1, 0.15, 0.2, 0.25 of the mean immediate wood bending strength of 8% moisture content. Applying the same levels of stresses, wood creep at the constant low and high moisture content was also determined.

KEY WORDS: pine wood, wood bending, mechano-sorptive wood creep, asymmetric moisture content changes, linear-viscoelastic behaviour

INTRODUCTION

Problems connected with the mechano-sorptive wood behaviour were investigated by a number of research centres as early as the middle of the previous century (e.g. Perkitny 1951, Perkitny et al. 1957, 1958, Perkitny 1960, Armstrong and Kingston 1960, Armstrong and Christensen 1961, Hearmon and Paton 1964, Schniewind 1967) and the interest in these issues has continued until today. These continued concerns can be attributed to the ever increasing utilization of wood in various types of constructions and the effectiveness of their protection against unpredictable changes of their dimensions and shapes (e.g. Toratti and Svensson 2000, Zhou et al. 2000, Bengtsson 2001, Kowal 2001, Navi et al. 2002, Takahashi et al. 2004).

Research associated with the recognition of wood behaviour subjected to the simultaneous action of stresses and moisture content changes can be divided, from the point of view of the character of these changes, into two main groups. The first of them concerns the behaviour of wood in conditions of the action of mechanical stresses and changes in its moisture content caused by changes in the conditions of the hygroscopic equilibrium. It can be assumed that, in the result of such changes, the distribution of moisture content in the stressed elements is symmetrical. Despite the fact that the behaviour of wood in such conditions has already been recognised satisfactorily, experiments continue to be conducted aiming at a better elucidation of the so called mechano-sorptive effect and its mathematical description (e.g. Liu 1994, Mårtensson 1994, Wu and Milota 1996, Svensson 1996, Kowal 2001).

The second group of investigations from the area of mechano-sorptive wood behaviour deals with asymmetric changes of its moisture content for example, compression or tension zones of bent beams. One of the practical examples of such changes of wood moisture content is bearing elements working in the so called semi--open space, condensed water vapour falling on wooden constructional elements, leaking roofs leading to seepage on elements of the rafter framing. The behaviour of wood in such conditions has already been investigated (e.g. Moliński and Raczkowski 1988, Moliński 1999, 2000, Moliński et al. 2000, Roszyk and Moliński 2003, 2004). Other studies only mention these problems, nevertheless, they emphasise their practical significance (e.g. Rybarczyk 1973, Ganowicz et al. 1988, Muszyński 1997, Guzenda 2004). However, the problem still seems to be unsolved.

On the basis of the investigations carried out so far, it appears that the creep compliance of bent samples, in conditions of asymmetric moisture content changes, depends on the stressed section in which the change of water content takes place (e.g. Moliński and Raczkowski 1988, Roszyk and Moliński 2003, 2004). Moliński and Raczkowski (1988) arranged the creep compliance of bent and asymmetrically moistened wood assigning its highest values to the cases of the simultaneous moistening of the compression and tension zones, lower – to the cases of moistening of only the compression zone and the lowest – to the moistening of only the tension zone. On the basis of these as well as other observations, it was found that changes in the water content evoked from the compression side determine the creep compliance of bent wood. In cases when the moisture content in this area was changed cyclically, it was found that the course of deformations was qualitatively similar to the cases of symmetric moisture content changes. It was found that the first cycle of moistening and all cycles of drying led to the increase of sample deflection, while the second and successive wetting cycles – to its decrease. On the other hand, when wood moisture content was changed only in the area of sample tensile stresses, then all moistening cycles resulted in the increase of deflection and the subsequent drying cycles – in its decrease (e.g. Roszyk and Moliński 2003, 2004).

