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ORIGINAL ARTICLE

Development of swelling pressure in paulownia and Norway spruce during moisture absorption

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Abstract

Wood hybrid materials have gained significant attention for advanced technical applications over the past decade. In contrast to other materials, wood's hygroscopic nature causes swelling and shrinkage, leading to differential expansion in hybrid systems under varying humidity conditions. When wood's swelling is restrained by surrounding materials, stresses develop within both the wood and its adjacent components. To study this phenomenon, swelling tests were conducted on kiln-dried paulownia (*Paulownia elongata*) and Norway spruce (*Picea abies*) in a climate chamber at 20 °C and 98% relative humidity, with expansion restricted in one direction. Moisture absorption initially exhibited a steep, linear increase, levelling off after approximately 2 h. Swelling pressures rose sharply, peaking after 30 h for paulownia and 19 h for spruce, before gradually decreasing due to increased moisture content and relaxation. The measured stresses were lower than the compressive strengths of both wood species at their respective moisture contents. Microscopic examinations showed no cellular damage in paulownia during moisture absorption due to swelling pressure. In contrast, spruce wood displayed cell wall deformations and ray's kinking in the early wood region of radial samples, as well as cell wall bending in tangential samples. This indicates that maximum stress is determined by the localised failure of the wood's cellular structure rather than its overall properties. Such local effects were more pronounced in spruce than in paulownia due to their different structure. As a result, paulownia shows excellent potential for use in hybrid structures due to its low swelling and shrinkage properties and uniform structure.

1 Introduction

Wood is a highly hygroscopic material that is subjected to swelling and shrinkage due to moisture uptake. Water absorption can be explained by the numerous free hydroxyl groups of components of the cell wall (Hon and Shiraishi. 2001; Xie et al. 2010). Oven dry wood, therefore, absorbs water from the humid ambient air. The rate of moisture absorption is explained by diffusion processes and thus by Fick's law. According to more recent findings, the time-dependent moisture absorption corresponds to a so-called parallel exponential kinetics model (Okubayashi et al. 2005; Hill et al. 2009; Xie et al. 2010; Guo et al. 2017).

The intricate dynamics of water absorption and desorption in wood are influenced by its micro- and nanostructure, along with its chemical properties. Changes in moisture content lead to dynamic changes in both material and structural properties (Xie et al. 2010). Beyond considerations of chemical and material science, it is crucial to also consider the significant impact on wood's technological properties, including dimensional stability, strength, modulus of elasticity, energy absorption, and creep behaviour. Additionally, these changes in moisture content have notable implications for wood's natural durability against fungi and other biological attacks (Xie et al. 2010).

Moisture absorption and equilibrium moisture content under different climatic conditions have been excellently studied and analysed in the scientific literature for the different wood species and therefore does not need to be discussed in detail here. However, time-dependent moisture absorption and desorption is scarcely described in the literature. Using new measuring systems such as dynamic vapour

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sorption analysis (DVS), the water absorption behaviour of wood was investigated in more detail (Xie et al. 2010). However, these measurements are limited to very small samples and cannot be transferred directly to larger wooden components.

The large differences in swelling and shrinkage in the radial, tangential and axial directions of the various types of wood are also known (Wagenführ and Wagenführ 2021) and are described as the degree of swelling (i.e. total swelling in per cent or percentage swelling per percent moisture absorption).

At low moisture levels, water is very tightly bound to the wood. According to Kollmann (1982), the swelling pressure of the wood cell wall under these conditions is relatively high and exceeds the strength of the cellular wood structure many times over. Accordingly, high compression forces and thus plastic deformation occur with kiln dried wood when exposed to moisture. Transverse pressure failure in dried wood due to swelling from water absorption leads to permanent dimensional changes if the proportionality limit is significantly exceeded (Kollmann 1982). When such a sample is dried again after water absorption, it exhibits smaller dimensions in the direction of the limited swelling due to these permanent changes.

