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Electronic Supplementary Material for "Residual stresses in adhesively bonded wood determined by a bilayer flexion reporter system"

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Abstract

This electronic supplementary material contains photos of the experimental setup, a verification of the moisture content of the adhesive in the FEM simulation, and tables of the material parameters utilized in the simulation models related to the paper "Residual stresses in adhesively bonded wood determined by a bilayer flexion reporter system".

Keywords: residual stresses, hygro-elastic behavior, bilayer, adhesive bonding , cross-laminated timber

A Photos of the experimental setup

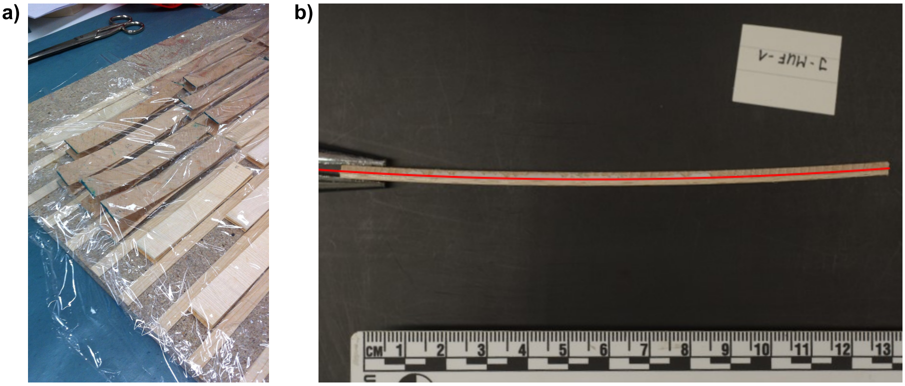

Figure S1 Photos of the bilayer experiments. a) Bilayer preparation. The wooden layers are sealed with plastic foil and adjusted with guiding rails. b) Measurement of the bilayer curvature. Curvature is obtained by fitting a second order polynomial onto the deformation obtained by image analysis (red line).

B Verification of the adhesive's moisture content

To simulate the moisture field in Abaqus, an equivalency between the Fourier equation $(\rho c_T)\partial T/\partial t = \nabla.(\mathbf{K}\nabla T)$ and Fick's law of diffusion $\partial\omega/\partial t = \nabla.(\mathbf{D}\nabla\omega)$ with respect to the moisture content ω is assumed by setting $(\rho c_T) = 1$. ρ is the dry density, c_T the specific heat, T the temperature, t the time, $\mathbf{K}$ the conductivity matrix and $\mathbf{D}$ the diffusion matrix.

This assumption leads to the fact that both, the wood's and the adhesive's moisture content, are simulated with respect to the same density. For considering the correct amount of water that the adhesive induces into the wood, this means that the adhesive's moisture content will not be described by its "real" moisture content, but as a theoretical value in respect to the wood density. Experimentally, the weight loss between applying the liquid adhesive and reaching equilibrium at a 65%/20°C climate is measured. This weight loss m_{loss} equals the amount of water the adhesive releases into the bilayer above its equilibrium moisture content $\omega_{\text{adh,equib}}$ at 65%/20°C. The effective initial moisture content of the adhesive $\omega_{\text{adh,init}}$ can then be described with respect to the wood density in the FEM model, following Eq. 3 of the paper, as

$$\omega_{\text{adh,init}} = \omega_{\text{adh,equib}} + \frac{m_{\text{loss}}}{m_{\text{wood,dry}}/V_{\text{wood,fem}} \cdot V_{\text{adh,fem}}}, \tag{S1}$$

where $m_{\text{wood,dry}}$ is the experimental oven dry mass, $V_{\text{wood,fem}}$ the FEM volume of both wooden layers and $V_{\text{adh,fem}}$ denotes the FEM volume of the adhesive layer. The influence of the initial moisture content is crucial for the response of the FEM model. Therefore, the initial moisture contents are verified for all wood-adhesive combinations of the bilayer, namely beech/MUF, beech/PRF, spruce/MUF and spruce/PRF.

The verification is done by transient simulations, where the calculated initial moisture content is applied to the adhesive. The moisture transport to and from the environment is suppressed and the moisture content equilibrating over the whole domain is measured. This moisture content is compared to the experimental average moisture content of the

Table S1 Equilibrated average moisture content of the bilayers from (a) experimental data with original bilayer mass balance, (b) experimental data respecting that adhesive density and wood density are equalized in the numerical model by using a corrected mass balance and (c) simulated data.

Wood/adhesive	Initial moisture adhesive [%]	Average moisture content equilibrium [%] Orig. mass (a)	Corr. mass (b)	Simulated (c)
Spruce/MUF	325.42	20.83	22.55	21.84
Spruce/PRF	163.31	16.65	17.44	16.70
Beech/MUF	205.67	17.44	18.22	17.88
Beech/PRF	78.81	13.85	14.02	13.85

bilayer, determined from the mass balances, directly after releasing the pressure of the gluing process. Since the FEM model does not respect the adhesive's dry mass correctly, a corresponding correction of the experimental masses is considered as well. The solutions are shown in Table S1. The equilibrating average moisture content over the bilayer in the FEM simulation lies always between the experimental average moisture content without and with mass correction and shows a good agreement with the experimental data.

