WCTE
WORLD CONFERENCE ON TIMBER ENGINEERING
2010

WITHDRAWAL CAPACITY OF SCREWS IN EUROPEAN ASH (*FRAXINUS EXCELSIOR* L.)

Ulrich Hübner[1], Mathias Rasser[2], Gerhard Schickhofer[3]

ABSTRACT: The accrescence of hardwoods in Austria, Germany and Switzerland exceeds the current demand by about one third. The medium quality log classes B and C of European hardwoods according to EN 1316 (1997) can be used for the production of glue laminated timber (GLT). The European ash (*Fraxinus excelsior* L.) is the third frequent deciduous trees in the aforementioned countries and impresses by very good mechanical properties, the relatively low shrinkage and the good gluing behaviour.
Wood screws are commonly used and powerful connectors in load bearing timber structures. The calculation model for the withdrawal capacity according to ON EN 1995-1-1 (2009) is based on withdrawal tests with spruce (*Picea abies* (L.) Karst.). The wood species influences the withdrawal strength by means of charakteristic density. Due to the considerably higher mean density of European ash compared to spruce it seems reasonably to verify the given calculation model for hardwoods.
2571 withdrawal test results will be presented and analysed regarding the influence of screw diameter d (4 to 20 mm), nominal penetration length l_{nom} and effective penetration length l_{ef} (3 d to 8 d), the angle of the screw axis to the grain α (0°, 15°, …, 90°) and the density ρ on the withdrawal capacity R_{ax}. A modified calculation model for the withdrawal capacity of European ash will be suggested.

KEYWORDS: Screws, hardwood, ash, withdrawal strength

1 INTRODUCTION

The entire stock of deciduous trees in Austria increased by 26 % between 1986 and 2001, in detail European beech *(Fagus sylvatica* L.) 19 %, oak 22 % and European ash (*Fraxinus excelsior* L.) 65 %. The stock of deciduous trees in the western part of Germany showed the same trend with an increase of 32 % between 1987 and 2002. Only 30 % of this accrescence of oak (*Quercus spp.* L.) was used (beech 46 % and deciduous trees in general 37 %). Two thirds of the raw material, including trunk with bark, crown and branches, are used for energy recovery in Austria. About 15 % of the raw material are logs with mean diameter greater than 20 cm.
Therefore, it is a necessity to put more effort into the utilisation of sawn timber from mean quality deciduous logs. The mechanical properties and the precious aesthetic suggest using hardwoods for load bearing structures.
European ash shrinks and swells less than beech timber. Therefore the stresses due to alterations of moisture content (MC) should be less than in beech and bond lines of GLT. The mechanical properties of ash are slightly better than those of beech. In order to tap the full potential of hardwoods it is indispensable to investigate the material properties as well as to verify or adapt the calculation models. The following work makes a contribution to increase the practical use of hardwood products like GLT where the external parts or the whole section are made of hardwoods. The investigation of the withdrawal capacity of screws and threaded rods according to DIN 7998 (1975) in European ash follows the investigations on strength grading of boards (Hübner and Leeb 2007), the determination of compression and tension strength perpendicular to grain (Hübner 2009), the shear modulus (Hübner 2010), and the embedment strength of dowel type fasteners (Hübner et al. 2008).

2 LITERATURE RESEARCH

Fairchild (1926) inserted over 10,000 screws in yellow poplar, cypress, sycamore, North Carolina pine, Georgia pine, hard maple and white oak. "The effect of various sizes of lead holes, of screw lubrication, of cracks in the wood, and of the dimensions and finish of the screws is described" (Fairchild, 1926).
The withdrawal capacity of screws (ø 3.51 mm to 4.83 mm) was determined by Cockrell (1933) in green and dried 19 mm boards out of four soft- and six hardwoods. The recalculation of the results showed that the withdrawal capacity for densities higher than 650 kg/m³ decreases 1.9 % when MC increased by 1 %. The best fit between the withdrawal strength at 12 % MC and the

[1] Ulrich Hübner, holz.bau forschungs gmbh, Inffeldgasse 24, 8010 Graz, Austria. Email: huebner@tugraz.at
[2] Mathias Rasser, Master student of the Institute for Timber Engineering and Wood Technology, Graz University of Technology, Austria
[3] Gerhard Schickhofer, Institute for Timber Engineering and Wood Technology and holz.bau forschungs gmbh, Inffeldgasse 24, 8010 Graz, Austria. Email: gerhard.schickhofer@tugraz.at

density shows a nearly identical power function for screws in radial and tangential direction with an exponent of about 1.55. An exponent of 1.32 was determined for screws parallel to the grain.

Newlin and Gahagan (1938) found a linear relationship between withdrawal capacity and penetration length.

Eckelman published more than a dozen articles concerning screws in furniture production. Eckelman (1975) found that the withdrawal capacity of screws in solid timber is better correlated to shear strength than to density.

The main objective of Bröker and Krause (1991) was to determine the dynamic withdrawal capacity of screws, but they also made static tests with screws (ø 3.5 to 5 mm) perpendicular to the grain in beech (ρ_{mean} = 720 kg/m³). The calculated mean withdrawal strength of 16.3 N/mm² for ø 4 mm in beech corresponds well with the 17.6 N/mm² in ash (ρ_{mean} = 746 kg/m³) of the own investigations.

Schneider (2000) analysed 911 withdrawal tests of EJOT window frame screws in beech and azobé (*Lophira alata* Banks ex Gaertn.) from Jablonkay (1999). He determined the influence of the angle to the grain, the density, the screw tip and the MC by means of regression analyses based on power functions. Schneider published an exponent of 1.78 for the density, 0.86 and 0.84 for the effective length parallel and perpendicular to the grain, respectively.

Bejtka (2005) calculated a regression model for 413 withdrawal tests perpendicular to the grain in spruce (*Picea abies* Kastn.) with five different screw types (6 mm, 7.5 mm, 8 mm, 10 mm and 12 mm) of three manufacturers. Blaß, Bejtka und Uibel (2006) continued this research and expanded it to 799 test considering angles to the grain of 0°, 15° … 90°. The tip of the screw was always outside of the specimen and the specimen's thickness was equal to 4 *d*. The characteristic withdrawal capacity in ON EN 1995-1-1 (2009) is based on the regression analysis of Blaß, Bejtka und Uibel (2006).

Koch and Dünisch (2008) reported no mechanical difference between juvenile and mature timber of Black locust (*Robinia pseudoacacia* L.) in general but also regarding withdrawal capacity. Screws in radial and tangential direction differed only insignificantly.