A well-known and striking example is the formation of joints in solid wood floors. In practice, this problem is mitigated by using wood-based materials such as plywood, designing intentional gaps with specified tolerances (e.g., in door and window constructions), and applying wood modification techniques like acetylation. Since swelling and shrinkage movements are of great importance for the use of wood, swelling pressures at interfaces where wooden components have restricted expansion have received great attention (Mishiro 1972; Virta et al. 2006; Mazzanti et al. 2014).

Virta et al. (2006) measured the swelling stress of tangentially restrained spruce wood during water uptake. According to their results, the maximum stress obtained after 1–3 h of immersion in water was about 1.2 MPa. A comparable value of 1.3 MPa was measured in restrained solid pine samples along the tangential direction (Spulle et al. 2018). The peak stress was reached after six hours.

Mazzanti et al. (2014) investigated the swelling pressure of poplar wood between a humidity range of 30 to 80% at 30 °C over long cycles of 42 days. The maximum swelling pressure in the tangential direction peaked during the first absorption cycles at 1 MPa and decreased to around 0.6 MPa during the third cycle.

Ellis and Steiner (2002), Blomberg et al. (2006), and Almusawi et al. (2024a, 2024b) observed structural changes in different types of wood at different wood moisture contents under compressive loads as well as spring back after loading based on microscopic inspections. Different wood moisture contents lead to very different responses with regard to the measured stress–strain curves. The structural changes at higher degrees of compression are also strongly dependent on the moisture content of the wood.

This study is conducted within the framework of the Bio-LiB project (Biobased Multifunctional Laminates in Battery Housings), which aims to develop sustainable battery trays using wood-hybrid materials. The project leverages the complementary structural, mechanical, and thermal properties of these materials to achieve multifunctional performance, including temperature management, crash resistance, and fire protection, while maintaining low weight and a reduced ecological footprint. Specifically, the project focuses on creating a tray frame consisting of a thin metal shell reinforced by a laminated wood core, with the wooden body enclosed within the metal shell. However, changes in the moisture content of the wooden component can induce swelling and generate stresses in both the wood and the metal shell.

Estimating these stresses using theoretical or computational models is challenging due to the viscoelastic nature of wood. Current elastic theories often oversimplify or entirely neglect the effects of viscoelasticity, resulting in significant overestimations of swelling pressures. This study addresses these limitations by providing experimental data on the swelling behaviour and stress relaxation of two distinct wood species: paulownia (*Paulownia elongata*) and Norway spruce (*Picea abies*). These findings are crucial for developing advanced models that account for viscoelastic and mechano-sorptive effects, enabling more accurate stress predictions. Such insights are particularly valuable for applications involving wood-hybrid materials in battery trays, where dimensional stability and effective stress management are critical.

Paulownia species are ring-porous or semi-ring-porous (Kalaycioglu et al. 2005) and the tree is native to east Asia. Paulownia (*Paulownia elongata*) has recently been grown in controlled plantations in Central Europe owing to its rapid annual growth and the promising mechanical and physical properties of its wood (Huber et al. 2023). Paulownia has a relatively low volumetric swelling coefficient (6.7% for *Paulownia elongata* (Müller and Stingl 2019) and 6.3% for *Paulownia tomentosa* (Koman et al. 2017)), which offers a great potential for hybrid applications.

A special test set-up was constructed to investigate swelling stresses occurring in the wood as a result of moisture absorption. The swelling pressures in the different anatomical directions for paulownia were quantified and compared with those of Norway spruce, a widely used and extensively studied wood species, serving as a benchmark for understanding the performance of less conventional species like paulownia. The development of plastic deformations was investigated in more detail using microscopy images.

2 Materials and methods

The swelling tests were carried out in a programmable climate chamber (Weiss, Austria). A climate of 98% relative humidity and 20 °C was set for the tests. The climate data of the climate chamber were recorded every minute with a data logger (Testo 400, Testo, Vienna, Austria).

Flawless spruce wood (*Picea abies* (L.) H.Karst.) and paulownia (*Paulownia elongata* S.Y.Hu) were used as sample material. The spruce wood (joinery quality) was purchased from a specialised dealer (Frischeis, Austria). The paulownia wood was provided by the company Plantownia (Plantownia GesbR, Bairisch Kölldorf, Austria). A detailed description of the origin of the material is given elsewhere (Moog 2022).

