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Mechanical properties of compressed wood

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A B S T R A C T

Wood is a natural composite material. One the strength of wood is its good ratio of mechanical properties with respect to density, which can be further improved by densification technology. Compressed Wood (CW), with superior mechanical properties, could be utilised in timber products and timber connections as an alternative to energy-intensive adhesives and metals. However, the limited literature available on the mechanical properties of CW makes it chanllenging to utilise them in the development of new products and structures. To address this issue, this paper presents a comprehensive test programme and an extensive database of CW materials. It includes experimental results of over 720 material tests that were conducted on CW materials. The fundamental tests under compression, tension, bending, embedment, yield moment, shear and impact tests were undertaken. The results obtained from this study will help engineers utilise more CW to develop new products and connections. The results are also compared with the characteristic values of solid wood from the literature. As the densification of wood significantly improves strength and stiffness, this work will contribute towards the substantial uptake of CW in the building and construction industry with great benefits to the environment.

1. Introduction

The construction sector has a significant impact on the environment and climate, as material and energy resources are consumed and greenhouse gas emissions are produced in the manufacturing of building materials, as well as in the planning, construction, operation, and demolition of buildings. Building and construction are responsible for 39 % of all carbon emissions in the world [1]. In light of the issue of climate change and environmental problems, it is therefore important to reduce the carbon footprint and embodied energy of construction materials used in buildings and infrastructure, over their entire life cycle. As a result of some of these environmental challenges, more sustainable engineered wood products (EWPs) are increasingly being developed [2] and optimised for structural applications as an alternative to conventional building materials such as steel and concrete.

Among EWPs, the use of mass timber products is increasing rapidly. The term mass timber products refer to EWPs with large section sizes comprising timber lamellas, which are glued or mechanically fastened using adhesives or metallic connectors. The common examples are Cross-laminated timber (CLT) and glued laminated wood. According to UNECE/FAO Forest Products Annual Market Review 2018–2019 [3], the production of CLT alone is expected to double by 2020 compared to that in 2018 in Europe.

Although there is a rising demand for EWPs, nevertheless, there are concerns over the increasing use of synthetic adhesives and metallic fasteners in production and assembly processes [4,5]. The synthetic adhesives and metal fasteners compromise the sustainability credentials of these products. More specifically, their predominant use (e.g. Urea-formaldehyde (UF)) in EWPs is harmful to the environment due to the possible emission of toxic gases (e.g. formaldehyde and Volatile Organic Compounds (VOCs)) [6,7]. Also, products with synthetic adhesives and metallic components are difficult to recycle at the end of the service life. This requires an alternative way of production and assembly of EWPs, possibly a complete wood solution with a limited or without the use of synthetic adhesives and metals. Therefore, it may be favourable to develop all-wood solutions to produce EWPs without using any metal

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and synthetic adhesives.

Compressed wood (CW) is produced by thermo-mechanical compression resulting in a substantial increase in its mechanical properties and also an increase in its competitiveness compared to other structural materials. CW is produced by compressing wood through a high temperature compression process to enhance the mechanical and physical properties. By doing so the pore volume decreases and therefore, its density and other related properties increase [8,9,10]. By appropriate compression, the following properties can be improved [11,12] dimensional accuracy, surface hardness, elastic modulus, and shear strength.

In addition, recent studies have shown that CW can be used as alternatives to metallic fasteners and synthetic adhesives, in timber-to-timber connections and EWPs [13]. However, in the literature, the use of wood fasteners in practice is limited due to scarce information on their mechanical properties. Furthermore, Sotayo et al., [14] recently reviewed the processing conditions and mechanical properties of CW in the literature and highlighted the significant potential of using low-density wood in more advanced and diverse structural applications.

Therefore, this paper aims to create a database on the structural and mechanical properties of CW and CW connectors. Comprehensive experimental work was carried out at four institutions University of Liverpool (UOL), National University of Ireland Galway (NUIG), Technical University of Dresden (TUD) and University of Lorraine (UL), as part of a European Project called Adhesive Free Timber Buildings (AFTB) [15]. This work provides information on mechanical properties for bending, compression, tension, embedment, double shear, yield moment and impact tests that will help engineers and researchers to design and develop more sustainable and environmentally friendly products and structures.

2. Materials and methods

2.1. Compressed wood (CW)

Wood can be compressed in two of the three main directions (i.e. radial and tangential directions). In contrast, compression of wood in the longitudinal direction leads to severe damage and reduction in strength. When compressed in the tangential direction, the early and latewood cells are pushed into each other and zigzag patterns are formed, as shown in Fig. 1b [16].

However, if the compression takes place in the radial direction, only the earlywood cells are compressed. Therefore, compression in the radial direction is common and typically provides the best results, as shown in Fig. 1c.

Compression of wood typically takes place in a hot press with a constant displacement rate at a high temperature (120 – 160 °C). After pressing, if the press is opened immediately, the CW will spring back partially or return to its original shape. To avoid this, the specimen needs to be cooled down to below 80 °C in the compressed state. Subsequently, and if necessary, post-treatment can limit this effect to ensure dimensional stability. Recovery describes the property of CW to achieve partial or full recovery of its original dimensions when exposed to water or high humidity. This effect is called shape memory. In this project, to avoid springback of the CW, the spciemens were cooled down to 40 °C after compression to reach a stable dimension.

Fig. 2 shows the scanning electron microscope comparison between normal wood and CW.

The compression process is influenced by several factors such as temperature, species, the orientation of annual rings, degree of compression (or compression ratio) and post-treatment.

In this paper, the compression ratio is defined as the percentage reduction in the sample dimension in the radial direction per its initial value. Depending on the type of wood, the compression ratio is varied from 50% (for hardwood species) to 68% (for softwood species). The direction of compression in this research is always in the radial direction. The compression ratio (CR) is calculated using Eq. (1):

$$C_R = \frac{t_0 - t_{comp}}{t_0} \times 100\% \quad (1)$$

With:

t_0 Thickness before compression (in compression direction)

t_{comp} Thickness after compression (in compression direction)

The pressure is adjusted depending on the desired degree of densification. Also, the type of wood and consequently the pore content can affect the necessary pressure. To be able to use the specimens for load-bearing application, pressure and speed must be controlled in such a way that the cell structures are not irreversibly damaged for load-bearing application.

In this project, the samples were manufactured in the laboratory (A and C) and industry (B) settings which consequently affect the material properties. This is because in the laboratory setting, wood has been compressed only in the radial direction. However, this was not the case for the industry setting, several planks were arranged in the press, which did not show a uniform orientation of annual rings.

