F O L I A F O R E S T A L I A P O L O N I C A

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EFFECTS OF STEAMING ON TENSILE STRESS DEVELOPMENT AND CHECK RISK DURING KILN-DRYING OF EUROPEAN BEECH (*FAGUS SYLVATICA* L.) WOOD

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SYNOPSIS. The tensile drying stress development of steamed and unsteamed wood was analysed in order to determine the influence of the treatment on check risk of the wood during the initial phase of the kiln drying. The tests were performed using a load cell for total mechanically restraint shrinkage of dried samples. The reliability theory was used to describe difference of the failure rate of steamed and unsteamed wood. The results of the investigations showed that the wood steaming causes check which occurred under lower tensile desorption stress. The analysis of the results of the experiments proved that drying of steamed beech wood is accompanied by the significantly higher risk of checking as compared to unsteamed wood.

KEY WORDS: restraint shrinkage, Weibull failure distribution, thermal treatment

INTRODUCTION

The objectives of heat treatment of beech wood before kiln drying are sterilization, increasing intensity and homogenization of wood colour, as well as decrease of growth stress (Ławniczak 1995). The already obtained results show that the heat treatment may influence wood drying. It was found by Harris et al. (1989) that the drying intensity of oak timber after steaming is higher as compared to unsteamed wood. Majka and Olek (2007) reported that higher intensity of drying was primary found in the initial phase of the drying process, i.e. for timber moisture contents higher than 30%. It was found in the initial phase of kiln-drying that the drying rate of steamed beech flooring strips was ca. 3 times higher as compared to the unsteamed ones. It was also proved that steamed beech wood drying with the use of schedules developed for unsteamed wood was associated with uncontrolled increase of drying gradient in the initial phase of the process. The authors stated that the application of the same drying schedule for steamed and unsteamed beech wood is improper. The intensity of drying in the initial phase of the process is specially important because of the development of drying stress (McMillen 1958, Siergovskij 1969).

The high intensity of drying in the near surface layers of wood causes intensive decrease of moisture content leading to desorption shrinkage which is accompanied by the dynamic increase of stresses. The tensile stress development in that layers makes special risk of surface checks and decrease of drying quality (Kass 1965, Vanek 1986). Ławniczak (1965) found that beech wood steaming before kiln drying causes reduction tensile stresses during the drying process. In the reported investigations the tensile stress was determined by its generation due to permitted insignificant shrinkage of a wood sample and next extending the sample to its initial dimension. The stress value in the sample (called as critical) was calculated as the algebraic sum of cycle loads by the area of the cross-section perpendicular to the direction of the load. However, it was later proved by Raczkowski et al. (1992) that the required in the method cyclic loading of a sample causes underestimation of the value of stress. Also Widłak (1993) found that the critical value of tensile desorption stress generated during cyclic loading were significantly lower as compared to the value observed in experiments in which the axial force was not totally restraining the shrinkage.

Moreover, the knowledge of the critical value of tensile desorption stress has special importance to predict checks formation. As the previous research on the wood steaming influence on phenomena related to kiln drying were only partially describing the conditions and mechanism of the desoprtion stress development, it is justified to perform investigations aiming to verify current views on the wood steaming influence on the desoprtion stress development. Additionally, there will be performed the risk estimation of checks formation accompanying the development of tensile desorption stress. The additional analysis should improve drying quality of steamed timber.

MATERIAL AND METHODS

The investigations were made for European beech (*Fagus sylvatica* L.) wood due to its special susceptibility to check during the kiln drying. The samples were obtained from the green wood in the way presented in Figure 1. The final dimensions of the samples were 5 × 10 × 90 mm corresponding to longitudinal (L), radial (R) and tangential (T) directions, respectively. The assumed orientation of growth rings in the relation to samples dimensions (Fig. 1) was the consequence of the assumption of the consistence of the direction of the force restraining shrinkage with the tangential direction (T). The above mentioned assumption was made due to the following reasons:

- high desorption shrinkage of beech wood in the tangential direction, which can be effectively restraint during drying and therefore, cause high tensile desorption stress easily measurable with simple measuring techniques,
- restraint of desorption shrinkage in the tangential direction is related to

high risk of check formation because the force restraining the shrinkage is responsible for wood tissue damage especially in the plane of wood rays due to their low strength (Bodig and Jayne 1982).