Investigations of the wood creeping processes carried out so far in conditions of asymmetric changes of its moisture content have not described satisfactorily how this process is affected by the values of the operating stresses. In the case of symmetric water content changes, it was proved that the level of stresses at which wood still responds in a linear-viscoelastic way is considerably lower than in the case of the pure mechanical creep (e.g. Gril 1996). Mårtensson (1994), quoting, among others, Hunt's experiments (Hunt 1989), maintains that this level is 10-20% of critical stresses at compressing and about 20-30% – at tension and bending. According to Hoffmeyer and Davidson (1989), it amounts to 15-20% of critical stresses, both in the case of wood compression and bending. The knowledge of this level is extremely important because once it is exceeded the loaded elements can easily be destroyed.

Bearing in mind the above arguments, we decided to undertake at the Department of Wood Science of the Agricultural University of Poznań investigations aiming at the determination of the impact of the level of bending stresses on the wood creep in conditions of asymmetric changes of its moisture content.

METHODS

Measurements of the mechano-sorptive creep were carried out on samples derived from the pine's sapwood (*Pinus sylvestris* L.) measuring 10(T) × 25(R) × 450(L) mm. The density of the examined wood at moisture content of 8% (moisture equilibrium content in laboratory conditions) ranged from 500 to 550 kg/m^3.

Experiments were conducted on a prototype laboratory creep testing machine which employs a four-point bending system with the support distance of 360 mm and the loading shoes distance of 120 mm. The bending force was applied parallel to the sample smallest dimension, i.e. tangentially. The sample arrangement (R/T = 2.5) resulted from the need to limit the time necessary to change the moisture content as well as from the desire to study their relatively large, measurable deflections with a satisfactory accuracy. This sample height allowed obtaining distinctly asymmetric distribution of the moisture content throughout its cross section in a relatively short time. It is well known that the value of mechano-sorptive deformations caused by a single cycle of wood moisture content change depends, primarily, on the absolute value of the moisture content change, whereas in the case of cyclic moisture content changes – on the sum of their absolute values but it does not depend on the rate of these changes (e.g. Hoffmeyer and Davidson 1989, Mårtensson 1994, Toratti and Svensson 2000). That is why the author decided not to extend unnecessarily the duration of the described experiments.

The bending load was applied gravitationally by hanging an appropriate weight on the lever arm of the creep testing machine. The load value was selected in such a way as to ensure the bending stresses of: 0.10, 0.15, 0.20 and 0.25 of the mean immediate strength determined at the wood moisture content of about 8%. The absolute values of the acting bending stresses amounted to: 11.8, 17.7, 23.6 and 29.5 MPa.

The experimental samples were cyclically wetted and dried between loading shoes. The moistening was achieved by fixing filter paper to the radial surface of the sample and dipping its ends in containers with distilled water of room temperature. Two treatments of the moistening and drying process of loaded samples were applied. In the first case, the moistening process was carried out from the side of the application of compression stresses, while in the second – from the side of action of tensile stresses. In both treatments, moistening processes were initiated directly after their loading. The moistening process continued until wood moisture content increased in the opposite, outermost sample layers. This state of moisture content distribution in the examined samples was achieved after 5 h of wood moistening from the side of the application of compression stresses and after 24 h moistening from the side of the tensile stresses (Fig. 1). Afterwards samples were dried in laboratory conditions until they reached the initial moisture content. This was achieved after 168 h in the case of the prior moistening of the compression zone and after 144 h in the case of the tension zone. For comparative purposes, the creeping of bent samples at 8% moisture content and wet conditions (MC > FSP) was also investigated.

The creeping process of the examined samples was recorded measuring the total deflection with 0.001 mm accuracy using for this purpose a displacement meter coupled with a PC computer. The applied measuring device allowed automatic recording of deformations at 15 s time intervals.

Wood moisture content distribution was determined on control samples moistened and dried in conditions identical to those maintained in the proper experiments. At definite time intervals, their middle fragment 5 cm long was cut out and then split along the radial plane into 5 layers of 2 mm thick. The moisture content of these layers was determined gravimetrically.