The material was dried and stored in a standardised climate (20 °C and 65% relative humidity) until equilibrium moisture content was reached. The samples were then cut longitudinally, radially, and tangentially into dimensions of 40 × 40 × 40 mm.

The samples obtained were then dried in a kiln at 103 +/- 2 °C for 12 h until constant weight was achieved and then stored in a desiccator over a desiccant (silica gel) for cooling.

To determine the swelling pressure, the samples were clamped between a steel yoke and a 2.5 kN load cell (Zwick/Roell, Ulm, Germany). The test setup is shown in Fig. 1. Two U-shaped profiles according to DIN EN 10279 (2000) with a height of 140 mm and a width of 60 mm were used as the steel yoke. The distance between the two U-profiles was maintained by M14 threaded rods of strength class 5.8 (according to DIN 976-1, 2016). The surface of the lower U-profile was milled flat to ensure full contact with test specimens on both sides. A 10 mm thick structural steel plate, also milled flat, was inserted between the specimen and the load cell.

The wood moisture content was determined by electrical resistance measurement using the Material Moisture Meter GMH 3831 (Greisinger, Germany). The wood moisture content was measured on a sample that was cut out directly next to the sample used for the swelling pressure measurement. As with the swelling pressure sample, the two surfaces in the direction of the force measurement were completely covered with steel plates so that the moisture could only be absorbed via the free side surfaces.

The signal conditioning for force measurement was done by a Measurement System from National Instruments (cDAQ-9148 with measurement modul 9219). The Software for logging force and wood moisture on a computer, was realised in LabView (National Instruments).

Like the climate data, the wood moisture and force measurement data were recorded every minute. The exact specimen dimensions were measured before and after the experiment at the same predefined locations on the specimen using a dial gauge (500 series, Mitutoyo, Wels Austria) with an accuracy of ± 0.04 mm.

After the stress measurement, the samples were sanded using 1000-grit sandpaper and examined in the transverse direction under a light microscope (Olympus DSX 1000 digital microscope, Shinjuku, Tokyo, Japan) to optically observe any structural changes. Statistical evaluation and Levenberg–Marquardt data fitting were performed with SPSS software (IBM SPSS Statistics 27).

It is worth noting that the restrained swelling tests conducted in this study are inherently time-consuming, as each specimen must be tested individually using the load cell setup within the climate chamber, which was maintained at 98% relative humidity. The total testing period amounted to approximately 2390 h (around 100 days). Extending the

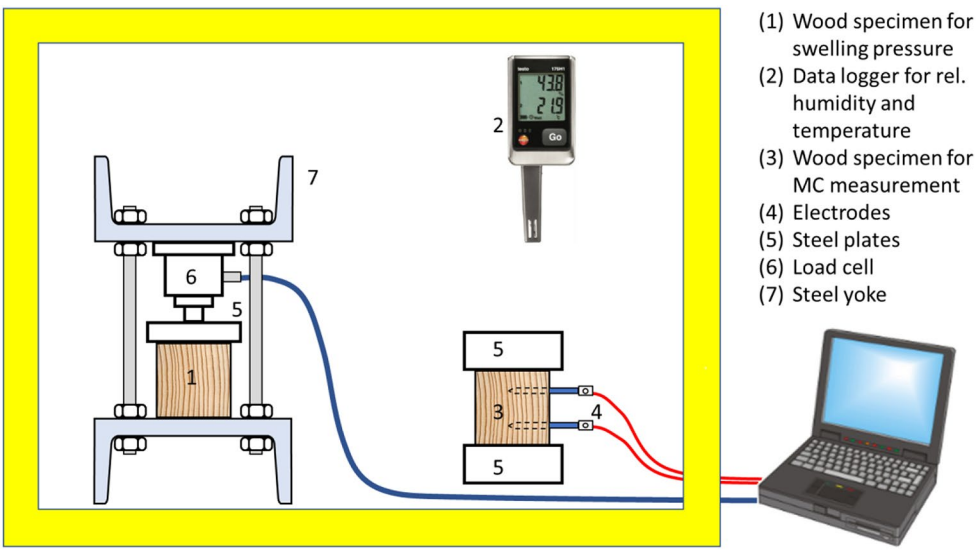


Fig. 1 Test set-up for swelling pressure measurement

testing duration further was not feasible due to practical constraints, as the climate chamber is part of a shared laboratory facility and must be available for use by other researchers. Consequently, the sample size in this study reflects these logistical limitations while ensuring the quality and validity of the obtained data.