The samples were divided into 2 groups. The first group of the samples was subjected to steaming in a laboratory steaming chamber using treatment parameters typical for industrial conditions (temperature 85°C, treatment time 36 h). The second group consisted of twin samples which were stored without steaming and protected against drying in order to prevent their high initial moisture content (the samples in this group will be called as unsteamed ones). As the samples had to be mounted during the experiments their dimension in the direction of the force restraining the shrinkage was only a portion of the total dimension and equal to the distance between mounting grips, i.e. equal to 50 mm.

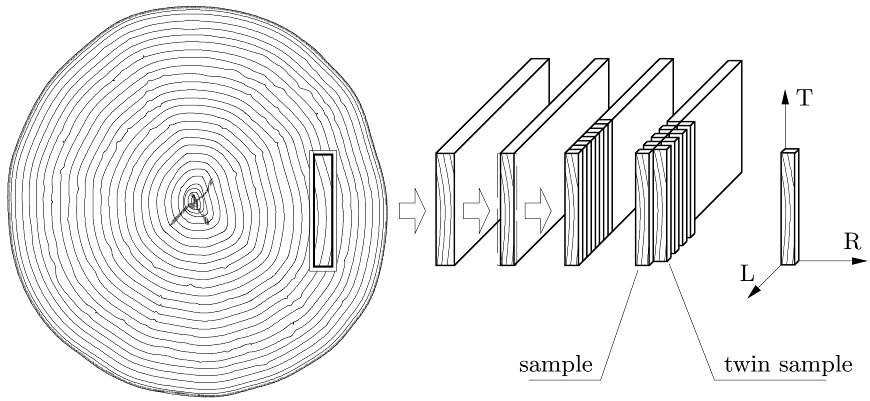


Fig. 1. Scheme of samples preparation

In order to reproduce the tensile desorption stress development in the near surface layers in the initial phase of drying, the method of mechanical uniaxial restraint of desorption shrinkage was used. The method was already applied in a number of earlier investigations, e.g. Widłak and Dudziński (1993), Widłak (2003). The stress value in a sample was calculated as the force divided by the area of the cross-section perpendicular to the direction of the force action. The axial force was measured with a S-beam load cell type UTC-5882/S/1 made by SPAIS, which allowed to preserve the initial sample size. The tensile stress at failure was calculated as the maximum tensile axial force divided by the area of the cross-section perpendicular to the load direction.

$$\sigma_{\max} = \frac{P_{\max}}{A} \tag{1}$$

where: $P_{\max}$ – maximum tensile axial force [N],
A – area of the cross-section perpendicular to the direction of loading [mm^2].

The experiments were performed in the set-up schematically presented in Figure 2. The steamed as well as unsteamed samples were placed in the dryer chamber of the set-up. During each experiment a set of two samples was placed in the dryer. It consisted of a sample with mechanically restrained shrinkage and a twin sample. The decrease of mass of the twin sample was used to determine the moisture content of the sample during failure. Air circulation in the chamber was forced by the fan, while the relative humidity was controlled by a psychrometer. It has to be mentioned that the values of air parameters which were applied in earlier investigations made by Ławniczak (1965) should be recognized as differing from the values applied in industrial kiln drying of beech timber. In order to use the results of the present study in practice the parameters of air used in the experiments were corresponding to the industrial drying conditions during the initial phase of convective kiln drying of beech timber. The dry-bulb and wet-bulb temperatures in the chamber corresponded to 50 and 46.5, respectively. Consequently, the equilibrium moisture content (EMC) was equal to 15% (Brunner 1987, Cividini 2000, Denig et al. 2000). The applied air parameters let to reproduce industrial drying condition in the laboratory scale. Moreover, the parameters are characteristic for the conditions in which tensile stress develops in the near surface layers of timber. The experiments had been continued until the stress at failure occurred. During the experiments the values of the force in time as well as the maximum force at failure were registered. The obtained measurements were stored by the data acquisition system. After finishing the experiments the twin samples were placed in a laboratory dryer and their oven-dry mass was determined. The value of tensile stress at failure and moisture content corresponding to tensile drying stress at failure for samples obtained from steamed or unstemed wood was the average of 13 and 16 measurements, respectively.

