Hygro-mechanical behavior of thermally treated beech subjected to compression loads

CrossMark

Aleš Straže [a],*, Gorazd Fajdiga [a], Stjepan Pervan [b], Željko Gorišek [a]

[a] *Department of Wood Science, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia*
[b] *Faculty of Forestry, University of Zagreb, Zagreb, Croatia*

HIGHLIGHTS

- Thermal treatment (TT) causes weight loss and reduction of wood hygroscopicity.
- Increase of compression stiffness along the grain of TT wood is confirmed.
- TT reduces transverse compression strength and plastic deformability of wood.
- TT has no impact on wood relative hygro-mechanical behavior.

ARTICLE INFO

ABSTRACT

The physical and mechanical properties of beech wood (*Fagus sylvatica* L.) were determined after industrial thermal treatment in a steam atmosphere. Parallel clear uniaxial compression specimens ($20 \times 20 \times 20$ mm) were made from control and thermally treated wood, conditioned in a series from an oven dry to saturated atmosphere ($20\,°C$) and compression loaded parallel and transverse to the grain. The reduced density of thermally treated beech was reflected in the decreased stiffness and, especially, strength of wood transverse to the grain. No impact of thermal treatment on the longitudinal compression strength of wood was confirmed. Lower hygroscopicity was additionally detected with thermomodified wood, whereas the relationship between wood moisture content and stiffness (MOE/MOE_0), as well as strength (σ/σ_0), along and transverse to the grain of the beech wood remained identical.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Thermal treatment of wood at high temperature ($160\,°C$–$260\,°C$) is one of the modification methods used to enhance the dimensional stability and bio-durability of timber and wood-based composites. Its properties and performance have been studied for decades [1–6]. Several processes are nowadays available on an industrial scale, including Bois Perdure (F), OHT-Prozess (D), Plato-Process (F), Retification Process (F), ThermoWood Process (FL) and ArborWood (USA) [7,8]. The common factor of these processes is modification of the chemical structure of timber. They vary in terms of furnace design, type and condition of the heating medium, and treatment schedules. Carbonic acids, mainly acetic acid, are known to form during thermal treatment of wood, as a result of the cleavage of the acetyl groups of particular hemicelluloses [9–11].

Important aspects of thermally treated wood are strength reduction and stiffness alteration, which vary with the anatomical direction of the wood, testing method and wood species. Many studies have shown a reduction in bending strength of thermally treated wood [12–17]. A reduction is also generally confirmed with the stiffness of wood in bending (Modulus of elasticity – MOE), although there are some exceptions [12,13,18]. The exceptions might be related to the finding that the decrease in MOE only becomes significant when the mass loss exceeds a particular value [19]. It is assumed that the increase in MOE is related to the formation of new chemical bonds with higher binding energy than cleaved hydrogen bonds, as well as to the bonding of cellulose chains, which is only possible up to a certain level.

Thermal treatment has also been found to reduce wood toughness [16,20,21] and shear strength [17]. Since wood density is commonly decreased after thermal treatment [16,17,21], one might expect a similar trend with the material compression strength. However, a slight increase in compression strength along the grain was found with poplar, beech and ash wood after thermal modification [21,22]. The authors linked the increase in compression

---

strength to the relative increase of lignin content and its condensation, confirmed by NIR spectroscopy [22]. Similarly to the compression strength, hardness generally increased with several wood species after thermal treatment [17], whereby only a slight reduction was confirmed in radial and tangential directions with some pines and maple [13].

The moisture content (MC) is also known to affect the strength properties of wood [23–27]. The reduced hydrogen bonding and decrease in free accessible hydroxyl groups in thermally treated wood [28–30], which leads to a decrease in the equilibrium moisture content (EMC) [31–33], is therefore additionally responsible for alterations in material strength and stiffness. To the best of the authors' knowledge, the relationship between the mechanical properties of wood and wood MC after thermal treatment has been less researched. The present study therefore investigate the influence of MC and wood thermal treatment on the mechanical behavior of beech, equilibrated over a wide atmosphere range and subjected to compression loads.

2. Material and methods

2.1. Material

Ten radially oriented beech wood boards (*Fagus sylvatica* L.) of 32 mm thickness and 2 m long, with no visible defects, were randomly selected from the conditioned warehouse (T = 20 °C; RH = 65%) of an industrial heat treatment company. The selected boards were divided into two halves (L = 1 m), for control (C) and thermally treated board samples (TT). Industrial heat treatment in an unsaturated steam atmosphere (P_{atm} = 1.2 bar) was then performed at Evolen d.o.o. (HR) on TT board samples, with a pre-drying phase (T = 105 °C; t = 24 h), stepwise heating phase (ΔT = +15 °C/h), heating at maximum temperature of 210 °C for 4 h, followed by cooling (ΔT = −15 °C/h) and conditioning (T = 20 °C; RH = 65%). The treatment is regarded as intensive modification and is intended to provide a compromise between good stability and durability, on the one hand, and an assumed decrease in mechanical properties, on the other. However, the detailed process data are confidential and thus cannot be published.

Two oriented bars of 20 × 20 mm² cross section (L = 0.6 m) were sawn from each control and thermally treated board, for transverse (T) and longitudinal mechanical testing (L). Prismatic wood specimens (L × R × T = 20 × 20 × 20 mm) were then made in a series (n = 8) from each oriented bar of unmodified (C) and thermally treated wood (TT) (Fig. 1).