2.1 Analytical investigations

As discussed, moisture absorption in wood generates stresses when the material is restrained. In earlier publications, the authors have explored stress states in wood across different anatomical directions and under different climatic conditions. Following the publication of Al-musawi et al. (2024c), the following Eq. (1xsx) can be attempted to simulate the stress development over time perpendicular to the grain:

$$\sigma = \sigma_0 \frac{\beta \left[\frac{t}{t_0}\right]}{\beta - 1 + \left[\frac{t}{t_0}\right]^{\beta}} \quad (1)$$

Where:

σ is the current compressive stress, σ_0 is the maximum compressive stress, β is a material parameter, t is the elapsed time, and t_0 is the time at which the maximum compressive stress (σ_0) is observed. During the fitting process, the maximum stress was constrained, and the parameter β was restricted to a range of 1.3–2.1. These constraints were applied to ensure that the fitting procedure remains consistent with the physical behaviour of the material and aligns with observed experimental data.

3 Results and discussion

The development of the average MC for the different specimens is shown in Fig. 2, while the individual MC curves for each wood species are provided in the Supplementary Material.

As illustrated in Fig. 2, water absorption occurred in two distinct stages. During the initial phase, due to the high humidity in the climate chamber and the extremely low initial moisture content of the specimens (close to 0%), moisture uptake occurred very rapidly. This rapid absorption may have been further facilitated by microcracks in the wood structure formed during kiln drying. However, after approximately two hours, the rate of moisture absorption significantly decreased, transitioning into the second phase. In this phase, the moisture content gradually approached the so-called fibre saturation point.

Both paulownia and spruce specimens exhibited consistent and uniform moisture absorption curves. The relationship between moisture absorption and time (u_t) can be modelled as a two-phase exponential increase, as detailed in Supplementary Material.

For the radial and tangential direction of the paulownia specimens, Fig. 3a and b show a mean curve and a data fit for the developed stresses according to Eq. (1). The maximum stress of 0.97 MPa and 1.1 MPa was reached after about 30 h for the radially and tangentially orientated specimens, respectively. On average, this corresponded to a stress of 0.8 MPa and 0.91 MPa for the radially and tangentially orientated specimens, respectively. After reaching the peak stress, the stress exhibited a gradual decrease over time, tapering off at later stages until the test was aborted. The average peak stress corresponds to an average MC of 14.1% and 16.5% for all radially and tangentially orientated specimens.

In accordance with EN 408, the compressive strength of paulownia wood was determined to be 1.8 MPa in both the radial and tangential directions. The tested material had a moisture content (MC) of 10%. These results align closely with the values reported by Huber et al. (2023), as the material analysed in this study originated from the same plantation as that used in their research.

According to Kollmann and Cote (1968) (p. 347), the strength between 8 and 18% MC can be estimated using Eq. (2):

$$\sigma_2 = \sigma_1 \frac{32 - MC_2}{32 - MC_1} \quad (2)$$

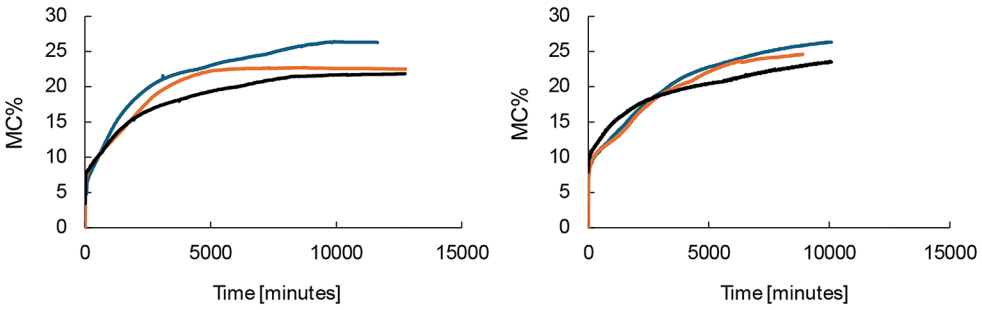


Fig. 2 Development of the average moisture content (MC) of paulownia (left) and spruce specimens (right), measured in the radial (blue line), tangential (red line), and axial (black line) directions

