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MOISTURE DEPENDENCE OF MECHANICAL PROPERTIES OF BEECH AND BIRCH IN COMPRESSION PERPENDICULAR TO GRAIN AND ROLLING SHEAR

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ABSTRACT: The forests in Europe are changing in response to climate change, resulting in an increased proportion of hardwood species in mixed forests. Mechanical characterization of hardwood species, an understudied area in the past, is now gaining prominence in research. Our experimental investigation of moisture dependence of mechanical strength of South Swedish hardwoods encompassed the species beech and birch and relative humidity levels of 40, 65, and 85 % at 20 °C. Mechanical strength was determined on two different scales, namely on the board level, which includes effects of the cylindrical orthotropy of the annual ring structure of wood, and on the material level, where this influence is minimized due to the small specimen size. For these different scales, different experimental setups were used, with a similar experimental evaluation. The results showed that compressive strength perpendicular to the grain increased with decreasing moisture content at both scales. Material level tests resulted in higher compressive strengths compared to the board level. Conversely, rolling shear strength was consistently higher on the board level than on the material level. The dependence of the rolling shear strength on the moisture content was distinct on the board level, but not on the material level.

KEYWORDS: hardwood, moisture dependence, compression test, rolling shear test, strength evaluation, different length scales

1 – INTRODUCTION

The Scandinavian forests are not exempt from climate change [1] and a general shift towards mixed forests is expected as a response to the changing climate, as increasing species admixture greatly reduces the negative effects of unfavourable climate conditions [2]. Increasing temperatures and precipitation during the growth period affect the growth rates of hardwood positively and the growth rate of softwood negatively [3]. Thus, the wood supply from the Scandinavian forests is changing [4]. This development in the wood supply has led to an increasing interest in hardwood for structural purposes. For instance, the dominant softwood in engineered wood products (EWP) could be complemented with hardwood, as the mechanical properties are generally higher than those of softwood.

However, the application of hardwood for structural purposes is rare, besides some niche products like laminated veneer lumber (LVL) made from beech. This is partly rooted in the limited number of available and standardized material properties of hardwood. To overcome this issue, research projects are investigating hardwood properties for building up an experimental database. Al-musawi et al. [5] investigated the compressive strength in longitudinal, radial, and tangential direction of birch and beech at different moisture and temperature levels (20/100/140 °C). Their experimental results at 20 °C confirmed the general expected increase in strength with decreasing moisture content. Boruvka et al. [6] investigated the static and dynamic bending properties perpendicular to the grain of softwood and hardwood. They identified the elastic stiffness of birch and beech amongst other species. Milch et al. [7] and Niemz et al. [8] investigated stiffness and strength properties of European beech in longitudinal, radial and tangential directions at 65 % relative humidity (RH) at 20 °C. Ehrhart et al. [9] investigated mechanical properties of

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glued laminated timber made of beech and added strength and elastic stiffness results in bending and compression in grain direction to the database. Collins and Fink [10] performed tension tests on birch boards differentiating in clear wood sections and sections with knots, which yielded strength and stiffness values in tension for birch. Ehrhart and Brandner [11] investigated rolling shear properties of European soft- and hardwood with different test configurations, as these properties have gained importance in the use of cross laminated timber. They extended the database by rolling shear strength and stiffness for birch and beech amongst others. Not only the rolling shear (RS) properties, but also compression perpendicular to the grain (CPG) properties can be a limiting factor in the design of EWPs, e.g. at the support areas of wide spanning glued-laminated timber beams.

Comparing advanced material modeling of timber and standardized experimental testing for structural applications, which is subsequently linked to mechanical properties in timber product standards, often yields a gap. Advanced material modeling considers the hierarchical structure of timber from a very small scale upwards (components of cellulose, hemicellulose, lignin, etc.) and provides radial and tangential material properties, e.g. [12]. In standardized testing for structural applications, in turn, the required dimensions of specimens are generally at a board level, where the cylindrical orthotropy of wood caused by the annual ring structure has an influence on the experimental results.

