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ORIGINAL

Identification of moisture-induced stresses in cross-laminated wood panels from beech wood (*Fagus sylvatica* L.)

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Abstract The crosswise bonding of the layers in laminated solid wood panels results in internal stresses when the humidity varies. The layers hinder one another as a result of the anisotropy of wood. The purpose of this study was to determine the internal stress state in free and constrained swelling. The expansion properties in the three panel directions were measured. Furthermore, the swelling of samples was constrained while the resulting forces were recorded. Hygroscopic warping experiments were carried out inducing a climate gradient within the panels. Afterwards the stresses were calculated from released deformations and non-destructive measurements of the Young's modulus. The materials used were untreated and heat-treated beech wood, the latter modified in two levels. In addition to homogenously structured panels, treated top layers were combined with an untreated middle layer. Swelling, swelling pressure, warping and internal stresses considerably decreased from untreated to treated wood. If layers from treated and untreated material were combined, stresses and deformations increased as compared to the variants produced only from treated wood. It was concluded that the lower equilibrium moisture content of heat-treated beech wood improves its dimensional stability, which results in smaller deformation differences between the layers. Hence, the stresses were less distinctive.

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Introduction

Multilayer cross-laminated solid wood panels that are also used as static load bearing elements are of increasing significance in the Central European building industry (Tobisch and Krug 2001). The crosswise gluing of layers leads to an improvement of mechanical properties but also to internal stresses when panels are exposed to a varying humidity due to the swelling and shrinkage anisotropy of wood. Broad research activities have been started. Former studies concerned the determination of mechanical properties mainly in bending tests of beams (Krug et al. 1999a, b; Tobisch and Plattes 2000; Niemz and Bencat 2001; Tobisch and Krug 2001; Donzé et al. 2003) and in panel bending tests of large-sized samples (Czaderski et al. 2007). Diffusion processes, thermal conductivity and the equilibrium moisture content (EMC) of cross-laminated solid wood panels were also tested (Popper et al. 2004a, b; Bader et al. 2007). Other studies concerned the non-destructive evaluation of elastic parameters by means of eigenfrequencies (Gülzow et al. 2007), testing of joints and fastening devices (Sigrist et al. 2007; Uibel 2007) and the fire performance (Frangi and Bochicchio 2007). The main wood species tested was spruce (*Picea abies* [L.] Karst).

The objective of the present study was to evaluate the application of beech wood and heat-treated beech wood as cross-laminated wood panel. Heat treatment leads to improved dimensional stability and durability of wood but also reduces its mechanical properties and EMC (Kollmann and Schneider 1963; Burmester 1973; Giebeler 1983; Bekhta and Niemz 2003; Militz and Hill 2005; Popper et al. 2005). Obviously the decrease is larger for bending strength than for the Young’s modulus (Bekhta and Niemz 2003). Thermal treatment is commonly accompanied by a darkening of the wood. Swelling, swelling pressure, hygroscopic warping and internal stresses were measured.

Since a 1% change in the moisture content (MC) has a ten times greater effect on wood dimensions than a 1 K change in the temperature (Niemz 1993), our investigations were confined to the influence of moisture on stresses and deformations. The temperature was kept constant at 20°C during all experiments.

Material

The raw material was provided by Balz Holz AG (Switzerland). Untreated beech wood (*Fagus sylvatica* L.) was used, indicated as type 0 in the following. Additionally, two types of heat-treated beech wood were investigated. Type 1 points to treated wood of the level 1 and type 2 to treated wood of the level 2. The latter denotes a higher grade of modification. The heat treatment was performed in an autoclave under a nitrogen atmosphere. Temperature, pressure and retention time vary for both types. However, the exact parameters are not released by the manufacturer.