Horvath et al. (2008) analyzed the influence of the MC on the shear strength (LR, LT, RL and TL) of spruce, beech and oak clear wood specimens. The relative decrease of the shear strength within one species for different shear planes and for loads parallel or perpendicular to the grain is linear between 6 % and 27 % MC and similar for one species. The mean relative decreases of the shear strength are 2.24 % for spruce, 1.29 % for oak and 2.67 % for beech with each percent raising MC. The influence of MC on the withdrawal strength should be in the same range (see Cockrell, 1933).

Pirnbacher (2009) investigated the influence of MC, temperature, density, screw tip, angle to the grain, predrilling and embedment of partly threaded screws on the withdrawal capacity of self-tapping screws in spruce. Pirnbacher (2009) measured and explained the different withdrawal capacities of screws with full thread and partly threaded screws, where the thread begins under the surface of the specimens. If a fully threaded screw is charged with axial tension load, the load distribution near the surface is disturbed. Figure 1 shows one half of the specimen after pulling out a rod ø 20 mm perpendicular to grain. The fibres were bended in load direction. The effected length in fibre direction is much longer near the surface as visualised by the black curves. Chips of wood are near the surface.

Pirnbacher (2009) demonstrated that the withdrawal capacity of a partly threaded screw ø 8 mm with a nominal length of 100 mm is 15 % higher if the top pitch of the thread is 2 *d* under the surface. This effect is not covered by the presented paper.

ON EN 1995-1-1 (2009), SIA 265 (2003) and DIN 1052 (2008) consider the angle between the axial loaded screw and the grain direction with the function published by Hankinson (1921).

Frese and Blaß (2009) published a calculation model for self-tapping screws in softwood with diameters between 4 and 14 mm, for penetration depths between 20 and 140 mm which is applicable independent of the angle between 45° and 90°. The power of the diameter is −0.3423.

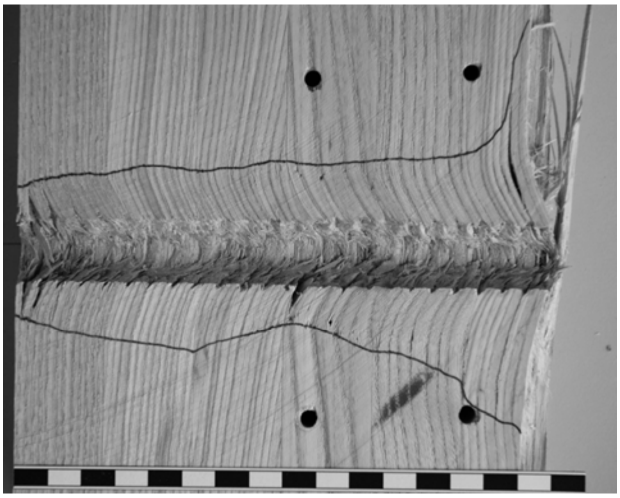

Figure 1: *Specimen after pulling out a rod ø 20 mm*

3 SPECIMEN

3.1 EUROPEAN ASH FOR GLT

The raw material for investigations presented here was harvested in the Austrian region "Bucklige Welt" in the growth area "Östliche Randalpen". The Boards (27 mm) were glued with MUF Kauramin 683 and hardener Kauramin 688 to GLT. The specimen for investigations on angles from 15° to 75° were sawn from six GLT beams. The regular spacing and edge distance was 5 *d*. The minimum width of specimen for the rods (ø 20 mm) threaded according to DIN 7998 (1975) was 140 mm. Pilot tests showed the need for reinforcement normal to the rod axis with four or eight screws ø 8/160 mm to prevent splitting. All specimens were stored under normal conditions with (20±1) °C and (65±5) % relative humidity (RH) until constant mass was reached.

a) Test with ø 6mm b) displacement transducer c) clamping device on ø 20 mm rod

Figure 2: *Test configuration*

3.2 SCREWS AND THREADED RODS

The following screws and threaded rods were used:

- ø 4/70 and ø 6/300 Schmid Star Drive partial thread (Z-9.1-435)
- ø 8/300 Schmid Star Drive full thread (Z-9.1-656)
- ø 10/300 and 12/300 Spax-S screw (Z-9.1-519)
- ø 20/600 SFS WB threaded rod

The diameter of the pilot hole was equal to 0.7 *d* for all screws and equal to the minor diameter of 15 mm for the threaded rods. The maximum screw tensile force was tested on 36 screws Schmid Star Drive 8/300 from six different production charges. The rupture was mostly located at the beginning of the thread under the screw head. The mean value was 25.9 kN ($CoV = 1.27$ %, $R_{t,min} = 25.1$ kN). The German technical approval indicates the characteristic capacity of $R_{t,u,k} = 23{,}0$ kN.

4 TEST CONFIGURATION

4.1 TEST SERIES

Each test series contains 60 specimens. The angle between screw axis and grain direction varies from 0°, 15° to 90° for the diameters 6 mm, 8 mm, 10 mm and 12 mm. For diameters 4 mm and 20 mm only 0° and 90° were tested. The tip of the screws and the serrated thread were as a rule not embedded in the specimen. Generally the wood specimen's thickness was 6 *d*, but for ø 12 mm it was 5 *d* and 8 *d* for the threaded rods. The influence of the penetration length on the withdrawal capacity of screws ø 8 mm was studied with penetration lengths of 4 *d*, 6 *d* and 8 *d* perpendicular and longitudinal to the grain. Eight series with embedded tips were tested to analyse the influence of the tip on the withdrawal capacity. In total 2571 tests in 42 series were executed. In the names of the series *ESDD_WW_LL* the first two letters *ES* denote the species European ash, *DD* the diameter of the screw, WW the angle between screw axis and grain direction and *LL* the penetration length of the thread. If the tip was embedded in the specimen *S* was attached.

4.2 TEST CONFIGURATION FOR SCREWS

The screw was inserted into the lead hole of the specimen. Then the head of the screw was inserted through the hole of the bearing plate (Figure 2 a). The screws were auto centred in a snugly countersunk of a thick washer in the T slot of the holder. The hole in the bearing plate was defined with a diameter of 4 *d* (a slight deviation from EN 1382 (1999) which defines "no part may be nearer than 3 *d* "). The preload allowed centring of the screw in the bearing plate with custom made thick washers. The test machine was manufactured by *Zwick-Roell* and is equipped with a 250 kN load cell of the accuracy class 0.5 according to DIN EN ISO 7500-1 (2004). Two clamping devices allowed the measurement of the displacement of screw or rod above the bearing plate with displacement transducers (Figure 2 c). The displacement of the tip of the screw – if it was outside the specimen – and of the lower end of the rod was recorded as well. The monotonic loading rate was adapted for each screw diameter to reach the maximum load after (90 ± 30) s according to EN 1382 (1999), for screws with ø 6 mm it was 1 mm/min.

