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Mechanical Characterisation of Densified Hardwood with Regard to Structural Applications

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Abstract: The demand for high-performance, yet eco-friendly materials is increasing on all scales from small applications in the car industry, instrument or furniture manufacturing to greater dimensions like floorings, balcony furnishings and even construction. Wood offers a good choice on all of these scales and can be modified and improved in many different ways. In this study, two common European hardwood species, Beech (*Fagus sylvatica* L.) and Ash (*Fraxinus excelsior* L.) were densified in radial direction by thermo-mechanical treatment and the densified product was investigated in an extensive characterisation series to determine all relevant mechanical properties. Compression in the three main directions (longitudinal, tangential, radial) and tension perpendicular to the grain (tangential, radial) were tested and compared to reference specimens with native density. Strength and modulus of elasticity were determined in all tests. In addition, a Life Cycle Assessment was carried out to evaluate the environmental impact associated to the densification process. The experimental investigations showed that strength and stiffness of hardwood in the longitudinal and tangential directions improve significantly by radial densification, whereas some properties in the radial direction decrease. The Life Cycle Assessment showed that artificial wood drying has higher impact than wood densification. Furthermore, the transport distance of the raw material highly influences the environmental impact of the final densified product. The paper then also offers an overview of possible applications in structural timber construction. Densified hardwood is a viable option as local reinforcement, where high compressive or tensile strength is needed. The wood densification process offers an alternative to the use of carbon-intense steel components or hardwoods from tropical forests.

Keywords: Hardwood; densification; high-performance construction materials; thermo-mechanical treatment; mechanical characterisation; life cycle assessment; timber structures

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1 Introduction

For the last decades, the wood inventory in Swiss forests has been undergoing a process of change. Although spruce still forms the majority of the Swiss wood stock, the hardwood stock increased by 24% since the first National forest inventory in 1984 [1]. With regard to the environmental change, this transition is appreciated and even intended. Mixed forests are less prone to natural hazards such as disastrous storm events or heat waves which become more and more frequent [2].

Hardwood has excellent mechanical properties. Beech and ash wood shows higher strength and stiffness than spruce [3,4]: Tensile and bending strength increase by 50% when testing hardwood samples instead of softwood samples; the modulus of elasticity (MOE) improvements are possible in ranges of 20% for ash and 40% for beech [1,3,4]. In addition, hardwood shows great efficiency for all kind of connections. The performance of dowels, screws and threaded rod connectors is substantially higher due to the high density of the hardwood, without losing stiffness or ductility [5–7].

Wood modification is a measure to achieve targeted improvements of the performance for a particular application. Most wood modification methods include the use of chemicals such as in acetylation or mineralisation and thus complicate the processing and waste water disposal. Thermo-Mechanical (TM) or Thermo-Hydro-Mechanical (THM) treatments [8,9] represent environmentally friendly methods: The combination of high temperature, moisture and mechanical action such as bending or compression was discovered centuries ago as a way to form and strengthen wood for tools, furniture and vehicles [10,11].

Various investigations and research work exist on the densification of wood since more than one century [12,13]. Recently, good overviews to this topic were given by [14] and [15]. Mainly softwood or soft hardwood (e.g., poplar) is compressed—sometimes only partially near the surface—to get higher (surface) strength and hardness similar to the properties of hardwood (e.g., [15–17]); equally, it is applied for subsequent moulding [14,18,19]. For very high requirements on strength and hardness, hardwood with high density in the native state is treated. A product of densified beech wood is e.g., Lignostone, recently only produced as laminated densified wood by Röchling Engineering Plastics KG in Haren, Germany. The suitability of densified ash, black locust, aspen and beech wood for wooden nails investigated in [20]. In addition, comprehensive investigations on densification of beech wood were carried out amongst others by [21] and [8].

Although many investigations were carried out on densified beech wood, these are scarcely found for ash wood. Values for tension perpendicular to the grain of densified wood are in general widely lacking. Beech and ash are two hardwoods with a high potential in the European construction market and have been used in various projects in Switzerland as supplement to spruce. The demand for high-performance yet eco-friendly construction materials is considerably increasing.

The objective of the paper is to determine the mechanical properties and to evaluate the improvement of mechanical strength and stiffness of beech and ash wood when densified. First, the densification process in radial direction is described. Then, the elastic and strength properties of TM treated beech and ash wood were investigated in the three main anatomical directions longitudinal, tangential and radial (L, T, R). The results are presented and discussed. A following question was the environmental impact of the densification process, which may negatively influence the eco-friendliness of the material. Therefore, the environmental impact of the densification process was calculated using Life Cycle Assessment (LCA) following the ISO 14040 (2007) [22]. The individual steps of the manufacturing process and transport within Switzerland were considered. In the conclusion section, further applications of the material in timber construction are discussed.

2 Materials and Methods

2.1 Densification

The densification was conducted in the laboratory of the Institute for Building Materials at ETH Zürich. Beech (*Fagus sylvatica* L.) and ash (*Fraxinus excelsior* L.) wood from the surroundings of Zurich, Switzerland were used in this investigation.

The densification procedure consists of preparation, conditioning, compressing under heat, cooling and storage in controlled climate. In the preparation step, three side boards per wood species and densification level of dimensions 65 cm × 25 cm × 6 cm (length × width × thickness) were cut. In the conditioning step, the boards were stored at normal climate 20/65 (20°C ± 1°C and 65% ± 3% relative humidity according to DIN 50014 (2018) [23]). In the compressing step, the boards were then compressed in a 4,000 kN lab press during 180 min–200 min. The used forming pressure was about 7 MPa to 8 MPa for a target density of 1 t/m^3 and about 14 MPa for a target density of 1.2 t/m^3 (see Fig. 1). The densification was carried out at 105°C in the preheated press until the end of the maximum pressure hold (cf. Fig. 1). In the cooling step, the temperature was slowly decreased at reduced pressure to about 70°C until the end of the pressing procedure. The last step was the storage of the boards again in standard climate 20/65 after the densification.

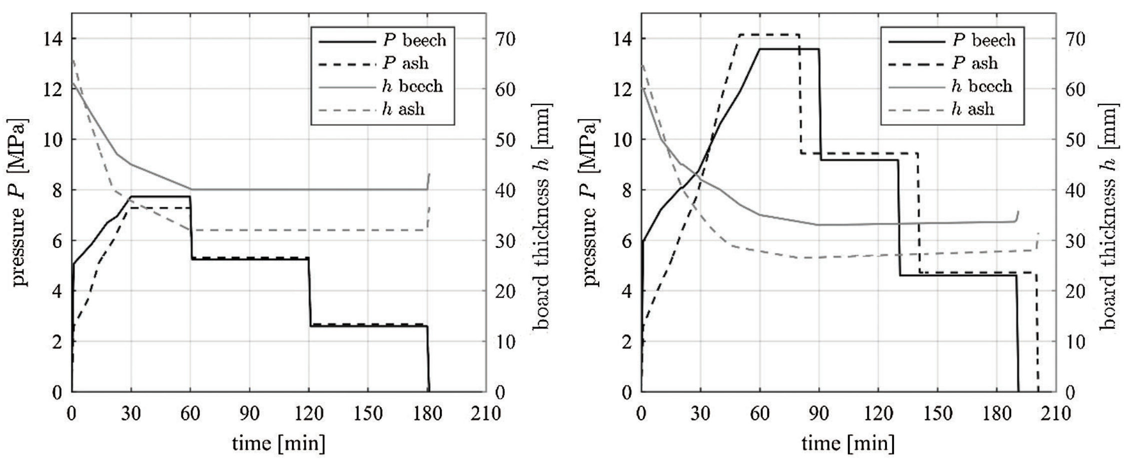

Figure 1: Pressing procedure and corresponding thickness reduction for beech and ash densified to 1.0 t/m^3 (left) and 1.2 t/m^3 (right)

The thickness of the boards was measured by a pre-installed ruler in the press at several points in time during the pressing and after removing the press panel. The spring-back of the boards was measured by their thickness change before and after releasing the pressure.