The characteristics of the raw material obtained by means of three-point bending tests of beams according to DIN 52186 (1978) are summarized in Table 1. Furthermore, the swelling from the oven-dry state to different climates was tested

Table 1 Properties of the investigated beech wood under standard climatic conditions (20°C/65% RH)

Wood type[a]	Density ρ (g cm^{-3})	Moisture content ω (%)	Bending strength f_b (MPa)	Ultimate bending strain ε_b (%)	Young's modulus E (MPa)
0					
$\bar{x}$	0.738	10.9	132.8	2.07	13140
CoV (%)	2.4	4.6	4.2	8.2	5.6
1					
$\bar{x}$	0.692	9.1	76.7	0.78	11092
CoV (%)	4.3	3.3	28.4	24.4	16.1
2					
$\bar{x}$	0.656	8.7	53.8	0.51	11776
CoV (%)	4.7	1.1	24.5	31.4	10.8

$\bar{x}$ mean value, *CoV* coefficient of variation

[a] 0, untreated beech wood; 1, treated beech wood level 1; 2, treated beech wood level 2

according to DIN 52184 (1979) (Table 2). The results from both investigations clearly show the influence of the heat treatment. The treatment reduces the density, the EMC, the bending strength, the ultimate bending strain and the Young's modulus (Table 1). The swelling is larger in untreated wood, especially at higher relative humidity changes (Table 2).

Lamellas without knots with dimensions of 620 × 105 × 14 mm^3 were sawn from the raw material. They were stored until equilibrium in constant climatic conditions of 35% relative humidity (RH) and 65% RH, respectively. Afterwards, they were glued to layers with a one-component polyurethane (1C PUR). The adhesive was chosen from preliminary tensile-shear tests. After a curing time of 7 days, the layers were planed to the final thickness of 10 mm. Subsequently, three layers were assembled crosswise to one panel. The 1C PUR was applied with 200 g/m^2. Layers previously stored in 35% RH were pretreated with 50 g/m^2 water to ensure a durable bonding. The samples were pressed during 3 h with a forming pressure of 0.8 N/mm^2. Within each panel, identically treated layers were used

Table 2 Swelling (%) of the investigated beech wood from the oven-dry state to the respective climate

Wood direction	Wood type	Temperature (°C)/relative humidity (%)				
		20/35	20/50	20/65	20/80	20/93
Tangential	0	1.4	1.5	2.6	5.3	9.5
	1	1.4	1.5	2.2	4.0	6.4
	2	1.3	1.5	2.0	3.6	5.7
Radial	0	1.0	1.1	1.7	2.8	4.4
	1	1.0	1.1	1.5	2.5	2.9
	2	0.8	0.9	1.1	1.9	2.6

(indicated as 0/0/0, 1/1/1, and 2/2/2). Moreover, treated wood in the outer layers was combined with untreated wood in the middle layer to compensate for the loss in strength due to the thermal treatment (indicated as 1/0/1 and 2/0/2). Finally, $300 \times 300\ \text{mm}^2$ specimens were sawn from the panels stored at 65% RH to investigate the hygroscopic warping. The specimens to test the swelling properties ($250 \times 250\ \text{mm}^2$) and to test the swelling pressure ($200 \times 200\ \text{mm}^2$) were manufactured from the panels stored at 35% RH.

Methods

Identification of moisture-induced stresses

The procedure is illustrated in Fig. 1. The panels were sawn into approximately $200 \times 20\ \text{mm}^2$ wide stripes with a circular saw. The length was quantified immediately before (L_0) and after (L_1) sawing them into slices of each layer. Released deformations were measured by a linear gage (MITUTOYO) with direct contact at the boundaries of the specimen. The contact of the gage head on the small surface was at the same place in both measurements. Compressive stress leads to an extension and tensile stress to a contraction of the slices. In Jönsson and Svensson (2004) a contact-free method based on a digital camera technique to determine internal stresses in glued laminated wood (glulam) is presented. A similar approach was out of question in the present study since buckling of the sliced specimens was observed which could be manually adjusted with the introduced technique. Neglecting the transverse contraction, the mean stress (σ_m) in each slice is

$$\sigma_m = E\varepsilon_m \quad \varepsilon_\mathrm{m} = \frac{L_0 - L_1}{L_0} \tag{1}$$

where ε is the strain and E is the Young's modulus or modulus of elasticity (MOE). This is not the maximum stress in the slices, since there is no uniform stress distribution throughout the slices, and the stress at the ends must be zero. For glulam samples Jönsson and Svensson (2004) calculated the maximum stress to be 30% higher than the mean stress.

