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Investigations on densified beech wood for application as a swelling dowel in timber joints

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Abstract: For robotic fabrication of wooden structures, the simple, quick and tight joining of elements can be solved using swelling hardwood dowels. This topic has been the focus of the present study, and the set-recovery capacity of densified wood (dW) as dowel material was investigated. European beech was compressed in the radial direction at 103°C and 10% moisture content (MC) to a compression ratio of 40%. Multiple swelling and shrinkage cycles were applied to measure swelling behavior, swelling pressure development and combined swelling and creep under compressive loading. It has been demonstrated that dW shows increased swelling and more persisting swelling pressures than native wood (nW). The set-recovery prevents significant contact-stress relaxation over multiple cycles of MC change. Application as a structural joining element for robotic fabrication was studied by shear lap joint tests on round double-dovetail swelling dowels.

Keywords: creep, densified wood, dovetail swelling dowel, European beech, robotic fabrication, set-recovery, swelling coefficient, swelling pressure

Introduction

Wood and wood-based products are well-suited materials in the emerging field of digital fabrication of engineering structures (Gramazio and Kohler 2014; Adriaenssens et al. 2016; Menges et al. 2017a,b), which are assembled by robotic fabrication. Optimization of such processes strongly depends on the connection of pre-fabricated wood elements composing a structure. Standard joining methods such as adhesive, nail, bolt and screw joints are based on a form-and-friction locking effect leading to a high rigidity of the assembled joint. Such joints require application of mechanical pressure to insert steel fasteners, or precise application of adhesives that imply significant impact on fabrication because of working and curing times of the adhesives. Simpler joining techniques would favor faster robotic fabrication routines.

Examples for joining of wood without adhesives or steel fasteners are hardwood pegs in historical timber constructions (Sandberg et al. 2000). The joining of elements with a certain degree of freedom for an initial movement, which is the case when swelling dowels or pegs are applied, is a tailored advantage for robotic fabrication. The concept allows for spatially arranging single parts after joining and for compensating tolerances in frame or truss structures during assembly. The hygroscopic behavior of wood resulting in swelling and shrinkage in response to changes in moisture content (MC) below the fiber saturation point (FSP) facilitates form-and-friction locking of dowels or pegs. Therefore, such a joint geometry can be designed in a predictive manner as a function of MC change and time.

Mechanically loaded wood, however, shows a rheological behavior because of the presence of amorphous polymers in the wood cell wall (Holzer et al. 1989). This can result in creep or relaxation via diminishing of internal stresses over time. Relaxation is highly affected by MC variations (Hering 2011; Ožyhar 2013). The contact pressure between connectors based on friction locking can, thus, decrease down to zero in the course of time as a function of relative humidity (RH) decrement.

Compressed wood (densified wood, dW) as a connector can be a remedy because sufficient swelling pressure for

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friction-locked joints may be maintained because of the set-recovery effect (Navi and Heger 2005; Blomberg et al. 2006). dW was already developed and applied over a century ago (Blomberg 2006; Sandberg et al. 2013), while the wood is compressed at temperatures above the glass transition temperature (T_g) of lignin. In this state, compression stiffness perpendicular to the fiber direction is drastically reduced allowing for a significant densification. However, the initially stable compressed state below T_g becomes unstable upon contact with moisture or heat. The extent of shape recovery (set recovery) is dependent on the parameters of densification such as MC, heat and applied stress. In fact, wood is a composite polymer with shape-memory effects (Ugolev 2014), which limits the industrial application of dW. Research on dW often focuses on permanent fixation of the densified state based on methods of chemical or thermal treatment before, during or after densification (Morsing and Hoffmeyer 1998; Navi and Girardet 2000; Wolcott and Shutler 2003; Blomberg 2006; Kutnar et al. 2008; Skyba 2008; Laine 2014; Palma et al. 2016). In contrast, shape recovery is beneficial in the case of dW as a structural swelling component (Jung et al. 2008; Guan et al. 2010). However, the mechanical behavior of dW as a swelling dowel has not yet been studied.