Hence, this research aims on the one hand to extend the existing experimental database of mechanical properties of beech and birch perpendicular to the grain, i.e., RS and CPG, at three different ambient climate conditions. On the other hand, experimental investigations are performed on two different length scales to quantify the influence of the annual ring structure (and the cylindrical orthotropy of wood) at the board level compared to the material level. Thus, the experimental test program included 8 test series - 2 species (birch and beech), 2 test types (CPG and RS), and 2 length scales (board and material level).

2 – MATERIALS AND METHODS

Birch (Betula pendula Roth) **and beech** (Fagus sylvatica L.) boards from Southern Sweden were investigated in this study. The mean density of the 10 birch boards was 644 kg/m^3 with a standard deviation of 51 kg/m^3 and the mean density of the 10 beech boards was 711 kg/m^3 with a standard deviation of 36 kg/m^3. RS strength and CPG strength at different, but constant, ambient climates were investigated. In addition to the **standard climate** with 65 % RH at 20 °C, a **dry climate** with 40 % RH at 20 °C and a **wet climate** with 85 % RH at 20 °C were investigated. Hence, before testing, all specimens were stored in climate-controlled chambers to ensure the desired ambient climate. The dry, standard, and wet climate resulted in a mean moisture content of 8.6 %, 12.2 %, and 16.0 % for the birch specimens, and in a mean moisture content of 8.3 %, 11.6 %, and 15.7 % for the beech specimens.

Furthermore, RS and CPG strengths were tested on different scales, i.e., on the **board level**, which includes effects of the cylindrical orthotropy of the annual ring structure of wood, and on the **material level**, where the influence of the annual ring curvature is assumed to be negligible. These two different scales required different experimental setups and test specimens. To get similar density and annual ring inclination distributions in all test series, the required specimens for the different tests were cut from the same board.

2.1 EXPERIMENTAL SETUPS

RS on the board level was tested on inclined 3-layer specimens. The specimens (150 mm / 18 mm / 100 mm) were prepared for an inclination of 14 °, and displacements were measured digitally using a video extensometer (VEM) and reference markers with a distance of 20 mm, see Fig. 1(a). As for the **CPG on the board level**, prismatic specimens with a height of 90 mm,

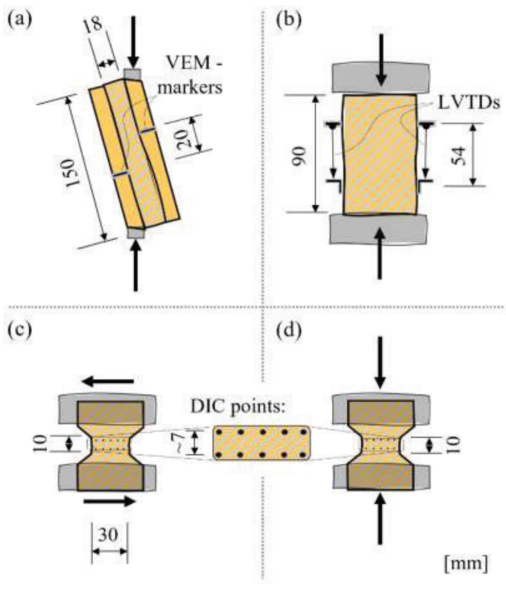

Figure *1:* Sketch of the applied experimental setups: (a) board level RS, (b) board level CPG, (c) material level RS, and (d) material level CPG.

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a width of 70 mm, and a thickness of 40 mm were tested in a uniaxial testing machine. The required displacement measurement was done with LVDTs (linear variable differential transformers) with a gauge length of 54 mm on two opposite sides in the middle section of the specimen, see Fig. 1(b).

Investigating **RS and CPG on the material level** was done in a biaxial setup. The compact dog bone specimens with a neck width of 30 mm, a neck height, and depth of 10 mm were clamped into the testing machine. For the CPG tests, the compressive force was applied in vertical direction, and the horizontal force was kept at zero. For the RS tests, the shear force was applied via the horizontal load application and the vertical force was kept at zero. Displacements were measured by a digital image correlation (DIC) system. Hence, a speckle pattern was applied on the surface of the specimens. The displacement was determined based on ten measuring points in the neck area of the specimen, see Fig. 1(c) and 1(d).