RESULTS

Figure 2 presents an example course of the creep function of wood subjected to the stress equal to 0.15 of the ultimate bending strength. In this figure, the creep function, determined as the arithmetic mean from three repetitions, was presented in the form of relative creep compliance understood as the quotient of the compliance at a given moment of the duration of this process $J(t)$ to the immediate compliance J_0. In conditions of the employed method of bending stress application, these values were calculated from the following formula:

$$J(t) = \frac{108\,bd^3}{23\,Pl^3}\,y(t)$$

where: $J(t)$ – creep compliance at moment t of the duration of the process [mm^2/N],
b – sample width (dimension in radial direction) [mm],
d – sample thickness (in tangential direction) [mm],
P – load [N],
l – support distance [mm].

Even a superficial analysis of the data presented in Figure 2 allows concluding that the obtained research results corroborate former observations in this field. The relative value of the creep function, following 42 days of the process, is – for the case of wood moisture content changes in the compression zone of bent samples after 6 full cycles of moisture content changes – over two times higher in comparison with its value determined for the wood of constant low moisture content. On the other hand, in the case of cyclical moisture content changes in the tension zone of the bent samples, this relationship amounts to 1.6 times. Following

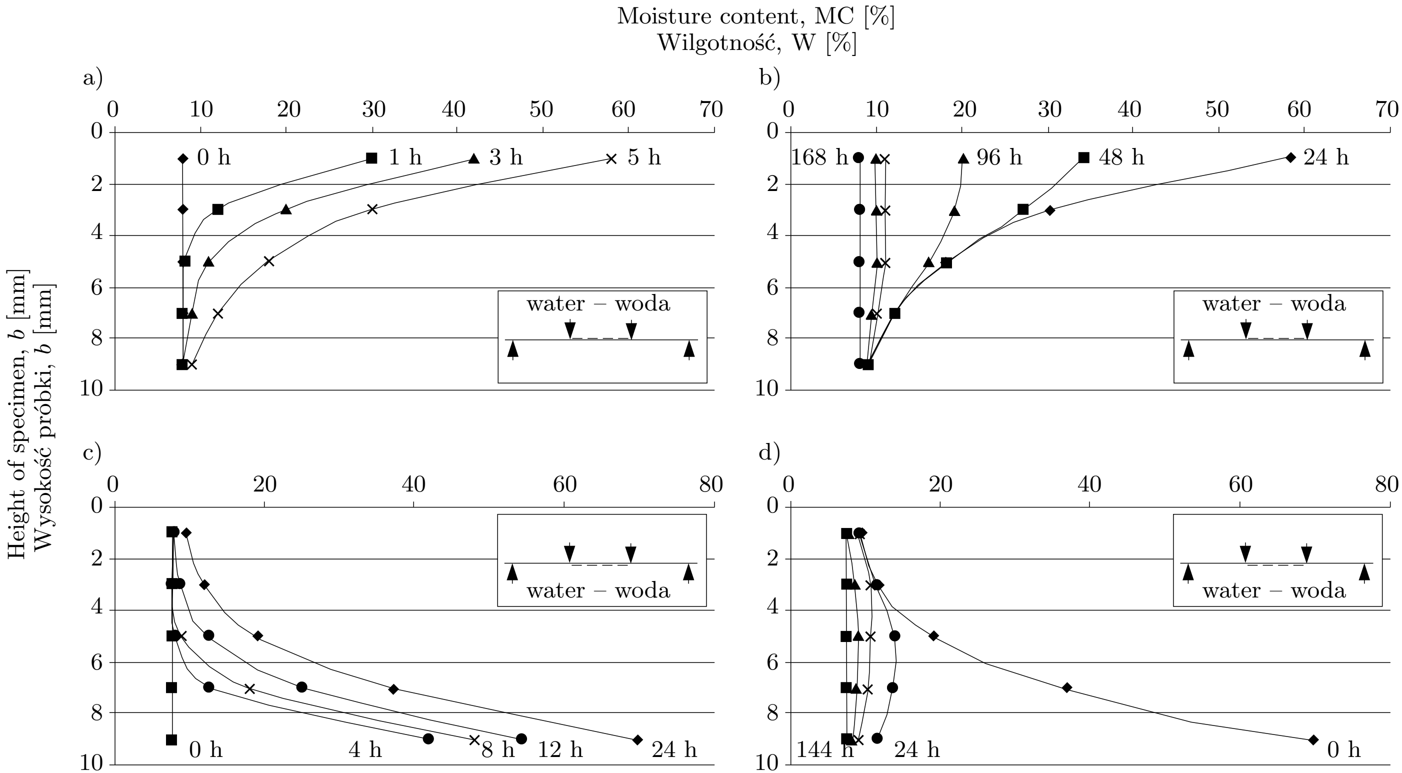

Fig. 1. Moisture content distribution on the cross section of bent samples during their moistening on the compression (a) and tension (c) sides and during their drying after moistening from the compression (b) and tensions (d) sides

Rys. 1. Rozkład wilgotności na przekroju poprzecznym zginanych próbek podczas ich nawilżania od strony ściskanej (a) i rozciąganej (c) oraz podczas ich suszenia, po uprzednim nawilżaniu od strony ściskanej (b) i rozciąganej (d)

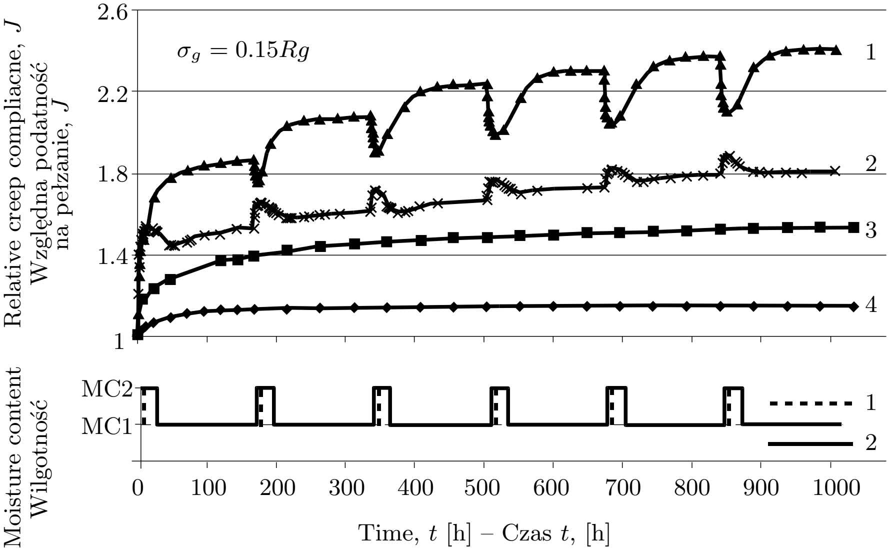

