IAWA Journal, Vol. 25 (2), 2004: 231–243

EFFECTS OF MACRO- AND MICRO-STRUCTURAL VARIABILITY ON THE SHEAR BEHAVIOR OF SOFTWOOD

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SUMMARY

Longitudinal shear strength and shear modulus of spruce and larch wood with a maximum of micro- and macro-structural variability was determined using a new testing method. Oven-dry density and slope of grain were measured after the shear tests. For the spruce wood samples, a data set of fiber and cell wall properties, i.e., lignin content, microfibril angle, fiber length, lumen diameter, cell wall thickness, latewood proportion, and ring width, was available. A multiple linear regression analysis of all fiber and cell wall properties showed a significant, but not very strong effect on the variability of shear strength ($R^2 = 0.21$). It is thus demonstrated that micro-structural variability plays a minor role in the variability of shear properties. By contrast, a multiple linear regression involving shear modulus, density, and slope of grain as three independent variables revealed an excellent possibility to model the variability of shear strength ($R^2 = 0.72$). This study demonstrates the potential for non-destructive evaluation of the shear strength of solid wood.

Key words: Compression wood, density, European larch (*Larix decidua* Mill.), multiple linear regression, normal wood, shear Modulus, shear strength, slope of grain, Norway spruce (*Picea abies* (L.) Karst.).

INTRODUCTION

With regard to mechanical properties, wood is a highly anisotropic material at any structural level. On the macroscopic scale, variability in mechanical properties mainly can be attributed to slope of grain (i.e., the direction of the wood fibers with respect to the longitudinal axis), and wood density (Kollmann & Côté 1968; Dinwoodie 1975; Bodig & Jayne 1982). On the micro- and ultra-structural level, the variability in mechanical properties is caused by anatomical features, microfibril angle (MFA), and by the chemical composition of the cell walls (Dinwoodie 1975; Côté 1981; Bodig & Jayne 1982; Bergander 2001). In contrast to the numerous studies investigating mechanical properties of axially loaded wood and their relationship to structural and physical characteristics, there are few studies on longitudinal shear behavior with respect to physical and structural properties of wood. Besides the reliable relationship between shear strength and density (Biblis & Fitzgerald 1970; Ryianto & Gupta 1996; Müller et al. 2003), correlations with other physical characteristics or structural properties are lacking (Senft & Suddarth 1967). So far, no correlation between rigidity and shear strength has been reported, since only a few methods allow the determination of shear strength and shear modulus of solid wood in a single test (Zhang & Sliker 1991; Szalai 1992). Efforts to prove a positive correlation between shear behavior parallel to the grain, modulus of elasticity (MOE), and modulus of rupture (MOR) were inconclusive (Krahmer & Sieben 1968; Larsson et al. 1998). A recent study including shear properties of visually and machine graded lumber showed a decrease of shear strength with increasing (tensile) strength classes (Schickhofer 2001). On the structural level, the tree-ring orientation perpendicular to the grain (i.e., radial and tangential direction) showed no significant influence on the longitudinal shear strength (Ryianto & Gupta 1996).

In a deflected load-bearing beam, there are shear stresses. Therefore, besides modulus of rupture and modulus of elasticity, tolerable shear stresses also are of high importance for wood structural applications. Especially in short deep beams, shear strength becomes a critical factor (Keenan & Selby 1973; Schickhofer 2000). Basic studies that focus on the effects of macro- and micro-structural variability on the shear behavior of wood are needed.

Besides the determination of shear strength (τ), shear modulus (G), and the causes for their variability, a non-destructive, simple and fast method to asses τ is desirable. Earlier work has focused on combining G and density (ρ) in a multivariate regression model, which has shown good estimates for τ (Müller et al. 2003). Since wood is highly anisotropic, slope of grain has a strong influence on all mechanical properties (Bodig & Jayne 1982), which can be also expected for shearing. Therefore, slope of grain (α) is considered an additional important parameter, which potentially influences shear properties.

MATERIAL AND METHODS

Wood from European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.) was selected for this study, since both species meet engineering requirements and they are preferred for heavy timber framing and construction uses. A maximum range of micro- and macro-structural variability of the testing material was desired to cover possible effects of wood structure on shear strength. In order to provide such variability, clear samples with different degrees of slope of grain from two different wood species were selected to include normal wood (NW), compression wood (CW), as well as juvenile and mature wood.