2.2. Experimental procedures

Wood specimens were vacuum dried (T = 50 °C; P = 20 hPa) to obtain the oven dry mass (m_0) and volume (V_0). Adsorption behavior was then studied at room temperature (T = 20 ± 0.1 °C) by putting one specimen of a series to equilibrate at a single relative humidity (RH), with a range from 0% to 97% (n_s = 8) by the use of chambers with saturated salt solutions (ΔRH = ±1%, $t_{cond.}$ = 5 weeks) (Table 1).

Specimens were precisely weighed (Δm = ±0.001 g) and measured (ΔL = ±0.01 mm) after the equilibrium state was reached. The density ρ of each single specimen was determined immediately prior to compression testing, from the
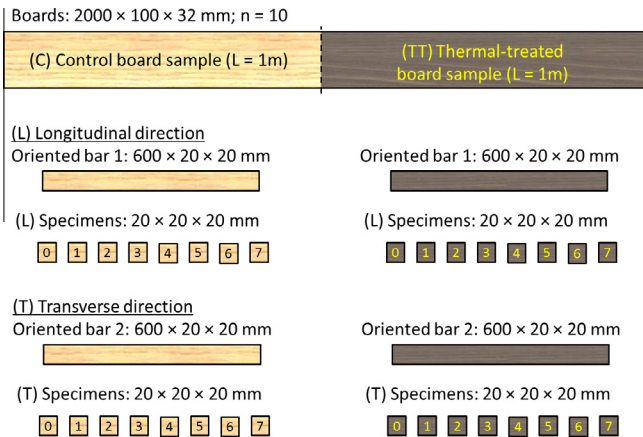
Table 1
Established atmosphere for the conditioning of specimens prior to mechanical testing (T = 20 ± 0.1 °C).

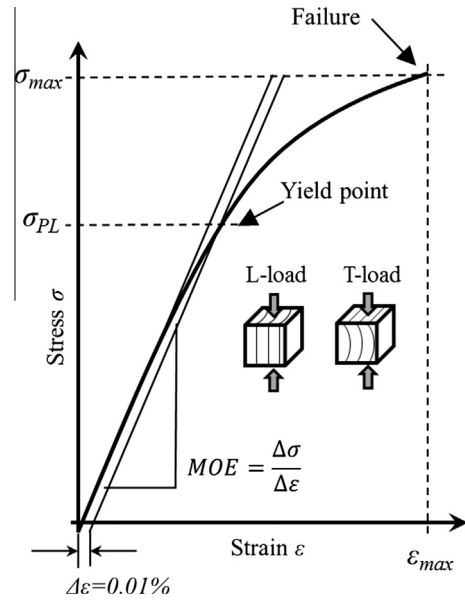| Climate	Medium	Rel. air humidity [%]
0	Vacuum drier (50 °C/2 hPa)	0
1	HCOOK	20
2	$MgCl_2$	33
3	K_2CO_3	44
4	$NaNO_2$	65
5	NaCl	75
6	$ZnSO_4$	87
7	Distilled water	97

Fig. 2. Determination of ultimate stress (σ_{max}), proportional limit stress (σ_{PL}) and modulus of elasticity (MOE) from the stress–strain relationship and principle of loading direction of wood.

mass divided by the specimen's volume. The gravimetric method was additionally used to determine the moisture content MC from the difference between the equilibrium (m_e) and oven-dry mass (m_0) of each specimen (Eq. (1))

$$MC = \frac{m_e - m_0}{m_0} \qquad (1)$$

Transverse (T) and longitudinal (L) displacement-controlled tests were conducted using a Universal Testing Machine (ZwickZ100) with load cell of 100 kN maximum capacity. The specimens were loaded until failure with a constant loading rate so that specimen failure was reached according to standard procedure in 90 ± 30 s [34], whereby the loading rate (LOR) was adjusted to both tested wood directions of two groups (LOR_L = 1.0 mm/min, LOR_T = 1.7 mm/min) (Fig. 2). The stress–strain data was captured at 0.1 s time intervals.

Young's moduli MOE were obtained from the ratio of the stress σ to the relative strain ε measured in the linear elastic range (Eq. (2)).

$$MOE_i = \frac{\Delta \sigma_i}{\Delta \varepsilon_i} = \frac{\sigma_{i,2} - \sigma_{i,1}}{\varepsilon_{i,2} - \varepsilon_{i,1}} \quad i \in L, T \qquad (2)$$

The specific stress boundaries $\sigma_{i,1}$ and $\sigma_{i,2}$ were set at 10% and 40% of the specimen strength and adjusted according to the wood direction. Two different strength criteria, the ultimate stress σ_{max} and the proportional limit stress σ_{PL} were used to characterize the compression strength properties of the wood in the tested wood directions. The ultimate strength σ_{max} was calculated from the maximum load F_{max} at the point of failure and the cross sectional area A of the unloaded specimen (Eq. (3)).

$$\sigma_{max} = \frac{F_{max}}{A} \qquad (3)$$

The proportional limit stress σ_{PL}, representing the stress at the specific yield point, was obtained from a measured stress–strain diagram based on the "offset yield method" at 0.01% plastic strain (Fig. 2).

Fig. 1. Sampling of unmodified (left) and thermally treated beech (right).