4.3 TEST CONFIGURATION FOR THREADED RODS

The specimens were reinforced perpendicular to the axis of the rod with 8 screws 8/160 to prevent splitting (see Figure 1). The rod standard length of 3000 mm was cut into 5 × 600 mm and on one end the thread was turned off to clamp the minor diameter with a *647 Hydraulic Wedge Grip* manufactured by *MTS Corporation of Minneapolis*. A four-speed drill DDsk 672-1 of *C. & E. Fein GmbH* was used to screw the threaded rods with 100 min^{-1} into the specimens. Two bearing plates were fixed on the top of the holder (Figure 2 b). The minimum edge distance was 3 *d*. The monotonic loading rate was 2 mm/min for the rods.

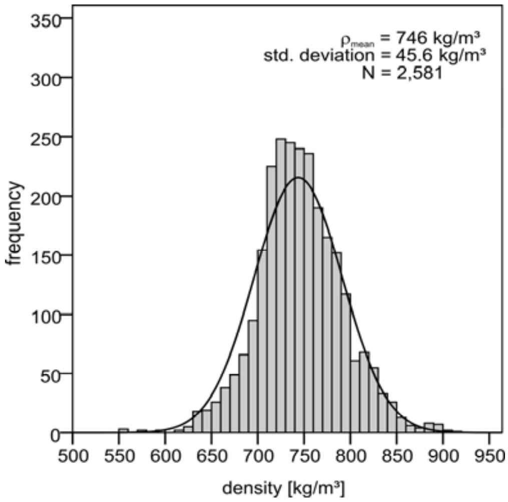

Figure 3: *Histogram of density at 12 % MC*

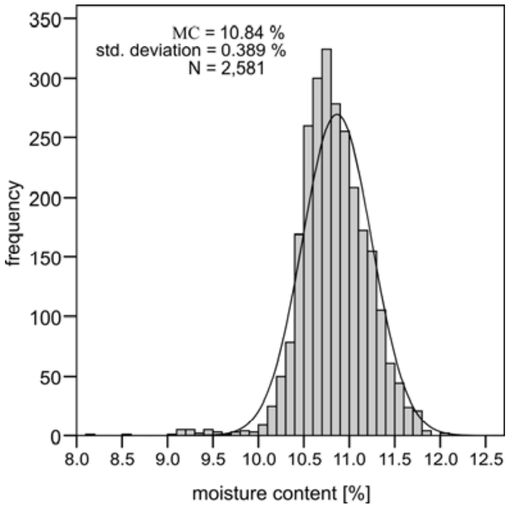

Figure 4: *Histogram of moisture content*

5 RESULTS

5.1 DENSITY AND MOISTURE CONTENT

The mean value of the density was $\rho_{mean} = 746$ kg/m³ ($CoV = 6.1$ %, $\rho_{05} = 673$ kg/m³ and $\rho_{95} = 822$ kg/m³) and Figure 3 shows the histogram.

The mean value of the MC according to EN 13183-1 (2004) was 10.84 % ($MC_{05} = 10.32$ %, $MC_{95} = 11.44$ % and $CoV = 3.6$ %,) and Figure 4 shows the histogram. Before the specimens were stored in the climate chamber they had lower MC. Therefore adsorption took place and the lower limit of hysteresis was reached. Kollmann (p. 74, 1941) published the hysteresis of adsorption and desorption at 20 °C. The low limit of MC at 65 % RH is 10.7 % the upper limit 14.1 %. In own tests a mean upper limit of 13.9 % was measured for 43 ash specimens.

The range of possible MCs at (20±2) °C and (65±5) % RH and the strong influence of the MC on the mechanical properties suggest adapting the withdrawal capacity on the reference MC of 12 %.

5.2 INFLUENCE OF THE SCREW TIP

The geometry of the screw tip causes a lower withdrawal capacity at the end of the screw than in the regular part of the embedded thread. Therefore, it is necessary to define a nominal length l_{nom} and an effective penetration length l_{ef} according to equation (1). The parameter x of was calculated with equation (2).

In the moment of rupture a cylindrical shell coating the screw shears of. The corresponding shear strength is f_{ax}. The withdrawal strength is defined as the quotient of the maximum axial force and the area of the cylindrical shell with the undisturbed length l_{ef}. Table 1 lists the parameters x for the different pairs of series. The noticeable values for ES08_90_32(S) and ES08_90_64(S) are 2.02 and 0.76, respectively. The disturbed load distribution near the surface is relative to the withdrawal capacity more important for the short penetration length of 32 mm than for 64 mm.

$$l_{ef} = l_{nom} - x \cdot d \qquad x = \left(1 - \frac{f_{ax}^{with\ tip}}{f_{ax}^{without\ tip}}\right) \cdot \frac{l_{nom}}{d} \qquad (1 + 2)$$