Three un-densified boards were also prepared and conditioned in the standard climate 20/65. The test specimens for the experimental investigations were then cut from the densified and un-densified boards (see Sections 2.4 and 2.5). The density of all test specimens was measured (see Section 3.1). For each test series, the wood moisture content was determined according to DIN 52183 (1977) [24] on a random selection of 48 samples per species (see Section 3.1).

2.2 Test Equipment

All tests were conducted on a universal testing machine with a load capacity of 100 kN (Z100/TL3S). The induced load was measured with an integrated load cell. A spherical calotte was installed between load cell and press plate (Fig. 2 left) to prevent bending moments due to eccentric loading for the compression tests. For the tension tests, lower and upper mobile jaws were applied (Fig. 2 right). The deformations on the specimens were recorded by a video extensometer.

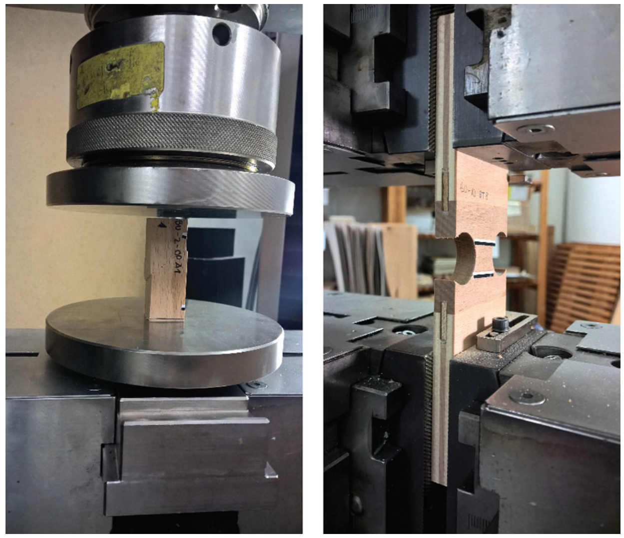

Figure 2: Test setup for compression and tension tests. Left: Beech specimen after compression test in fibre direction, right: Beech specimen during tensile test in tangential direction

2.3 Compression Tests in All Three Main Directions

2.3.1 Testing Procedure

The compression tests were conducted according to DIN 52185 (1979) [25] for compression parallel and DIN 52192 (1979) [26] for compression perpendicular to the grain. The occurrence of the first of the following criteria defined the end of the testing:

–maximum strain: 5.5%, decisive for compression radial and tangential

–maximum time of testing: failure, decisive for compression longitudinal

The load speed was adjusted so that the maximum load was reached within 90 s ± 30 s. All three main directions (longitudinal, tangential and radial) were tested with 15 specimens per direction and densification level for both wood species.

2.3.2 Compression Specimens

The compression tests were performed on cuboid specimens with a length of 60 mm and a cross-section of 20 mm × 20 mm. Fig. 3 shows how the samples were cut from the boards by considering the orientation of the annual rings. For radial compression, the height of the samples was determined by the maximum of available height of the board after densification and grinding: approximately 48 mm were available for native samples, 37 mm for 1.0 t/m^3 and 26 mm for 1.2 t/m^3.

2.3.3 Determination of Strength and Stiffness Values from Compression Tests

The stress-strain-behaviour for compression parallel to the grain showed a steep slope in the linear-elastic phase followed by a clear yielding stress level. Based on this behaviour, the compression strength $f_{c,0}$ and the MOE $E_{c,0}$ were determined as shown in Eqs. (1) and (2):

$$f_{c,0} = \frac{F_{max}}{A} \tag{1}$$

where F_{max} is the applied maximum load and A is the cross-sectional area of the tested cuboid.

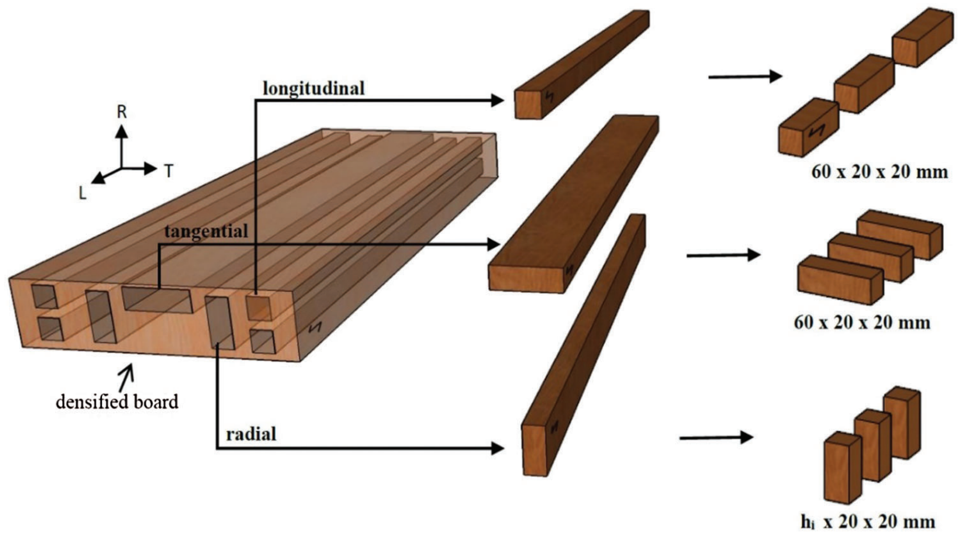

Figure 3: Cutting of compression test specimens from the boards

$$E_{c,0} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{2}$$

where $\Delta\sigma$ is the change in stress with corresponding change in strain $\Delta\varepsilon$. The range to determine the MOE was chosen as $\sigma_1 = 0.1 \times F_{max}$ and $\sigma_2 = 0.4 \times F_{max}$ according to EN 408 (2012) [27].

The material behaviour for compression perpendicular to the grain is different to the material behaviour of compression parallel to the grain; the stress-strain curves are characterised by no apparent yield stress level. Due to this fact, the compressive strength was determined as offset yield strength at two disproportionate strain levels according to DIN 52192 (1979) [25]:

−compressive strength at 2% strain: $f_{c,90,1} = \sigma_{2\%}$ (3)

−compressive strength at 5% strain: $f_{c,90,2} = \sigma_{5\%}$ (4)

For the determination of the MOE, the same approach as for compression parallel to the grain was applied (range between $0.1 \times F_{max}$ and $0.4 \times F_{max}$) with maximum load F_{max} at 5.5% strain.

2.4 Tension Tests Perpendicular to the Grain

2.4.1 Testing Procedure

The tensile properties of the densified hardwood were tested in the two directions perpendicular to the grain; Tangential (T) and Radial (R). The tests were performed in accordance to a test setup described in [28]. The load speed was 2 mm/min for all specimens.