In each individual slice, the MOE was determined dynamically by means of ultrasonic waves. The dynamic method was chosen because preliminary investigations by means of bending tests partly lead to a failure of the small specimens due

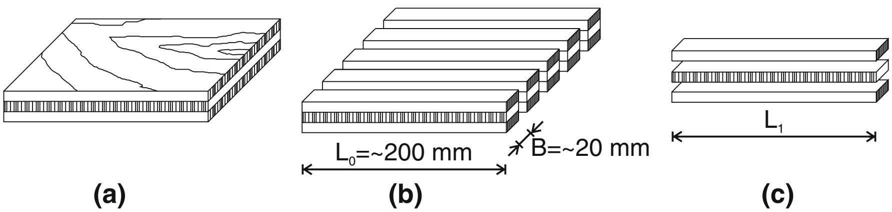

Fig. 1 Procedure to determine the internal stress state of cross-laminated wood panels: **a** test panel, **b** stripes, **c** release of strain by sawing in the adhesive bond line

to local density differences between early- and latewood especially when the fiber direction ran perpendicular to the specimen's longitudinal axis. The sound velocity measurements were carried out with an ultrasonic tester (BP 5, STEINKAMP, $f = 50$ kHz). A transmitter and a receiver were installed at each end of the slices and the sound running time of a constant pulse was measured over the sample length. Thus, the MOE is approximated by

$$E = c^2\rho \qquad (2)$$

with c as the sound velocity and ρ as the raw density (Bucur and Archer 1984; Bucur 1995). This is valid for bars only when their height and width are small compared to the wavelength. The smallest sound velocities measured in this study corresponded to a wavelength of around 100 mm which was larger than the dimensions of the cross-section of the slices. Even in an isotropic system the dynamic MOE is higher than the statically determined value. However, since we were mainly interested in a comparison between the different variants, the dynamic MOE was not transformed into a static one. In the transverse direction, the sound waves penetrate through one or two glue lines. Since the glue lines are very thin compared to the total length, its influence is negligible. Parameters such as contact pressure or placement of the transducers play a major role. Possible errors in determining the internal stress state in cross-laminated wood panels are:

- Inaccuracy in the strain measurements especially parallel to the grain due to the small change in length,
- errors in measuring the dynamic MOE,
- erroneous dimension measurements.

Swelling properties

The swelling properties were investigated during 14 days wetting from 35% RH to 85% RH. This period was chosen, since internal stresses should be determined afterwards. It was assumed that sufficient moisture profiles are present after this period, which lead to measurable stresses. However, since the EMC will not be reached, the swelling properties will not be the ultimate ones.

To exclude friction influences during swelling, the samples were positioned on point-supports which additionally allowed air contact from all surfaces. The changes in length were measured by means of inductive displacement transducers as it is shown in Fig. 2. Since free swelling occurred at the boundaries, which was different between the layers, the in-plane displacements were determined using screws that were turned in the samples over the whole height with a distance of 25 mm to the edges. The displacements were gripped at the screw heads while the thickness swelling was measured directly at the wood surface. Swelling properties were calculated as follows:

$$\alpha = \frac{a_{85} - a_{35}}{a_{35}} \times 100 \qquad (3)$$

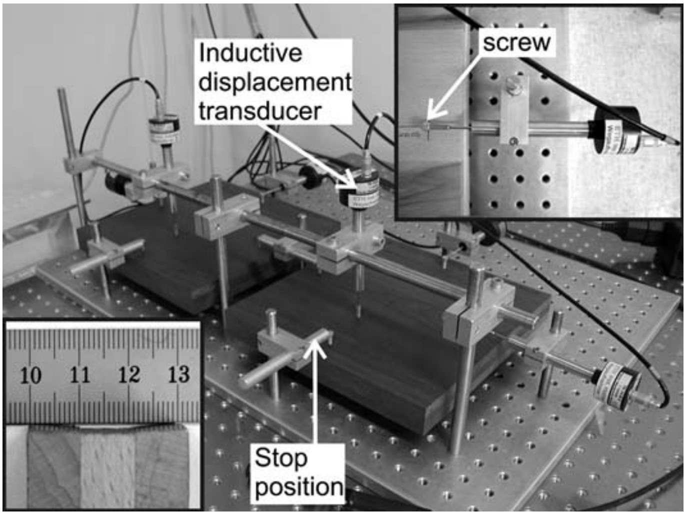

Fig. 2 Measurement equipment to determine swelling properties of cross-laminated wood panels and free swelling at the edges

$$q = \frac{\alpha}{\Delta\omega} \tag{4}$$

with
α linear swelling (%)
q swelling coefficient (%/%)
a_{35} dimension in the initial climate (m)
a_{85} dimension in the testing climate (m)
$\Delta\omega$ moisture content change (%)