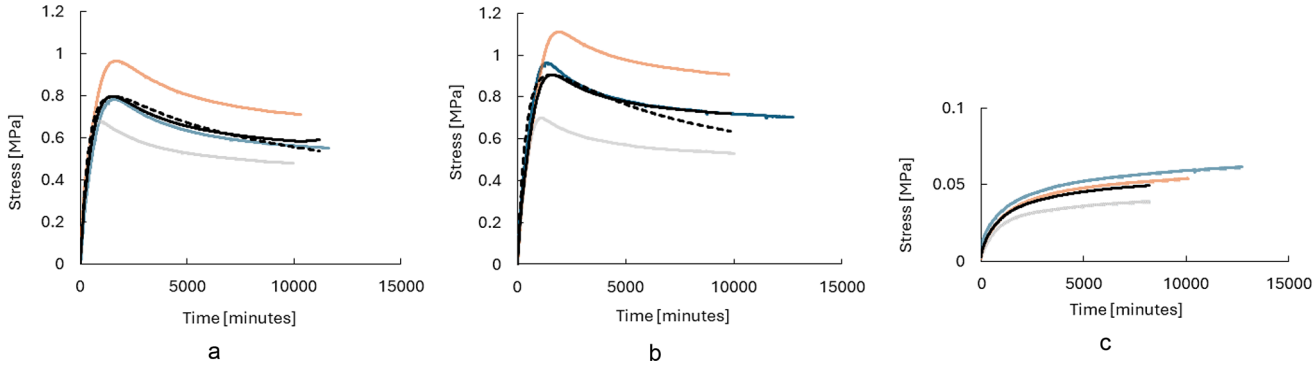


Fig. 3 Stresses over time of paulownia samples (blue, red, and grey lines) tested in (**a**) radial, (**b**) tangential and (**c**) axial directions. The black line marks the average curve of the three measured curves. The dash-dotted black line marks the data fitting according to Eq. 1 for the average curve

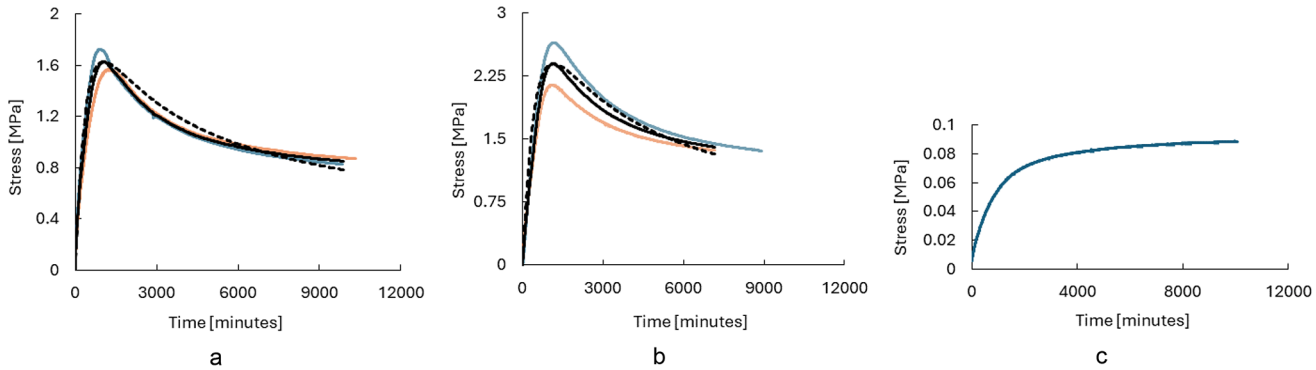


Fig. 4 Stresses over time of the two spruce samples (blue and red) tested in (**a**) radial, (**b**) tangential and (**c**) axial directions. The black line marks the average curve of the two measured curves. The dash-dotted black line marks the data fitting according to Eq. 1 for the average curve

where σ_2 is the required strength value at MC_2, σ_1 is the known strength at MC_1.