2.4.2 Tension Specimens

The specimens were composed of the test sample as centrepiece and two slats of laminated veneer lumber on both sides. The test sample had a thickness of 9 mm, width of 50 mm and height of 40 mm ± 5 mm. The two slats on both sides were attached by glued tongue and groove to the test sample. A one-component polyurethane adhesive was used to glue the pieces together. The samples were taken from the best location in the board according to the orientation of the annual rings as shown in Fig. 4. Tangential specimens feature vertical annual rings, radial specimens horizontal annual rings.

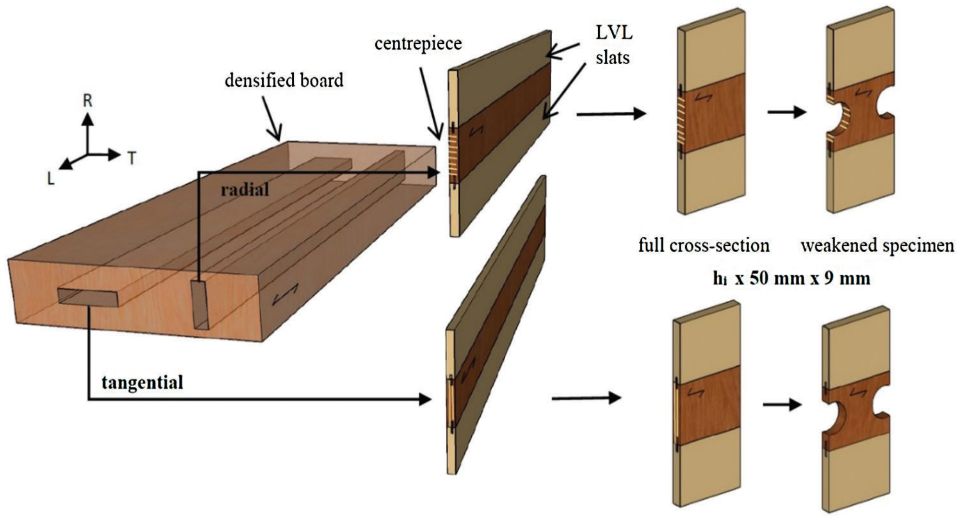

Figure 4: Cutting of radial and tangential tension specimens

Before testing, the specimens were weakened by narrowing the cross-section of the centrepiece to 15 mm width for radial specimens and to 20 mm width for tangential specimens to obtain failure in the densified wood.

2.4.3 Determination of Strength and Stiffness Values from Tension Tests

The MOE was determined as:

$$E_{t,90} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{5}$$

where $\sigma_1 = 0.1 \times F_{max}$ and $\sigma_2 = 0.4 \times F_{max}$. Linear regression was carried out to determine if the chosen section is an authentic depiction of the slope. For some curves, the upper boundary was adjusted to $\sigma_2 = 0.3 \times F_{max}$ to get a better fit. The determined MOE is an approximation to the real MOE due to the fact that the specimens are rounded in the measured area and it is useful for a first estimation and for comparison of the test variants.

The tensile strength was determined as the maximum reached stress:

$$f_{t,90} = \sigma_{max} \tag{6}$$

The tensile strength and the tensile MOE were determined in the same way for both directions, tangential and radial.

2.5 Life Cycle Assessment

Life Cycle Assessment (LCA) was used to assess the environmental impacts from the production of the densified wood products. LCA is a well-established methodology described in ISO 14040 (2007) [22] and has been in use for over four decades. LCA proposes a relation input-output between human activities and the environment [29]. LCA can be used to identify the processes with the highest contributions to the environmental impact. Thus, the results from LCA can be used in a production optimisation process to target their environmental hotspot.

The LCA models for densified wood were developed using the software OpenLCA [30] and the database EcoInvent v3.1. The Life Cycle Impact Assessment was done with the evaluation method IPCC2013 100a

[31]. The calculations were geographically located in Switzerland, were the extraction and processing of the wood occurs. The life cycle inventories were developed using the data at laboratory conditions extrapolated for a wooden board factory. To calculate the potential transport distance of the wood within Switzerland, the approach developed by [32] was used. This approach proposes a relation between the size of a country and the potential transport distances of construction materials. Three potential transport distances were calculated: (i) Minimum 100 km, (ii) Median 152 km, and (iii) Maximum 288 km. The LCA model considers three phases of product stages according to ISO 21930 (2017) [33]: (i) Raw Material Supply, (ii) Transport of raw materials, and (iii) Manufacturing process. The Life Cycle Inventories for densified hardwood are presented in Tab. 1.

Table 1: Densified wood—Life Cycle Inventories

	Process	Amount	Unit
Output	Densified Wood	1.0	m^3
Input	Sawn hardwood, kiln dried, planed	3.0	m^3
	Electricity, high voltage, CH	2569.0	kWh
	Transport, lorry 16 t-32 t Min	216.0	t × km
	Transport, lorry 16 t-32 t Med	328.3	t × km
	Transport, lorry 16 t-32 t Max	622.1	t × km
	Wooden board factory	5.78E-09	item (s)

3 Results and Discussion

This section presents the results of the densification, the experimental tests including compression and tensions tests, then the evaluation of the application in structural elements and finally the results for the Life Cycle Assessment.

The different densification levels of the specimens are labelled according to their target density: 00 for native, 10 for a target density of 1.0 t/m^3 and 12 for a target density of 1.2 t/m^3.

3.1 Densities and Moisture Content

The densities obtained in the densification process are shown in Fig. 5. We can observe that although the same densification process was used for both wood species, the density of the densified ash boards shows a much wider scatter than the density of densified beech for the first two boards. The densified ash boards were also less dense in the inner part of the board than near the two end grain sides, which was visible by eye as a slight concavity of the boards after removing them from the press. The spring-back of the boards measured as the change before and after releasing the press was in the range of 5%–11% for beech and 12.5%–19.2% for ash.

With the results from the densification process of the first two boards per wood type and densification level, it was therefore decided to amend the densification process of ash wood. The pressing time of the two cooling-off periods was increased for the third ash board from 60 min to 90 min. This change resulted in a more homogeneous thickness and density over the whole board. The scattering of the obtained density decreased significantly and the spring-back was lowered to 9.7% for ash-3-10 and even to 3.33% for ash-3-12.

The pressing procedure defined by pressing levels and time has a major influence on the resulting density. The procedure has to be adapted to the wood species to obtain target density with low scattering. Also, the set-recovery is an important issue and can partly be controlled by the pressing procedure [9]. However, this topic is not further dealt with in this paper, as the boards were stored and tested in standard