Fig. 2. The creep compliance of bent wood in conditions: 1 – cyclic moisture content changes of the compression zone, 2 – cyclic moisture content changes of the tension zone, 3 – constant high moisture content (MC > FSP), 4 – constant low moisture content (MC ∼ 8%)

Rys. 2. Podatność na pełzanie zginanego drewna w warunkach: 1 – cyklicznych zmian wilgotności strefy ściskanej, 2 – cyklicznych zmian wilgotności strefy rozciąganej, 3 – stałej wysokiej wilgotności (W > PNW), 4 – stałej niskiej wilgotności (W ∼ 8%)

the same creep period, samples with constant high moisture content exhibited the creep compliance only by 30% higher than the state of wood at 8% moisture content.

However, quantitative relations between the examined cases depend on the level of the applied bending forces. As evident from Figure 3, the relative creep compliance of wood of constant low moisture content and of wood cyclically changing its moisture content in the tension zone after 42 days of the process is, practically speaking, independent of the value of the applied bending stresses. On the other hand, the creep compliance of wood cyclically changing its moisture content in the compression zone increases together with the increase of the value of the applied bending stress. In comparison with the remaining examined cases, the relative wood creep compliance of constant high moisture content increases rapidly, especially when it exceeds the level of bending stress of 0.2 Rg. At the stress equal 0.25 Rg, the creep compliance of wet wood is the highest of all the examined cases. At the above stress, wet wood exhibits 4.4 times higher relative creep compliance in comparison with the wood of constant low moisture content. In the case of samples cyclically changing their moisture content in their compression and tension zones these relations amount to 3 and 1.5 times, respectively. This can probably be attributed to varying, for individual experimental conditions, stress levels at which wood continues to behave in a linear-viscoelastic way.