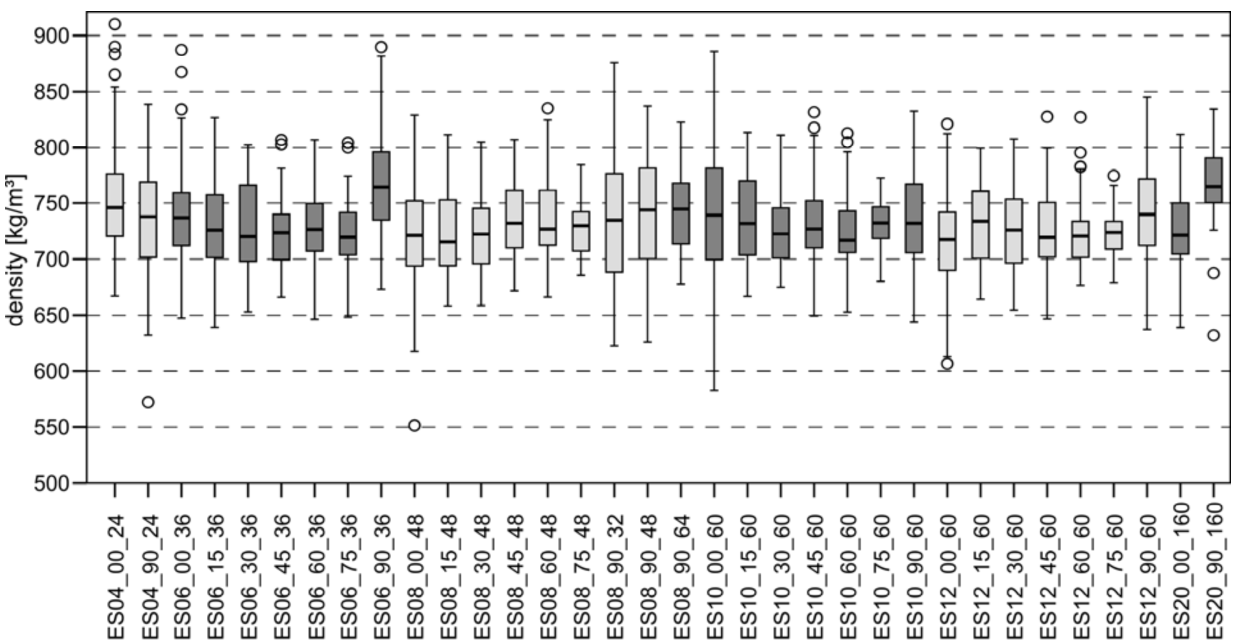

Figure 5: *Box plots of the density at 12% moisture content*

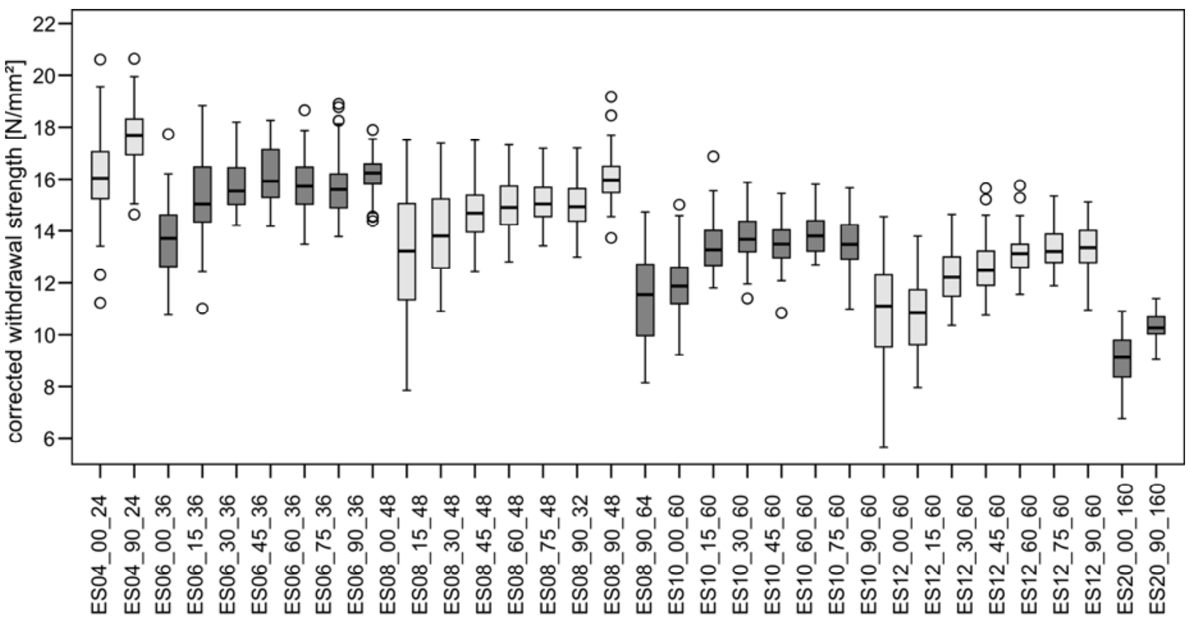

Figure 6: *Corrected withdrawal strength for the main part of the series*

Because the effect of disturbed load distribution near the surface is not considered separately the parameters *x* for the series ES08_90_32(S) and ES08_90_64(S) are extreme values (see Table 1). To compensate the influence of the embedded tip, the nominal penetration length should be reduced with 1.11 *d*. The Swiss code SIA 265 (2003) and the old ON EN 1995-1-1 (2006) subtract 1 *d*.

5.3 WITHDRAWAL STRENGTH

The withdrawal strength is influenced by the penetration length, the wood species, the screw diameter, the angle between screw and fibre direction, the MC and the temperature. The withdrawal strength was corrected with the term $(\rho_{mean} / \rho_i)^{1,7}$ according to equation (9) and plotted for the series where the screw tip was outside of the specimen in Figure 6.

The withdrawal strength increases considerably with the angle to the grain between 0° and 30°. For higher angles no uniform trend could be found.

The inner quartile range of the box plots for 0° is larger than for 15° and greater angles to the grain. The mean quotient of the mean withdrawal strength perpendicular and parallel to the grain $f_{ax,mean,90} / f_{ax,mean,0}$ is 1.19 for diameters ranging from 6 mm to 20 mm. The corresponding quotient for the 5%-percentiles is 1.42 due to the higher variation of the test results at an angle to the grain of 0°. If a Hankinson (1921) function should be adapted on the 5%-percentiles of 0° and 90° it would be necessary to implement $\sin^2 \alpha + 1.42 \cos^2 \alpha$.

The quotients of the withdrawal strength 90° and 30° to the grain $f_{ax,mean,90} / f_{ax,mean,30}$ and $f_{ax,05,90} / f_{ax,05,30}$, respectively, are nearly the same with 1.05 and 1.06. If the calculation model should cover only angles $\alpha \geq 30°$ the Hankinson function for the mean values can be parallel shifted to the 5%-percentiles because the higher variation of the withdrawal strength is excluded.

On the one hand it is necessary to use a Hankinson function with a higher amplitude if the 5%-percentiles of 0° and 90° should be fitted. A term $\sin^2 \alpha + 1.5 \cos^2 \alpha$ in the calculation model of the Swiss code SIA 265 (2003) allows designing screws from 0° to 90°. On the other hand the ON EN 1995-1-1 (2009) limits the angle to the grain with $\alpha \geq 30°$ and $\sin^2 \alpha + 1.2 \cos^2 \alpha$ can be used.