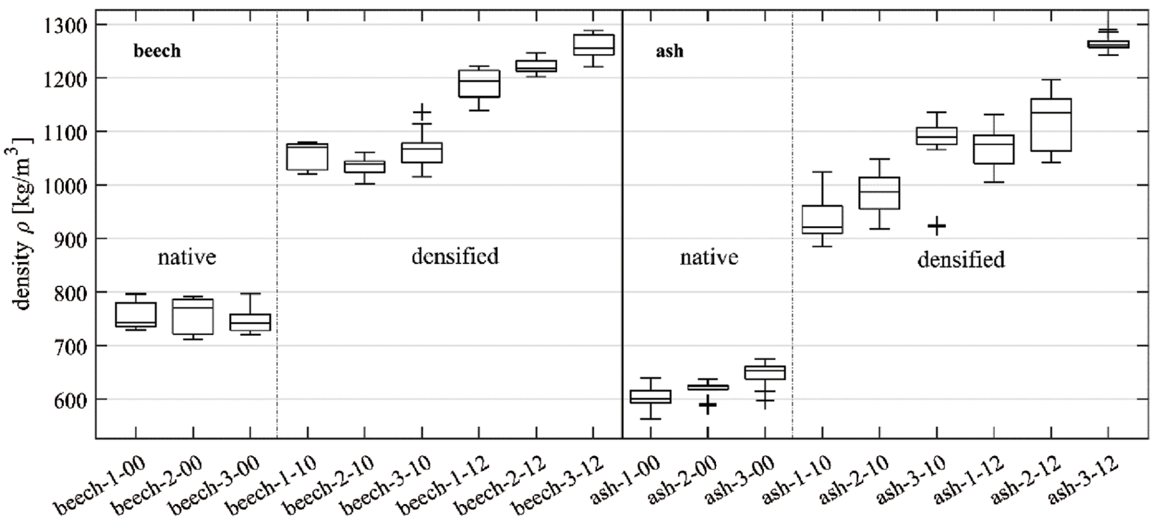

Figure 5: Obtained densities after densification as boxplot diagram. Whiskers display values within 1.5 × the interquartile range, values out of this range are displayed as outliers in form of a cross. Board labels: wood type—No. of board—densification level (00 = native, 10 = 1.0 t/m^3 and 12 = 1.2 t/m^3 target density)

climate after the densification. The densified boards were in a meta-stable condition, where further set-recovery is only possible by exposing the wood again to high temperature and/or moisture.

An average moisture content of 13.4% was measured for ash samples and 12.2% for beech specimens.

3.2 Compression Tests

The results of the performed compression tests are summarised in Tab. 2. Mean values x, coefficient of variation CoV and number of specimens n are given for reference density 00 and the densification levels 10 and 12. The highlighted columns give the change in values compared to the reference density.

Tab. 2 shows a significant increase of both strength and stiffness values of ash and beech wood with increased densification level for the directions longitudinal and tangential. The results are described and discussed in further detail in the following chapters.

3.2.1 Compression Parallel to the Grain

The MOE in compression and the compression strength in relation to the density are plotted in Fig. 6. The correlation is modelled by linear regression.

Fig. 6 shows that the compression strength correlates positively and with a high coefficient of determination ($R^2 \geq 0.96$) with the wood density. For both beech and ash, strength in longitudinal compression nearly doubles by densification from native to 1.2 t/m^3. Indeed, the strength values of native and densified specimens relating to density are rather low compared to literature data [33–35], but lie within the range of the corresponding wood species [4].

The values for MOE of densified wood show wider scattering and the correlation with density is less significant. However, the MOE also increases for both beech and ash with increasing density. The radial densification does not damage the longitudinal wood fibre structure. Densified specimens contain more longitudinal wood fibres in the same cross-section as native specimens. Therefore, there is a direct relation between compressive strength in longitudinal direction and the density of the specimen. The stiffness also increases, yet the relation to density is less clear.

Table 2: Properties of native and densified beech and ash on compression

Compression				00			10				12			
				754 kg/m³			1043 kg/m³				1205 kg/m³			
				x̄ *[N/mm²]*	*CoV* *[%]*	*n* *[-]*	*x̄* *[N/mm²]*	*CoV* *[%]*	*n* *[-]*	[%]	*x̄* *[N/mm²]*	*CoV* *[%]*	*n* *[-]*	[%]
Beech	**L**	$f_{c,0}$		**52.4**	3.5	15	**69.0**	3.0	13	+ *32*	**80.3**	4.3	16	+ *53*
		$E_{c,0}$		**13,240**	12.4	15	**18,569**	27.8	13	+ *40*	**20,125**	21.6	16	+ *52*
	T	$f_{c,90,T}$	2%	**8.5**	2.7	16	**16.9**	5.1	16	+ *98*	**22.4**	5.0	16	+ *162*
		$f_{c,90,T}$	5%	**10.1**	2.6	16	**22.3**	7.1	16	+ *121*	**29.6**	5.0	16	+ *193*
		$E_{c,90,T}$		**775**	4.6	16	**1,359**	2.2	16	+ *75*	**1,883**	2.0	16	+ *143*
	R	$f_{c,90,R}$	2%	**14.1**	8.7	16	**13.1**	4.9	16	− *7*	**23.2**	6.4	16	+ *64*
		$f_{c,90,R}$	5%	**15.0**	10.7	16	**25.4**	8.5	16	+ *69*	**47.6**	2.8	16	+ *217*
		$E_{c,90,R}$		**1,658**	6.41	16	**670**	4.4	16	− *60*	**1,228**	6.2	16	− *26*
Ash	**L**	$f_{c,0}$		**33.0**	3.3	16	**53.9**	5.2	16	+ *63*	**62.4**	8.1	16	+ *89*
		$E_{c,0}$		**8,229**	14.8	16	**14,500**	17.4	16	+ *76*	**16,219**	22.3	16	+ *97*
	T	$f_{c,90,T}$	2%	**7.1**	8.6	15	**15.1**	10.1	16	+ *121*	**21.6**	6.7	15	+ *202*
		$f_{c,90,T}$	5%	**8.5**	8.0	15	**19.7**	10.5	16	+ *132*	**27.8**	6.8	15	+ *228*
		$E_{c,90,T}$		**612**	9.5	15	**1,339**	8.4	16	+ *119*	**1,963**	7.8	15	+ *221*
	R	$f_{c,90,R}$	2%	**8.0**	7.6	16	**7.5**	10.8	16	− *6*	**8.7**	8.9	16	+ *9*
		$f_{c,90,R}$	5%	**8.5**	3.4	16	**13.2**	17.7	16	+ *55*	**15.1**	17.6	16	+ *76*
		$E_{c,90,R}$		**1,244**	7.0	16	**396**	8.1	16	− *68*	**453**	6.8	16	− *64*

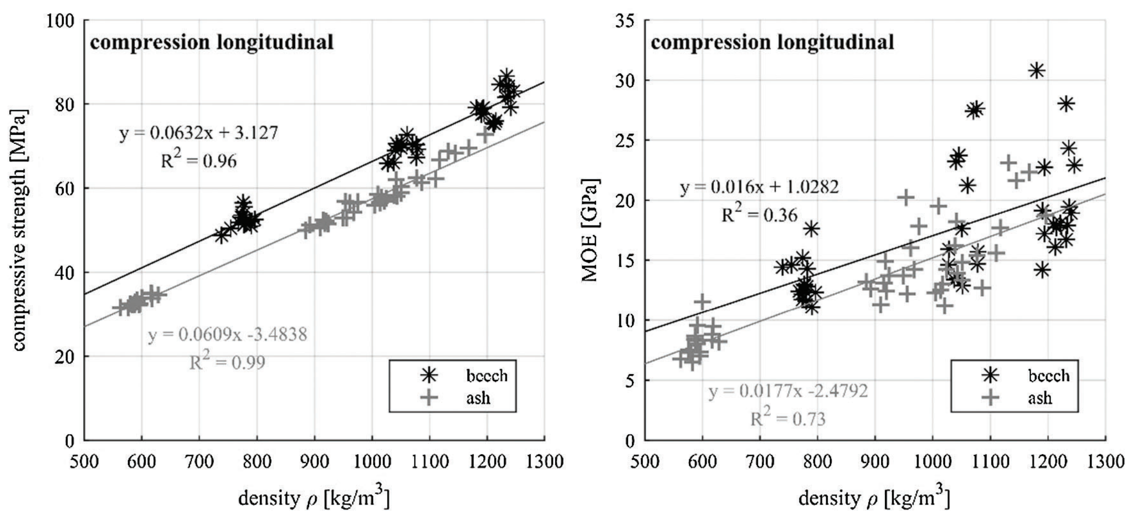

Figure 6: Compression strength (left) and MOE (right) parallel to the fibre (longitudinal) in relation to the density

3.2.2 Compression Perpendicular to the Grain: Tangential

The resulting MOE and compressive strength as a function of the obtained density for compression perpendicular to the grain, in tangential direction, are plotted in Fig. 7.