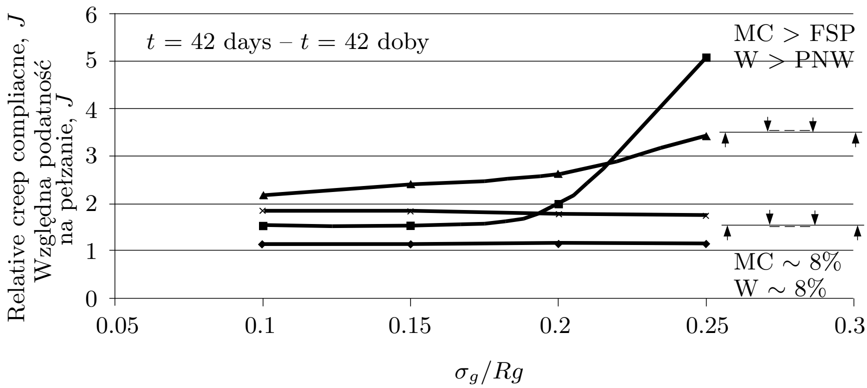

Fig. 3. Effect of bending stresses on the creep compliance of bent wood in different moisture content conditions
Rys. 3. Wpływ naprężeń zginających na podatność na pełzanie zginanego drewna w różnych warunkach wilgotności

On the basis of the analysis of creep isochors shown in Figure 4, it can be stated that wood of constant high moisture content behaves like a linear-viscoelastic material only to the level of stress not exceeding 0.15 of the mean immediate bending strength of this wood determined at 8% moisture content. This can probably be attributed to the fact that the levels of bending stresses applied in these investigations constituted, respectively: 0.18, 0.27, 0.36 and 0.45 of the mean immediate bending strength of this wood in the wet state. The boundary of proportionality between the stress and deformation of wet wood bent immediately, on average, amounts to 0.36 of the breaking stress. The wood creep at the stress reaching 0.2 of its mean immediate bending strength at 8% moisture content, in wet conditions, could have exceeded the linear-viscoelastic range.

In the case of cyclic moisture content changes of loaded elements, it is possible to draw conclusions concerning the linearity of their behaviour only during the period of the first change of the moisture content (e.g. Liu 1994). That is why data presented in Figure 4 refer to the first moistening cycles. It is evident from them that wood which was subjected to cyclic moisture content changes in the compression zone during bending continues to behave linearly at stresses which do not exceed 0.2 of its mean bending strength determined at 8% moisture content. This is probably the effect of a significant difference between the strength of the already moist compression zone of the bent sample and the tensile strength of its dry zone. It is quite clear from the data in Table 1 that this difference in more than six fold. Therefore, it is possible that, at the highest stress applied in the described investigations, compression stresses could have exceeded the proportionality limit in the terminal layers of the moist compression zone of bent samples.

Samples in which moisture content was changed cyclically in the compression zone during bending, but also samples of constant low moisture content, behaved linearly in the entire range of the applied stresses. In these cases, extreme differences between the strength of the compression and tension zones of the bent samples amounted to 1.1 and 1.8 respectively.