2.2 EVALUATION

The loads and mean values of the locally measured displacements during the tests, as well as the specimen geometry, were the basis for the subsequent strength determination. After calculating the stresses and strains, the evaluation of RS and CPG strength for both scales followed EN 408 [13], even if the used specimens did not fulfill the criteria specified for the geometry of test specimen. The CPG strength was determined at the 1 %-strain offset of the linear slope of the stiffness secant modulus, which requires an iterative process to determine strength and stiffness based on the experimental data. As RS failure is a brittle failure mechanism, the strength could be identified by a sharp load drop in the stress-strain curve.

2.3 AMBIENT CLIMATE DEPENDENCY

The ambient climate dependency of the RS and CPG strength for each species was determined by a linear regression fitting the experimental strength data at the different climate classes or at the RH levels, respectively. The function 'polyfit' for a first-order polynomial ($y = kx + d$) in the software Matlab [14] was used, which gave an inclination of the linear fit (k-value) and a shift of the linear fit at the theoretical RH of zero (d-value). For comparison with literature, the climate dependency is expressed as the change of strength per change of RH in [MPa/RH%] and a reference value (RV) for the strength in standard climate is given in [MPa]. Notably, this RV is calculated separately from the mean value of the experimental results of the tests in standard climate.

2.4 STATISTICAL EVALUATION

For each investigated climate class, strength type, and species, the standard statistical parameters of mean value, standard deviation, and coefficient of variation (CV) were determined during the numerical evaluation. Furthermore, the statistically significant difference between the three climates in each test series was determined with a one-way analysis of variance (ANOVA). Based on the ANOVA of each test series, the statistical probability (P-value) that the difference between the investigated climate classes occurred by chance was calculated with the function 'anova1' in the software Matlab [14]. The common limit of a P-value less than 5 % to assume significance of the experimental results regarding the investigated climates was considered in the study.

3 – RESULTS AND DISCUSSION

3.1 EXPERIMENTAL RESULTS

The results showed an increase of the **CPG strength** with decreasing RH on both scales, based on the mean values of strength in each climate class, see Table 1. CPG strength on the **board level** of the tested beech specimens increased by 22 % for the dry climate (40 % RH) and decreased by 11 % for the wet climate (85 % RH) compared to the standard climate (65 % RH). The investigation of the birch specimens led to an increase of 19 % in the dry climate and a decrease of 17 % in the wet climate compared to the values in the standard climate. A similar behaviour was determined on the **material level**, with the same percentages for beech and a 15 % increase and 18 % decrease for birch.

Table 1: Experimental results of the CPG strength at the investigated ambient climates (dry - 40 % RH; standard - 65 % RH; wet - 85 % RH at 20 °C) with mean value in [MPa] and standard deviation (STD) in [MPa], and coefficient of variation (CV) in [%] for the different levels.

CPG strength		**birch**			**beech**		
		dry	*sta.*	*wet*	*dry*	*sta.*	*wet*
board level	mean	7.52	6.57	5.41	12.0	9.86	8.74
	STD	1.67	1.52	1.13	1.91	1.51	1.46
	CV	22	23	21	16	15	17
material level	mean	8.15	6.94	5.74	15.2	11.3	10.5
	STD	1.37	0.73	0.77	4.23	2.40	3.24
	CV	17	11	14	28	21	31

The CV within CPG strengths within one ambient climate for birch is between 11 and 23 % with higher variation at the board level. The variation of beech strength is a bit