The juvenile spruce wood originates from an earlier European project (PL97 3953 "Genetic improvement of wood quality" http://www.skogforsk.se/GENIALITY/). In this project, a number of cell and fiber properties (Table 1) were determined and could be further utilized for the present study. With the exception of lignin content and pulp yield, which were determined from specimens containing all (i.e. approximately 30) growth rings, all other cell and fiber properties listed in Table 1 were determined for

Table 1. Matrix of correlation between fiber and cell wall properties of the spruce wood samples and the principal components. MFA-EW = microfibril angle of earlywood tracheids, MFA-LW = microfibril angle of latewood tracheids, LW-prop. = latewood proportion, cw- = cell wall thickness, ld- = lumen diameter, EW = earlywood, LW = latewood, -r = radial direction, -t = tangential direction, tracheids in radial direction. Numbers correspond to the principal component extraction for the 15 parameters. The main loadings (i.e., most significant correlation coefficients) are bold-typed.

	PC 1: 'fiber properties'	PC 2: 'cell wall dimensions'	PC 3: 'ring properties'	PC 4: 'cell lumen dimensions'
Lignin content	**.802**	.053	-.201	.170
Pulp yiels	**-.766**	.137	.177	.054
MFA-EW	**.723**	-.175	-.449	-.264
MFA-LW	**.751**	-.230	-.354	-.212
Fiber length	**-.635**	-.043	.014	.043
Ring width	.300	-.181	**-.777**	-.279
LW-prop.	.064	.164	**.864**	.095
cw-ER-r	.070	**.893**	.073	.174
cw-LW-r	-.494	**.555**	.540	-.096
cw-EW-t	.081	**.858**	.251	.143
cw-LW-t	-.536	**.563**	.475	.025
ld-EW-r	.089	.109	.098	**.763**
ld-LW-r	.364	-.418	-.038	**.603**
ld-EW-t	-.319	.408	.367	**.601**
ld-LW-t	-.061	.165	.114	**.811**

individual growth rings, i.e. rings 5, 12, and 23, counting from the pith. The kiln dried larch wood used for the preparation of shear specimens was purchased from a sawmill.

From a total of 170 samples, 90 samples of juvenile spruce wood taken from the project mentioned above containing either the growth ring 5, 12, or 23 and 80 samples were taken from mature larch wood. Twenty-five of the larch samples contained substantial amounts of compression wood. Samples with a cross section of 14 × 14 mm and a total length of 135 mm were prepared so that the sides were parallel to the growth rings and the wood rays. From each of these 170 samples, a shear specimen 100 mm long and a specimen 30 mm long (wood density and grain angle) were cut.

Prior to testing, all samples were stored at 20 °C and 65% relative humidity for one month to ensure a uniform moisture content of about 11%. Oven-dry density (ρ_0) was calculated from the volume and the weight of the 30 mm long samples. After determining oven dry density, the samples were split radially using a steel wedge. The slope of grain with respect to the longitudinal specimen axis was measured on all samples by means of a goniometer as described by Gindl and Teischinger (2003a).