In the laboratory C setting, the shaping of the compressed wood into

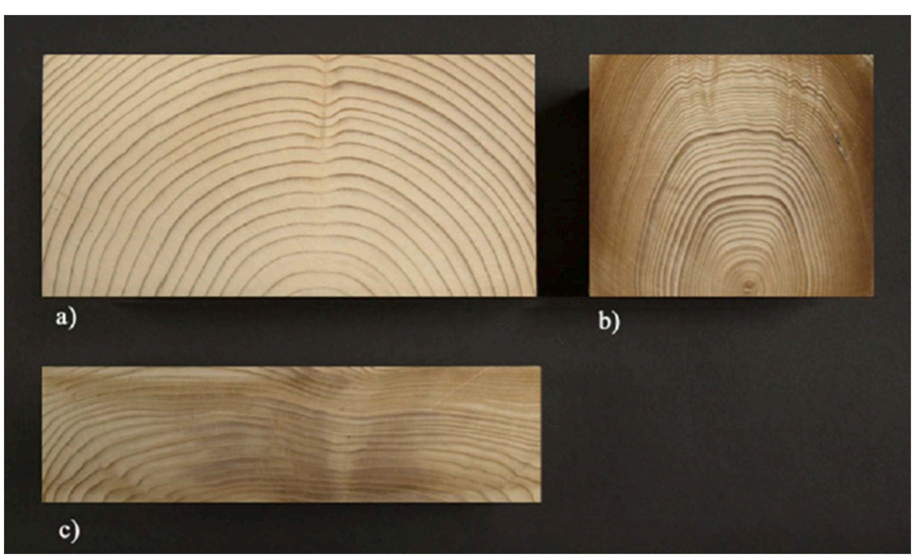

Fig. 1. a) Uncompressed Spruce, b) Compression in the tangential direction and c) Compression in the radial direction [9].

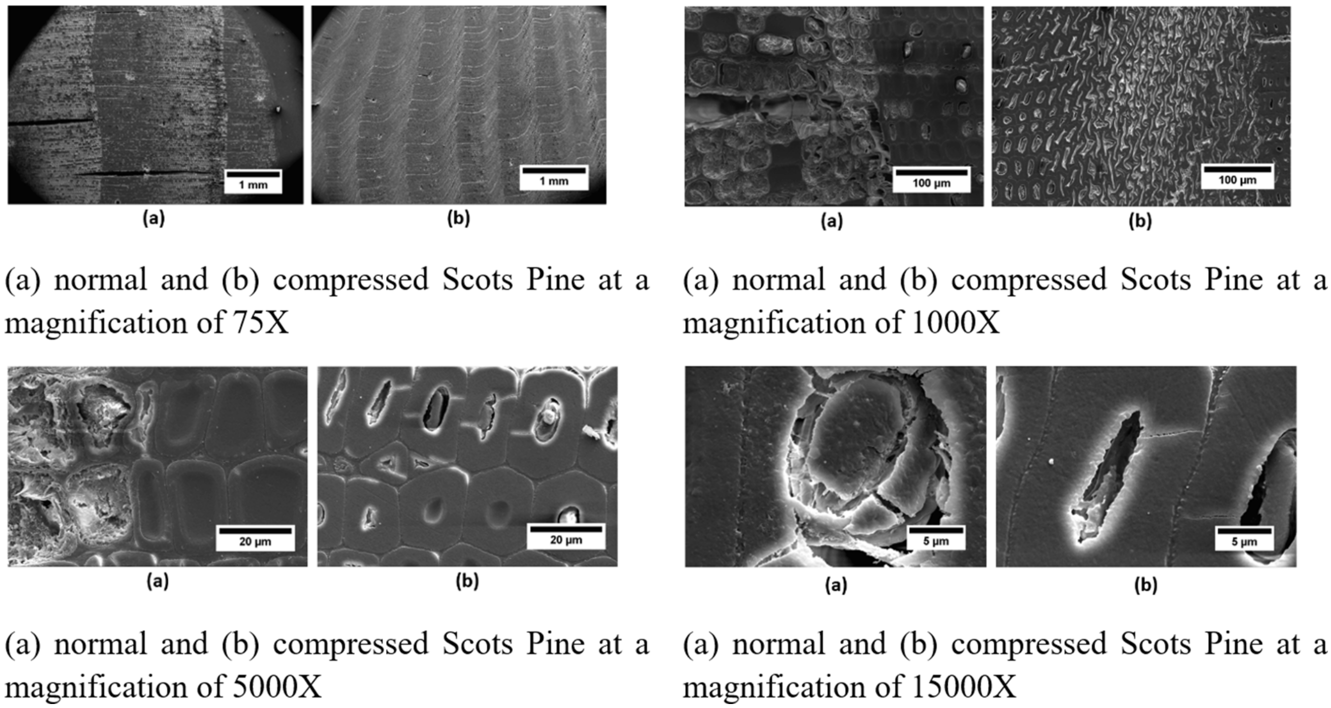

Fig. 2. Scanning electron microscope images of the Scots pine cross-section.

dowels has been performed in one step. In the A and B settings, compressed dowels were formed out of the CW planks. Fig. 3 shows the different in the manufacturing setups.

2.2. Methods

The experimental program included 23 test series with over 720 specimens. For each test series the average, standard deviation and 5% quantile according to EN 14,358 [17] (based on a sample) were calculated.

The tests were checked in design and execution for conformity with the standards for two reasons

Firstly, to draw conclusions about the comparability in the analysis of the material characteristics. Secondly, to be able to explain any differences between the test series. In Table 1, standards which have been used are shown.

Since the tests have been carried out on different wood species, the results were divided into softwood and hardwood categories. In this