The intention of the present study was to fill this gap focusing on the quantitative swelling behavior of beech dW as a function of MC variation over multiple cycles of moistening and drying. In this context, the swelling pressure (Blomberg and Persson 2007; Ispas 2013), the time-dependent mechanical response and swelling capacity of beech dW under load were addressed by measurements under RH change. Finally, cylindrical double-dovetail-shaped beech dW dowels were tested in comparison with native beech dowels in form-and-friction locking joints. Hereby, the joint geometry was designed based on the results of the previous characterization experiments.

Materials and methods

Wood densification: The samples were taken from two boards of European beech (*Fagus sylvatica* L.) [$650 \times 250 \times 60$ mm³ (L $\times$ T $\times$ R)] taken from the same stem originating from the region of Zurich, Switzerland. The boards were conditioned at 20°C/65% RH to a mean equilibrium MC (EMC) of 10% in adsorption. One board was compressed in the R-direction as illustrated in Figure 1 at 103°C, which is above the lignin T_g , and which does not change the original structural integrity and permits to keep the maximum shape recovery. The pressure was then increased to 5 MPa and further increased at 1 MPa per 10 min steps to a final pressure of ≈ 8 MPa, which was kept for 30 min. After 120 min cooling time, 70°C was

Figure 1: Densification procedure.

Applied pressure in the R-direction on board over time (blue, upper abscissa) and resulting compression strain (red, lower abscissa).

reached. The other board was left in the native state for reference specimens.

Free swelling behavior of beech dW: Samples with dimensions $20 \times 20 \times 10$ mm³ (R $\times$ T $\times$ L) were produced from beech dW [mean value $\bar{x}_\rho = 941$ kg m⁻³, standard deviation (StD) $s_\rho = 14$ kg m⁻³ at 0% MC, $n=8$] and from beech native wood (nW) ($\bar{x}_\rho = 703$ kg m⁻³, $s_\rho = 7$ kg m⁻³ at 0% MC, $n=8$) as reference. The dimensions are according to DIN 52184:1979-05. The samples were oven-dried (o.d.) at 103°C until reaching mass constancy (less than 0.1% weight gain/loss over 24 h), and then weight and dimensions were measured. Afterward, the samples were equilibrated at 85% RH. Weight and dimensions were recorded until mass constancy was reached. The samples were then again dried and this cycle was repeated 8 times. Differential swelling and shrinkage coefficients (α) were calculated in the R- and T-directions for all cycles by assuming a linear relation between swelling strain ($\epsilon^{sw} = \Delta l \cdot l^{-1}$) and MC change ($\Delta \omega$), i.e. $\alpha = \epsilon^{sw} \Delta \omega^{-1}$. MC (ω) was determined by the gravimetric method as $\omega = (m_\omega - m_0) m_0^{-1}$, where m_ω is the sample mass at an EMC of ω and m_0 is the o.d. sample mass.

Swelling pressure: One nW and one dW sample ($\rho = 696$ kg m⁻³ and 986 kg m⁻³ at 0% MC) [$30 \times 30 \times 10$ mm³ (R $\times$ T $\times$ L)] were separately placed inside a bulk steel frame and restrained in the R- and T-directions by plates connected to load recording cells via screw threads. The positive-locking screw threads combined with double-nut systems and counterclockwise-drilled internal threads at the restraining plates allowed for a controlled application of initial pressure on the samples in both anatomical directions. The o.d. samples were placed inside the restraint. An initial pressure of 0.15 kN was applied in the R- and T-directions, whereas the L-direction remained unrestrained. The samples were then conditioned at 70% and 35% RH for 168 h, respectively, in an alternating manner for three moistening cycles (ending up at 70% RH). Forces were recorded every 2 min.

Swelling under load: Swelling and simultaneous creep were analyzed under applied compressive load in the R-direction. Samples of

dW ($\bar{x}_p = 891 \text{ kg m}^{-3}$, $s_p = 13 \text{ kg m}^{-3}$ at 0% MC) and nW ($\bar{x}_p = 695 \text{ kg m}^{-3}$, $s_p = 3 \text{ kg m}^{-3}$ at 0% MC), $[30 \times 30 \times 10 \text{ mm}^3 (\text{R} \times \text{T} \times \text{L})]$ were initially o.d. and then placed inside a lever system loading device equipped with displacement recorders on the samples in the direction of the applied loads (Bachtar 2017). The upper limit of the uniaxial compression strength of the sample in the R-direction was taken from the maximum swelling pressure in the R-direction under biaxial constraints. Different loads were applied in the R-direction corresponding to 20, 40, 60 and 80% of the maximum swelling pressure. The samples were let to swell at 65% RH for 168 h and were then relocated to 85% RH conditions during 168 h. Then, the loading was removed and the samples were relaxed at 85% RH for 48 h. For both, dW and nW, one sample was let to freely swell.