Using Eq. (2), a MC of 16.5% and 14.1% (=MC at the time of the average peak stresses for the radially and tangentially orientated specimens, respectively) result in estimated radial and tangential compressive strengths of 1.27 MPa and 1.46 MPa. These values are higher than measured stresses of 0.8 MPa and 0.91 MPa.

The determined swelling stress shows slightly lower values in the radial direction (0.88 MPa) than in the tangential direction (1.02 MPa). These differences can be explained by the different swelling coefficients, which according to Huber et al. (2023) is 1.7% for the radial direction and 4.7% for the tangential direction.

The decrease in stress after reaching this peak stress can be explained by relaxation processes as described by Mazzanti et al. (2014).

In the case of the axially orientated specimens, the stress development tends to follow an exponential curve. However, due to the negligible dimensional changes (i.e. less than 0.2 mm), the corresponding stress development was also very low. At the end of the test, a stress of less than 0.07 MPa was achieved. A suitable data fit was not performed, as it can be assumed that the stresses developed are strongly influenced by interface phenomena, which are mainly due to the surface roughness of the cells cut across the fibre and depend less on the stress states inside the sample. Due to these interfacial phenomena, no linear increase in force is observed in compression tests in the axial direction at the beginning of the load, as the wood volume is not loaded uniformly at the beginning of the compression load due to the surface roughness.

The stress development over time for spruce wood is presented in Fig. 4. As shown, on average, a maximum stress of 1.63 MPa for radially oriented specimens and 2.4 MPa for tangentially oriented specimens was reached after about 19 h. Similar to paulownia, a gradual decrease in stress was observed after the peak stress, tapering off over time until the test was stopped. The average peak stress corresponds to an average moisture content (MC) of 12.3% for radially oriented specimens and 12.9% for tangentially oriented specimens. The radial and tangential strengths of spruce wood at these moisture contents were obtained by measuring the compressive strength (following EN 408) on samples from the same material used for swelling tests at a MC of 10%.

The strength at the MC corresponding to peak stress was determined using Eq. 2, yielding values of 5 MPa for radially oriented specimens and 7.7 MPa for tangentially

oriented specimens. The average resultant swelling stresses are by far less than the material's strength values.

Regarding the developed axial stresses in spruce, similar to paulownia, the measured stresses were very low, remaining below 0.1 MPa, due to the minimal dimensional changes observed.

Figure 5 shows the microscopic images captured after the completion of swelling tests. There were no visible deformations during restrained swelling in paulownia wood along either orientation. In contrast, spruce wood showed cell wall deformations and ray kinking in the early wood region for samples that were restrained in the radial direction while bending of the cell walls was observed in samples that were restrained in the tangential direction. As mentioned, for both wood species, the material's strength values were higher than the average swelling stresses.

Although the specimens used are small, it is anticipated that moisture gradients arose throughout the thickness of the sample. This resulted in non-uniform stress distributions, such as high localised compressive stresses exceeding the material's capacity, which can cause localised damage. Such local effects were more pronounced in spruce than in paulownia due to their differing wood structures.

Paulownia is a diffuse-porous hardwood species with a homogeneous structure, reflected by its equal tangential and radial strengths. It is also characterised by low swelling coefficients compared to other wood species and high porosity. The high porosity may facilitate diffusion and reduce the extent of uneven moisture distribution inside the samples. At any rate, other diffuse-porous hardwood species like beech and birch have been shown to exhibit a "spongy" behaviour when wet under compressive loading, displaying significant springback and recovery (Al-musawi et al. 2024b).

Spruce wood, on the other hand, is a soft wood species with clear contrast between early and late wood regions. Early wood regions have lower density (Müller et al. 2003) and higher microfibril angles than latewood areas (Lichtenegger et al. 1999). Thus, they dominate the wood response perpendicular to the grain of softwoods (Müller et al. 2003; Ellis and Steiner 2002; Tabarsa and Chui 2001).