Swelling pressure

If wood swelling is constrained, stresses termed swelling pressure are generated. These compressive stresses are of importance, e.g., in assemblies. In this study swelling pressure measurements were performed in the two in-plane directions while the panels were able to swell in the thickness direction. The forces were measured with one load cell (AHLBORN, 5kN) in each direction and recorded continuously during the measuring period (Fig. 3). First, a pre-load between 0.2 and 0.3 kN was applied to adjust a potential play between specimen and measuring device. While moisture adsorption through the small edges was restricted by the mechanical stops, it was possible in the thickness direction from both large faces. The MC was recorded with a capacitive moisture sensor in the middle layer of the panels.

Friction forces resulted from the swelling of the specimen against the boundaries (see Fig. 3). Therefore, the measured forces actually were the difference between the real swelling forces and the friction forces. It was assumed that the friction properties were similar on opposite surfaces, hence, equal friction forces can be

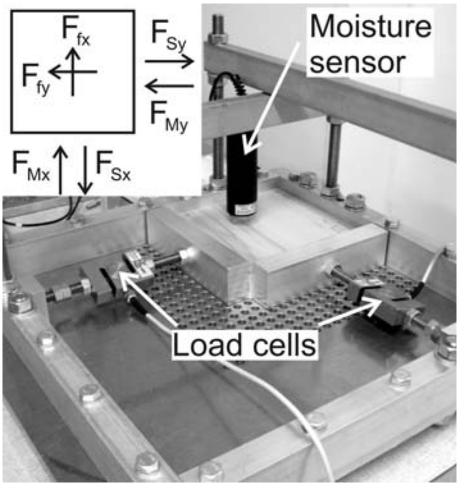

Fig. 3 Swelling pressure measurement device

presumed. The friction force F_f is the friction coefficient μ multiplied by a normal force F_N:

$$F_f = \mu F_N \tag{5}$$

In the case of two-dimensional constrained swelling the absolute value of the friction force along the x-axis depends on the value of the swelling force in the y-direction and vice versa. Referred to the cross-section, the swelling pressures are as follows:

$$p_{Sx} = \frac{F_{Sx}}{a_y a_z} \tag{6}$$

$$p_{Sy} = \frac{F_{Sy}}{a_x a_z} \tag{7}$$

with

$$F_{Sx} = F_{Mx} + \mu_{xy} F_{My} \tag{8}$$

$$F_{Sy} = F_{My} + \mu_{yx} F_{Mx} \tag{9}$$

Here p_S is the swelling pressure, F_S is the real swelling force, F_M is the measured swelling force, a is the dimension in the respective direction. The friction coefficients μ were determined directly in the measuring device individually for each specimen (see Eq. 5).

Hygroscopic warping

Dimensional stability is of main interest in the application of cross-laminated solid wood panels, e.g., the serviceability of a warped ceiling is reduced. Warping results from a moisture gradient which can be artificially induced, e.g., by a double-climate chamber (Jensen and Kehr 1995; Tobisch 2006) or by insulating all surfaces except one before wetting (Ganev et al. 2005).

To quantify the rate of warp a moisture gradient was induced over the panel thickness by different climates on both large surfaces. Since the small edges were sealed with lacquer, the diffusion of moisture into the panel was restricted to the large surfaces. The specimens were initially conditioned at 65% RH and afterwards separately stored on three-point supports (see Fig. 4) in boxes filled with water. The boxes were closed and insulated against the room climate, but the edges of the samples were still free to warp. The contact area between the specimen edges and the container cover was closed with a rubber joint. The distance between the water surface and the panel was 50 mm, i.e., a climate gradient of 65/100% RH was applied. Recordings of deformation in the thickness direction on the upper surface monitored the warp (Fig. 4). Stopping points at the edges guaranteed identical positioning of the measuring frame in every measurement.