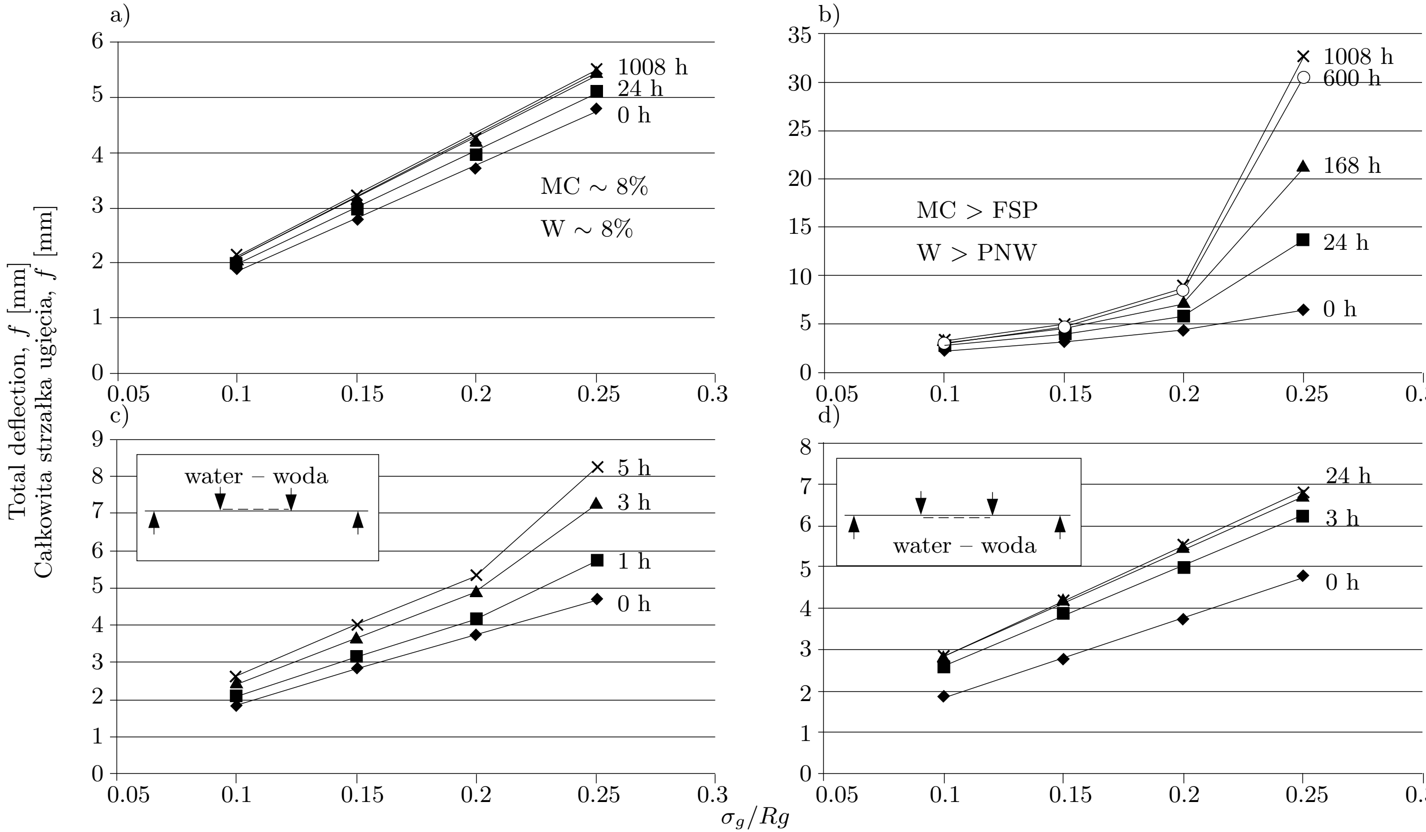

Fig. 4. Creep isochors of wood bent in conditions of constant low (a) and high (b) moisture content and in conditions of moistening of the compression (c) and tensions (d) zones

Rys. 4. Izochory pełzania drewna zginanego w warunkach stałej niskiej (a) i wysokiej (b) wilgotności oraz w warunkach nawilżania strefy ściskanej (c) i rozciąganej (d)

Table 1. Effect of wood moisture content on its compression and tensile strength along fibres
Tabela 1. Wpływ wilgotności drewna na jego wytrzymałość na ściskanie i rozciąganie wzdłuż włókien