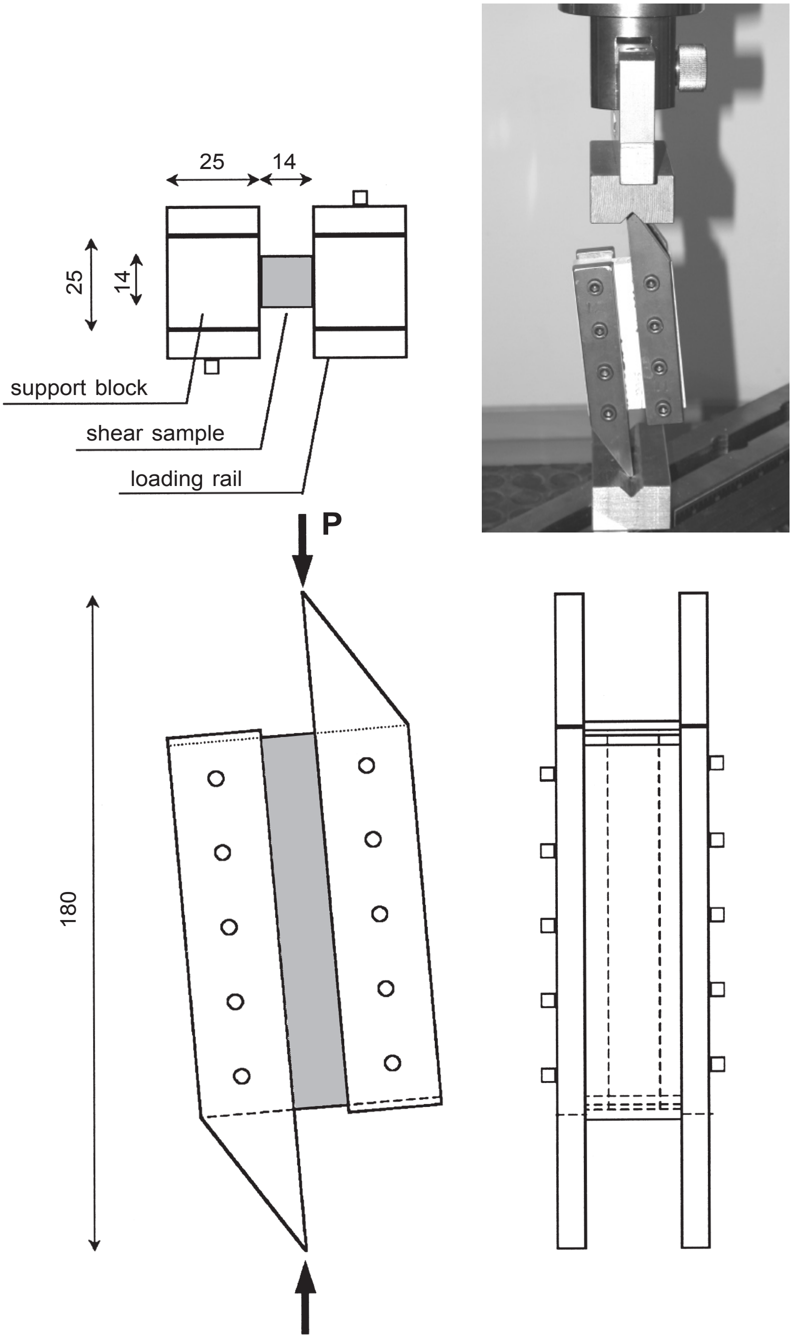

Fig. 1. Total length of the shear mounting = 180 mm, length of the loading rails = 150 mm, slope of the shear mounting = 4.6° and shear sample dimensions are length × width × thickness = 100 × 14 × 14 mm.

According to the terminology for describing fracture types by Bodig and Jayne (1982), Mode II experiments were conducted in tangential-longitudinal (TL) and radial-longitudinal (RL) direction. As an example, the notation RL indicates that the sample is loaded in longitudinal shear mode with the crack plane normal to the R direction and the crack front propagating in the L direction. Figure 1 shows the test set-up used for determining G and τ. The test specimens were glued between two support blocks of beech wood (25 × 25 × 100 mm) using a phenolic resin. Beech was chosen because of its high shear modulus ($G = 1600\ \text{N/mm}^2$) and shear strength ($\tau = 20\ \text{N/mm}^2$) (Keylwerth 1951). Finally, two pairs of steel loading rails were fixed to the beech support blocks by means of a rapidly hardening epoxy glue and additionally bolted together with four screws. All samples were tested in compression mode in a Zwick/Roell Z 100 kN universal testing machine, applying the load at a constant cross-head speed of 0.6 mm/min. Shear modulus was computed from the cross-head movement by using equation (1),

$$G = (\Delta F) * t/(\cos 4.6° * (\Delta u) * w * l) \tag{1}$$

where ΔF and Δu are the differences of force and deformation, respectively, between 10 and 40% of the maximum load, t and w are the sample thickness and width, l is the sample length, and 4.6° is the inclination of the loading rails. On the other hand, beside the sample deformation also the elastic deformation of the testing machine itself and of the test set-up give a contribution to the recorded deformation.

To correct the systematic error of the deformation measurement due to the elastic deformation of the steel loading rails and the testing machine itself, a 25 mm thick steel plate was clamped between the two pairs of steel loading rails instead of the sample. The steel plate within the set-up was loaded and a stress/strain curve recorded. This curve was superimposed on all stress/strain curves of all test data to obtain true shear deformation of the samples. Shear strength was calculated with equation (2),

$$\tau = F_{max} * \cos 4.6°/(w * l) \tag{2}$$

After the shear tests in the TL and RL system, thin slices (4 × 4 mm) were dissected from the fracture surfaces of selected NW and CW larch wood samples. A gold layer was sputtered on the samples and then they were observed under the scanning electron microscope (Philips, XL 30 ESEM) operating at 15 kV.

RESULTS

As no significant differences ($p \leq 0.05$) of τ and G were found between the TL and RL mode, no distinction was made between these two modes in further analyses. Table 2 lists mean values for ρ, τ, and G of the investigated specimens. Larch CW samples were characterized by a 77% higher maximum τ and a 48% higher G, compared to larch NW, the latter showing 36% higher τ and 22.5% higher G than spruce NW. All differences were significant at the $p < 0.05$ level (ANOVA).

All groups of specimens had a high variability of density, ranging from 0.28 to 0.52 g/cm^3 for spruce, from 0.32 to 0.62 g/cm^3 for larch NW, and from 0.66 to 0.77

Table 2. Oven-dry density (ρ), shear strength (τ) and shear modulus (G) of spruce and larch NW and larch CW.