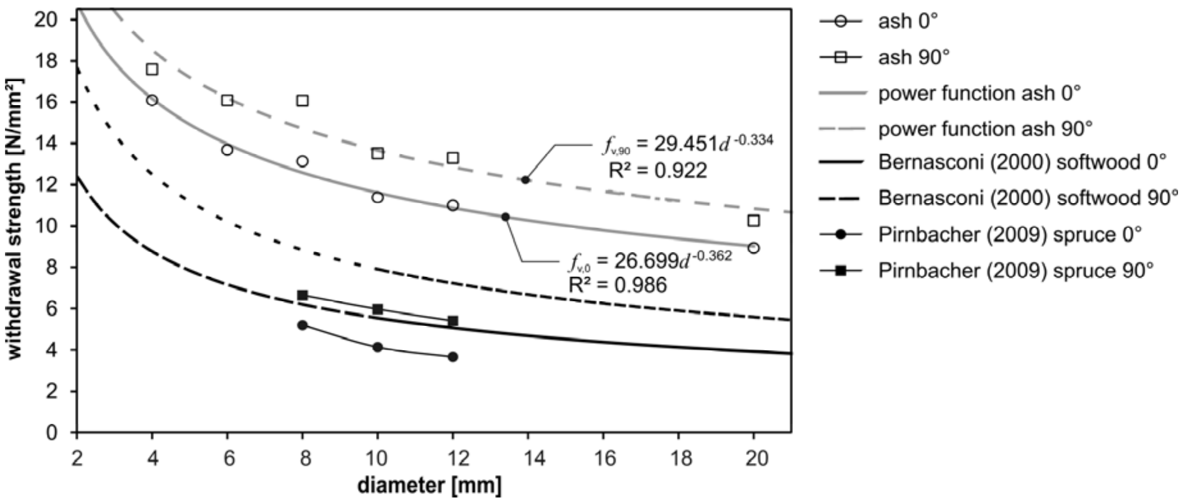

Figure 7: *Withdrawal strength versus diameter*

In general the withdrawal strength decreases if the screw diameter increases. In Figure 7 plots of the density corrected mean withdrawal strength of European ash versus the diameter (4 mm to 20 mm) is shown. The size effects parallel and perpendicular to the grain are described by power functions in equations (3) and (4). The units in following equations are N for R_{ax}, MPa for shear strength f_{ax}, mm for diameter d and penetration length l_{ef} and kg/m³ for the densities ρ_{05}, ρ_{mean} and ρ_{95}. As mentioned before Frese et al. (2009) published a power of –0.3423 for the diameter in the equation to calculate the mean withdrawal strength of self-tapping screws in softwoods.

$$f_{ax,90} = 29.451 \cdot d^{-0.334} \quad R^2=0.922 \tag{3}$$

$$f_{ax,0} = 26.699 \cdot d^{-0.362} \quad R^2=0.986 \tag{4}$$

Bernasconi (2000) proposed the characteristic shear strength of $f_{ax,90,k} = 25 \cdot d^{-0,5}$ perpendicular to the grain and $f_{ax,0,k} = 30 \cdot d^{-0,5} \cdot (l_e/d)^{-0,3}$ parallel to the grain for the calculation of glued-in rods in softwoods with a diameter $d_a \geq$ 10 mm according to the Swiss code. The curves in Figure 7 are calculated for the anchorage length $l_e = 6 d_a$. The curves from Bernasconi (2000) show a similar run to the curves for ash at a lower strength level.

The filled squares and circles stand for the mean values for withdrawal strength of test results from Pirnbacher (2009).

The maximum effective penetration lengths and slenderness's for screws with the ratio of minor to major diameter of 0.63 and steel tension strength of 900 N/mm² are listed in Table 2. Both assumptions can range due to the screw producer and screw type. The slenderness increase with increasing diameter ($\lambda = 4.8 \ldots 10.2$), but do not reach the common slenderness's of screws in softwood ($\lambda \approx 11 \ldots 27$). Less than half of the effective penetration length in softwood is needed for screws in European ash in order to effect steel rupture.

5.4 REGRESSION ANALYSES

The density was increased by 0.5 % for every percentage point difference in MC to the reference MC of 12 % according to ON EN 384 (2004). The relationship between moisture and density according to Kollmann (p. 67, 1941) leads to similar results. In default of specific information about the influence of the MC on the withdrawal capacity of European ash, the analysis of Cockrell's (1933) data as described before was used to adapt the withdrawal capacity with 1.9 % if the MC differs 1 % from reference MC.

The first regression analysis according to equation (5) was based on the series parallel and perpendicular to the grain. Equations (7) and (8) are the results with coefficients of determination according to equation (6) of 0.954 and 0.993, respectively. The higher variation of the withdrawal capacity at 0° causes the slightly lower coefficient of determination. The power of the diameters in equations (7) and (8) corresponds to 1 plus the power of equations (3) and (4).

$$R_{ax} = A \cdot l_{ef}^{B} \cdot \rho^{C} \cdot d^{D} \tag{5}$$

$$R^2 = \frac{\text{sum of squares of residue}}{\text{corrected sum of squares}} \tag{6}$$

$$R_{ax,0} = 0.322 \cdot 10^{-3} \cdot l_{ef}^{0.986} \cdot \rho^{1.886} \cdot d^{0.67} \tag{7}$$

$$R_{ax,90} = 2.169 \cdot 10^{-3} \cdot l_{ef}^{0.942} \cdot \rho^{1.652} \cdot d^{0.668} \tag{8}$$

The next regression analysis included all series where the tips of screws were not embedded. Equation (9) was calculated with a coefficient of determination of 0.976.

$$R_{ax,\alpha} = \frac{1.69 \cdot 10^{-3} \cdot l_{ef}^{0.94} \cdot \rho^{1.7} \cdot d^{0.65}}{\sin^2 \alpha + 1.15 \cdot \cos^2 \alpha} \tag{9}$$

Equation (10) shows the model for the characteristic withdrawal capacity with a Hankinson function.

$$R_{ax,\alpha,k} = \frac{1.42 \cdot 10^{-3} \cdot l_{ef}^{0.94} \cdot \rho_k^{1,7} \cdot d^{0.65}}{\sin^2 \alpha + 1.40 \cdot \cos^2 \alpha} \tag{10}$$

The box plots of standardised withdrawal strength (diameter 10 mm, ρ_{mean} = 746 kg/m³) are given in Figure 8. The square symbols stand for the 5%-percentiles of the standardised withdrawal strength for the corresponding angle to the grain. The Hankinson function connects as dashed polygon the 5%-percentile of 0° with the 5%-percentile of 90°. The bilinear model is constant between 30° and 90°, and decreases from 30° to 0° to 70 % of the 5%-percentile at 30°. Equations (11) describe the bilinear calculation model for the withdrawal capacity of screws in European ash.

$$R_{ax,\alpha,k} = 1.42 \cdot 10^{-3} \cdot l_{ef}^{0.94} \cdot \rho_k^{1.7} \cdot d^{0.65} \quad \text{for } \alpha \geq 30°$$

$$R_{ax,\alpha,k} = 1.42 \cdot 10^{-3} l_{ef}^{0.94} \rho_k^{1.7} d^{0.65} (1 - 0.01 \cdot (30° - \alpha)) \quad \text{for } \alpha < 30° \tag{11}$$

There are important differences between the Hankinson and the bilinear model, especially for the angle to the grain of 30° and 45°.