Double shear lap joint tests with cylindrical dovetailed dowels: Five timber shear lap joints were manufactured from spruce (*Picea abies*) wood and beech dW dowels ($\bar{x}_p = 1016 \text{ kg m}^{-3}$, $s_p = 10 \text{ kg m}^{-3}$ in 65% RH) and five joints with nW dowels ($\bar{x}_p = 720 \text{ kg m}^{-3}$, $s_p = 7 \text{ kg m}^{-3}$ in 65% RH). The connecting boards were manufactured with spruce wood ($\bar{x}_p = 365 \text{ kg m}^{-3}$, $s_p = 11 \text{ kg m}^{-3}$ in 65% RH). The dowels and the holes in the spruce boards were milled by means of computer numerical controlled (CNC) router milling ($\pm 0.025 \text{ mm}$ nominal precision). The geometry of the dowels and of the connecting boards is presented in Figure 2. The inclination angle of the rotational

symmetric double-dovetail dowels was 2° . The narrower diameter of the holes in the spruce boards was 30 mm and the inclination angle was again 2° . This allowed the initial insertion of o.d. dowels (outer diameter of 29.5 mm) with a tolerance of 0.5 mm. Then, a swelling of around 2 mm was needed for a stable friction locking. Before swelling, out-of-plane movements (separation of dowel and board) were impeded, while the rotational degree of freedom of the joint was kept until the dowel had been fully swollen. The assembled joint was then equilibrated at 85% RH and afterward mechanically tested using a displacement controlled universal testing machine. A load was applied on top of the middle spruce board on the joint (in the L-direction of spruce) so that the dowel-shearing occurred inside the symmetrically designed joint. The dowels were oriented in a way that the densified R-direction was aligned with the loading direction (annual rings perpendicular to the loading direction). For a better comparability, the loading was applied following the testing procedure according to DIN EN 26891:1991-07. The joint stiffness modulus K_s , required for dimensioning a wood structure in terms of serviceability, was calculated for the obtained force-displacement (F, v) curves. The mean value $\bar{X}_{K_s}$ over a configuration of n samples is: $\bar{X}_{K_s} = 0.75n^{-1} \sum_i^n [0.4F_{\max, \text{est}, i} (v_{40\%, i} - v_{10\%, i})^{-1}]$ with a reduction factor of 0.75.

Figure 2: Geometrical setup for double lap shear joint tests.

- (a) Geometry of rotational-symmetric double-dovetail swelling dowels, CNC milled, with an inclination angle of 2° (D: diameter).
 (b) Connecting spruce boards with two sideboards and a middle board, CNC milled negative dovetail forms with an insertion diameter of 30 mm. (c) Dowel insertion. (d) Assembled joint with geometry.

Results and discussion

Wood density after densification

A density of 1000 kg m^{-3} for beech wood at 10% MC was targeted by the applied compression routine. On an average, a compression ratio (CR, ratio of densities) of 40% was reached, although different regions in the board may have significantly different densities, for example, near the edges (980 kg m^{-3} , CR=36%) and in the middle (1084 kg m^{-3} , CR=50%). Bulging of the edges was observed as a result of the uniaxial compression. Samples, thus, needed to be cut sequentially along the L-direction for comparability. A variability over thickness can also be expected because of the transversal densification (Kutnar et al. 2009). Figure 3 shows sample images before and after densification. Growth rings remained parallel, whereas the rays were diagonally shifted. In earlywood (EW) zones, this shift appears to be larger than in latewood (LW) zones as the rays completely buckle in EW. Accordingly, there is a pronounced heterogeneous morphology of densification.