	ρ (± SD) [g/cm^3]	τ (± SD) [MPa]	G (± SD) [MPa]
Spruce	0.37 (± 0.05)	5.5 (± 1.4)	541 (± 107)
Larch NW	0.51 (± 0.08)	7.5 (± 1.6)	663 (± 119)
Larch CW	0.72 (± 0.03)	11.7 (± 1.9)	1027 (± 174)

g/cm^3 for larch CW. Consequently, high variability was observed for τ and G (Fig. 1). Considering all samples, a linear regression analysis between ρ on G yielded a coefficient of determination of $R^2 = 0.58$. The variability of G explained by the slope of grain α was less ($R^2 = 0.13$). With both ρ and α included in the regression model as independent variables G was estimated with a coefficient of determination of $R^2 = 0.63$. To summarize, it can be said that the shear modulus G of the tested samples is influenced by density, and to a lesser extent by the slope of grain. In the following, effects of wood density and slope of grain on shear strength τ, as well as the correlation between G and τ are examined.

Table 3. Simple linear regression analysis between shear strength (τ), shear modulus (G), density (ρ), and slope of grain (α) (*** linear regression is significant at the 0.001 level).

	G	ρ	α
τ	0.69***	0.48***	0.28***
G	—	0.58***	0.14***
ρ	—	—	0.03

Coefficients of determination for simple linear regressions analyses between τ, G, ρ_0, and α are given in Table 3. The strongest relationship between τ and G ($R^2 = 0.69$), is plotted in Figure 2. Figure 3 shows a scatter plot of shear strength τ against wood density; coefficient of determination was $R^2 = 0.48$. Finally, when τ is plotted with the slope of grain (Fig. 4), a modest linear relationship was obtained ($R^2 = 0.27$).

A multiple linear regression model (MLR, Eq. 3) with G, ρ_0, and α as the independent variables estimated τ with a coefficient of determination of 0.72.

$$\tau_{pred} = -0.5 + 7e\text{-}3\ G + 4\ \rho_0 + 3e\text{-}1\ \alpha \qquad (3)$$

In Figure 5 the modelled shear strength is plotted against the measured one.

Table 1 shows a variety of cell and fiber parameters that were available for the spruce samples. Many of these parameters show significant correlation with each other. When a multiple linear regression analysis is performed using correlated independent vari-

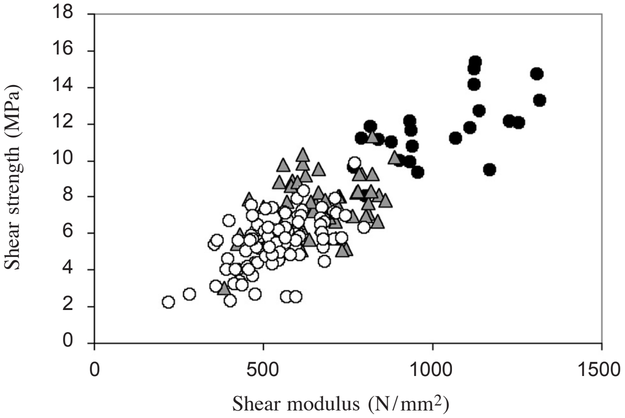

Fig. 2. Relationship between shear strength and shear modulus. ○ = spruce normal wood; ▲ = larch normal wood; ● = larch compression wood.

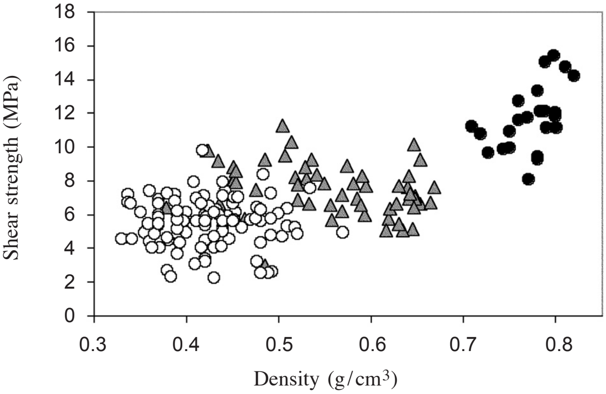

Fig. 3. Relationship between shear strength and kiln dry density. ○ = spruce normal wood; ▲ = larch normal wood; ● = larch compression wood.

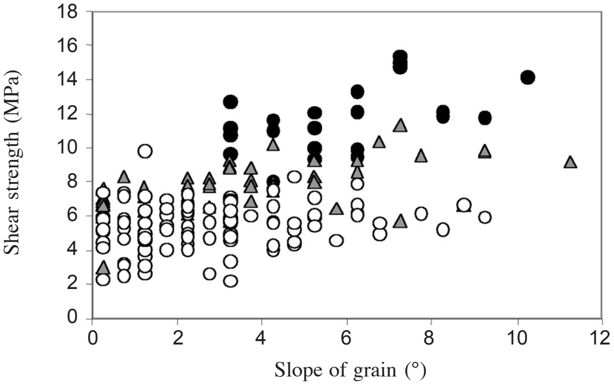

Fig. 4. Relationship between shear strength and slope of grain. ○ = spruce normal wood; ▲ = larch normal wood; ● = larch compression wood.