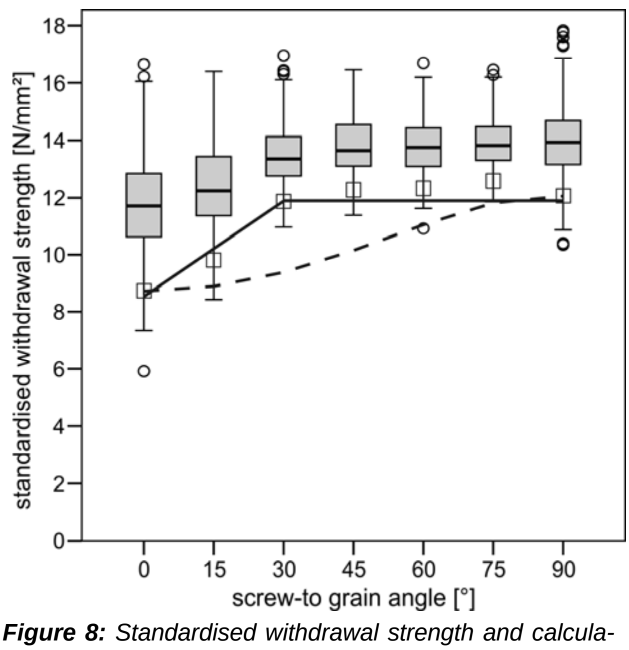

Figure 8: *Standardised withdrawal strength and calculation models* (d = 10 mm, ρ_{mean} = 746 kg/m³, MC = 12 %)

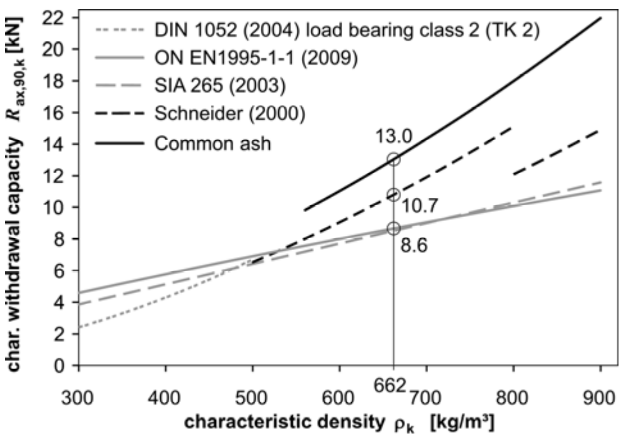

Figure 9: *characteristic withdrawal capacity versus characteristic density* (d = 8 mm, l_{ef} = 6 d, α = 90°)

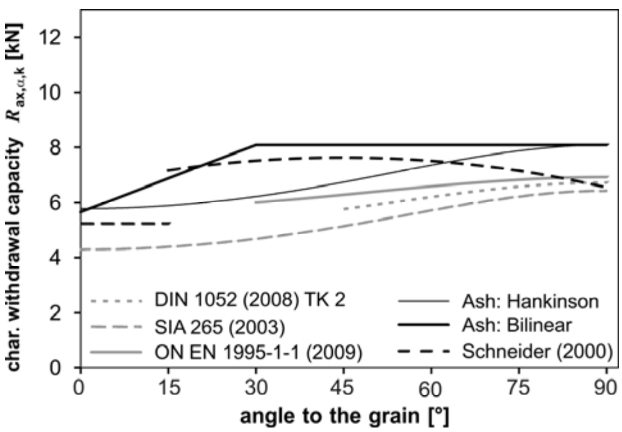

Figure 10: *characteristic withdrawal capacity versus angle to the grain* (d = 8 mm, l_{ef} = 6 d, ρ_k = 500 kg/m³)

5.5 APPRAISAL OF THE CALCULATION MODELS

The density, the effective penetration length and the angle are metric variables in the calculation model, while the diameter values are discrete. The withdrawal capacities were summed up for all combinations of the 5%-percentile of density (ρ_{05} = 673 kg/m³) with the diameters (4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 16 mm, 20 mm), load-to-grain angles 0°, 15°, … , 90° and effective penetration lengths of 4 d to 7 d. If the sum of the withdrawal capacities according to the ON EN 1995-1-1 (2009) is set to 100 %, the sum for the Hankinson model according to equation (5) and the sum for the bilinear model according to equations (11) are 145 % and 178 %, respectively. The bilinear calculation model is the most efficient and consequently uses the potential of the withdrawal capacity of European ash best.

Figures 9 to 11 illustrate three examples for the comparison of the different calculation models. The influence of the characteristic density on the withdrawal capacity is shown in Figure 9 for screw diameter 8 mm, angle to the grain of 90° and effective penetration length 6 d. SIA 265 (2003) and ON EN 1995-1-1 (2009) show a similar behaviour, just the dashed line of SIA 265 increases stronger with raising density. The curve for ash and the one for beech (ρ_{mean} = 680 kg/m³) according to Schneider (2000) are parallel and 14 % of the difference can be explained by the differing densities of ash and beech with $(\rho_{ash,mean} / \rho_{beech,mean})^{1.7} = 1.14$.

The characteristic withdrawal capacities calculated with the characteristic density of ash according to the ON EN 1995-1-1 is 8.6 kN (100 %), according to Schneider (2000) 10.7 kN (124 %) for beech and for ash 13.0 kN (150 %).