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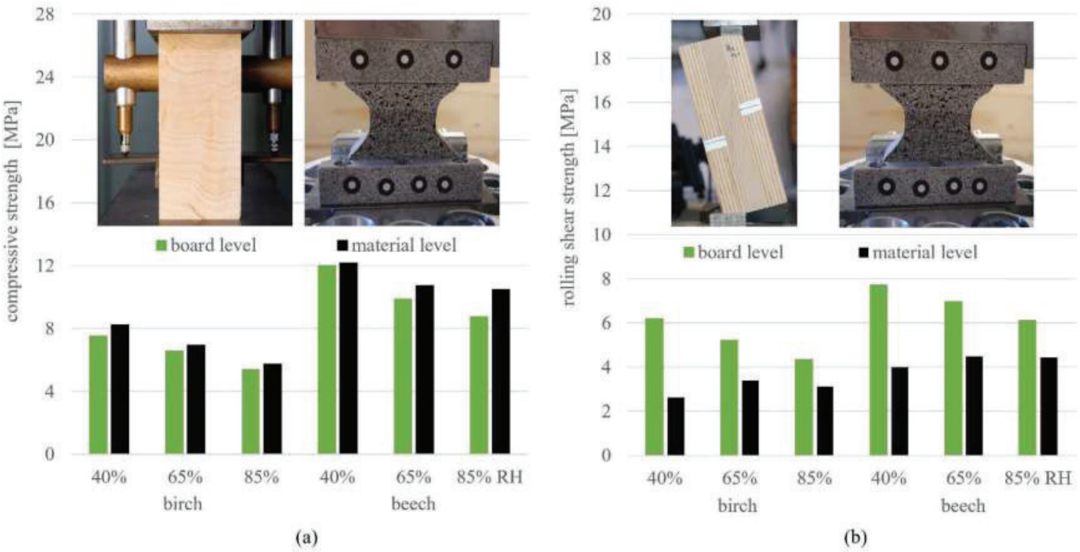

Figure 2. Experimental setups and results for (a) compressive strength perpendicular to grain (CPG) and (b) rolling shear (RS) strength: comparison of different RH levels at 20 °C and investigated scales (board and material level).

higher, with 15 to 31 %, but with the higher values at the material level. When comparing the CV values for different climates investigated for one species, whether at the material or board level, the values are quite uniform. This uniformity results from the careful selection of specimens from the same board, ensuring similar material composition in terms of density and annual ring inclination across different ambient climates. For further details of the CPG test results, see Table 1 and Fig. 2(a).

RS strength of the beech specimens on the **board level** increased by 11 % in the dry climate and decreased by 12 % in the wet climate compared to results from the standard climate. The RS strength of birch is more strongly influenced by the climate classes than the strength of beech with a 19 % increase in the dry climate and a 17 % decrease in the wet climate compared to the strength value related to the standard climate. On the **material level**, the RS strength for beech unexpectedly decreased by 11 % in the dry climate and decreased by 1 % in the wet climate for the tested beech specimen in comparison with the standard climate. Like on the board level, birch is stronger influenced by climate changes than beech and shows the same unexpected trend with a 23 % decrease in the dry climate and an 8 % decrease for the wet climate when compared to the results of the standard climate class. Regarding the variation within the results for one climate and one species, the CV values are overall lower for RS than for CPG, and the experimental results on the board level, resulted in the lowest values ranging from 7 to 8 %

Table 2: Experimental results of the RS strength at the investigated ambient climates (dry - 40 % RH; standard - 65 % RH; wet - 85 % RH at 20 °C) with mean value in [MPa] and standard deviation (STD) in [MPa], and coefficient of variation (CV) in [%] for the different levels.

RS strength		**birch**			**beech**		
		dry	***sta.***	***wet***	***dry***	***sta.***	***wet***
board level	mean	6.19	5.21	4.33	7.71	6.96	6.11
	STD	0.55	0.72	0.62	0.52	0.53	0.48
	CV	9	14	14	7	8	8
material level	mean	2.61	3.40	3.06	3.95	4.50	4.44
	STD	0.47	0.53	0.62	0.76	0.80	0.96
	CV	18	16	20	19	18	22

for beech and 9 to 14 % for birch. On the material level, the CV is between 18 and 22 % for beech and 16 to 20 % for birch. For further details of the RS test results, see Table 2 and Fig. 2(b). Like for the CPG results, the uniformity of the CV values within one species and one investigated scale is a result of the suitable selection of specimens from the same board with similar investigated material compositions.

Notably, the CPG strength values were higher on the material level than on the board level for all investigated climates, and exactly the opposite was determined for the

RS strength values when board and material levels are compared.