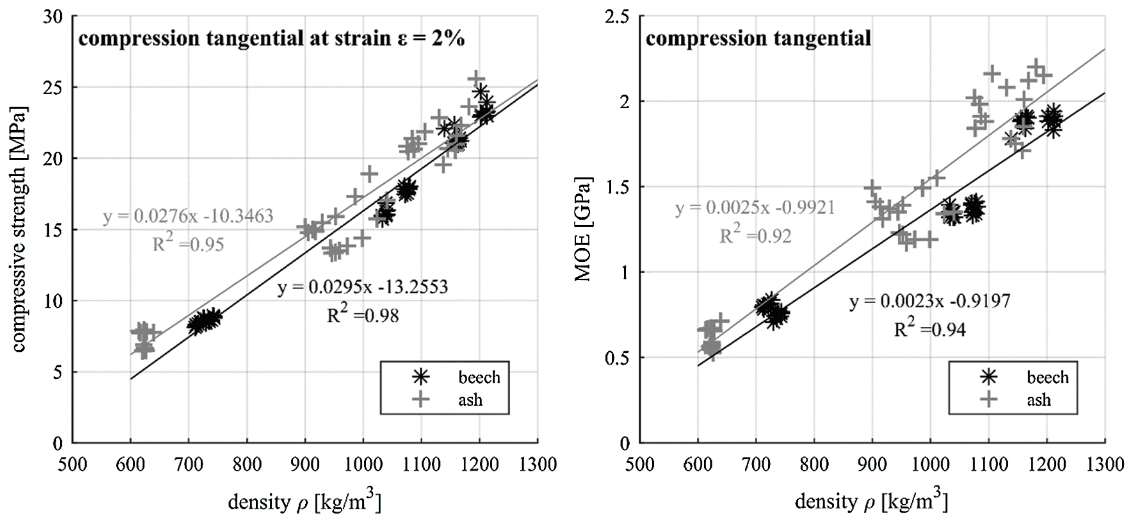

Figure 7: Compressive strength (left) and MOE (right) in tangential direction in relation to the density

Strength values for both beech and ash tripled by densification from native to 1.2 t/m^3. The MOE regarding tangential compression increased for beech from native to 1.2 t/m^3 by 143% and for ash even by 221%. The mechanical properties and the densities showed a very good positive linear correlation.

The material behaviour in tangential compression follows the same curve characteristic on all density levels (see stress-strain diagrams in Fig. 8 left). The improvement of tangential strength and stiffness is even higher than in the longitudinal direction. The radial densification deforms and damages the radial cell walls. This folding brings together the tangential cell walls that are more or less undamaged. The cross-section of densified specimens therefore contains much more tangential cell walls than the native specimen and the mechanical properties are higher.

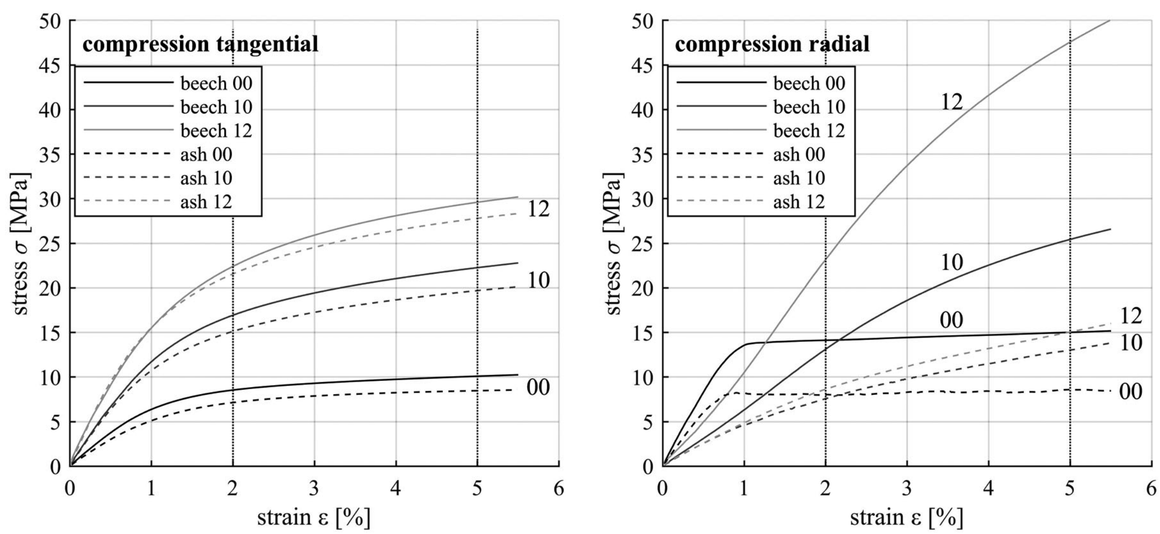

Figure 8: Stress-strain diagrams for compression perpendicular to the grain. Mean curves for densification levels 00 (native), 10 (1.0 t/m^3) and 12 (1.2 t/m^3)

3.2.3 Compression Perpendicular to the Grain: Radial

The stress-strain diagrams for the compression tests perpendicular to the grain are plotted in Fig. 8. The material behaviour regarding compression in the densified radial direction differs from compression in tangential direction significantly.

A reduction in stiffness is visible in the stress-strain diagram (see Fig. 8 right), where the slope of the native specimens for both beech and ash are steeper than the slopes of the densified specimens. The stress on the other hand increases continuously for the densified specimens whereas the native wood reaches its strength before 1% strain and then remains more or less constant.

The MOE does not relate to the density in a linear way (see Fig. 9 right); densification does not increase the stiffness of the material, it even decreases by 68% for ash and 60% for beech when densified from native to 1.0 t/m^3. Further densification to 1.2 t/m^3 however results in better results although the stiffness is still significantly lower than for native specimens. This effect is much more distinct for beech than for ash wood. [36] show a similar strong reduction of the MOE for radial compression of spruce wood that was however independent of the densification rate. In contrast, [8] measured about one quarter higher MOE values for 1.2 t/m^3 TM densified beech wood compared with native wood.