Mazzanti et al. (2014) reported that the tangential rigidity of poplar wood decreased by 13%, from 129 MPa to

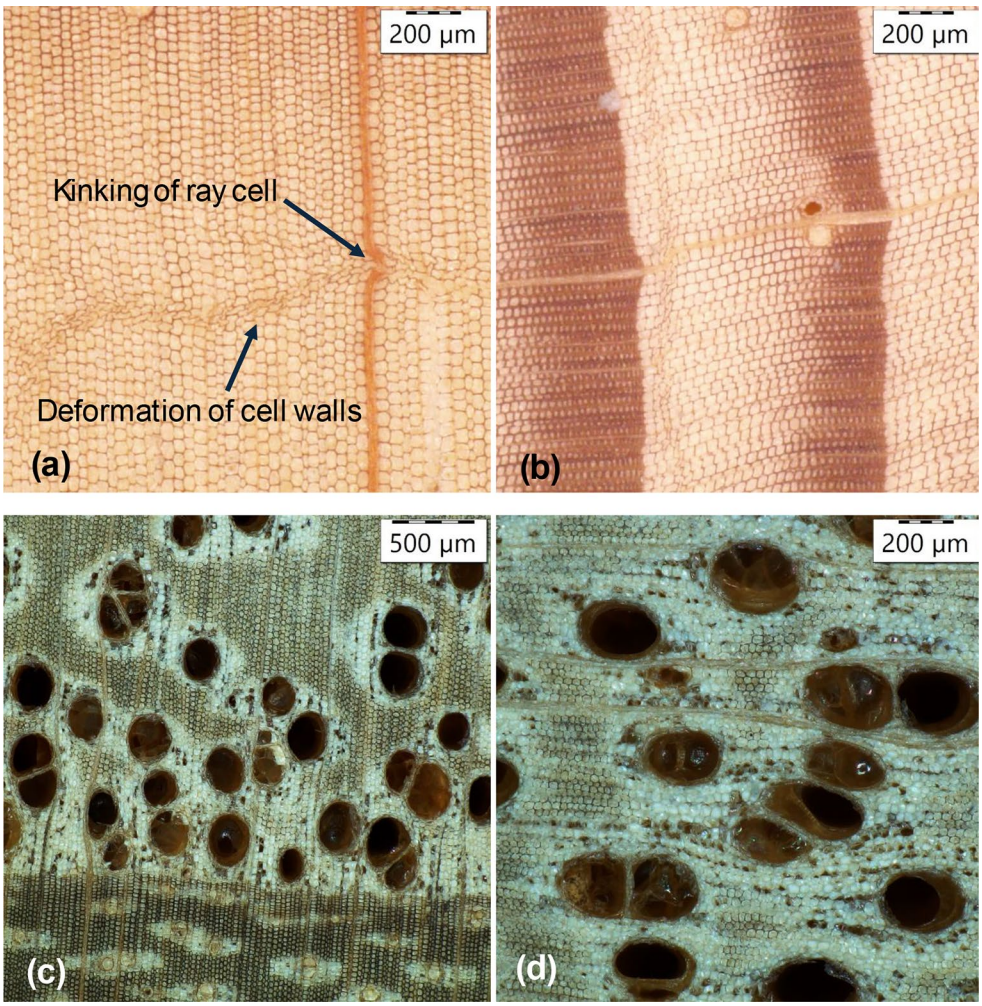


Fig. 5 Microscopic images of wood after swelling: (**a**) &(**b**) spruce; (**c**) and (**d**) paulownia, along radial and tangential directions, respectively

Table 1 Calculated swelling stresses of wood specimens at MC correspondent to the development of peak stresses during restrained swelling tests

Wood species	Radial orientation			Tangential orientation		
	ε^{*}	E^{**}	$\sigma_{swelling}{}^{***}$	ε	E	$\sigma_{swelling}$
Paulownia	0.01205	219	2.6	0.0294	116	3.4
Spruce	0.02084	830	17	0.04044	545	22

* Swelling strain values calculated from free swelling samples

** Corresponding elastic moduli obtained at the specific moisture contents, in MPa

*** Calculated (theoretical) swelling stresses using Hooke's law, in MPa

112 MPa, during subsequent adsorption cycles of restrained swelling tests. This indicates the occurrence of damage due to the development of compressive stresses.