In order to determine the influence of wood steaming on the tensile stress at failure, the Fisher test was performed. When the significance of differences of the mean values of the critical tensile desorption stress in steamed and unsteamed wood samples was found, the quantification of the differences was made by the use of the linear parametric function (also known as the basic contrast) and the following relation was applied (Kala 2002):

$$\varphi = c_1\mu_1 + c_2\mu_2 \qquad (2)$$

where: φ – contrast value,

μ_1, μ_2 – average tensile stress at failure corresponding to steamed and unsteamed samples, respectively,

c_1, c_2 – coefficients corresponding to steamed and unsteamed samples, respectively.

Moreover, the risk of wood failure related to tensile stress development was estimated by the application of the reliability theory. The theory assumes that time between the moment of the appearance of check risk (the begining of restraint desorption shrinkage) and the momemt of sample failure is a continuous random variable T (Bobrowski 1986). The variable T is characterized by the following functions continuous towards time (t) – probability density function, unreliability (cumulative distribution function), reliability and failure rate. Each function unequivocally defines the random variable T and therefore, it determines the form

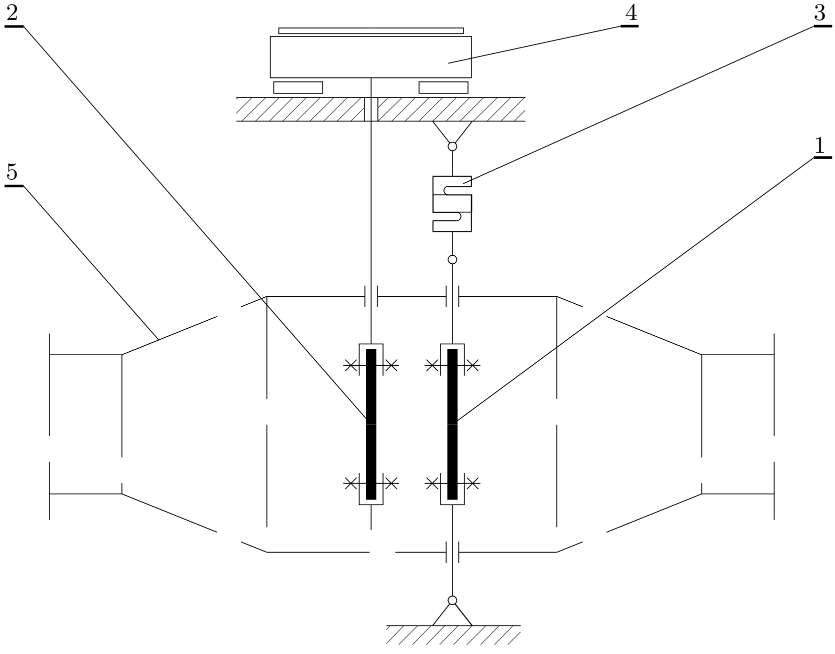


Fig. 2. Scheme of the experimental set-up: 1 – wood sample with mechanically restrained shrinkage for drying stress generation, 2 – twin wood sample for mass loss measurements, 3 – the S-beam load cell, 4 – balance, 5 – dryer chamber

of other functions (MIGDALSKI 1982). In order to estimate the check risk the 2-parameter Weibull distribution was applied as it is often used in fracture mechanics for mathematical modeling of the risk of wood failure (BODIG and JAYNE 1982). The selection of the proper values of parameters of the distribution leads to obtain high consistence of the distribution with the experimental results. The reliability function $R(t)$ for each $t \geqslant 0$ is equal to the probability of an event consisting in no failure of a sample up to a given time (MIGDALSKI 1982). The reliability function for the 2-parameter Weibull distribution can be then written as

$$R(t) = \exp(-\beta t^{\alpha}), \quad t > 0 \tag{3}$$

where: t – time at which a sample is broken (time measured from the begin of desorption shrinkage of a sample),
α – shape parameter,
β – scale parameter.

The cumulative distribution function (also known as unreliability) for the 2-parameter Weibull distribution is defined as the complement of the reliability function

$$F(t) = 1 - R(t) = 1 - \exp(-\beta t^{\alpha}), \quad t > 0 \tag{4}$$

where: $R(t)$ – reliability function expressed by Equation (3).