Free swelling behavior

The dW shows a pronounced shape recovery and swelled about 30% in the R-direction (ϵ_R) during eight cycles of o.d. and re-moistening at 85% RH (Figure 4). The o.d. state dimensions at $t=0$ served as reference lengths for strain calculation. About 50% of the entire swelling strain was already attained after the swelling step of the first cycle. The relative shape recovery decreased over further

Figure 4: Recorded swelling strains of R-densified and of native beech samples over eight swelling and eight shrinkage cycles. Oven-dry dimensions at $t=0$ represent reference lengths for strain calculation. Dotted lines represent linear interpolation between measured points. Vertical black dotted lines represent the end of swelling cycle, oven-drying (for 48 h, not considered on the time axis) and the start of new swelling cycle. Markers represent mean values and gray error-bars represent positive and negative standard deviations.

swelling-shrinkage cycles, while the total shape recovery increased and showed an asymptotic behavior in accordance with the literature (Heger et al. 2004; Anshari et al. 2011; Laine et al. 2013; Buchelt et al. 2014). In contrast to the R-expansion, i.e. in the densification direction, a retraction was observed in the T-direction, which is visible as negative strain in the o. d. state. Thus, a Poisson effect was seen caused by spring-back. The measurements were slightly disturbed in this cycle by a climate chamber

Figure 3: Photographs of beech samples before (left) and after densification (right) in the RT-plane cut with a circular saw blade from the middle region of the boards. Distance of black lines on scale bar corresponds to 1 mm.

breakdown during the second swelling cycle, but most likely, the behavior of further cycles was not affected.

Figure 5 shows the mean density and mass of the samples in the course of the swelling-shrinkage cycles. A density decrement of the dW samples is visible but the absolute mass remains constant measured under identical conditions. Density seems to converge to $\approx 830 \text{ kg m}^{-3}$, while the density of the reference samples is about 740 kg m^{-3} conditioned at 85% RH. Thus, the CR decreased from initially 43% to about 8% (back-calculation to 10% MC). While the volume of dW samples increased, their capacity for water adsorption was not affected, because the mass changes were at a constant level. For both dW and nW, the EMCs of $\approx 15\%$ (at 85% RH) were calculated in each cycle. Repeated o.d. at 103°C for 48 h did not influence the capacity of moisture uptake.

Calculating the differential swelling and shrinkage coefficients for the different cycles (Figure 6) leads to further insights into the behavior of dW, as the strains are scaled over differences in MC; thus, the absolute water uptake mass is cancelled out. Here, the reference state for strain calculation in each cycle is the initial (dry) state of the cycle itself. For dW samples, the swelling and shrinkage coefficients are converging, i.e. the spring-back decreases. Surprisingly, both coefficients of dW samples in the R-direction converged to a value of 0.007 per %, whereas this value was 0.003 per % in the T-direction.

The data of dW samples in the R-direction are remarkably higher than those of the nW, whereas they are lower in the T-direction. The nW references display a reversible swelling and shrinkage with differential coefficients of 0.002 per % in the R-direction and 0.004 per % in the T-direction, which correspond to the literature values of beech wood (Niemz et al. 2015).

The much higher swelling coefficients obtained after significant shape recovery within multiple cycles of moistening and drying indicate a weaker structural arrangement of the amorphous cell wall constituents. The same amount of water (same relative mass uptake) exerts an internal imbibition pressure, which is able to strain the partially recovered wood cell wall to a greater extent than for nW. In a phenomenological sense, swelling is stopped, when polymer network stresses are in equilibrium with the imbibition pressure of adsorbed water at a given MC (Kulasinski et al. 2015). The extent of internal damage to the cell wall (as observed in Bao et al. 2017) and its influence, however, needs further confirmation. Densification temperature, targeted CR and cooling rate significantly influence the resulting physical properties (Hill et al. 2012; Kutnar and Kamke 2012; Dubey et al. 2016).

The shape recovery, on the other hand, which could be observed as a separate process within the swelling of dW, originates from preserved residual stresses of the densification procedure. The elastic energy responsible for

Figure 5: Recorded densities and samples weights over eight swelling and eight shrinkage cycles.

States before and after initial oven-drying are shown at $t=0$. Dotted lines represent linear interpolation between measured points. Vertical black dotted lines represent the end of swelling cycle, oven-drying (for 48 h, not considered on the time axis) and the start of new swelling cycle. Markers represent mean values and gray error-bars represent positive and negative standard deviations.