The second example in Figure 10 shows the function of the characteristic withdrawal capacity versus the angle to the grain for the parameters ø 8 mm, l_{ef} = 6 d and ρ_k = 500 kg/m³. DIN 1052 (2008) limits the characteristic density with ρ_k = 500 kg/m³ because it is based on softwood test results. The minimal density of ash was 550 kg/m³. So both models, DIN 1052 (2008) and equations (11) for ash, are on their limits. The fine black curve for ash is nearly parallel to the gray dashed curve according to SIA 265 on a higher level of withdrawal capacity. The curve of Schneider (2000) is constant between 0° and 15° and reaches its maximum at 45°. The difference between Schneider (2000) and ash depends strongly on the angle to the grain. The differences of the withdrawal capacity according to DIN 1052 (2008) and ON EN 1995-1-1 (2009) are relatively low because the low angles to the grain with the higher variations of the withdrawal capacity are excluded.

The size effect of different diameters on the withdrawal strength was shown in Figure 7. As Figure 11 indicates the size effects are considerably different included in the European standards. The current ON EN 1995-1-1 (2009) limits the diameter with 6 mm ≤ d ≤ 12 mm. The cures in Figure 11 are plotted in the wide range of screw diameters between 2.5 mm and 24 mm according to ON EN 14 592 (2009) to show the differences better. The diameter limits according to the standards are marked in Figure 11. Rods with a wood screw thread according to DIN 7998 (1975) are available with diameters of 16 mm or 20 mm and it is allowed to calculate their withdrawal capacity according to DIN 1052 (2008).

The calculation model of the ON EN 1995-1-1 (2009) is based on test with softwoods and screw diameters between 6 mm ≤ d ≤ 12 mm. Future calculation models should cover the diameter range of ON EN 14 592 (2009), the densities of soft- and hardwoods and angles between 0° and 90°.

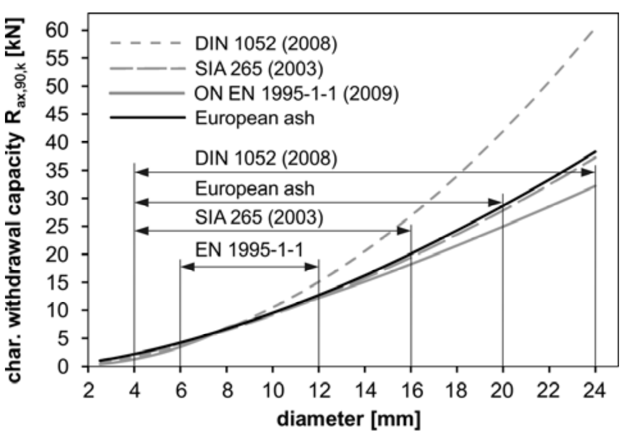

Figure 11: *characteristic withdrawal capacity versus diameter* (α = 90°, l_{ef} = 6 d, ρ_k = 500 kg/m³)

6 CONCLUSIONS

The presented results of withdrawal tests in order with ON EN 1382 (1999) of screws and rods threaded according to DIN 7998 (1975) in GLT made of European ash proof the high potential of hardwoods for load bearing timber structures. 2571 tests in 42 series were executed to establish a basis that contains a sustainable range of diameters, a systematic grid of angles to the grain and to cover the influence of the screw tip. The regression analyses of the withdrawal capacities lead to the following calculation model:

$$R_{ax,\alpha,k} = 1.42 \cdot 10^{-3} \cdot l_{ef}^{0.94} \cdot \rho_k^{1.7} \cdot d^{0.65} \quad \text{for } \alpha \geq 30°$$

$$R_{ax,\alpha,k} = 1.42 \cdot 10^{-3} l_{ef}^{0.94} \rho_k^{1.7} d^{0.65} (1 - 0.01 \cdot (30° - \alpha)) \quad \text{for } \alpha < 30° \qquad (10)$$

The influence of the tip of the screw should be considered by the effective penetration length $l_{ef} = l_{nom} - 1.11 \cdot d$.

The calculation model is a short expression for angles to the grain $\alpha \geq 30°$. The reduction below 30° with 1 % for each degree is simple and memorable.

In comparison to softwood it is possible to reduce the necessary effective penetration length nearly to the half due to the high withdrawal strength of European ash. This advantage could be important for the slender sections of posts and bars of timber and glass facades.

7 FURTHER RESEARCH

It is scheduled to compare the withdrawal capacity of screws in European ash with European beech (*Fagus sylvatica* L.) and Black locust (*Robinia pseudoacacia* L.) as well as to analyse if the anatomical differences between deciduous trees are sufficiently presented by the density in the calculation model for the withdrawal capacity. Another subject for further research will be the influence of MC on the withdrawal capacity and the embedment of partly threaded screws, where the thread begins under the surface of the specimens in various depths. Previously this embedment effect will be considered with a second reduction of the nominal length.

Screws should have an optimal ratio of minor to major diameter. It would be favourably to increase this ratio for screws in hardwoods comparing with self-tapping screws in softwood to obtain a higher axial resistance of the screws. Another step to more economic timber connections would be the reduction of the minimum spacing (perpendicular to the grain).

ACKNOWLEDGEMENT

This research work is part of the COMET-project 1.2.3_hardwood_connections of the competence centre holz.bau forschungs gmbh and was carried out in collaboration with the Institute for Timber Engineering and Wood Technology at the Graz University of Technology and industrial partners *HAAS Fertigbau GmbH & Co.KG* and *SPAX International GmbH & Co. KG*. The withdrawal tests were executed with the aid of Bernd Heissenberger, Markus Kummer, and Manuel Lögl. The research work was financed through the Austrian State Ministry of Economic Affairs and Employment, the Ministry of Transport, Innovation and Technology as well as by the *Steirischen Wirtschaftsförderungsgesellschaft mbH* and the federal state Steiermark.