Strength of wood Wytrzymałość drewna	Moisture content Wilgotność	n	$X_{\min}$	$\overline{X}$	$X_{\max}$	$\pm S$	V
			[MPa]				[%]
Tensile	~ 8%	10	120	138	147	9.3	6.7
Rozciąganie	>FSP >PNW	10	79	86	92	5.0	5.8
Compression	~ 8%	10	71	76	79	2.2	2.9
Ściskanie	>FSP >PNW	10	20	21	22	0.5	2.4

It is worth emphasizing, as evident from the data presented in Table 1, the difference between the compression and tensile strength of wood at 8% moisture content and wet states. In the case of wood at 8% moisture content, the longitudinal tensile strength is almost twice bigger (1.8 times) than the compression strength in the same direction. On the other hand, when the moisture content exceeds FSP, this difference increases to over four times. On the basis of these results, employing the Bielankin formula (Krzysik 1974), it was calculated that in the case of moistening of only the compression zone of bent samples, the displacement of the neutral axis towards tension zones can attain, in extreme cases, even 2.71 mm. In such conditions, only – of the sample cross section carries tensile loads. In the case of moistening of the tension zone of bent samples, the maximum displacement of the neutral zone towards tensile layers reaches only 0.27 mm. This observation appears to have a significant practical value which should be taken into consideration when designing constructions that may be exposed to asymmetric moisture content changes of bent elements during utilisation.

CONCLUSIONS

1. The relative wood creep compliance cyclically changing its moisture content in the compression zone of bent samples increases with the increase of the bending stress. In the case of wood cyclically changing its moisture content in the tension zone, this value is practically independent of the stress, at least in the range of up to 25% of the immediate breaking stress.
2. During the first moistening of the compression zone of bent samples, the level of stress at which they continue to behave in a linear-viscoelastic manner amounts to about 20%.
3. The strength of the compression zone of the bent sample during its moistening above FSP decreases to the level over six times lower in comparison

with the strength of the dry tension zone. At 8% moisture content, the wood longitudinal compression strength is, on average, two and, in the moist state, over four times lower in comparison with the tensile strength.

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WPŁYW NAPRĘŻEŃ ZGINAJĄCYCH NA PEŁZANIE DREWNA W WARUNKACH NIESYMETRYCZNYCH ZMIAN JEGO WILGOTNOŚCI

Streszczenie

Zbadano wpływ naprężeń zginających na pełzanie drewna sosnowego w warunkach cyklicznych zmian wilgotności jego różnych stref naprężeniowych. Eksperymenty przeprowadzono przy naprężeniach zginających wynoszących 0,1; 0,15; 0,2; 0,25 przeciętnej doraźnej wytrzymałości tego drewna na zginanie przy wilgotności 8%. Przy tych samych poziomach naprężeń oznaczono także pełzanie drewna przy stałej niskiej i wysokiej wilgotności. Na podstawie przeprowadzonych badań stwierdzono, że względna podatność na

pełzanie drewna zmieniającego cyklicznie wilgotność w ściskanej strefie zginanych próbek rośnie wraz ze wzrostem naprężenia zginającego. Dla drewna zmieniającego cyklicznie wilgotność w strefie rozciąganej wielkość ta jest praktycznie niezależna od naprężenia, przynajmniej w zakresie do 25% doraźnego naprężenia niszczącego. Podczas pierwszego nawilżania ściskanej strefy zginanych próbek poziom naprężenia, przy którym zachowują się one jeszcze w sposób liniowo lepko-sprężysty, wynosi około 20%. Ponadto zauważono, że wytrzymałość ściskanej strefy zginanej próbki, podczas jej nawilżania powyżej PNW, zmniejsza się do poziomu ponad sześciokrotnie niższego, w porównaniu z wytrzymałością suchej strefy rozciąganej. Przy wilgotności 8% wytrzymałość drewna na ściskanie podłużne jest prawie dwa razy, a w stanie mokrym ponad cztery razy mniejsza w porównaniu z wytrzymałością na rozciąganie.

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