The derivative of the cumulative distribution function (Eq. 4) is the probability density function

$$f(t) = \frac{d}{dt}F(t) = \alpha\beta t^{\alpha-1}\exp(-\beta t^{\alpha}), \quad t > 0 \tag{5}$$

The probability density function $f(t)$ means the absolute decrease of reliability at time unit (Migdalski 1982). The failure rate $\lambda(t)$, also known as the hazard function, is the ratio of the probability density function $f(t)$ (Eq. 5) to the reliability function $R(t)$ (Eq. 3) and given by

$$\lambda(t) = \frac{f(t)}{R(t)} = \alpha\beta t^{\alpha-1}, \quad t > 0 \tag{6}$$

The failure rate $\lambda(t)$ determines the relative decrease of the reliability in time unit (Migdalski 1982). The failure rate is the frequency at which dried wood fails, expressed in failures per time unit. In order to estimate the parameters of the Weibull distribution the algorithm of reliability analysis was applied as it was implemented in STATISTICA (StatSoft, Inc.). The statistical analysis of data was performed at a significance level $\alpha = 0.05$.

RESULTS AND ANALYSIS

Figure 3 shows the differences in the tensile desorption stress development registered during the experiments of the uniaxial restraint of shrinkage in the tangential direction of steamed and unsteamed beech wood samples. The comparison of the obtained critical values of tensile desorption stress (Table 1) shows that in the case of the steamed wood samples, the critical values of stress are significantly lower as compared to the values registered for unsteamed wood. It was stated on the basis of the performed statistical analysis for $\alpha = 0.05$ that during drying the tensile stress mean value at failure of steamed samples is at least 25.4% lower as compared to the mean value registered for samples from unsteamed wood, however, it was not more than 33.0% (29.2% on the average). The observed significant decrease of tensile desorption stress is in accordance with the earlier findings on the influence of steam on tensile stress development during drying (Ławniczak 1965). According to Ławniczak (1965) the lower desorption stress in steamed wood may be caused by the reduction of cohesion forces between components forming wooden tissue due to the changes of elements forming cell walls especially in the middle lamella.

Table 2 presents results of moisture content determination of samples as registered at their failure. It can be generally stated on the basis of the results that the samples failed before the set value of the equilibrium moisture content was achieved. In order to qualify the statement it has to be mentioned that the mean moisture content, at which the steamed samples failure was registered, was significantly higher (on the average 33.6%) as compared to the values found for unsteamed samples during their failure (on the average 23.8%).