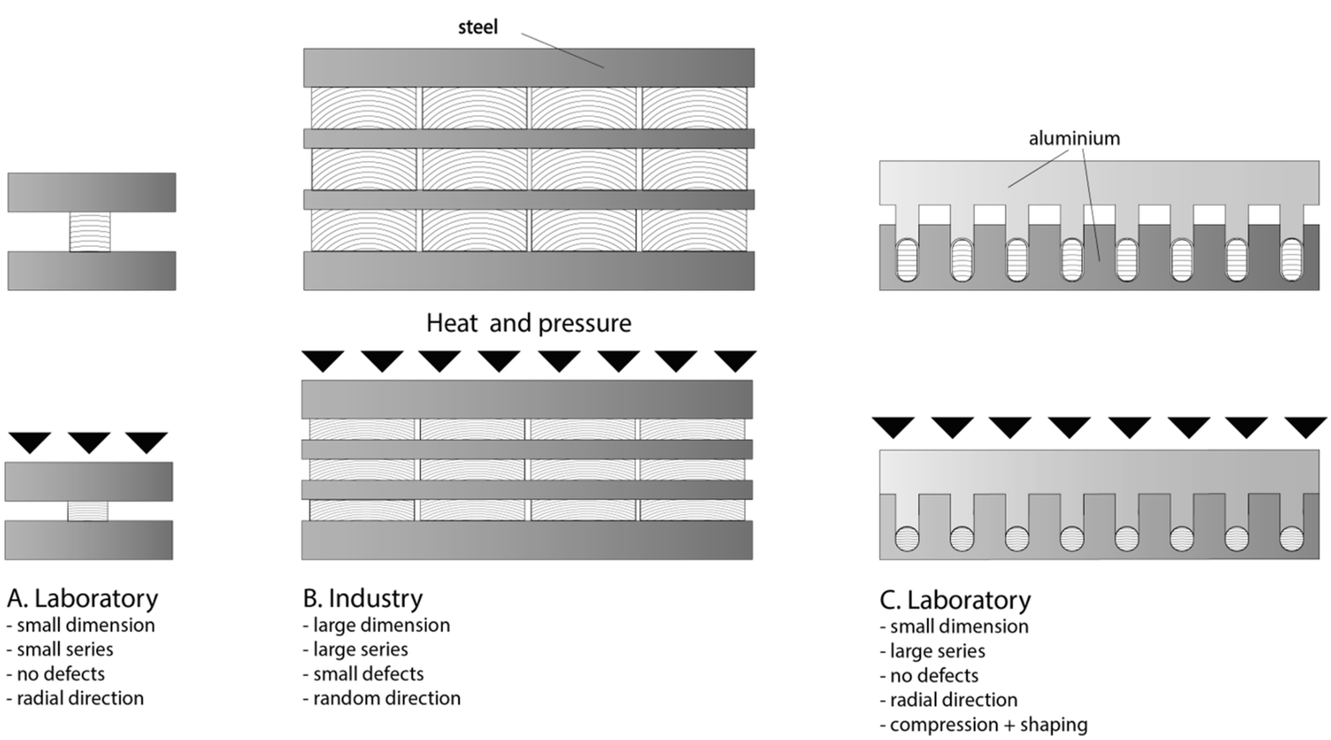

Fig. 3. Different manufacturing setups for compressed wood production.

Table 1
Standards used for experiments.

Type of test	Orientation	Number of replications	References
Compression	longitudinal	30	CEN EN 408 [18]
	radial	100	
	tangential	30	
Tensile	parallel	35	CEN EN 408
Bending		155	
Embedment	parallel	25	CEN EN 383 [19]
	perpendicular	25	
Yield moment		30	ASTM D4475-02 [20]
Push-out shear		120	CEN EN 26,891 [21]
Charpy test		150	DIN 52189–1 [22]

paper, the results for all test series are presented, analysed and compared with the literature.

3. Results

3.1. Compression tests

Test standard EN408 requires a full cross-section for the test specimen, the length of which measures 6 times the smaller cross-sectional dimension [18]. However, due to manufacturing constraints, it was not always possible to get CW specimens with dimensions that followed the test standard's requirements.

3.1.1. Compression tests in the longitudinal direction

The coefficient of variation of the mean values for the compressive strength of compressed hardwood are below 30 % and for compressed softwood slightly over 30 %. The coefficient of variation of the mean values for modulus of elasticity, on the other hand, are 66 % for normal softwood and 84 % for compressed softwood. This means that they require a more detailed analysis the comparative diagrams of the parallel to the grain compression tests confirm this, as shown in Fig. 4.

The stiffness of compressed pine differs significantly from that of the compressed spruce. This is presumably due to the different wood species and test specimen geometry since the test specimens of the series carried out at UOL were following the standard EN408, i.e. with a length that measures 6 times the smaller cross-sectional dimension (60 mm × 10 mm × 10 mm). The length of the UL test specimens, on the other hand, only corresponded to three times the smaller cross-sectional dimension, namely 60 mm × 20 mm × 20 mm and therefore, did not fulfil the requirements of the test standard.

The mean strength of normal spruce wood is reported as 40.2 MPa by Niemz and Sonderegger [23]. The mean value of normal softwood in the current study is of the same order of magnitude at 47.3 MPa. The mean strength of compressed softwood is 102.5 MPa, which is close to the value of 108 MPa determined by [9] for 50 % compressed spruce wood. A value of 10000 MPa for modulus of elasticity of normal spruce wood and 11000 MPa for normal pinewood have been reported [23]. For compressed softwoods, the compressive strength increases by 1.15 times in the parallel to the grain direction, by 16.30 times in the radial direction and by 4.7 times in the tangential direction, in comparison to uncompressed softwood. For hardwood, the increase in compressive strength is 2.2 times in the radial direction and 2.70 times in the tangential load direction.

3.1.2. Compression tests in the radial direction

The strength for compressed softwood with a CR of 50% is 10.6 MPa. Fig. 5 represents the average stress–strain diagram for compression in the radial direction for each test series.

For compressed softwood, the compression strength in the radial direction is 58.9 MPa with a coefficient of variation of 68 %. The high degree of spread is mainly due to the high compressive strength from the UL test series with a value of 98.6 MPa. This value is twice as large as one reported by the UOL, whereby both test series were carried out with the same specimen geometry. According to the findings of Skyba et al., [24], the compressive strength for high-density spruce wood in the radial direction is 68.7 MPa (for 70 % compressed spruce wood radial for the grain direction). The mean of the elastic modulus of compressed softwood is adjusted by excluding the results of the test series of the TUD (470.8 MPa) since the value is significantly below that of the other test series.

3.1.3. Compression tests in the tangential direction

As seen in Fig. 6, the average compressive strength of 4.0 MPa for normal softwood Spruce is obtained. The mean modulus of elasticity for the normal softwood is 183 MPa and thus deviates from the literature value of 450 MPa according to Niemz et al., [23], but the value almost matches with 200 MPa from [9]. Similar to the radial compression tests, it is assumed that the literature values of both sources are representative.