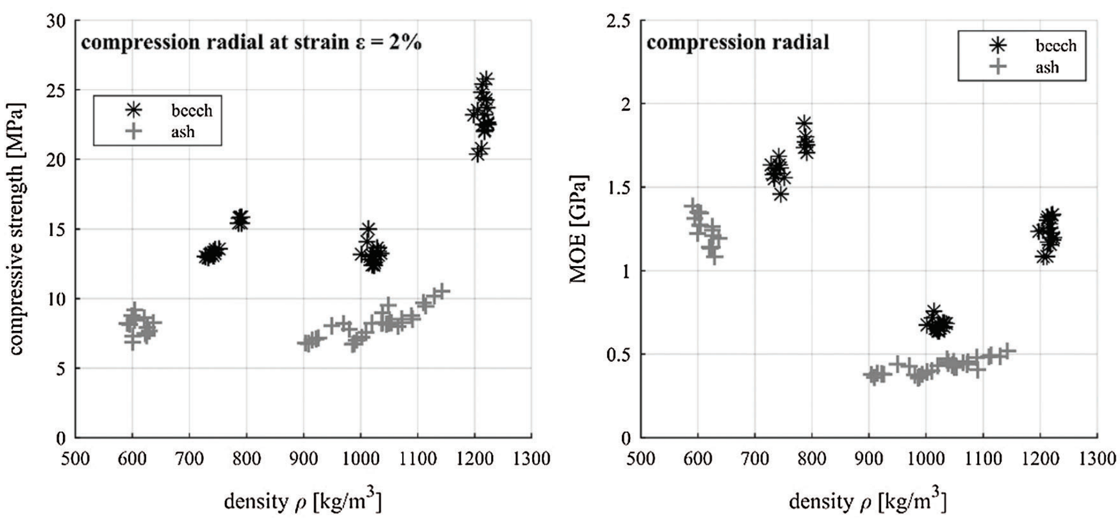

Figure 9: Compressive strength at 2% strain and MOE radial in relation to the density

Radial densification has an unchanged or positive effect on the radial compression strength if it is measured at 2% strain (see Fig. 9 left). In contrast, [34] show clearly reduced compression strength of densified wood compared to native wood. However, [34] measured the strength at the proportional limit, this means at a clearly lower strain level. At 5% strain, the densified beech and ash specimens of the own measurements can even absorb up to three times more stress than the native wood (Tab. 2) which is in accordance with measurements from [8].

The densified wood was in a subsequent step set to radial pressure, meaning that the board obtained in a first phase again the maximum deformation reached during the densification. The densified wood could easily take the same applied stress levels as the native wood, but the stiffness was immensely reduced due to the folding and subsequent damage of the radial cell walls. If the densification continues to more than 1.0 t/m^3, the strength and stiffness increase again.

Fig. 10 shows representative curves of single native specimens for both species. As mentioned above, the native specimens reached their yield strength at around 1% strain and then deform plastically. The

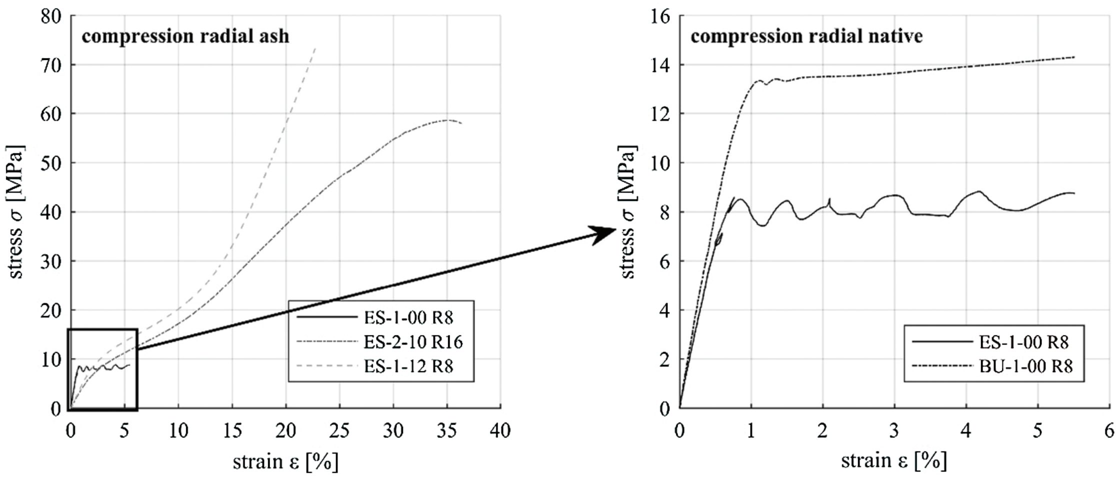

Figure 10: Stress-strain curves of individual specimens from the compression tests in radial direction. Comparison of the three density levels of ash (left), enlarged for the native specimen and compared with native beech (right)

difference between the two wood-species however is crucial: beech has a diffuse-porous structure; the strengths of early and late wood are similar. The plastic deformation of the native beech subjected to radial compression is uniform, the corresponding stress-strain diagram curve straight. On the contrary, ash shows wavelike stress-strain curves in the plastic phase. The reason for this is the ring-structure of the pores, which leads to a substantially weaker zone in the early wood near the annual rings. Subjected to compression, ash wood collapses ring by ring. The weakest early wood ring collapses first. Then, as soon as the cell walls are pushed together and thus lead to a higher stiffness, the load increases until the next early wood ring gives in and so forth.

The radial compression tests were conducted until 5.5% strain, but none of the specimens broke. After load release, they returned nearly to their previous shape. Therefore, some tests with ash specimens were continued until failure. These elongated tests showed that the ductility of radial densified ash samples is enormous; the maximum obtained deformation (specimen ES-2-10 R16) was 37.4% of strain until the specimen finally yielded.

3.3 Tension Tests Perpendicular to the Grain

The results of the performed tension tests are summarised in Tab. 3. Mean values $\bar{x}$, coefficient of variation *CoV* in percentage and number of specimens *n* are given for reference density 00 and the densification levels 10 and 12. The highlighted columns give the change in values compared to the reference density.

The material behaviour for native and densified beech and ash specimens under tangential and radial tension is displayed in stress-strain diagrams with the mean values per specimen group (Fig. 11).

3.3.1 Tension Tangential

The stress-strain curves for tension tangential to the grain is similar to the curves for compression perpendicular to the grain: the material behaviour of all specimen groups is determined by an approximately linear-elastic phase until around 0.2% strain, followed by the transition to a more plastic behaviour with reduced stiffness.

Fig. 12 displays the relation between the tensile strength/MOE and density under tension in tangential direction. Both strength and MOE increased with increasing density. The linear correlation for both MOE and

Table 3: Properties of native and densified beech and ash in tension

Tension			00			10				12			
			611 kg/m³			960 kg/m³				1096 kg/m³			
			$\bar{x}$ *[N/mm²]*	*CoV [%]*	*n [-]*	$\bar{x}$ *[N/mm²]*	*CoV [%]*	*n [-]*	[%]	$\bar{x}$ *[N/mm²]*	*CoV [%]*	*n [-]*	[%]
Beech	**T**	$f_{t,90,T}$	8.6	9.9	15	12.0	9.6	15	+ *41*	13.7	4.5	14	+ *60*
		$E_{t,90,T}$	747	9.7	15	1,089	12.0	15	+ *46*	1,217	16.2	14	+ *63*
	R	$f_{t,90,R}$	17.6	12.3	14	9.6	7.3	14	− *46*	8.9	8.8	14	– *50*
		$E_{t,90,R}$	1,774	10.29	14	480	17.9	14	− *73*	499	30.1	14	– *72*
Ash	**T**	$f_{t,90,T}$	7.5	28.3	15	17.0	3.9	15	+ *128*	18.6	3.2	14	+ *149*
		$E_{t,90,T}$	826	17.9	13	2,017	9.4	15	+ *144*	2,569	10.1	14	+ *211*
	R	$f_{t,90,R}$	13.2	10.4	15	4.4	6.6	15	− *67*	4.1	8.2	13	– *69*
		$E_{t,90,R}$	1,516	7.0	15	289	23.2	9	− *81*	355	24.2	6	– *77*