C Involved parameters

Table S2 Mean and standard deviation of the experimental physical properties of the wood layers at 65%/20°C climate. The Young's moduli and swelling coefficients are measured in radial (R) direction for the active layers and in longitudinal (L) direction for the passive layers. The swelling coefficients are measured between 65% to 85% and 85% to 95% RH.

Material	Parameter		Passive layer (L)	Active layer (R)
Beech	Density	[kg/m^3]	725.93 ± 22.89	754.11 ± 9.27
	Moisture content	[%]	11.73 ± 0.18	11.61 ± 0.13
	Young's modulus	[MPa]	17894.38 ± 1049.85	1654.79 ± 86.87
	Swell. coeff. 65%–85%	[1/%]	0.00016 ± 0.00020	0.00203 ± 0.00005
	Swell. coeff. 85%–95%	[1/%]	0.00046 ± 0.00010	0.00247 ± 0.00013
Spruce	Density	[kg/m^3]	456.53 ± 19.90	435.48 ± 7.36
	Moisture content	[%]	11.60 ± 0.44	12.07 ± 0.37
	Young's modulus	[MPa]	14530.8 ± 1433.00	961.30 ± 106.10
	Swell. coeff. 65%–85%	[1/%]	0.00021 ± 0.00006	0.00093 ± 0.00004
	Swell. coeff. 85%–95%	[1/%]	0.00036 ± 0.00004	0.00142 ± 0.00005

Table S3 Moisture dependent elasticity parameters for European beech (Hering et al., 2012) and Norway spruce (Neuhaus, 1981; Gereke, 2009). The parameters are taken from Hassani et al. (2015). Moisture dependence of each parameter P is respected in the form $P_b(\omega^*) = b_0 + b_1\omega^*$ for beech and $P_s(\omega^*) = s_0 + s_1\omega^* + s_2\omega^{*2} + s_3\omega^{*3}$ for spruce. $\omega^* = \omega[\%]$.

		Beech		**Spruce**			
Parameter		b_0	b_1	s_0	s_1	s_2	s_3
E_{R}	[MPa]	2565.6	−59.7	999.64	3.61	−2.09	0.0467
E_{T}	[MPa]	885.4	−23.4	506.08	5.0	−1.35	0.0297
E_{L}	[MPa]	17136.7	−282.4	12791.75	15.22	−9.01	0.1885
G_{RT}	[MPa]	667.8	−15.19	61.33	−1.07	−0.06	0.0017
G_{RL}	[MPa]	1482	−15.26	762.8	5.93	−1.99	0.0477
G_{TL}	[MPa]	1100	−17.72	880.75	1.39	−1.39	0.0277
ν_{TR}	[10^{-3}]	293.3	−1.012	153.4	10.8	0.398	−0.0191
ν_{LR}	[10^{-3}]	383.0	−8.722	232.0	−8.6	2.8784	−0.07862
ν_{LT}	[10^{-3}]	336.8	−9.071	285.7	−41.0	7.1907	−0.1642

Table S4 Moisture dependent isotropic Young's moduli E_{adh} for MUF, PRF, and PUR (Kläusler et al., 2013). The parameters are taken from Hassani et al. (2016). Moisture dependence is respected in the form $E_{\mathrm{adh}}(\omega^*) = a_0 + a_1\omega^* + a_2\omega^*2 + a_3\omega^{*3}$ with $\omega^* = \omega[\%]$. $\nu_{\mathrm{adh}} = 0.3$ for MUF, PRF, and PUR.

Parameter		a_0	a_1	a_2	a_3
E_{MUF}	[MPa]	2565.6	−59.7	999.64	3.61
E_{PRF}	[MPa]	885.4	−23.4	506.08	5.0
E_{PUR}	[MPa]	17136.7	−282.4	12791.75	15.22

Table S5 Moisture dependent diffusion coefficients for European beech (Hering, 2011) and Norway spruce (Saft and Kaliske, 2011). The parameters are taken from Hassani et al. (2015). The diffusion coefficients in each direction i is calculated as $D_i(\omega) = D_{i0}\mathrm{e}^{\alpha_{i0}\omega}$.

Material	Direction	D_{i0} [mm^2/h]	α_{i0} [−]
Beech	Radial	0.02630	0.199724
	Tangential	0.00370	0.265280
	Longitudinal	21.8999	−0.038545
Spruce	Radial	0.288	4
	Tangential	0.288	4
	Longitudinal	0.720	4

Table S6 Moisture dependent diffusion coefficients for MUF, PRF, and PUR (Volkmer et al., 2012; Wimmer et al., 2013). The parameters are taken from Hassani et al. (2016). The diffusion coefficients are isotropic and calculated as $D_{\mathrm{adh}}(\omega) = D_0\mathrm{e}^{\alpha_0\omega}$.

Material	D_0 [mm^2/h]	α_0 [−]
MUF	$9.792 \cdot 10^{-4}$	0.231
PRF	$4.047 \cdot 10^{-4}$	0.231
PUR	$3.067 \cdot 10^{-3}$	0.057

Table S7 Swelling coefficients α_i for European beech (Hering, 2011) and Norway spruce (Neuhaus, 1981; Gereke, 2009) in direction i. The parameters are taken from Hassani et al. (2015).

Swelling coefficient		Beech	Spruce
α_{R}	[1/%]	0.00191	0.00170
α_{T}	[1/%]	0.00462	0.00330
α_{L}	[1/%]	0.00011	0.00005

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