3.2 AMBIENT CLIMATE DEPENDENCY

Linear dependency of the strength on different, but constant surrounding RH levels was calculated for RS and CPG, independent of the calculated mean values for each climate, which were presented in Section 3.1. As for the **RS strength** on the board level, the influence is the same for both hardwood species, i.e., a 0.04 MPa increase by a 1 % decrease in RH. The dependency of the strength at the material level on the moisture is unexpected with increasing RH the strength is increasing too, but with only a 0.01 MPa change with a 1 % change in RH the influence is smaller. The dependencies and RVs for both investigated levels and species are documented in Table 3 and plotted in Fig. 3.

Table 3: RS strength dependency (k-value) on the RH at 20 °C with a reference value (RV) at 65 % RH for the investigated hardwood species.

RS strength		**birch**	**beech**
board level	k-value [MPa/RH%]	-0.04	-0.04
	RV [MPa]	5.17	6.87
material level	k-value [MPa/RH%]	+0.01	+0.01
	RV [MPa]	3.05	4.31

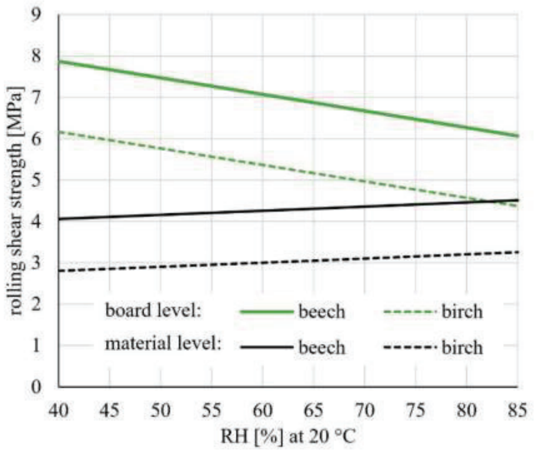

Figure 3: Linear dependency of the RS strength on different ambient cilmate conditions for investigated hardwood species.

CPG strength on the board and material level follow the expected trend of decreasing values with increasing RH. The strength of birch increases by 0.05 MPa with the RH decrease of 1 % on both investigated levels. The experiments on beech yield an increase of 0.07 MPa on the board level and an increase of 0.11 MPa on the material level per 1 % decrease in RH. The dependencies and RVs for both investigated levels and species are documented in Table 4 and plotted in Fig. 4.

Table 4: CPG strength dependency (k-value) on the RH at 20 °C with a reference value (RV) at 65 % RH for the investigated hardwood species.

CPG strength		**birch**	**beech**
board level	k-value [MPa/RH%]	-0.05	-0.07
	RV [MPa]	6.42	10.08
material level	k-value [MPa/RH%]	-0.05	-0.11
	RV [MPa]	6.85	12.2

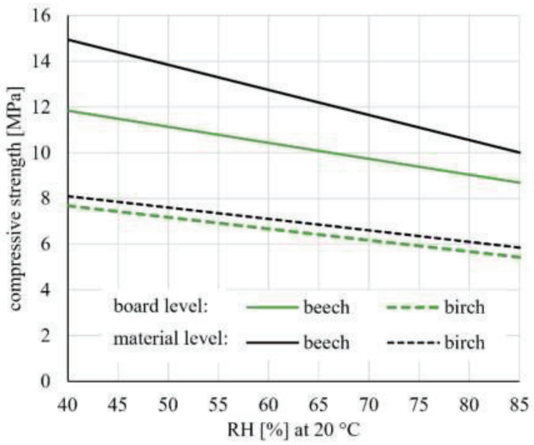

Figure 4: Linear dependency of the CPG strength on different ambient cilmate conditions for investigated hardwood species.

Comparing the RVs identified at 65 % RH and presented in this section with the independently calculated mean values of the strength tests performed at the standard climate, shows that the two calculation methods do not yield exactly the same values. For example, for RS strength of birch on the board level, the RV is 5.17 MPa and the mean value at the standard climate is 5.21 MPa.

3.3 STATISTICAL SIGNIFICANCE

Based on the one-way analysis of variance (ANOVA), the P-values for the statistical significance of the three investigated ambient climates for the strength in RS and CPG on the board and material levels were determined (see Table 5).