The mean compressive strength of the test specimens made of normal hardwood is comparatively high at 14.1 MPa compared to the value of 9.0 MPa according to Niemz and Sonderegger [23]. The compressive strength of compressed beech wood in the tangential direction is 52.0 MPa, which is around 10 MPa higher than that in the radial direction

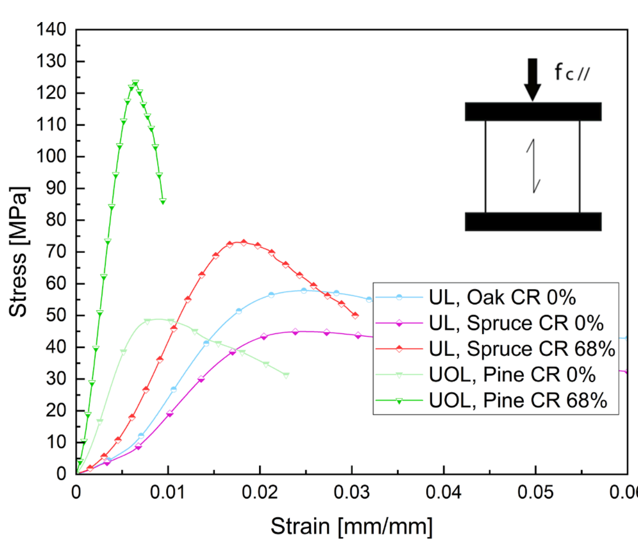

Fig. 4. Average stress–strain compression test curves in the longitudinal direction.

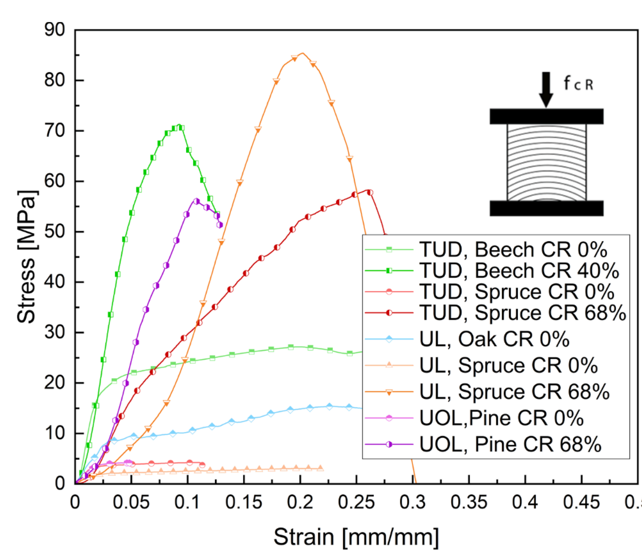

Fig. 5. Average stress–strain compression test curves in the radial direction.

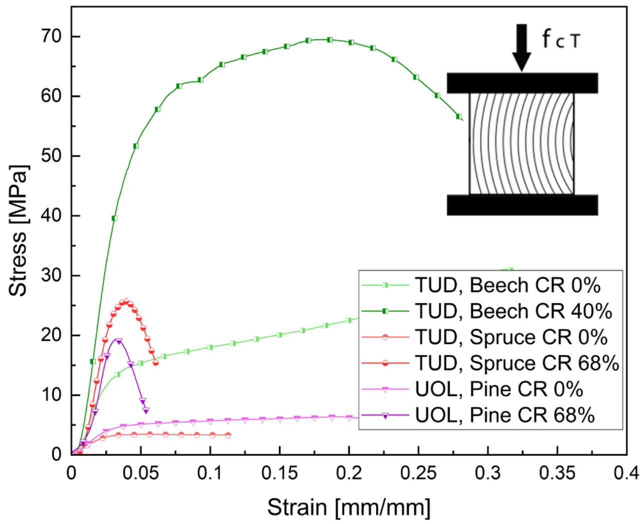

Fig. 6. Average stress–strain compression test curves in the tangential direction.

with the same degree of compression. The value is close to that from Skyba et al., [24], published on the compressive strength in the radial direction. The mean modulus of elasticity (tangential) is also higher than that in the radial direction and agrees with the values determined by Skyba et al., [24].

3.2. Tensile tests

The tensile strength parallel to the grain of compressed softwood is doubled in comparison to that of normal spruce. The tensile strength for the compressed hardwood is 1.4 times that for the normal wood. The modulus of elasticity of CW increases by 1.9 times for softwood and 1.6 times for hardwood in comparison to the normal wood counterpart. Fig. 7 shows the corresponding average stress–strain curves for tension parallel to the grain. The diagram clearly indicates the deviations between the results from UL and TUD for spruce wood.

These are presumably due to the different specimen geometries. According to the standard [18], a tensile test parallel to the grain requires a constant cross-section with a length of at least 9 times of the cross-sectional dimension. It was not possible to produce CW test samples according to the standards due to manufacturing restrictions. Therefore, the institutions chose different sizes to overcome this issue.

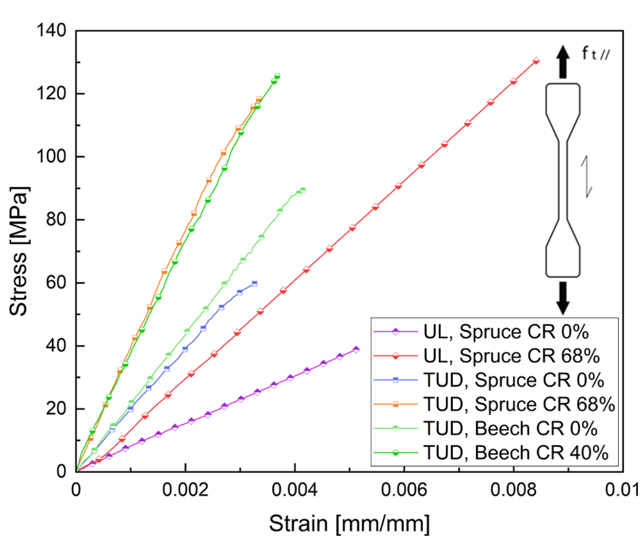

Fig. 7. Average stress–strain curves for tension parallel to the grain.

For the tests on normal softwood, the average strength was 51.0 MPa with an associated coefficient of variation of 34%. Niemz & Sonderegger specified a tensile strength of 87.2 MPa for spruce wood [23]. Haller and Wehsener [9] stated 73 MPa as the tensile strength of normal spruce wood. Due to the deviation of the mean value from the literature by around 36 and 22 MPa respectively, the tensile strength from the TUD test series is used in Table 2.

3.3. Bending tests

The bending strength of compressed softwood is increased by 2.45 times compared to uncompressed softwood. Similarly, the bending strength of compressed hardwood is twice as high as that of normal hardwood and is around 30 MPa higher than that of compressed softwood, as shown in Fig. 8.

The flexural modulus of elasticity is increased by a factor of 1.8 for compressed softwood and by a factor of 2.5 times for compressed hardwood. The mean flexural modulus of elasticity of compressed softwood is 2500 MPa higher than that of compressed hardwood.

The bending strength of spruce, Douglas fir, pine and hemlock are between 75 and 100 MPa according to [23] and [25]. The mean value of 97.1 MPa for the test series agrees with the literature values. These two references indicate that the elastic modulus for the same types of wood are between 10,000 and 13000 MPa, which is in good agreement with the average of the test series at around 11000 MPa. The bending strength of normal hardwood is 151.2 MPa on average and has been determined on beech wood test specimens.