Results and discussion

Swelling properties and internal stresses due to single climate step

The main results from the swelling measurements after 14 days of wetting from 35 to 85% RH can be summarized as follows (Table 3):

- The thickness swelling was dominant compared to the in-plane directions in all specimens.
- The linear thickness swelling decreased considerably in treated wood with the degree of the thermal treatment in homogenously structured panels ($\alpha_{z,0/0/0} = 1.74\%$, $\alpha_{z,1/1/1} = 0.60\%$, $\alpha_{z,2/2/2} = 0.56\%$) and composite panels ($\alpha_{z,1/0/1} = 1.26\%$, $\alpha_{z,2/0/2} = 0.52\%$).
- The differences disappeared for the swelling coefficient.

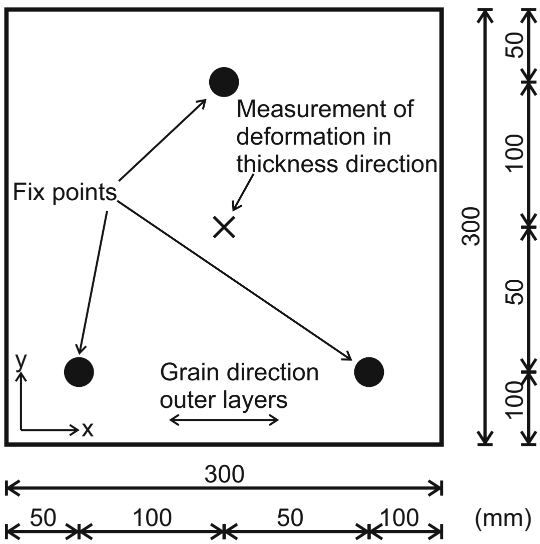

Fig. 4 Characteristics of the samples used in the hygroscopic warping experiments. Fix points indicate the points supported from the bottom side and the points of the displacement of the frame with the dial gauge

Table 3 Swelling properties and moisture content change ($\Delta\omega$) after 14 days wetting from 35 to 85% RH

Panel notation	$\Delta\omega$ (%)	Linear swelling (%)			Swelling coefficient (%/%)			Anisotropy y/x
		α_x^a	α_y^b	α_z^c	q_x^a	q_y^b	q_z^c	
0/0/0	7.7	7.3×10^{-2}	8.5×10^{-2}	1.74	9.0×10^{-3}	1.1×10^{-2}	0.23	1.2
1/1/1	3.0	5.5×10^{-2}	0.13	0.60	1.8×10^{-2}	4.4×10^{-2}	0.20	2.4
2/2/2	3.2	4.7×10^{-2}	0.11	0.56	1.5×10^{-2}	3.3×10^{-2}	0.18	2.3
1/0/1	3.5	7.8×10^{-2}	7.3×10^{-2}	1.26	2.2×10^{-2}	2.1×10^{-2}	0.36	0.9
2/0/2	3.7	3.2×10^{-2}	3.3×10^{-2}	0.52	9.0×10^{-3}	9.0×10^{-3}	0.14	1.0

[a] x direction parallel to the grain of the outer layers, [b] y direction perpendicular to the fibers of the outer layers, [c] z thickness direction

- The swelling parallel to the grain of the outer layers (x-direction) was smaller compared to the transverse direction (y-direction) in homogenously structured panels (e.g., 1/1/1: $q_x = 0.018$ %/% and $q_y = 0.044$ %/%).
- The swelling differences between the two in-plane directions were negligible in composite panels (e.g., 2/0/2: $q_x = q_y = 0.009$ %/%).
- The swelling in y-direction was larger in treated panels than in the untreated variant.

The differences between thickness- and in-plane swellings were a result from the crosswise gluing of the layers. Our results are comparable to Schwab et al. (1997) and Popper et al. (2004b), who investigated spruce panels. Schwab et al. (1997) found $q_x = 0.011\ldots0.018\%/\%$ and $q_y = 0.031\ldots0.038\%/\%$ for panels with a thickness of 20 mm and Popper et al. (2004b) found $q_z = 0.30\ldots0.50\%/\%$ for panels with a thickness of 30 mm. This is higher compared to spruce wood in longitudinal direction (Dahlblom et al. 1999: 0.003–0.007%/% $\Delta\omega$) but negligible compared to spruce wood perpendicular to the grain (Sell 1997): radial 0.15–0.19%/% $\Delta\omega$, tangential 0.27–0.36%/% $\Delta\omega$). Due to the reduced EMC of heat-treated wood, the change in MC was reduced. Therefore, the largest change in MC was observed in untreated panels ($\Delta\omega_{0/0/0} = 7.7\%$) while it was around 60% smaller in treated panels ($\Delta\omega_{1/1/1} = 3.0\%$, $\Delta\omega_{2/2/2} = 3.2\%$). With the lower amount of water absorption, fewer water molecules accumulated to the intermicellar and interfibrillar hollow spaces. Thus, the cell wall extension was smaller and the total swelling was reduced. Furthermore, the swelling coefficient was influenced in terms of disappearing of the significant differences between untreated and treated material. In y-direction the effect of the lower MC change was overlaid by the lower stiffness due to the thermal treatment. Thus, the highest swelling in y-direction was observed in 1/1/1 and 2/2/2.