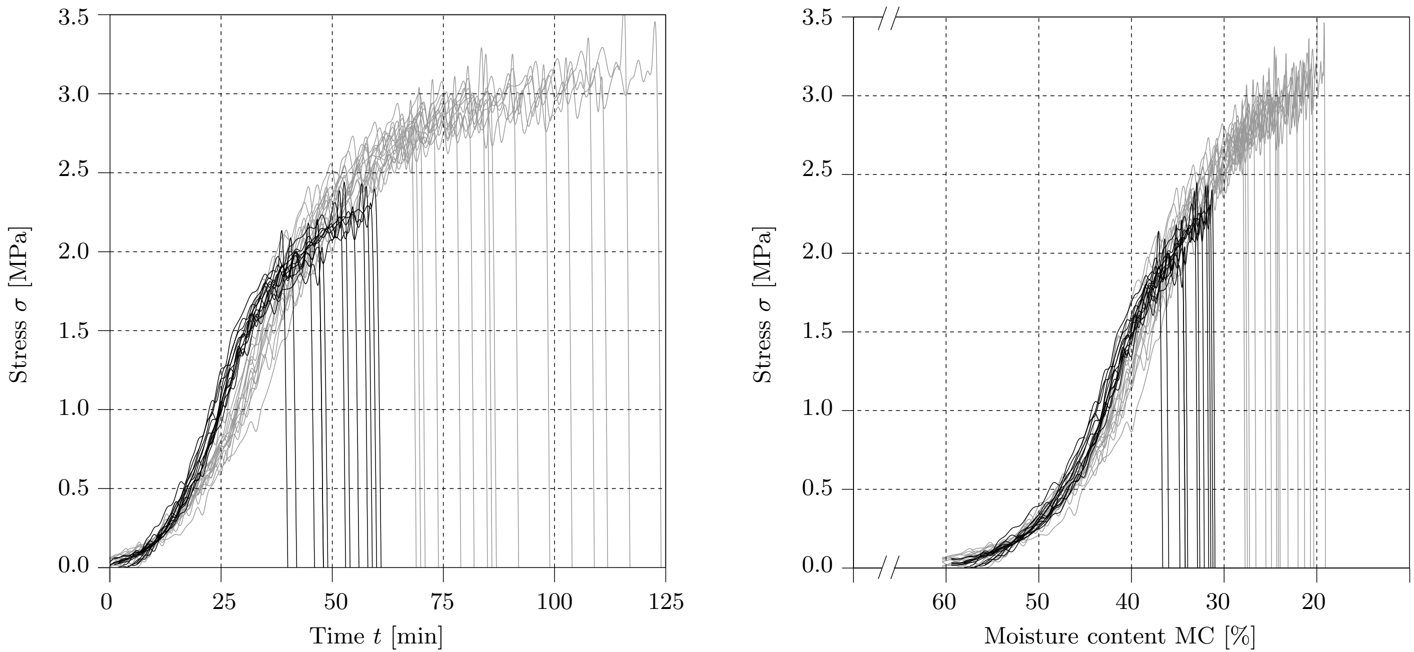
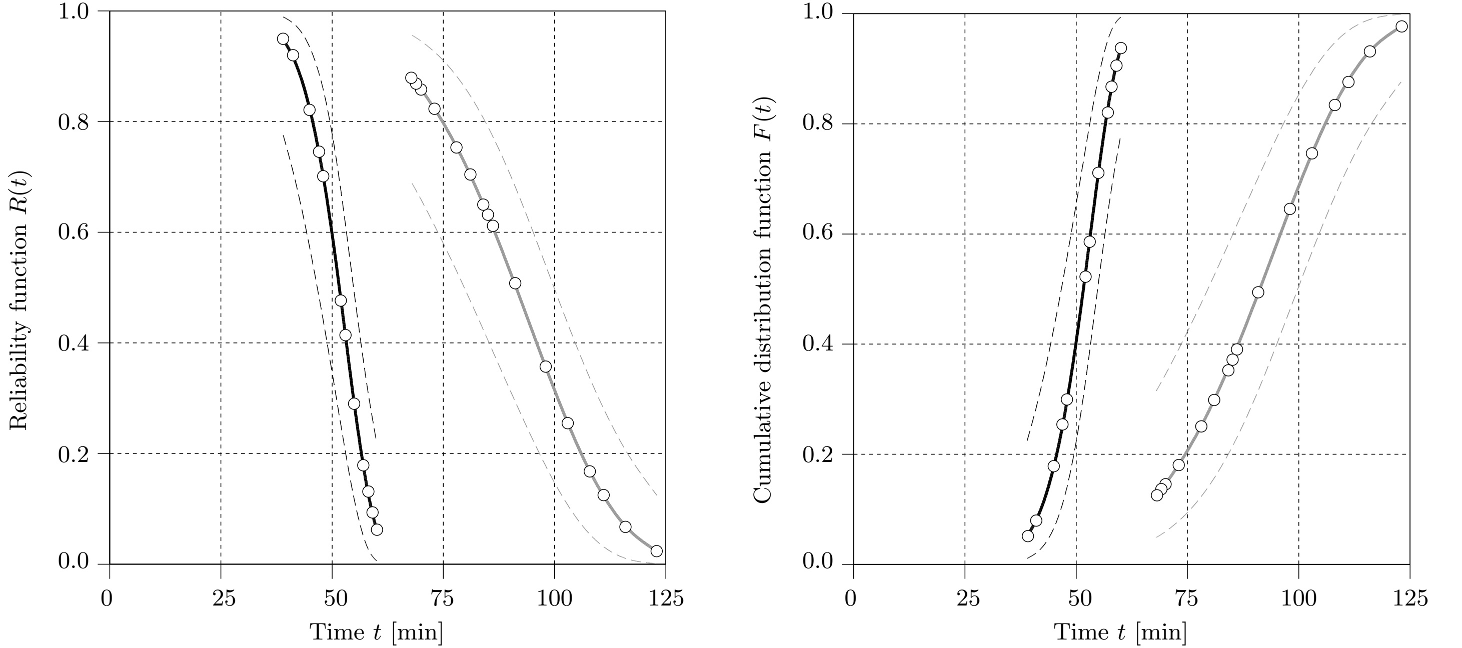