3.4. Embedment tests

The size of the specimens for normal wood subjected to embedment loading parallel and perpendicular to the grain is in accordance with the standard EN383 (2007) [19]. However, the dimensions of CW specimens had to be adapted due to the limited thickness and width of the CW material available. The width of the CW specimens used for parallel and perpendicular to grain direction was half (5d = 50 mm) of the width required by the standard (10d = 100 mm). The length of the CW specimen tested in perpendicular to the grain direction was 50 mm shorter than that specified in the standard. However, the length of CW specimens tested in parallel to the grain direction was compliant with the requirement of the standard. Fig. 9 represents the average load–displacement curves for the embedment test.

The mean embedment strength of the CW specimens parallel and perpendicular to the grain was approximately 4 and 5 times higher than that of the normal softwood in the corresponding directions. The embedment strength of CW specimens was similar in both parallel (221 MPa) and perpendicular (218 MPa) to the grain directions. This may be attributed to less variation in the density distribution in a unit volume of CW resulting from the compression process. The embedment strength of the normal softwood was about 11 MPa higher in the parallel to the grain direction than the perpendicular direction.

The mean embedding modulus of CW specimens in parallel and perpendicular to the grain direction was approximately 2 and 4 times higher than that of the normal softwood in the corresponding directions. The embedding modulus of normal softwood tested parallel to the grain was 3 times higher than the specimens tested in the perpendicular direction. For CW specimens, the embedding modulus was 1.5 times higher in parallel to the grain direction than perpendicular.

The availability of embedment strength data on CW specimens is relatively scarce in the literature. Thus, the test results obtained were compared with high-density Densified Veneer Wood (DVW), which is a commercial product [26]. The embedment strength of CW was approximately 1.13 and 1.10 times higher than those of the DVW tested by Palma et al., [26], respectively. When the suitability of Eurocode 5 empirical formulas [27] was assessed to estimate the embedment strength of the CW specimens, it was found that Eurocode 5

Table 2
Material properties of CW.

	Parameter	Unit	Softwood		Hardwood	
Compression ratio			0 %	**60–68 %**	0 %	**40–50 %**
Compression, longitudinal [A]	$\mathbf{f_{c,0}}$	MPa	47.3	102.5	58.3	–
	St. Dev.	MPa	2.5	34.7	0.0	–
	Var. Coeff.	%	5.2	33.9	0.0	–
	Change	%	–	116.7	–	–
	$\mathbf{f_{c,0,k}}$	MPa	39.3	80.5	48.9	–
	$\mathbf{E_{c,0}}$	MPa	9260.0	25960.0	–	–
	St. Dev.	MPa	0.0	0.0	–	–
	Var. Coeff.	%	0.0	0.0	–	–
	Change	%	–	180.3	–	–
	$\mathbf{E_{c,0,0.05}}$	MPa	5340.9	21564.2	–	–
Compression, radial [A]	$\mathbf{f_{c,90}}$	MPa	3.4	58.9	12.4	40.0
	St. Dev.	MPa	1.1	37.9	6.3	30.8
	Var. Coeff.	%	32.7	64.3	50.6	76.9
	Change	%	–	1632.9	–	223.6
	$\mathbf{f_{c,90,k}}$	MPa	2.8	36.4	9.6	35.5
	$\mathbf{E_{c,90}}$	MPa	388.0	884.6	1067.5	1708.2
	St. Dev.	MPa	165.4	278.8	510.6	540.3
	Var. Coeff.	%	42.6	31.5	47.8	31.6
	Change	%	–	128.0	–	60.0
	$\mathbf{E_{c,90,0.05}}$	MPa	173.3	437.1	795.3	1164.5
Compression, tangential [A]	$\mathbf{f_{c,90}}$	MPa	4.0	22.9	14.1	52.0
	St. Dev.	MPa	1.0	4.1	0.0	0.0
	Var. Coeff.	%	26.0	18.1	0.0	0.0
	Change	%	–	470.8	–	268.6
	$\mathbf{f_{c,90,k}}$	MPa	2.7	12.7	12.5	44.6
	$\mathbf{E_{c,90}}$	MPa	183.4	1107.9	641.2	1688.2
	St. Dev.	MPa	25.7	105.4	0.0	0.0
	Var. Coeff.	%	14.0	9.5	0.0	0.0
	Change	%	–	504.1	–	163.3
	$\mathbf{E_{c,90,0.05}}$	MPa	71.9	571.0	562.3	1427.9
Tensile, parallel [A]	$\mathbf{f_{t,0}}$	MPa	63.3	124.4	89.6	125.7
	St. Dev.	MPa	0.0	8.5	0.0	0.0
	Var. Coeff.	%	0.0	6.9	0.0	0.0
	Change	%	–	96.4	–	40.2
	$\mathbf{f_{t,0,k}}$	MPa	49.3	93.3	47.3	99.4
	$\mathbf{E_{t,0}}$	MPa	9774.3	18555.8	10829.1	17354.8
	St. Dev.	MPa	0.0	61.9	0.0	0.0
	Var. Coeff.	%	0.0	0.3	0.0	0.0
	Change	%	–	89.8	–	60.3
	$\mathbf{E_{t,0,0.05}}$	MPa	8493.0	12473.3	7410.0	12205.9
Bending [A, B, C]	$\mathbf{f_m}$	MPa	97.1	236.7	134.2	264.1
	St. Dev.	MPa	19.9	49.5	0.0	10.2
	Var. Coeff.	%	20.5	20.9	0.0	3.9
	Change	%	–	143.8	–	96.8
	$\mathbf{f_{m,k}}$	MPa	68.2	149.5	88.9	182.6
	$\mathbf{E_m}$	MPa	10842.2	26560.3	13709.6	24032.8
	St. Dev.	MPa	1979.2	2805.1	1837.9	307.6
	Var. Coeff.	%	18.3	10.6	13.4	1.3
	Change	%	–	145.0	–	75.3
	$\mathbf{E_{m,0.05}}$	MPa	6917.0	13950.2	9845.2	17453.8
Embedment strength, parallel [C]	$\mathbf{f_{h,0}}$	MPa	54.0	221.1	–	–
	St. Dev.	MPa	0.0	0.0	–	–
	Var. Coeff.	%	0.0	0.0	–	–
	Change	%	–	309.5	–	–
	$\mathbf{f_{h,0,k}}$	MPa	39.7	191.4	–	–
	$\mathbf{K_{s,0}}$	N/mm	18.4	41.2	–	–
	St. Dev.	N/mm	0.0	0.0	–	–
	Var. Coeff.	%	0.0	0.0	–	–
	Change	%	–	123.9	–	–
	$\mathbf{K_{s,0,0.05}}$	N/mm	7.0	7.7	–	–
Embedment strength, perpendicular [C]	$\mathbf{f_{h,90}}$	MPa	43.0	218.1	–	–
	St. Dev.	MPa	0.0	0.0	–	–
	Var. Coeff.	%	0.0	0.0	–	–
	Change	%	–	406.7	–	–
	$\mathbf{f_{h,90,k}}$	MPa	24.6	152.0	–	–
	$\mathbf{K_{s,90}}$	N/mm	6.2	26.6	–	–
	St. Dev.	N/mm	0.0	0.0	–	–
	Var. Coeff.	%	0.0	0.0	–	–
	Change	%	–	327.2	–	–
	$\mathbf{K_{s,90,0.05}}$	N/mm	1.5	12.1	–	–
Yield moment [C]	$\mathbf{M_y}$	Nmm	–	8787.8	5495.3	–
	St. Dev.	Nmm	–	2680.9	310.1	–