Subsequent measurements to determine the internal stress state resulted in tensile stresses parallel to the grain in the top layers and in compressive stresses perpendicular to the grain in the middle layer. As not mentioned otherwise the results are presented for the middle layer in the following, since the variation in the measured strains parallel to the grain of the top layers was very large. The main results are (see also Fig. 5):

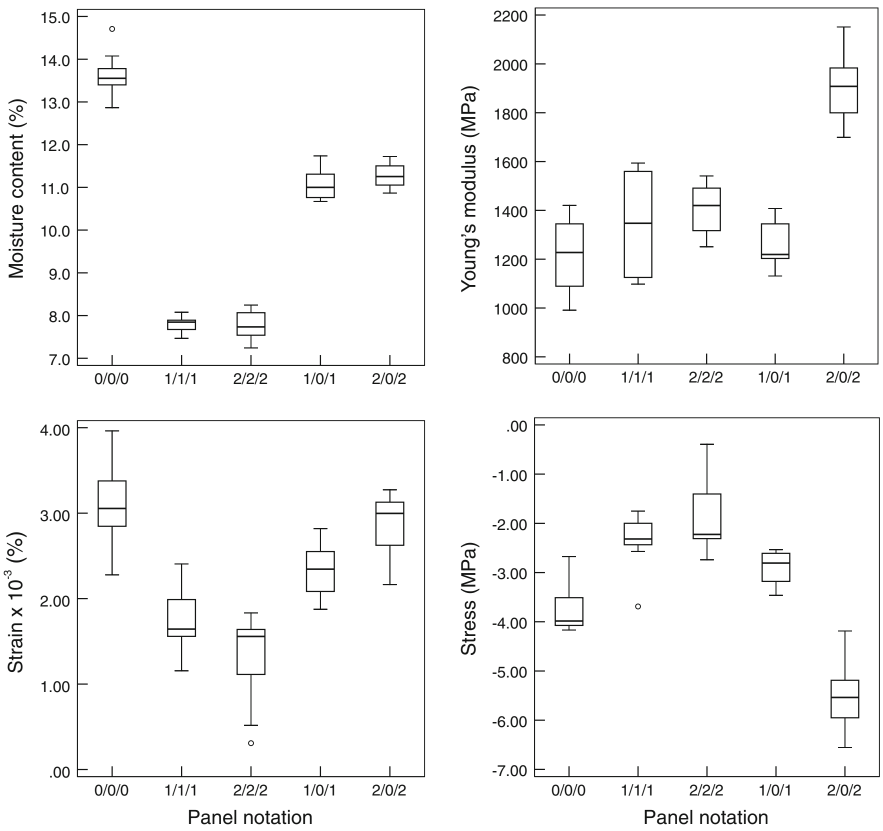

Fig. 5 Moisture content, Young's modulus, strain and stress in the middle layer of three-layered cross-laminated wood panels perpendicular to the grain after 14 days wetting from 35 to 85% RH; the *box* and *whisker plots* show the median (*horizontal line in the box*), the 50% interquartile range (*box*) and the 5 and 95% quantile (*whiskers*)