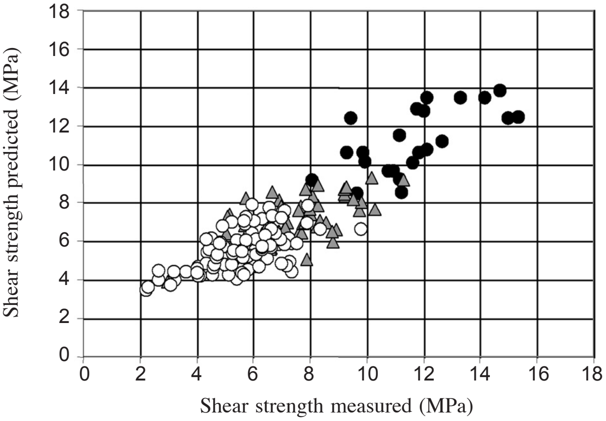

Fig. 5. Relationship between the prediction of the shear strength calculated from the multivariable regression model including the independent variable G, ρ, and slope of grain and experimentally measured shear strength. ○ = spruce normal wood; ▲ = larch normal wood; ● = larch compression wood.

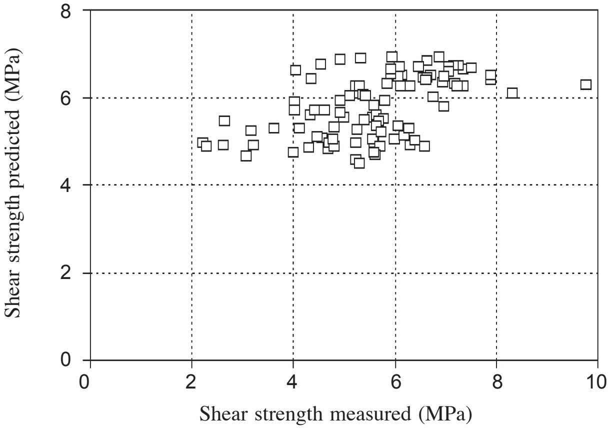

Fig. 6. Relationship between the shear strength predicted from a multivariable regression model including cell wall and fiber properties and experimentally measured shear strength of spruce wood samples.

ables, the resulting regression equation and coefficient of determination become untrustworthy due to mathematical reasons (SPSS Handbook). Principal component analysis is a mathematical method available in SPSS, which transforms a set of variables into a set of new variables, which are correlated to the original data set. The new set of variables represents the total variability of the original data set with the advantage that the new variables are not correlated with each other (i.e., they are orthogonal). Out of the transformed set of variables (or principal components, PCs), SPSS identified four significant PCs which represented 74% of the initial variability. Table 1 lists the correlation coefficients between these 4 PCs and the original variables. The first component is interpreted as "fiber properties", including fiber length, microfibril angle (MFA) of earlywood and latewood, kraft yield, and lignin content; ; PC2 = "cell wall dimensions", including radial and tangential width of earlywood and latewood tracheids; PC3 as "ring properties", containing ring width and latewood proportion; and PC4 = "cell lumen dimensions" including radial and tangential lumen diameter of earlywood and latewood tracheids. Although no significant relationship existed between the four principal components and the shear modulus, a significant relationship was present with shear strength ($R^2 = 0.21$, $p < 0.001$). Figure 6 is a plot showing the modelled and the actual shear strength values.

SEM micrographs of the fracture surfaces of NW tested in the TL system showed transwall failure in the earlywood (Fig. 7A). Transwall failure was also observed in the latewood regions without rays (Fig. 7A upper micrograph), whereas latewood cells between wood rays were typically characterized by intrawall failure with the compound middle lamella and the S_1 involved (Fig. 7A bottom micrograph). NW loaded in the RL system was solely characterised by transwall failure of earlywood tracheids (Fig. 7B). CW tested in the TL system appeared to fail primarily by intrawall fracture (Fig. 7C). The intrawall failure takes place at the interface of compound middle lamella and S_1 or somewhere close to it. Intrawall failure was also seen for CW tested in tangential shear (RL system). The cell walls failed either at the compound middle lamella, in the S_1 or S_2, or at their interface (Fig. 7D).