Fig. 3. Comparison of the tensile drying stress as a result of totally restraint shrinkage of the steamed (black line) and unsteamed (gray line) samples of European beech (*Fagus sylvatica* L.) wood in the tangential direction; drying conditions: temperature T = 50°C, equilibrum moisture content EMC = 15%


Reliability function $R(t)$
1.0
0.8
0.6
0.4
0.2
0.0
0
25
50
75
100
125
Time t [min]
Cumulative distribution function $F(t)$
1.0
0.8
0.6
0.4
0.2
0.0
0
25
50
75
100
125
Time t [min]

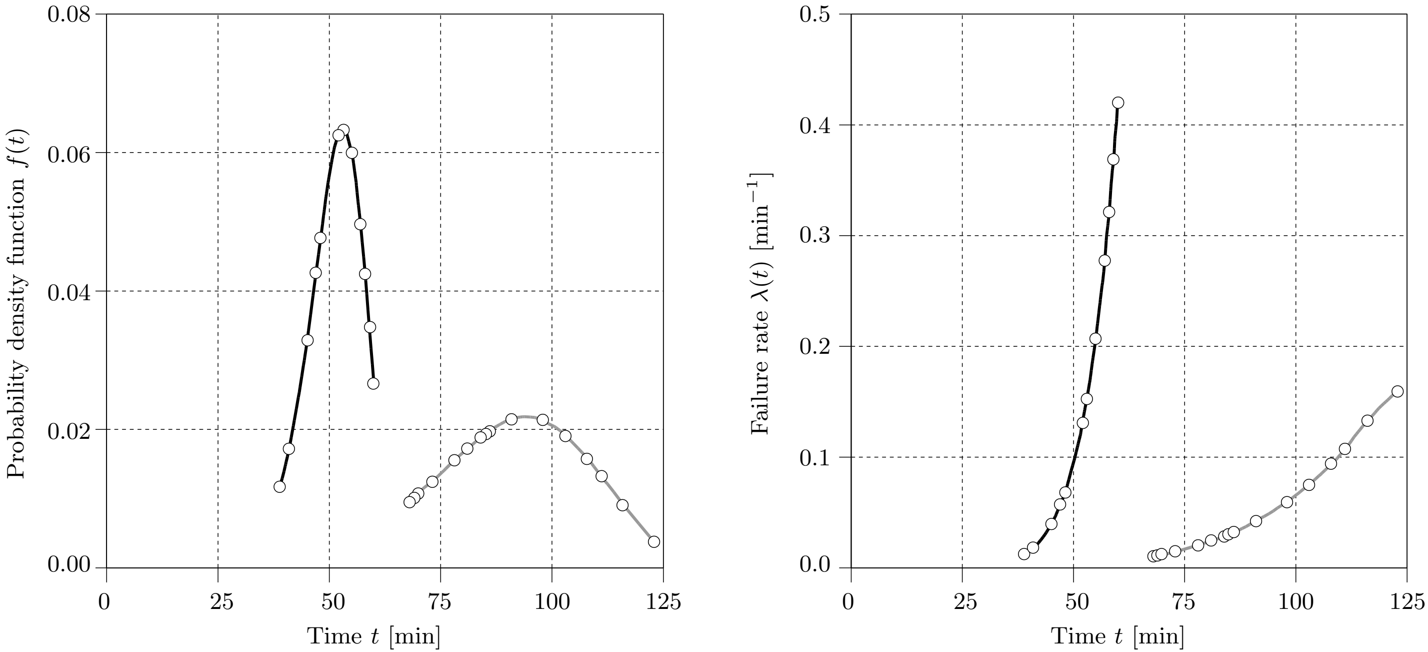


Fig. 4. Reliability function $R(t)$, cumulative distribution (unreability) function $F(t)$, probability density function $f(t)$ and failure rate $\lambda(t)$ obtained for the steamed (black line) and unsteamed (gray line) beech wood (the dashed lines represent the 95% confidence limits)