- The stresses were identified as $\sigma_{m,0/0/0} = -3.77$ MPa, $\sigma_{m,1/1/1} = -2.29$ MPa, $\sigma_{m,2/2/2} = -1.89$ MPa, $\sigma_{m,1/0/1} = -2.89$ MPa, $\sigma_{m,2/0/2} = -5.49$ MPa.
- The MC can be subdivided into three groups: lowest MC in treated panels 1/1/1 and 2/2/2 (7.8%), middle MC in composite panels 1/0/1 (11.1%) and 2/0/2 (11.3%), and highest MC in untreated panels 0/0/0 (13.6%).
- The moisture difference between middle and outer layers $d\omega$ was largest in the composite panels ($d\omega_{1/0/1} = 2.8\%$, $d\omega_{2/0/2} = 3.5\%$). Here the inner layer attained a higher MC, while in homogenously structured panels the outer layers were moister. Here the MC difference decreased with the degree of the thermal treatment: $d\omega_{0/0/0} = 1.6\%$, $d\omega_{1/1/1} = 0.7\%$, $d\omega_{2/2/2} = 0.2\%$.
- The measured strains decreased considerably with the level of the treatment in the homogenous samples. In untreated middle layers covered with treated material, larger strains were released with an increasing treatment level of the outer layers.

The results were mainly affected by the low EMC of the treated material. As described above, this resulted in smaller swelling deformations and for this reason in smaller constrained swelling between the layers. But the MC also affected the MOE: the great amount of $E = 1{,}905$ MPa in 2/0/2 is conspicuous. In samples with the same material $E = 1{,}215$ MPa (0/0/0) and $E = 1{,}253$ MPa (1/0/1) were determined. The loss in stiffness with a thermal treatment was neutralised by the lower MC. But this does not explain why the MOE was that high in 2/0/2 and not in 1/0/1 as well since the observed layers had the same MC and were from the same material.

Thus, smaller compressive stresses in samples only produced from treated material were a result of the smaller released strains and the slightly decreasing MOE ($E_{1/1/1} = 1{,}346$ MPa, $E_{2/2/2} = 1{,}402$ MPa) compared to samples only produced from untreated material. The highest compressive stress in 2/0/2 was the result of the large MOE and the large released strain, which itself was a result of the high swelling constraint between the layers.

Swelling pressure due to single climate step, RH 35 to 85%

As expected, the friction coefficients μ_{xy} as a result of the friction between the wood surface and the aluminium stopper were smaller than μ_{yx} (Table 4). In conditioned wood the friction coefficient of the end-grain surface (cross section) is larger than those of the radial and tangential cut (Möhler and Herröder 1979; Niemz 1993). Since in three-layered cross-laminated wood panels the quota of end-grain surface is smaller in the *xz*-plane than in the *yz*-plane; the friction of this surface is smaller (μ_{xy}). Friction of wood is obviously dependent on the MC. As expected, the swelling pressure was smaller in the *x*-direction (Table 4). This resulted directly from the cross-lamination of the layers. The thermal treatment affected the friction coefficient, the measured swelling forces and as a result the swelling pressure decreasing values with an increasing degree of thermal treatment were determined. Furthermore, the anisotropy ratio increased. The tendencies in the internal stress state after constrained swelling are similar to the aforementioned results in free swelling (Table 5):

- The stresses considerably decreased in treated wood compared to the untreated case due to a dramatic decrease of the released strains and a slight decrease of the MOE.

Table 4 Moisture content change ($\Delta\omega$), friction coefficients μ and swelling pressure p_S after 14 days constrained swelling, wetting from 35 to 85% RH

Panel notation	$\Delta\omega$ (%)	μ_{xy} (–)	μ_{yx} (–)	p_{Sx} (MPa)	p_{Sy} (MPa)	p_{Sy}/p_{Sx} (–)
0/0/0	7.4	0.66	0.73	−0.74	−0.87	1.2
1/1/1	3.0	0.41	0.53	−0.24	−0.36	1.5
2/2/2	2.1	0.30	0.47	−0.15	−0.33	2.2
1/0/1	4.6	0.38	0.60	−0.28	−0.40	1.4
2/0/2	2.1	0.25	0.34	−0.22	−0.26	1.2

Table 5 Internal stress state in the middle layer perpendicular to the grain after 14 days constrained swelling from 35 to 85% RH