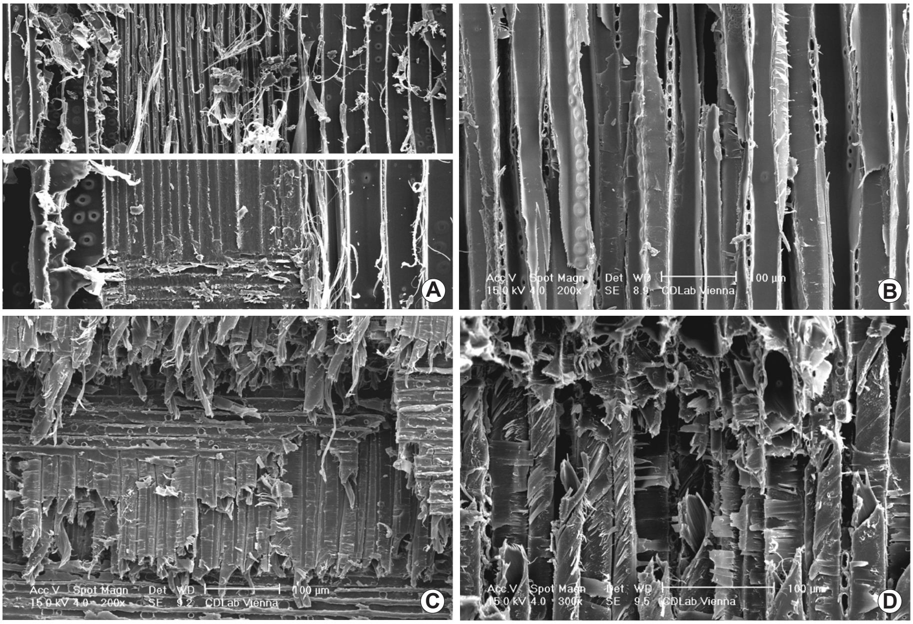

Fig. 7. Fracture surfaces of NW samples failed in the TL (**A**) and TR plane (**B**) and of CW samples tested in the TL (**C**) and TR plane (**D**).

DISCUSSION

A statistical analysis of the shear test data showed no significant relationship between τ and ring orientation (i.e., no difference in shear strength between the TL and RL system, respectively). This finding agrees well with results published by Ryianto and Gupta (1996). The lack of a significant difference of shear strength in the TL and RL system could be explained by the failure pattern observed in the SEM. While the plane of fracture was parallel to the tracheid axis and the growth rings in the RL mode, it was parallel to the wood rays in the TL mode. In the RL mode only transwall fracture of earlywood tracheids was observed (Fig. 7B). In the TL mode, earlywood fractured also in transwall failure (Fig. 7A), whereas two different failure mechanisms were present for latewood in this mode. In regions without rays, latewood tracheids were characterised by transwall failure (Fig. 7A upper micrograph), while latewood cells in the vicinity of rays showed intrawall failure. Due to the presence of thick-walled latewood tracheids in the TL mode fracture plane, higher shear strength could be expected compared to the RL mode with only thin-walled earlywood tracheids involved. On the one hand, rays may act as reinforcing elements in RL mode (Burgert et al. 1999; Reiterer et al. 2002). On the other hand, rays potentially cause negative effects on the strength in the TL mode due to their exposition to shear stress normal to their longitudinal axis. Failure under such a stress status is called rolling shear, and maximum stresses obtained in rolling shear are drastically lower than for shear strength obtained in longitudinal direction (Bendtsen 1976; Dumail et al. 2000). As was the case for shear strength, no significant effects of ring orientation on G were observed. These mechanisms leading to the same shear strength in the RL and the TL mode, might also be true for the shear modulus, i.e. no difference between TL and RL mode. It was proposed that wood rays act as reinforcements equivalent to bolts in RL mode shearing (Burgert et al. 1999; Reiterer et al. 2002), whereas they may have a negative effect in TL mode shearing, where they possibly serve as initiation points for fracture (Dumail et al. 2000).

One of the major drawbacks of most methods for measuring shear properties (ASTM D-143; DIN 52187; EN 408; EN 789; Biblis & Fitzgerald 1970; Liu 1984; Zhang & Sliker 1989; Janowiak & Pellerin 1991; Lang 1997; Divos et al. 1998) is that either τ or G is measured, but not both. With the proposed shear test set-up used here, G and τ can be measured simultaneously, which allows directly relating both properties (Fig. 2). Stress grading of lumber, an important non-destructive and widespread testing technology, takes advantage of the strong correlation between bending strength and the dynamic or static MOE as a main predictor parameter (Divos & Tanaka 1997). For shear strength, such a predictor parameter has not been defined yet. The effects of a variety of macro- and microstructural parameters on shear strength are discussed below.

In general, mechanical properties increase with density (Kollmann & Côté 1968). In comparison to axial tensile, compression, and bending properties, only a modest increase in shear strength with increasing density was observed for spruce and larch NW samples. Compared to NW samples, CW samples showed a significantly higher average shear strength, even when the shear strength values were corrected for differences in density (Table 2, Fig. 3). In a recent study, the differences in shear strength between larch NW and CW were explained by differences in cell wall structure and chemical composition (Gindl & Teischinger 2003b). Regardless of the slight abnormalities of CW in shearing, a sound linear relationship existed between τ and ρ.