(*continued on next page*)

Table 2 (*continued*)

	Parameter	Unit	Softwood		Hardwood	
	Var. Coeff.	%	–	30.5	5.6	–
	Change	%	–	–	–	–
Push-out shear [A, B, C]	$\mathbf{K_s}$	N/mm	–	4384.5	2939.8	5406.2
	St. Dev.	N/mm	–	993.7	819.8	3263.4
	Var. Coeff.	%	–	22.7	27.9	60.4
	Change	%	–	–	–	83.9
	$\mathbf{K_{s,0.05}}$	N/mm	–	1252.0	1444.9	1905.1
Charpy test [A]	$\mathbf{w_B}$	J/cm^2	4.4	7.7	5.7	15.5
	St. Dev.	J/cm^2	1.3	0.8	0.1	0.2
	Var. Coeff.	%	29.6	9.9	2.2	1.4
	Change	%	–	73.6	–	174.5

A) Samples Manufactured in Laboratory
B) Samples Manufactured in Industry
C) Samples Manufactured in Laboratory with shaping

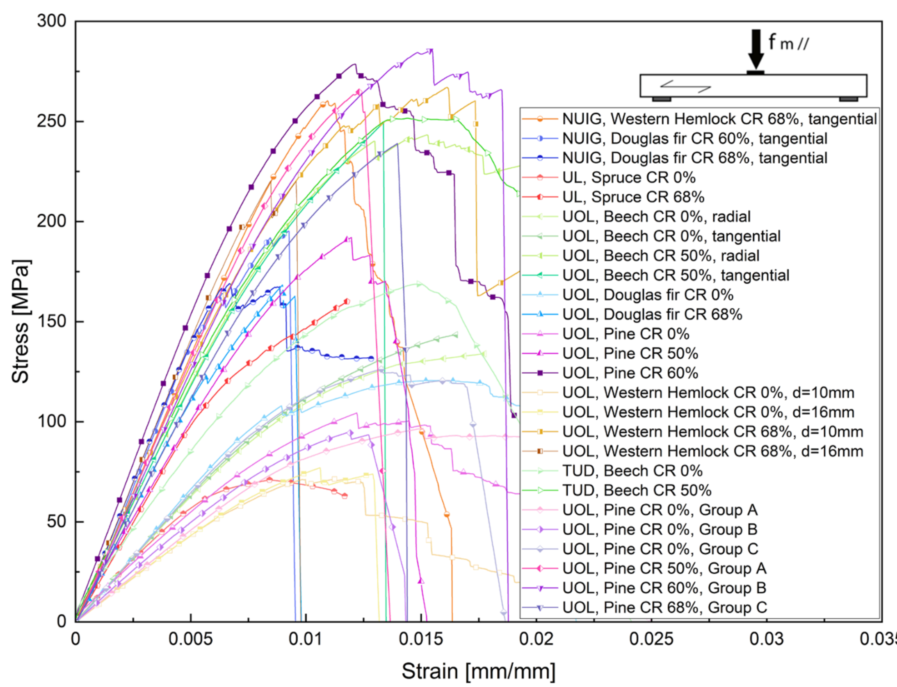

Fig. 8. Average stress–strain curves for bending tests.

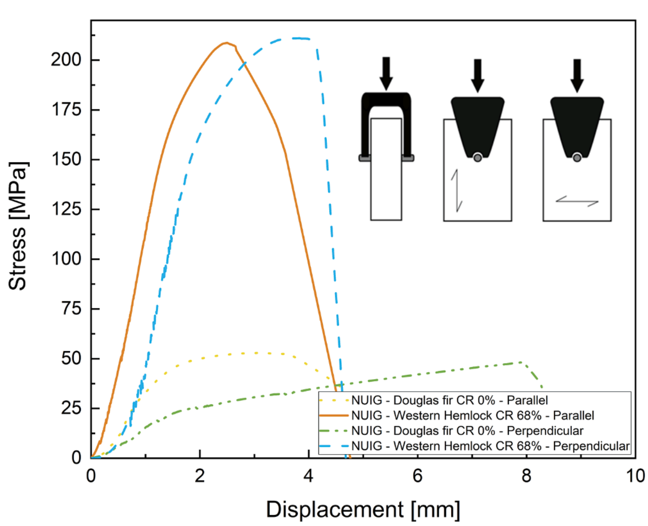

Fig. 9. Average load–displacement curves for the embedment test.

underestimates the embedment strength of CW materials by a factor of 2.5 and thus requires further research using statistically valid sample sizes to derive new equations for CW material.

3.5. Yield moment tests

The yield moment tests were carried out as 3-point bending tests on a single dowel with two supports and a small span. Tests were conducted on Scots pine CW dowels and normal beechwood dowels. The load was applied at 0° (R), 45° and 90° (T) angle to the growth rings of the dowels. The test set up was as per ASTM-D4475-02:2016 [20] and yield moment capacity was calculated using the following expression [28]:

$$M_{y,eff} = \frac{3}{8}.F_y.d \quad (2)$$

where F_y is the yield load (N) and d is the dowel diameter (mm).