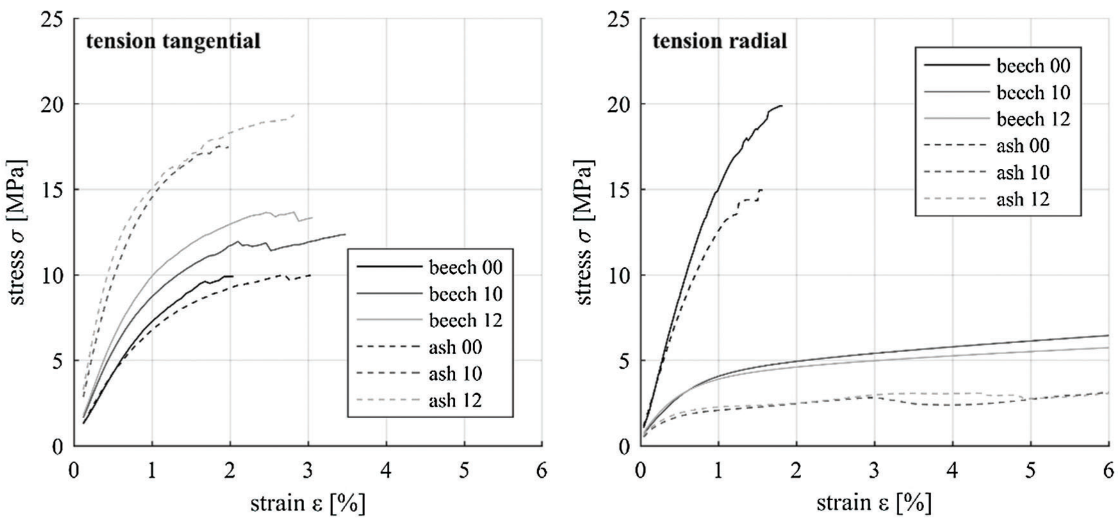

Figure 11: Stress-strain diagrams for tension perpendicular to the grain. Mean values for densification levels 00 (native), 10 (1.0 t/m³) and 12 (1.2 t/m³)

strength was better for ash than for beech. The values for the native specimen scatter significantly because the strength was defined as the maximum reached stress. The tensile strength of densified ash improves from native to 1.2 t/m³ by 249% and the MOE by 311%. The effect of densification was not so significant on beech: strength increased by 60% and the MOE by 63%.

3.3.2 Tension Radial

The material behaviour in radial tension greatly depends on the densification just like the material behaviour in radial compression. Native specimens behave very brittle: After a very stiff linear-elastic phase, both native beech and native ash failed at less than 2% strain. Densified specimens on the other hand approached the linear-elastic, ideal-plastic behaviour. The linear-elastic phase of the densified wood reached a yielding point at much lower tensile stress than the failure strength of native wood, after which

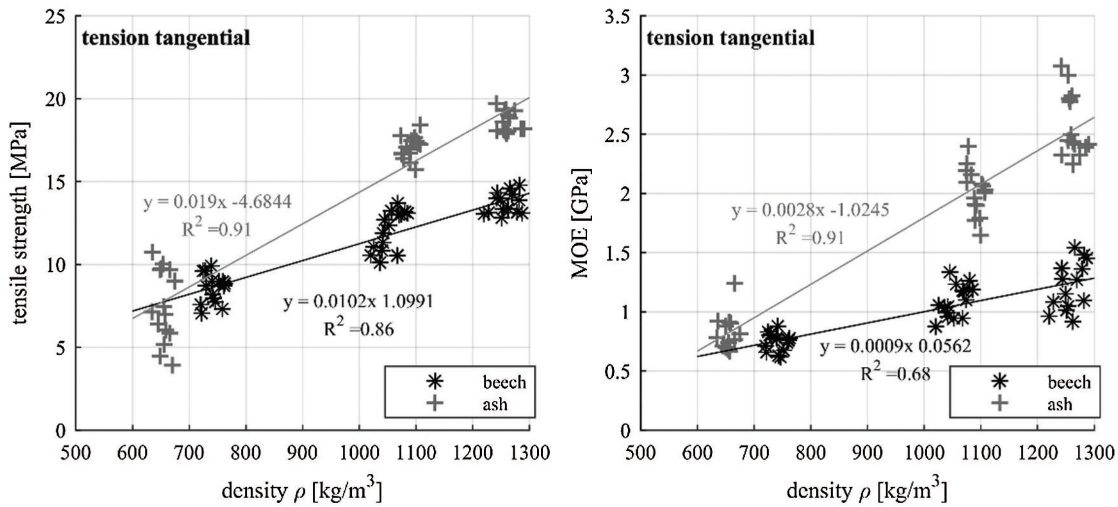

Figure 12: Tensile strength (left) and MOE (right) in tangential direction in relation to the density

the tensile load led to a reversion of the densification. The compressed cell structure was pulled apart in a prolonged, ductile manner until failure. The difference among the wood species in this pulling apart action was due to the porosity of the wood: diffuse-porous beech showed a smooth plastic deformation, whereas ring-porous ash wood was pulled apart annual ring by annual ring and produced an undulating curve in the plastic phase (see Fig. 11 right).

The effect of density on the strength and MOE in tension radial are shown in Fig. 13. Radial densification significantly reduced the stiffness of both beech and ash. Thereby, the achieved densification level was of no importance. The linear relation is therefore not given. Radial densification also weakened tensile strength rapidly by factors in the range of 2 up to 3 for a densification from native to 1.2 t/m^3 density.

The material behaviour under tension in the densified radial direction was similar to the material behaviour under compression in radial direction: the cell structure in radial direction was irreversibly damaged and thus lowers the stiffness. Other than in compression, strength was also lost.

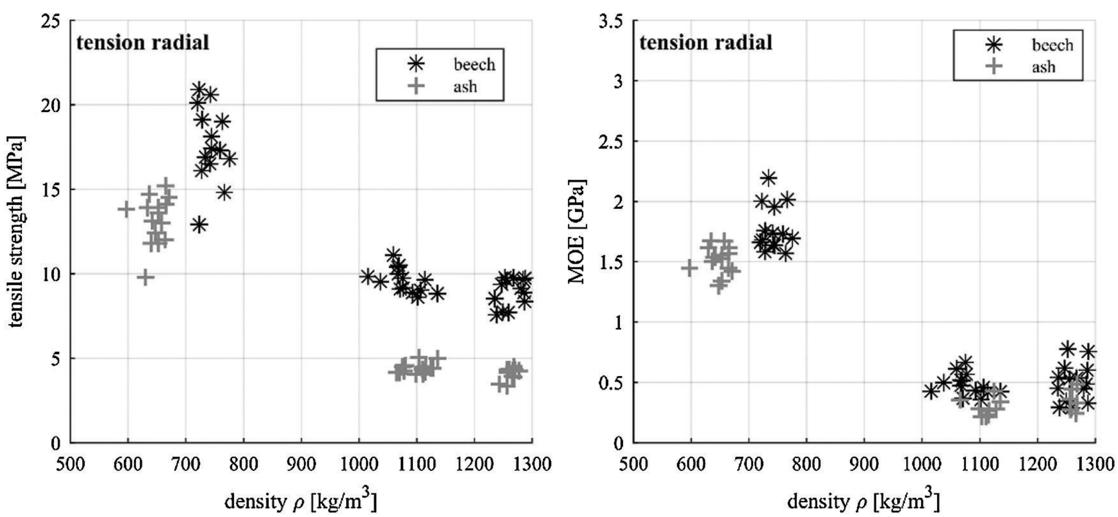

Figure 13: Material behaviour under tension in radial direction in relation to the density