Figure 6: Calculated differential swelling and shrinkage coefficients over eight cycles for densified and native samples in the R- and T-directions.

Reference lengths for strains necessary for coefficient calculation at cycle n are lengths from shrinkage of cycle $n-1$ for swelling coefficients, and lengths from swelling of cycle n for shrinkage coefficients. Lines represent linear interpolation between calculated points. Markers represent mean values and gray error-bars represent positive and negative standard deviations.

spring-back is stored mainly in the crystalline cellulose (Navi and Heger 2004). Over multiple swelling cycles, the additional internal stresses are eventually depleted by releasing strains. Each time the material swells, the sum of residual and applied imbibition forces is able to overcome the forces restraining the compressed shape, i.e. strains get released until an internal equilibrium is reached. In a next imbibition cycle, less residual stress will allow for less strain release. The strains are thus directly attributed to shape recovery, i.e. to unbuckling of the cell walls to some extent. This is in accordance with the observed asymptotic behavior of the shape recovery component converging to a limit value.

Swelling pressure

Measurement of biaxial swelling pressure (Figure 7) demonstrates that higher swelling pressures (in both R- and T-directions) are generated by the dW than the nW. Swelling pressure depends in a complex manner on swelling capacity, material stiffness and boundary conditions, which make an interpretation difficult. Likely, several results are due to the biaxial restraining, such

Figure 7: Biaxial restrained swelling pressures of native and densified wood in the R- and T-directions starting from the dry state at $t=0$ over three moistening cycles along recorded RH.

as the shape recovery entailing the highest contribution to swelling pressure of dW, and the higher value in the T-direction compared to the nW. The higher values of dW are in accordance with the literature data (Blomberg and Persson 2007). A maximal swelling pressure of 9.3 MPa was reached in the R-direction for the R-densified samples. Considering the pronounced shape recovery, this value is slightly lower or equal to the compression strength of the sample under these conditions (in the biaxial stress state and changing MC). For swelling-shrinkage cycles with varying RH between 70 and 35% (Figure 6), corresponding to a realistic indoor climate variation within Central Europe, swelling pressures in both R- and T-directions of dW did not decrease in the same extent as in the case of nW. Considering an application as swelling dowels in timber joints, dW shows enhanced reliability compared to nW, where the contact pressure in the dry state is eventually completely lost (Figure 6, after 500 h) caused by complex coupled mechanisms such as visco-elasticity, mechano-sorption and plasticity.

Swelling under load

For an application as a swelling dowel in a timber joint, the conducted swelling pressure measurement represents the extreme case of very stiff connecting elements (e.g. wood on steel). In reality, the connecting elements

that represent the bearing for the swelling of the dowel are made out of timber products with a limited transverse stiffness. The swelling behavior within an elastic embedding represents a more realistic investigation scenario. There, the swelling happens against an unknown restraining pressure. Figure 8 shows the obtained swelling strains over time under different applied loads for two subsequent different climates (65 and 85% RH). Based on an analogous rheological model of wood, the total strain can be interpreted as an additive effect of hygro-elastic, elastic, visco-elastic and mechano-sorptive strains, while the plasticity can be largely excluded under loads below a significant yield (Fortino et al. 2009; Hassani et al. 2015). As is visible, elastic strains, which instantly appear at $t=0$, are fully recovered after 336 h for both nW and dW. In the case of dW, the elastic strain was higher than for nW for the same loads meaning that the transverse compression stiffness has been decreased as a result of densification. This observation is in accordance with the cell wall damage leading to higher hygroscopic swelling coefficients as observed earlier. The visco-elastic strains recovered at least partly within the 48-h interval after unloading.

In the graph of the nW (Figure 8a), it can be recognized that the visco-elastic strain dominated the swelling strain under a stress of up to 7.44 MPa in swelling from 0 to 65% RH and up to 5.58 MPa in swelling from 65 to 85% RH only. At these stresses, the limit of linearity in creep is

Figure 8: Combined swelling and creep strains measured under different uniaxial loadings over time (and eventual unloading) while reaching sorption equilibrium of samples in 65% RH and 85% RH climates from an initially dry state.