The yield moment capacity of the CW dowels was higher than the normal beechwood dowels in each tested grain angle (0°, 45° and 90°). As it can be seen in Fig. 10, the yield moment capacity of CW dowels in radial, tangential directions and at 45° angle were 1.15, 2.28 and 1.42 times higher than the normal beechwood dowels tested in the corresponding directions. The beech dowels loaded in the tangential direction

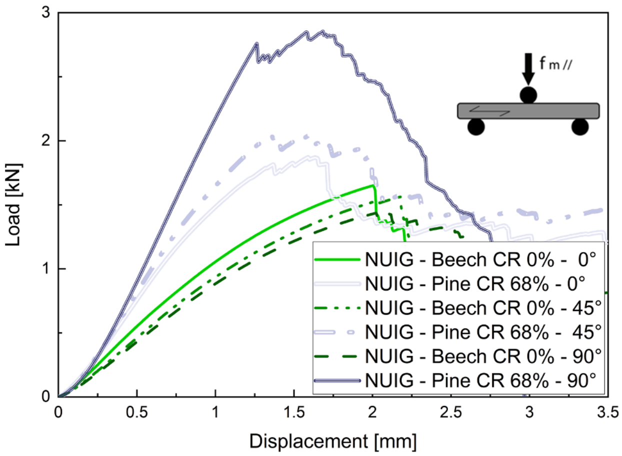

Fig. 10. Average load–displacement curves of yield moment tests.

showed the highest ductility, whereas this was least for CW dowels loaded in this direction.

For CW dowels, the yield moment capacity increased as the angle between the load and growth rings increased (from 0° to 90°). Based on the results, it can be concluded that the angle between the orientation of growth rings of CW dowels and loading direction is a decisive factor in determining the load-carrying capacity and ductility of the dowel.

The literature review showed scarce availability of data on yield moment capacity of the CW dowels. For this reason, the results of the current study were compared with calculated (using Equation 8.30 of EC5 [27]) yield moment capacity of S235 grade (ultimate tensile strength of 360 MPa) steel dowels of 10 mm diameter. The yield moment capacity of S235 grade steel dowel is 42,995 Nmm, which is approximately 3.6 times higher than the CW dowels tested at 90°. Although non-metallic dowels show relatively lower yield moment capacity, it may be possible to use them at a closer spacing than the steel dowels to achieve a similar load carrying capacity per unit area as steel connections. In structural applications where a higher load carrying capacity is required, CW dowels with larger diameter can be used.

3.6. Push-out shear tests

In the push-out shear tests, two side members are dowelled to one at the middle (double lap joint). EN 26,891 [21] sets out the guidelines for determining the load-bearing capacity and the slip. Dimensions close to structural size are required. Besides, the edge distances and minimum wood thicknesses according to EC5 [27] must be satisfied. In Fig. 11, the average load-slip curves for each test series with different dowel diameters are shown.

The mean value for compressed softwood is shown in Table 2. However, the results of the test specimens of test series by UL was not presented in the Table 2. Since the middle and side wood members of the test specimens were made of oak (in other tests spruce has been used).

3.7. Charpy tests

The Charpy or pendulum impact tests were carried out to characterize the dynamic behaviour of CW. The brittle fracture behaviour of the samples was investigated by clamping them in a test device and striking them with a pendulum. The deformation of the test specimens, energy absorption and time was measured to determine the fracture work. Fig. 12 shows the average load–displacement diagram for uncompressed and compressed wood in the radial and tangential direction.

The standard DIN 52189–1 [22] specifies the determination of the impact energy and the requirements for the test device. The standard requires a square sample cross-section with an edge length of 20 mm and a sample length of 300 mm. From Fig. 12, it can be seen that the higher the compression ratio the higher toughness.

3.8. Dependence of strength on density

The characteristic values of CW were categorized according to the CR (depending on the dimensions). Another measurement is the differentiation based on density. Since the density fluctuates based on the type of wood and is also subject to natural scattering for the wood of the same tree, a bulk density-controlled compression process could allow a much more precise estimation of the material quality. To this end, the relationship between the flexural strength and density is investigated in more depth.

Fig. 13 shows the bending strength-density curve, with the softwoods in green and the hardwoods in red. The graphs of the linear regression for all types of wood and one without Douglas fir are shown. The tables under the legend contain the basic parameters of the approximation functions. The diagram shows the different densities and strengths of different types of wood at the same CR. The values in the diagram clearly show the significant spread of the strengths within the CRs. Depending on the CR, the strength values fluctuate by around 25–50 MPa and the density by around 100–200 kg / m^3.

The observation in Fig. 13 shows that there is a linear relationship between the density and the strength, and the correlation coefficient of 0.98 (without Douglas fir) confirms this. The linear regression without

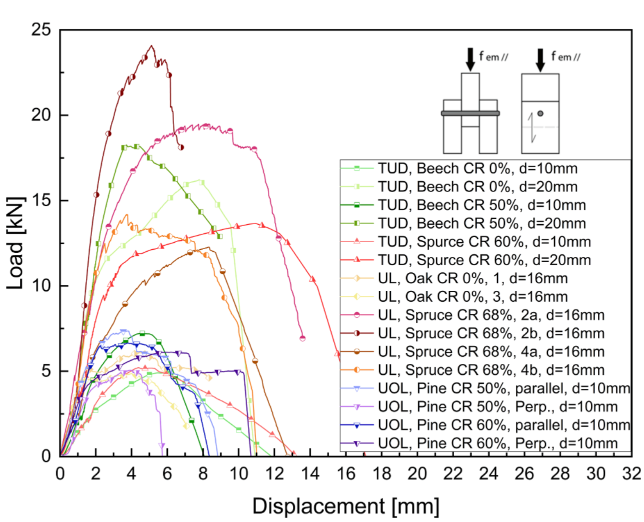

Fig. 11. Average load-slip curves of the push-out shear tests.

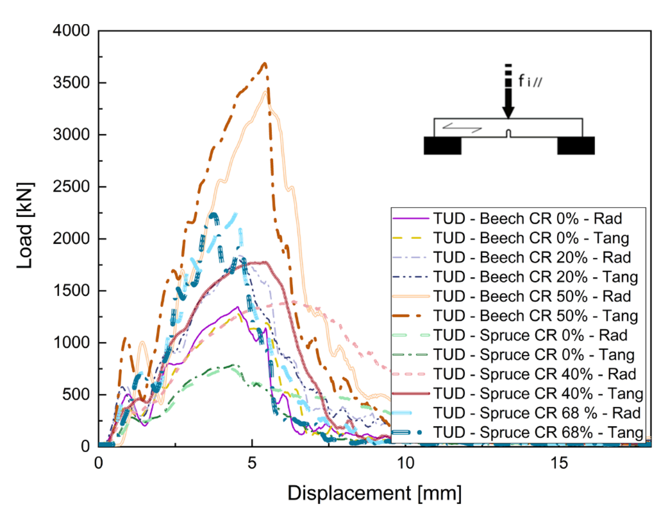

Fig. 12. Average load–displacement curves for Charpy test.