***Table 1:** Parameter x of equation (1)*

without embedded tip	with embedded tip	x
ES08_00_48	ES08_00_48S	1.28
ES08_90_32	ES08_90_32S	*2.02*
ES08_90_48	ES08_90_48S	0.98
ES08_90_64	ES08_90_64S	*0.76*
ES10_00_60	ES10_00_60S	1.29
ES10_90_60	ES10_90_60S	0.98
ES12_00_60	ES12_00_60S	1.00
ES12_90_60	ES12_90_60S	1.10
mean value $\bar{x}$		1.11

***Table 2:** Maximum effective penetration length and slenderness (steel tensile strength 900 N/mm², minor diameter to major diameter 0.63)*

diameter	tension capacity of the steel	angle to the grain 0°			angle to the grain 90°		
		shear strength	max. effective penetration length	max. slenderness	shear strength	max. effective penetration length	max. slenderness
d	R_{ax}	$f_{ax,mean,0}$	$l_{ef,max,0}$	λ_0	$f_{ax,mean,90}$	$l_{ef,max,90}$	λ_{90}
[mm]	[N]	[N/mm²]	[mm]	[-]	[N/mm²]	[mm]	[-]
4	4,489	16.2	22	5.5	18.5	19	4.8
6	10,100	14.0	38	6.4	16.2	33	5.5
8	17,955	12.6	57	7.1	14.7	49	6.1
10	28,055	11.6	77	7.7	13.6	65	6.5
12	40,399	10.9	99	8.2	12.8	83	7.0
16	71,821	9.8	146	9.1	11.7	122	7.7
20	112,221	9.0	198	9.9	10.8	165	8.2

REFERENCES

Akamatsu, Akira: Effects of Withdrawal Resistance, Screw-Shank Diameter, Screw-Length and Specific Gravity on the Lateral Resistance of Screw-Wood Joints with Steel Side-Members. In *Mokuzai Gakkaishi* 36(1):15–21 (1990)

Bejtka, Ireneusz: *Verstärkungen von Bauteilen aus Holz mit Vollgewindeschrauben.* PhD thesis, vol. 2 of series Karlsruher Berichte zum Ingenieurholzbau, Universität Karlsruhe (TH), Lehrstuhl für Ingenieurholzbau und Baukonstruktion 2005

Bernasconi, Andrea: *Zum Kapitel 6 10 des Swisscodes: Verbindungen mit eingeleimten profilierten Stäben.* Geesthacht, Germany 2000

Blaß, Hans Joachim; Bejtka, Ireneusz; Uibel, Thomas: *Tragfähigkeit von Verbindungen mit selbstbohrenden Holzschrauben mit Vollgewinde.* vol. 4 of series Karlsruher Berichte zum Ingenieurholzbau, Universität Karlsruhe 2006

Bröker, Friedrich-Wilhelm; Krause, H. A.: Orientierende Untersuchungen über das Haltevermögen dynamisch beanspruchter Holzschrauben. In *Holz als Roh- und Werkstoff* 49(10): 381–384 1991

BWI 2: *Die zweite Bundeswaldinventur.* Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, Bonn 2002

Cockrell, Robert A.: *A Study of the Screw-Holding Properties of Wood.* New York State College of Forestry, Technical Publication No. 44, Syracuse, New York, USA1933

Eckelman, Carl A.: Screwholding performance in hardwoods and particleboard. In *Forest Products Journal* 25(6): 30-35 (1975)

Fairchild, Iler James: *Holding power of wood screws.* Technologic papers of the Bureau of Standards, No. 319, vol. 20, Washington: Department of Commerce 1926

Frese, Matthias and Blaß, Hans Joachim: Models for the calculation of the withdrawal capacity of self-tapping screws. In *Proceedings of CIB-W18*, Paper 42-7-3, Dübendorf, Schweiz 2009

Hankinson, R. L.: Investigation of Crushing Strength of Spruce at Various Angles to the Grain. Materials Section Paper No. 130, In: *Air Service Information Circular* vol. 3 n° 259, Washington, DC.: U.S. Army, Engineering Div. 1921

Horvath, Norbert; Molnár, Sándor; Niemz, Peter: Untersuchungen zum Einfluss der Holzfeuchte auf ausgewählte Eigenschaften von Fichte, Eiche und Rotbuche. In *Holztechnologie*, 49(1): 10–15, 2008

Hübner, Ulrich; Leeb, Wolfgang: Grading Criteria for Beech and Ash used as Building Material. In *Proceedings of the 3rd European Hardwood Conference 'The Beauty of Hardwood'*, pages 37–43, Sopron, Ungarn, 3.–4. September 2007

Hübner, Ulrich; Bogensberger, Thomas; Schickhofer, Gerhard: Embedding strength of European hardwoods. In *Proceedings of CIB-W18*, paper 41-7-6, St. Andrews, Canada August 2008

Hübner, Ulrich: *Compression and tension perpendicular to the grain of glulam out of ash and beech.* DoktorantInnen-Seminar TU Graz, 23. June 2009

Hübner, Ulrich: *Laubholzforschung an der TU Graz – Institut für Holzbau und Holztechnologie und holz.bau forschungs gmbh.* Vortrag im Kolloquium Verwendung von Laubholz – Stand und ausgewählte aktuelle Arbeiten, ETH Zürich: 11. January 2010

Jablonkay, Peter: *Schrauben unter Ausziehbeanspruchung.* Masterthesis an der Professur für Holztechnologie, ETH Zürich 1999

Kollmann, Franz Friedrich Paul: *Die Esche und ihr Holz.* Series Eigenschaften und Verwertung der deutschen Naturhölzer, Berlin: Julius Springer 1941

Pirnbacher, Gernot; Schickhofer, Gerhard: Base parameters of self-tapping screws. In *Proceedings of CIB-W18*, paper 42-7-1, Dübendorf, Schweiz 2009

Pörtner, Carsten; Seim, Werner: In Holz eingeklebte stiftförmige faserverstärkte Kunststoffe – Experimentelle Untersuchungen und mechanische Modellierung. In *Bautechnik* 85 (4):219–232, 2008

Schneider, P.: *Auszugsfestigkeit von EJOT-Rahmenschrauben.* ETH Zürich 2000 (?)

DIN 1052: *Entwurf, Berechnung und Bemessung von Holzbauwerken – Allgemeine Bemessungsregeln und Bemessungsregeln für den Hochbau.* Berlin: Dezember 2008

DIN 7998: *Gewinde und Schraubenenden für Holzschrauben.* Berlin: Februar 1975

ÖNORM EN 13 183-1: *Feuchtegehalt eines Stückes Schnittholz – Teil 1: Bestimmung durch Darrverfahren.* Wien: 1. Februar 2004

ÖNORM EN 1382: *Holzbauwerke – Prüfverfahren – Ausziehtragfähigkeit von Holzverbindungsmitteln.* Wien: 1. November 1999

ÖNORM EN 1995-1-1: Eurocode 5: *Bemessung und Konstruktion von Holzbauten – Teil 1-1: Allgemeines – Allgemeine Regeln und Regeln für den Hochbau.* Wien: November 2006

ÖNORM EN 1995-1-1: Eurocode 5: *Bemessung und Konstruktion von Holzbauten – Teil 1-1: Allgemeines – Allgemeine Regeln und Regeln für den Hochbau.* Wien: 1. Juli 2009

SIA 265: *Holzbau.* Zürich: 1. März 2003