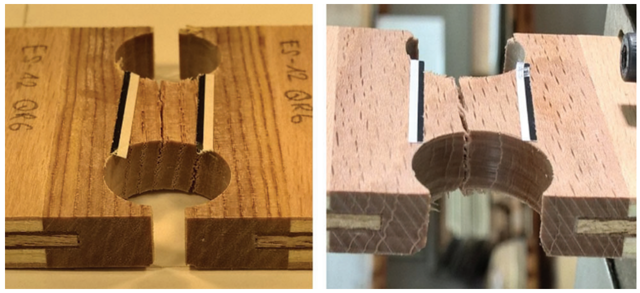

Figure 14: Failure pattern for tension in radial (left) and tangential (right) direction

Failure in tangential tension occurred along the wooden rays, failure in radial tension along the annual rings (Fig. 14.).

3.4 Life Cycle Assessment

The results of the LCA under three potential transport distances are presented in Tab. 4. The results for the contribution analyses are presented alongside. The table shows that the environmental impact of densified wood is mainly driven by the preparation of the raw material with around 52% to 67% followed by the transport of the material from 14% to 32% contribution.

Table 4: LCA and contribution analyses

		Contribution to the environmental impact			
Transport distance	kg CO_2eq	Sawnwood, kiln dried, planed	Electricity, high voltage, CH	Transport, lorry 16 t–32 t	Wooden board factory
Min (100 km)	**262.2**	66.8%	19.0%	14.1%	0.15%
Med (152 km)	**281.4**	62.3%	17.7%	19.9%	0.14%
Max (288 km)	**331.5**	52.8%	15.0%	32.0%	0.12%

These results show that an increase of the proposed transport distance from 100 km (Min) to 288 km (Max) would result in 26% higher emission. Moreover, once this threshold is passed, the contribution to the total environmental impact from the transport of raw materials increases from 14% to 32%. At this level the environmental impact associated to the transport of the material is higher than those impacts associated to the densification process.

Tab. 4 shows that the contribution from manufacturing process and type of electricity mixture used on these processes are of great relevance. Within the manufacturing process, the energy used in the debarking and sawing contribute the most emissions, around 30% of the total. This means that the environmental impact of densified wood products can be improved by either optimising the manufacturing process of the wood raw materials, using low energy drying processes, or a renewable energy source to drive these processes. Finally, the contribution from electricity is directly related to the type of electricity mixture used. In the case of Switzerland, the major amount of emission comes from the generation of electricity from fossil fuels and nuclear sources. In the current process, most electricity is consumed in the generation of heat as presented on Tab. 4. Thus, in order to improve the environmental performance of the process, an alternative source of heat and/or electricity could be used.

4 Conclusions and Outlook on Structural Application Possibilities

Densification of beech and ash wood was performed with high mechanical pressure in a heated press in a procedure lasting for approximately 3 h–3.5 h. The target densities 1.0 t/m^3 and 1.2 t/m^3 could be reached for both species. Wide scattering in the density results and large spring-back after the densification of the first four ash boards led to an alteration of the process for ash, which could reduce both issues.

An extensive mechanical characterisation was carried out. Densification of beech and ash wood in radial direction increases strength and stiffness properties in the non-densified directions (longitudinal and tangential) significantly. The improvement of the mechanical properties reaches values of up to 217% for beech and up to 228% for ash when densified to 1.2 t/m^3. In general, the mechanical properties correlate with the density, whereby the linear relation with strength is very accurate with R-square values up to 0.99 (for ash in longitudinal compression). The relation between density and MOE displays very wide scattering in some cases (ash in longitudinal compression).

On the other hand, the mechanical properties of the hardwood deteriorates in the densified radial direction. Both under compression and under tension, radial densified wood loses significantly in stiffness. Strength properties depend on the loading: radial compressive strength increases especially for high strains, whereas radial tensile strength is reduced significantly. In both loading conditions, radial densified hardwood has become a very ductile material.

The further investigations on the environmental impact of the densification process executed in a LCA adapted for Switzerland show that the densification process does not account for a large share of emissions in the whole manufacturing process. The drying of the raw material and the transport weigh more heavily. However, to lower the environmental impact of the densification process itself, the energy used for the heating of the press should be generated from renewable sources.

The results of this study are promising for the greater use of hardwood and wood in general in different application fields where high loads are expected. The mechanical properties of beech and ash hardwood clearly improve by densification using the TM-treatment. The substantially higher strength and stiffness offer a range of opportunities for problems in structural timber engineering.

Dimensions of columns or trusses, which encounter compression parallel to the grain, can be chosen more slender. A column made out of beech densified to 1.2 t/m^3 can take up 3.6 times higher loads than the same column made out of spruce and 1.7 times higher loads than the same column made out of beech. However, the production of densified wood can only be economically if industrialised. For now, market-ready products like BauBuche (beech laminated veneer lumber), are the better option for large building components, especially since they reach similar strength values in compression parallel to the grain. More efficient is the use of densified hardwood as local reinforcement. Compression and especially tension perpendicular to the grain is often avoided in timber structure design due to the weak properties of softwood in that direction. The amazing strength values of compression and tension perpendicular to the grain and the shear strength determined in this study cannot be reached by BauBuche. Purposefully deployed densified hardwood can solve problems wherever timber is loaded perpendicular to the grain. A load application plate made out of densified beech for instance in the area of column-to-beam connections allows again smaller cross-sections of the column. Another application are areas with tension perpendicular to the grain such as notches, openings or transverse connections. External reinforcements out of densified wood could be a better option than corresponding steel components, which are detrimental in case of fire. Furthermore, substituting steel junction plates and dowels in connections with densified hardwood could bring a huge benefit regarding fire safety [37] and enable structures purely made out of wood.

The reduction of strength and stiffness regarding compression and tension in the densified radial direction has to be considered carefully in the design process and especially in the installation of densified wood. Apart from the reduced strength and stiffness, the observed ductility of densified ash in both compression and tension and of densified beech in tension is remarkable. Ductile wood—not only in the TM-process to form wood into furniture or profiles as presented by [38], but also in the long-term state after the process—may find its implementation.

The problem of set-recovery is major issue for densified wood in general. Set-recovery can be controlled to some extent by the pressing procedure and also by the climatic conditions (dry state, low temperatures). For structural applications, densified wood should be used in indoor climate (service class I), where moisture change is limited. Service class I is given for many of the above mentioned applications as reinforcement components. However, further attention should be brought to this issue to guarantee a safe usage.

The use of densified beech and ash wood opens new possibilities in structural and non-structural fields likewise. The immense enhancement in the mechanical properties can be obtained in a process low in emissions. The densification of local hardwood can substitute energy wasting and ecologically harmful steel parts and release pressure in diminishing sources like tropical wood.

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