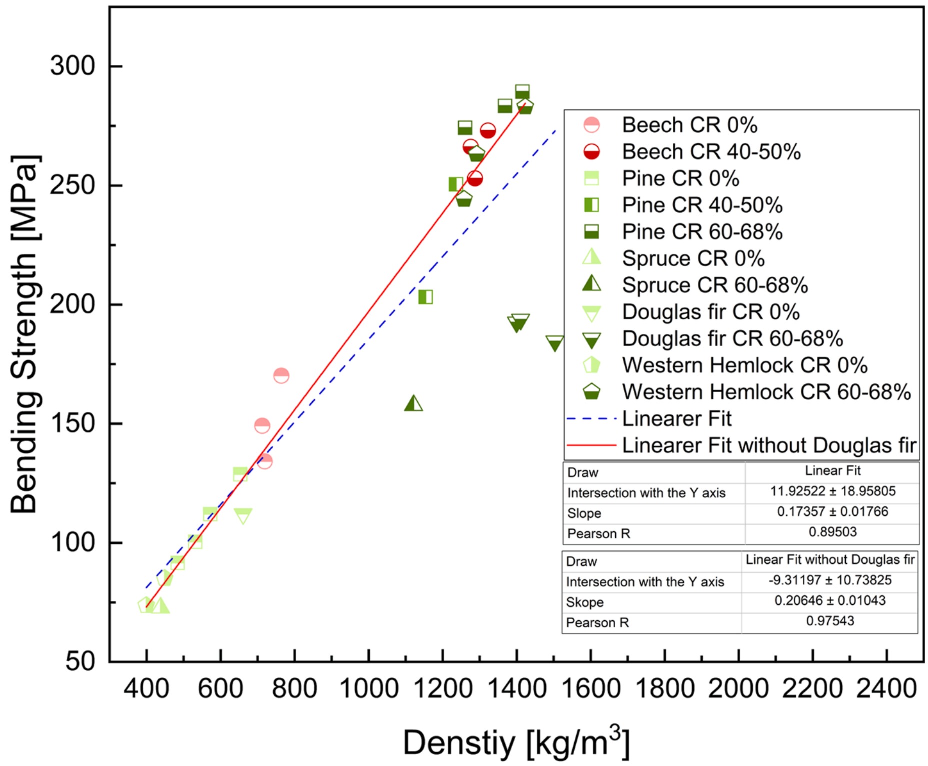

Fig. 13. Flexural strength-density correlation.

the test specimens made of Douglas fir has a higher correlation coefficient because the bending strength for compressed Douglas fir is lower than that of the other types of wood.

The same applies to the data point of 68% compressed spruce. It is not practical to carry out compression to more than 1500 kg / m^3 because the density of the cell wall of softwood is also approximately 1500 kg / m^3.

3.9. Mechanical properties of CW

Table 2 shows the mean values of the material parameters for uncompressed and compressed softwood and hardwood. The tests quantify the increase of strength and stiffness for CW compared with uncompressed wood. It was also mentioned that, in some cases, the minimum dimension required by the test standard could not be achieved due to the manufacturing limitations of CW. This led to the use of different geometries, which caused variations in the results.

Table 2 comprises a total of 23 test series with over 720 evaluated test specimens. The table is structured according to the type of material testing, wood species, and CR with zero 0 % being related to normal wood (i.e. uncompressed wood).

The table shows the average value and standard deviations with coefficients of variation for each test series. Based on design requirments, the 5% quantile values were calculated according to EN 14,358 [17]. In general, the 5 % quantiles represent the values at which the probability of the occurrence of lower values is 5 %. In EN 14,358 [17], the calculation of the strength properties is based on a logarithmic normal distribution, and a normal distribution is assumed for the stiffness properties. The level of confidence was chosen to be $\alpha = 75$ %. The statistical factor ks (n) is required to calculate the characteristic value and is read from a table in EN 14,358 [17] depending on the number of test specimens.

The scatter of the result values is due to various reasons that influence the comparability of the tests. The structure and execution of the tests, as well as the geometry of the specimens were found to have a significant influence on the results. Since standards for CW are lacking, manufacturing and testing were not carried out uniformly. With different specimen geometries, the size effect, which increases the likelihood of defects with increasing size, becomes influential. The load introduction and the loading rate also influence the results of the material tests. Another factor influencing the results is the dispersion of the wood properties due to the natural growth, which causes defects such as knots and fluctuations in the bulk density. This means that those test specimens which were made from the same wood and had the same geometry showed different levels of mechanical resistance. Strength and stiffness are therefore subject to natural fluctuations. When the material properties of different types of wood are offset against the average values for hardwood and softwood, the flexibility, bulk density, and cell structure of the different wood species are also influential factors.

4. Conclusion

In this paper, comprehensive material characterisation tests have been carried out on CW and CW connectors and the mechanical properties have been presented. The test results show that CW and CW connectors offer a significant increase in the strength and stiffness properties compared to normal softwood or hardwood. More precisely, the compressive strength perpendicular to the grain has increased by a factor of 10. The tensile and bending strength (in the longitudinal direction) also increased by 1.4 and 2.4 times, respectively. The results of the embedment tests show that the embedment strength of CW specimens in parallel and perpendicular to the grain direction were approximately 4 and 5 times higher than the normal softwood in corresponding directions. Similarly, yield moment tests show that the CW offers a relatively high yield moment capacity compared to normal beechwood dowels. The improvement of material properties becomes evident for wood with initial low densities. This confirms that thermo-mechanical compression is an effective method to enhance the mechanical properties of wood considerably.

The comparison of test results showed that in some cases coefficient of variation was high and 5% quantile values were low. This indicates the further experiments with larger sample sizes could improve the values presented in this paper. As far as quantile values are concerned, it is necessary to analyse the distribution of the strength and stiffness properties of CW using a larger dataset. Future research work can focus on the characterisation of CW for all degrees of compression using various softwood and hardwood species.

The literature review also shows that the CW without post-treatment depends on the different factors, which includes moisture dependent swelling/shrinkage and springback. This could be a potential area of research to understand the long-term behaviour of this material. In this context, the air conditioning of CW should also be explored further. The effect of compression techniques and post-treatment require further investigation to establish unified guidelines for the production of CW materials.

CRediT authorship contribution statement

Siavash Namari: Writing - original draft, Investigation, Visualization, Validation. **Lukas Drosky:** Investigation, Software. **Bianka Pudlitz:** Investigation. **Peer Haller:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing. **Adeayo Sotayo:** Investigation, Writing - review & editing. **Daniel Bradley:** Project administration. **Sameer Mehra:** Investigation, Writing - review & editing. **Conan O'Ceallaigh:** Supervision, Investigation, Writing - review & editing. **Annette M. Harte:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Imane El-Houjeyri:** Investigation, Writing - review & editing. **Marc Oudjene:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Zhongwei Guan:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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