Slope of grain is another primary factor with strong effects on a number of mechanical properties (Dadswell 1958; Panshin & DeZeeuw 1964; Dinwoodie 1975). Spiral grain, stem taper, and knots are causes for longitudinally oriented cells to deviate from the vertical axis. In spite of the rather low variability of the grain angle between 0° and 11° present in the investigated samples, a linear relationship between shear strength and slope of grain was found (Fig. 4). In the presence of knots, fiber deviations may reach 50° (Karsulovic et al. 2000). Therefore, stronger effects of slope of grain on shear strength can be expected in structural and glued laminated timber than in small and defect free samples as tested in this study. Schickhofer (2001) investigated shear strength of whole glulam beams consisting of visually and machine graded timber and reported a positive relationship between knottiness and shear strength. He also observed better shear properties for lamellas consisting of juvenile wood, which is usually characterised by higher spiral grain (Krempl 1970). This indicates that slope of grain is an important parameter with respect to shear behavior.

We found that shear properties of larch NW differ slightly from CW, despite pronounced cell structural and chemical differences between NW and CW (Timell 1985). Similarly for spruce, no correlation was obtained between the shear modulus and microstructure represented by the four principal components. For shear strength, only 21% of the variability was explained by microstructure. Such modest effects of varying microstructure on shear properties, contrasting with the significant effects on Young's modulus and tensile and bending strength (Kollmann & Côté 1968; Salmén & De Ruvo 1985; Reiterer et al. 1999), may be partially explained by linear orthotropic elasticity theory (Müller et al. 2003). When the shear modulus G of a cell wall is modelled by using laminate theory, high G is caused by an increase of MFA, whereas an increasing lignin content reduces G. With increasing compression wood content, greater microfibril angles are always accompanied by an increase of lignin content (Timell 1985; Gindl 2002). Therefore, the increasing and decreasing effect of MFA and lignin content, respectively, may compensate each other to a large degree, keeping changes in shear modulus low (Müller et al. 2003). A similar mechanism may be present for shear strength.

The variable achieving the best linear relationship with shear strength was the shear modulus G. This parameter can be quickly and precisely determined through a torsional vibration technique (Divos et al. 1998), and is therefore most promising for the non-destructive evaluation of shear strength. Density measurement of wood and wood based materials by means of X-ray measurement is state-of-the-art in the forest products industry and could be easily used to enhance the quality of the prediction of shear strength. Finally, there are ways to determine the slope of grain non-destructively (e.g. McLauchlan et al. 1973), which would allow including this parameter for shear property prediction.

The results from this study clearly demonstrate that a multiple regression model on the basis of the three independent variables shear modulus, wood density, and slope of grain has high potential to describe the variability of shear strength. Therefore, grading of lumber with respect to shear strength based on the shear modulus, the wood density, and slope of grain should be possible in the future. In combination with stress grading to predict bending strength, shear-strength grading could help to ensure the reliability of wooden structures.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support by the Austrian Science Fund FWF (Project P15410-B03).

REFERENCES

American Society of Testing and Materials (ASTM). 1992. Standard methods of testing small clear specimens of timber. ASTM D 143-83. Vol. 04.09. Wood. ASTM, West Conshokocken, Pa.

Bendtsen, B. A. 1976. Rolling shear characteristics of nine structural softwoods. Forest Prod. J. 26 (11): 51–56

Bergander, A. 2001. Local variability in chemical and physical properties of spruce wood fibers. PhD thesis, Royal Institute of Technology, Stockholm.

Biblis, E. J. & J. D. J. Fitzgerald. 1970. Shear properties of loblolly pine growth zones. Wood Sci. 2: 193–202.

Bodig, J. & B. A. Jayne. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold Co. Inc., New York, NY.

Burgert, I., A. Bernasconi & D. Eckstein. 1999. Evidence for the strength function of rays in living trees. Holz Roh Werkstoff 57: 397–399.

Côté, W. A. 1981. Ultrastructure. Critical domain for wood behavior. Wood Sci. Technol. 15: 1–29.

Dadswell, H. E. 1958. Wood structure variations occurring during tree growth and their influence on properties. J. Inst. Wood Sci. 1: 1–24.

DIN 52187. 1979. Testing of wood; determination of ultimate shearing stress parallel to grain. Normenausschuß Holz im DIN.

Dinwoodie, J. M. 1975. Timber – a review of the structure-mechanical property relationship. J. Microscopy 104: 3–32.

Divos, F. & T. Tanaka. 1997. Lumber strength estimation by multiple regression. Holzforschung 51: 467–471.

Divos, F., T. Tanaka, H. Nagao & H. Kato. 1998. Determination of shear modulus on construction size timber. Wood Sci. Technol. 32: 393–402.

Dumail, J-F., K. Olofsson & L. Salmèn. 2000. An analysis of rolling shear of spruce wood by the Iosipescu method. Holzforschung 54: 420–426.