Table 5: Results of the ANOVA for the statistical significance.

P-values [%]		**birch**	**beech**
board level	RS strength	0.003	0.0003
	CPG strength	0.31	0.047
material level	RS strength	1.16	26.97
	CPG strength	0.005	1.19

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The statistical probability that the difference between the investigated climates is due to chance (P-value) and thus not actually rooted in the change in ambient climate is less than 0.5 % for the RS and CPG strength investigated on the board level of birch and beech. For the material level, the probability is at a similar level for CPG strength of birch, a bit higher than 1 % for CPG strength of beech and RS strength of birch, and quite high with 27 % for the RS strength series of beech.

Considering the desired P-value of less than 5 % for assuming a significant difference between the investigated climates, the RS strength series for beech on the material level is the only one not fulfilling the criterion, while for the other strength properties there is a clear significance of the influence of the ambient climate.

3.4 DISCUSSION

In this work, the dependency of the RS and CPG strength of birch and beech on the ambient climate was determined based on two different calculation methods. The first approach was based on the mean values calculated for each of the three investigated climates and the relative change of strength values when comparing the mean value from the dry and wet climate with the standard climate. This confirmed the expected trend for 6 out of the 8 test series (2 material levels, RS and CPG, and 2 species), of increasing strength with decreasing RH. The RS strength on the material level did not follow the expected trend with the highest mean value at the standard climate and quite low values in the dry climate, see Fig. 2. To identify an overall trend for all test series, the second approach with a linear regression analysis was run for all experimental results. As expected, this method confirmed the general trend for the same 6 test series and quantified the dependency. Furthermore, it was also possible to calculate a representative number for the dependency of the RS strength at material level on the ambient climate for both investigated species, which did not follow the general expectations. As both approaches led to the same unexpected trend, further investigations on the origin of these results are required.

As quite high CVs were identified for some of the test series, see Tables 1 and 2, the question about statistical significance needed to be raised and therefore the probability that the differences in strength between the three investigated ambient climates are only by chance was determined for all test series. Only one of RS series on the material level did not meet the commonly applied 5 % limit, i.e., the RS strength of beech on the material level with almost identical mean values at the standard and wet climate, see Table 2. Notably, this test series did not show the highest CV values from the 8 test series, CPG of beech on the material level did. Further statistical analysis is required.

As for the influence of the cylindrical orthotropy of the annual ring structure of wood on the strength results, the determined CPG strength on the material level were slightly higher than on the board level, i.e., around 6 % higher for birch and 20 % higher for beech. This would indicate that the annual ring curvature contributes negatively to the CPG strength of birch and beech. The same comparison for the RS strength showed an opposite influence of the cylindrical orthotropy of the annual ring structure of wood. The strength values on the material level were on average 41 % lower for birch and 37 % lower for beech on the material level compared to the results on the board level, which would indicate a positive influence of the annual ring curvature on the RS strength. But it is also worth mentioning that the difference in strength results could also be based on the different setups, as horizontal movement is prohibited on the board level and not on the material level. The horizontal movement could be reducing the restraints.

4 – CONCLUSION

The expected influence of different ambient climates on the CPG strength could be confirmed on the investigated board and material level, i.e., a dryer climate resulted in higher strength values, while a wetter climate led to reduced strengths. CPG strength of birch decreases by 0.05 MPa with an increase of 1 % in RH on both investigated levels; for beech, there is a slightly higher decrease of 0.07 MPa/RH% on the board level and 0.11 MPa/RH% on the material level.

A similar influence of the ambient climate on RS strength could be identified on the board level; the RS strength decreases by 0.04 MPa with a 1 % higher RH. The results on the material level did not agree with the general trend for different moisture contents and thus need further investigation. This need was further confirmed by the statistical investigation of the conducted experimental tests, which yield that the statistical significance for the beech RS results of the three investigated climates was not given.

When comparing the results across different length scales, the cylindrical orthotropy of the annual ring structure on the board level contributed positively to the RS strength and negatively to the CPG strength.

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