(a) Native (reference) beech samples, and (b) R-densified beech samples.

reached and a non-linear pattern is observed for the nWs at higher stresses. Such a limit of linearity is not visible for the dWs. Shape recovery due to water uptake is observed even under loading. Forty-eight hours after unloading (at 384 h), all densified samples exhibited positive strains, although no systematic patterns are visible among the samples. Accordingly, the long-term swelling pressure of nW will be limited to a threshold value of the non-linear creep. This can also be recognized in Figure 7, where the initially high swelling pressures of 6 and 8 MPa in the T- and R-directions, respectively, decreased quickly due to pronounced and fast relaxation. This problem, however, did not affect dW. Superior properties of dW in terms of higher and reliable swelling pressures, especially under variable climatic conditions, could be demonstrated.

Double shear lap joint tests with cylindrical dovetailed dowels

Force-displacement curves of the tested joints are presented in Figure 9. For the joints with densified dowels, a mean joint stiffness of $\bar{x}_{K_s} = 4.58 \text{ kN mm}^{-1}$ with $s_{K_s} = 0.31 \text{ kN mm}^{-1}$ is obtained. For the joints with nW dowels, slightly lower values of $\bar{x}_{K_s} = 4.21 \text{ kN mm}^{-1}$ with $s_{K_s} = 0.52 \text{ kN mm}^{-1}$ are seen. This difference, though not statistically significant, is attributed to the higher swelling pressures of the densified dowels. Both stiffness and ultimate load were affected by densified dowels. All joints failed beyond the bearing

capacity of spruce boards because of internal dowel rotation in the load direction. This is not an optimal failure mode of such a joint, because in structural timber engineering the connectors should preferably fail and not the connecting elements. However, the geometrical and physical constraints for manufacturing suitable swelling dovetail dowels did not allow for another possible joint design. Constraints such as initial insertion of the dowel, degree of freedom for initial rotation of the dowel, while preventing out-of-plane movement until friction locking, and reliable contact pressures need to be considered. Thus, it is recommended for structures using such a joint geometry to be designed based on the bearing capacity of the spruce boards at the joint.

Advantages of the presented joints are as follows: (i) an easy joint assembly that can be automated by computer-controlled systems, (ii) an initial degree of freedom of rotation for achieving final assembly after joining the wood parts and for correcting assembly tolerances (e.g. for wooden truss structures), (iii) a long-term rigidity by achieving form-and-friction locking due to high and reliable swelling pressures, (iv) a generic higher ductility at failure load compared to native hardwood dowels, given a dowel failure (Jung et al. 2008) and (v) use of the highly abundant beech wood. Disadvantages can be seen in the more complex production process including a densification step and a CNC milling step, and in the fact that the beech dowels do not permit applications under outdoor conditions because of the low durability. So far, the dimensioning of any such dowel connections can only be done under consideration of minimum swelling as a sum of the hygro-elastic swelling and the shape recovery. Precise predicting dowel deformation is not yet possible, as the material behavior of dW is by far too complex and scarcely known. An in-depth characterization and the development of a comprehensive non-linear model for predicting swelling would be required. Despite such restrictions, the data provided in this study can be useful for simple design as was demonstrated by the application examples with double-dovetail swelling dowel.

Figure 9: Force-displacement curves for double shear lap. Samples loaded until 40% of presumed maximal force $F_{\max, \text{est}}$, then load removed until 10% of $F_{\max, \text{est}}$, then loaded until failure (following standard EN 26 891:1991). An initial load of 0.1 kN was applied before start of measurement.

Conclusions

The exposure of dW to alternating dry and humid conditions provided new insights. The shape recovery and the hygroscopic swelling could be separately assessed. The differential swelling coefficient in the densification direction, which is independent of shape recovery, was found to be around 3.5 times higher for beech dW than for beech nW in the same direction after spring-back had ceased

for 0–85% RH cycles. Beech dW showed higher and more persistent swelling pressures than beech nW. Whereas nW showed non-linear creep for swelling under mechanical load, dW was able to swell under load. Based on these observations, R-densified beech shows superior properties for use as a swelling dowel compared to nW, even though there are densification damages in the cell wall structure. In a design study for robotic fabrication, a reliable form-and-friction locking was achieved after simple assembly and initial rotational degree of freedom.

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