Table 1. Tensile drying stress at failure as a result of totally restraint shrinkage for the steamed and unsteamed samples of European beech (*Fagus sylvatica* L.) wood in tangential direction; drying conditions: temperature $T = 50°C$, equilibrium moisture content EMC = 15%

Descriptive statistics	Symbol	Unit	Wood treatment	
			steamed wood	unsteamed wood
Number of measurements	n	pcs.	13	16
Minimum	σ_{min}	MPa	1.91	2.65
Average	$\sigma_{average}$	MPa	2.10	2.97
Maximum	σ_{max}	MPa	2.31	3.33
Variance	Var	MPa	0.027	0.016
Standard deviation	SD	MPa	0.128	0.164
Standard error	SE	MPa	0.035	0.041
Confidence interval*	$\langle L;\ U\rangle$	MPa	⟨2.03; 2.18⟩	⟨2.88; 3.06⟩
Coefficient of variation**	CV	%	6.1	5.5

*Level of significance $\alpha = 0.05$.
**Defined as: $(SD/MC_{mean})\cdot 100\%$.

Table 2. Moisture content corresponding to the tensile drying stress at failure for the steamed and unsteamed samples of European beech (*Fagus sylvatica* L.) wood in the tangential direction; drying conditions: temperature T = 50°C, equilibrium moisture content EMC = 15%

Descriptive statistics	Symbol	Unit	Wood treatment	
			steamed wood	unsteamed wood
Number of measurements	n	pcs.	13	16
Minimum	MC_{min}	%	31.2	19.2
Average	$MC_{average}$	%	33.6	23.8
Maximum	MC_{max}	%	37.0	28.0
Variance	Var	%	3.528	8.458
Standard deviation	SD	%	1.878	2.908
Standard error	SE	%	0.521	0.727
Confidence interval*	$\langle L;\ U\rangle$	%	⟨32.4; 34.7⟩	⟨22.3; 25.4⟩
Coefficient of variation**	CV	%	5.6	12.2

*Level of significance $\alpha = 0.05$.
**Defined as: $(SD/MC_{mean})\cdot 100\%$.

The results of the performed reliability analysis showed that the failure rate $\lambda(t)$, which is equivalent to the probability of the event of sample failure, is ca. 3 times higher for samples made of steamed wood. Table 3 presents the estimated values of the parameters of Weibull distribution. The higher value of the shape parameter (α), determined on the basis of the values of stress at failure as obtained

Table 3. The values of Weibull distribution parameters estimated for the steamed and unsteamed beech wood

Wood treatment	α – shape parametr	β – scale parametr
Steamed wood	9.19	53.73
Unsteamed wood	5.67	97.48

for the steamed samples, proves the statement that in the initial phase of drying of steamed wood there is higher risk of checking as compared to unsteamed wood. The increase of the checking risk, as accompanying the development of tensile desorption stress in steamed wood, may be an effect of the permanent changes in wooden tissue which occur during steaming. The changes can be related to the decrease of the values of the modulus of elasticity and wood strength (Kollmann and Côté 1968).

CONCLUSIONS

1. The heat treatment of beech wood is a significant factor reducing tensile desorption stress which accompanies wood checking during drying. It was found in the experiments of the uniaxial restraint of desorption shrinkage in beech wood samples in the tangential direction that for the air parameters corresponding to the industrial conditions ($T = 50°\text{C}$, EMC = 15%) the critical values of tensile desorption stress in steamed samples were on the average 29.2% lower as compared to unsteamed samples. The performed analysis let to state that the probability of the event consisting in failure of a sample during restraint of desorption shrinkage in the tangential direction was on average 3 times higher for the samples of steamed beech wood.
2. During the uniaxial restraint of desorption shrinkage of beech wood samples in the tangential direction the sample failure occurred before the equilibrium moisture content was achieved. However, the failure of the samples of steamed wood was at moisture content significantly higher (on the average 33.6%) as compared to the samples of unsteamed wood (on the average 23.8%).
3. The results of the performed reliability analysis showed that the highest failure rate of the samples of steamed wood during the uniaxial restraint of desorption shrinkage in the tangential direction was ca. 3 times higher as compared to unsteamed samples.
4. The results of the experiments as well as the reliability analysis showed that the development of tensile desorption stress in steamed wood was related to the significant increase of the risk of checking in the near surface layer during the initial phase of drying.

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