EN 408. 1999. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. Fachnormenausschuß 012 Holzbau.

EN 789. 2002. Timber structures – Test methods – Determination of mechanical properties of wood based panels. Fachnormenausschuß 012 Holzbau.

Gindl, W. 2002. Comparing mechanical properties of normal and compression wood in Norway spruce: the role of lignin in compression parallel to the grain. Holzforschung 56: 395–401.

Gindl, W. & A. Teischinger. 2003a. The potential of VIS- and NIR-spectroscopy for the non-destructive evaluation of grain-angle in wood. Wood Fiber Sci. 34: 651–656.

Gindl, W. & A. Teischinger. 2003b. Comparison of the TL-shear strength of normal and compression wood of European larch. Holzforschung 57: 421–426.

Janowiak, J. J. & R. F. Pellerin. 1991. Iosipescu shear test apparatus applied to wood composites. Wood Fiber Sci. 23: 410–418.

Karsulovic, J.T., L. A. León & L. Gaete. 2000. Ultrasonic detection of knots and annual ring orientation in Pinus radiata lumber. Wood Fiber Sci. 32: 278–286.

Keenan, F. J. & K. A. Selby. 1973. The shear strength of Douglas-fir glued-laminated timber beams. Publ. No. 73-01. Toronto, Dept of Civil Engineering. University of Toronto, Ontario.

Keylwerth, R. 1951. Die anisotrope Elastizität des Holzes und der Lagehölzer. Düsseldorf, Deutscher Ingenieur-Verlage GmbH.

Kollmann, F.P. & W.A. Côté. 1968. Principles of wood science and technology. I Solid wood. Springer-Verlag New York Inc.

Krahmer, R.L. & H.U. Sieben. 1968. Effect of span-to-depth ratio on modulus of elasticity of Douglas-Fir joists. Forest Prod. J. 18 (1): 81–83.

Krempl, H. 1970. Untersuchungen über den Drehwuchs bei Fichte. Mitt. Forstl. Bundesversuchsanstalt Wien 89.

Lang, E.M. 1997. An alternative method for shear strength assessment. Forest Prod. J. 47 (11/12): 81–84.

Larsson, D., S. Ohlsson, M. Perstorper & J. Brundin. 1998. Mechanical properties of sawn timber from Norway spruce. Holz Roh Werkstoff 56: 331–338.

Liu, J.Y. 1984. New shear strength test for solid wood. Wood Fiber Sci. 16: 567–574.

McLauchlan, T.A., J.A. Norton & D.J. Kusec. 1973. Slope-of-grain indicator. For. Prod. J. 23 (5): 50–55.

Müller, U., W. Gindl, A. Sretenovic & A. Teischinger. 2003. Modeling the longitudinal shear properties of softwood with regard to macro- and micro-structural variability . In: European Society for Wood Mechanics, 2nd International Conference of the European Society for Wood Mechanics, May 25–28, Stockholm, Sweden: p. 111–114.

Panshin, A.J. & C. DeZeeuw. 1964. Textbook of wood technology. Vol. 1. McGraw-Hill, New York.

Reiterer, A., I. Burgert, G. Sinn & S. Tschegg. 2002. The radial reinforcement of the wood structure and its implication on mechanical and fracture mechanical properties – A comparison between two tree species. J. Material Sci. 37: 935–940.

Reiterer, A., H. Lichtenegger, S. Tschegg & P. Fratzl. 1999. Experimental evidence for a mechanical function of the cellulose microfibril angle in wood cell walls. Phil. Mag. 79: 2173–2184.

Ryianto, D.S. & R. Gupta. 1996. Effect of ring angle on shear strength parallel to the grain of wood. Forest Prod. J. 46 (7/8): 87–92.

Salmén, L. & A. de Ruvo. 1985. A model for the prediction of fiber elasticity. Wood Fiber Sci. 17: 336–350.

Schickhofer, G. 2000. Determination of shear strength values for an economical design of full sized GLT elements and implementation of the results in national and international standards. Report of the project LR 9802/4. University of Technology Graz, Austria.

Schickhofer, G. 2001. Determination of shear strength values for GLT using visual and machine graded spruce laminations. CIB W18-Meetings, Venice.

Senft, J.F. & S.K. Suddarth. 1967. Critical shear stress in light framing lumber. Forest Prod. J. 17 (12): 48–49.

Szalai, J. 1992. Indirekte Bestimmung der Scherfestigkeit des Holzes mit Hilfe der anisotropen Festigkeitstheorie. Holz Roh Werkst. 50: 233–238.

Timell, T.E. 1985. Compression wood in Gymnosperms. Vol. 1. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Zhang, W. & A. Sliker. 1991. Measuring shear moduli in wood with small tension and compression samples. Wood Fiber Sci. 23: 58–68.