Panel notation	σ_m (MPa)	ε_m (%)	E_{dyn} (MPa)	ρ_u (g/cm^3)	ω (%)
0/0/0					
$\bar{x}$	−4.33	−0.28	1,570	0.714	12.4
CoV (%)	5.3	4.7	1.6	1.2	2.7
1/1/1					
$\bar{x}$	−1.21	−0.09	1,309	0.647	7.8
CoV (%)	18.5	19.1	1.6	1.0	14.1
2/2/2					
$\bar{x}$	−0.49	−0.04	1,234	0.631	7.2
CoV (%)	26.6	27.0	1.9	0.7	4.2
1/0/1					
$\bar{x}$	−2.72	−0.23	1,198	0.662	11.0
CoV (%)	11.9	11.2	1.4	0.9	0.6
2/0/2					
$\bar{x}$	−3.39	−0.16	2,153	0.804	10.9
CoV (%)	16.8	18.7	2.6	0.5	2.1

- High stresses in variant 2/0/2 were again a result of the high MOE, which this time was not only the effect of the low MC but also of the high density.

Compared to the results after free swelling, lower stresses were measured in treated samples which could be the effect of plasticizing processes (Table 6).

Hygroscopic warping and stresses due to climate gradient

A deformation towards the moist condition was observed in specimens exposed to the climate gradient 65/100% RH, produced and initially conditioned at 65% RH. Table 7 indicates the grade of warping as the midspan deflection. Untreated panels showed an excessive deformation of 1.21 mm after 21 days. No significant differences between the residual samples were found. Here the midspan deflection ranged from 0.55 to 0.76 mm. Identification of the internal stress state again resulted in tensile stresses parallel to the grain of the top layers and compressive

Table 6 Comparison of internal stresses after free and constrained swelling related to the moisture content change

Panel notation	$\sigma_m/\Delta\omega$ (MPa)		Free/constrained
	Free	Constrained	
0/0/0	−0.49	−0.59	0.84
1/1/1	−0.74	−0.40	1.83
2/2/2	−0.59	−0.23	2.54
1/0/1	−0.83	−0.59	1.40
2/0/2	−1.48	−1.61	0.92

Table 7 Midspan deflection and internal stresses in the middle layer perpendicular to the grain after 21 days of seasoning in 65/100% RH

Panel notation	Midspan deflection (mm)	σ_m (MPa)
0/0/0		
$\bar{x}$	1.21	−4.08
CoV (%)	51.1	19.5
1/1/1		
$\bar{x}$	0.55	−1.05
CoV (%)	19.5	34.3
2/2/2		
$\bar{x}$	0.74	−1.98
CoV (%)	1.9	27.0
1/0/1		
$\bar{x}$	0.76	−1.83
CoV (%)	12.1	29.6
2/0/2		
$\bar{x}$	0.66	−3.23
CoV (%)	7.6	15.3

stresses perpendicular to the grain in the middle layer (Table 7). Large compressive stresses in the middle layer were calculated in untreated panels 0/0/0 (4.08 MPa) and in opposition to the warping tendencies also in panels 2/0/2 (3.23 MPa). This corresponds to aforementioned observations. Significant swelling differences between the top layers and the middle layer in panels 2/0/2 cause a more intensive restraint of the investigated middle layer.

Conclusion

In the present study an application of beech wood as material for cross-laminated wood panels was evaluated. The results matched our expectations: moisture-induced stresses were lower in heat-treated than in untreated panels. Moderate swelling deformations were detected due to lower equilibrium moisture contents. The behavior in free swelling was as expected: linear swelling and swelling coefficient were dominated by the thickness direction. This was a result of the cross-lamination of the layers. Panels from untreated beech showed a huge deformation when a climate gradient was artificially induced. A better resistance of cross-laminated wood panels made from heat-treated beech wood against climatic variations can be concluded. However, one has to regard the lower mechanical strength as a result from the heat treatment. No significant improvement against moisture influences was found for combinations of treated and untreated material, but a higher mechanical strength compared to homogenously structured panels from treated wood is expected. However, this combination occurred with higher stresses in the layers. They were considerably larger the larger the differences between the materials in the layers. For a practical application of beech wood in cross-laminated wood panels the mechanical properties have to be tested in subsequent studies.

From our observations it can be concluded that the presented methods are valid for identifying the internal stress state in cross-laminated solid wood panels due to climatic variations. In further investigations the methods should be applied on samples with different structures with the aim of improving the resistance to crack formation and panel warping as a result of the development of internal stresses. It is necessary to determine the stress development with time, since it was not sure in the present study when the maximum stress appeared. Furthermore, it is evident to determine swelling properties and swelling pressure until an equilibrium state is reached.

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