Using Hooke's law, the maximum theoretical elastic swelling pressure developed during restrained expansion tests can be calculated. Assuming a linear relationship between moisture and swelling, the swelling strain was calculated at the MC corresponding to the peak stress measured for each wood species, as listed in Table 1. The modulus of elasticity of paulownia was taken from Huber et al. (2023) and adjusted to the required MC using the relationships stated in Gerhard (1982). For Spruce wood, the modulus of elasticity along radial and tangential orientations were taken from Akter and Bader (2020).

As shown in Table 1, the resultant (theoretical) swelling stresses exceeded the compressive strengths of both wood species. It is important to note that there was no visible macro or micro damage detected in paulownia samples restrained along radial and tangential samples. This highlights the significant role of viscoelastic creep and mechano-sorptive creep in lowering the values of swelling stresses during moisture adsorption (Virta et al. 2006). It also indicates that the maximum stress is not determined by the average global behaviour of the wood, but rather by the local failure of the material's cellular structure, as is the case for spruce wood.

Although the mechanical properties of paulownia wood are lower than those of many other wood species, it shows excellent potential for use in hybrid structures due to its low swelling and shrinkage properties. However, further studies on the mechano-sorptive creep and viscoelastic creep properties, as well as their interaction with the generated stresses in paulownia, are needed before final conclusions can be drawn about its suitability for such applications.

4 Conclusion

This study examined the swelling behaviour of paulownia and spruce wood under restrained conditions in radial, tangential, and axial orientations, providing insights into their anisotropic stress development and microstructural responses.

The orientation of wood influenced swelling stresses and stress relaxation behaviour, with average maximum swelling stresses of 0.8 MPa in the radial direction and 0.91 MPa in the tangential direction of paulownia. In the axial direction, the maximum stress was less than 0.1 MPa. These peak stresses, observed at moisture contents (MC) of approximately 14.1% (radial) and 16.5% (tangential), gradually decreased over time and tapered off until the test concluded.

Spruce wood exhibited higher swelling stresses, with average peaks of 1.63 MPa and 2.4 MPa for the radial and tangential directions, respectively, at MC values of 12.3% and 12.9%. Similar to paulownia, a gradual decrease in stress was observed after the peak stress. The mathematical models used in this study were shown to adequately describe the stress development over time as well as the moisture absorption behaviour of wood.

Microscopic analysis revealed no cellular damage in paulownia during swelling, suggesting its cellular structure effectively accommodates swelling pressure without localised failure. In contrast, spruce exhibited localised structural failures, including cell wall deformation and rays kinking in radial samples, as well as cell wall bending in tangential specimens. These observations indicate that swelling stresses in spruce are primarily governed by localised cellular failure rather than overall material properties.

The study also highlighted that elastic theories neglecting mechano-sorptive and viscoelastic creep effects significantly overestimate swelling stresses. This underscores the importance of incorporating time-dependent processes in models to more accurately predict stress development under restrained swelling conditions.

While paulownia has lower mechanical properties compared to spruce and other wood species, its lower swelling stresses and resistance to microstructural damage make it a promising candidate for hybrid structural applications. Further research is needed to explore the interaction of its mechano-sorptive and viscoelastic properties with long-term stress development under variable environmental conditions.

By introducing a methodology to evaluate swelling pressure and stress relaxation, this study also offers a framework for assessing the swelling behaviour of other wood species,

contributing to a broader understanding of wood performance under restrained conditions.

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Author contributions H.A. and U.M. conceived the presented idea. G.E. and H.A. performed the experimental tests. B.U. and G.B. contributed to the interpretation of the results. H.A. and U.M. analysed the data. U.M. and F.F. supervised the project and were in charge of overall direction and planning. H.A. wrote the original draft with a support from U.M. All authors have read and agreed to the published version of the manuscript.

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Data availability The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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