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Tensile strength classes for hardwoods

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1 Introduction

Generally, for structural timber the main properties are listed in a strength class system. In Europe EN 338 (2016) lists available strength class and their respective characteristic properties. Depending on the product application the bending or the tension properties are of main interest. For glulam lamellas, tension classes are preferred as through tension classes the mechanical properties of glulam can be better predicted. Also, machine grading allows for a better prediction of tensile properties compared to bending properties. So far, tension grades were regulated in EN 14081-4. Due to the increased demand on glulam products, the grades were recently analysed, and a tensile class table was introduced in EN 338 (2016). The new strength profiles are the preferred option for glulam production. The requirements for softwood glulam are regulated in EN 14080 (2013).

So far, no tension classes exist for hardwoods. The EN 338 lists for hardwood specimens only so-called “D” classes based on the bending strength. The other properties, like tension strength, are assigned by the default on the safe side using the equations listed in EN 384. For those classes, the ratio tension strength to bending strength is declared on the safe side 0.6. However as shown by Burger & Glos (1997) for higher quality timber higher ratio can be expected.

New tensile classes for hardwoods would allow utilising the properties of hardwoods more efficiently. Whereas the old European standards EN 1194 and EN 14080 (2005) did not regulate species, the most recent version of EN 14080 (2013) is restricted to softwoods only. This means that hardwood glulam producers in Europe face additional costs for obtaining approvals for their products.

In this paper material properties of structural sized medium-dense European hardwoods ash, beech, and maple are presented with regard to the tensile strength classes. Major characteristic properties containing tensile strength, tension modulus of elasticity, density, and their relationships, followed by the relationship between tensile strength and compression and bending strength are analysed. Also, perpendicular to the grain values are presented. A system of Tensile Strength Classes for medium dense European Hardwood is proposed.

2 Tensile strength class system

2.1 General on the strength classes

EN 338 is the European standard for the strength classes and the respective characteristic properties. The classes are defined either on bending or tension tests. Table 1 shows the tensile strength classes for the softwoods exemplarily.

In order to be assigned to a particular strength class, the characteristic properties are to be estimated in accordance with EN 384. EN 384 defines the requirements on the sampling procedure and the calculation of the property values. To assign a sample to class the major characteristic properties including 5th percentile of either tensile or bending strength, the mean static modulus of elasticity, and the 5th percentile of the density are used. If the characteristic properties match the required values for a particular class, the timber may be assigned to this class.

Other material properties are listed for each class in EN 338. Those properties are the bending strength for the tensile classes and the tensile strength for the bending classes, compression strength parallel to the grain direction and so on. The values for these material characteristic are deduced based on equations given in EN 384.

Table 1: Tensile strength classes (T-Classes) for softwoods listed in EN 338 (2016)

	Property	T11	T14	T18	T21	T24	T28	T30
Strength proper-ties [N/mm²]	$f_{m,k}$	17.0	20.5	25.5	29.0	33.0	37.5	40.0
	$f_{t,0,k}$	11.0	14.0	18.0	21.0	24.0	28.0	30.0
	$f_{t,90,k}$	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	$f_{c,0,k}$	18.0	21.0	23.0	25.0	27.0	29.0	30.0
	$f_{c,90,k}$	2.2	2.5	2.7	2.7	2.8	2.9	3.0
	$f_{v,k}$	3.4	4.0	4.0	4.0	4.0	4.0	4.0
Stiffness proper-ties [kN/mm²]	$E_{t,0,mean}$	9.0	11.0	12.0	13.0	13.5	15.0	15.5
	$E_{t,0,k}$	6.0	7.4	8.0	8.7	9.0	10.1	10.4
	$E_{t,90,mean}$	0.3	0.4	0.4	0.4	0.5	0.5	0.5
	G_{mean}	0.6	0.7	0.8	0.8	0.8	0.9	1.0
Density [kg/m³]	ρ_k	320	350	380	390	400	420	430
	ρ_{mean}	380	420	460	470	480	500	520

2.2 Major characteristic properties of hardwoods tested in tension

The ratios between the major strength properties for the T-Classes are derived from the tensile test data for softwoods, mainly spruce and pine. The underlying relationship between the material properties was recently analysed by Denzler (2012), and Bacher & Krzosek (2014). However, EN 338 gives the possibility to assign timber with similar properties into the tensile strength classes.

Even though for hardwoods the assignment to the tensile strength classes is possible, the property relationships differ from softwoods. Firstly, for medium density European hardwoods higher tensile strength values than the ones listed for T-Classes are reported. Glos & Denzler (2006) and Solli (2004) reported, for the highest grade of the visually graded European beech and Scandinavian birch, characteristic strength values that exceed the requirements of the highest T-Class T30.

Second, the relationship between characteristic tensile strength ($f_{t,0,k}$) and characteristic tensile modulus of elasticity ($E_{t,0,mean}$) is different from softwood. For hardwoods with $f_{t,0,k}$ meeting the requirements of the highest T-Class T30, $E_{t,0,mean}$ values below the required 15500 N/mm² are reported by Glos & Denzler for beech (14700 N/mm²) and Solli (2004) for birch (15130 N/mm²). Aicher et al. (2014) reported for chestnut lamellas a characteristic tensile strength of 22.3 N/mm² and $E_{t,0,mean}$ values of 12500 N/mm².

The different ratio of characteristic strength to bending E for hardwoods and softwoods is displayed in the bending strength class system. Hardwood strength classes (D-Classes) indicate lower E values than softwood strength classes, for same bending strength. Green (2005) has pointed on the steeper relationship between bending strength and E for North American hardwoods compared to softwoods. On the contrary, Ravenshorst (2015) indicates a slightly less steep relationship, but in general a rather consistent ratio of all soft- and hardwood species.

However, even within hardwoods differences in material properties and MOR/MOE ratios are reported for species tested in bending. Whereas visually graded oak (Grade LS10+ in accordance with DIN 4074-5) from Germany tested in bending, match the requirements for MOE of D30 (Glos & Denzler 2006), the values for beech and ash exceed the requirements of D30 with 15900 N/mm² and 14000 N/mm² respectively.

2.3 Relationship between values parallel to the grain

The existing strength classes for hardwoods are defined on the bending test basis only. EN 384 gives for hardwoods the $f_{t,0,k}/f_{m,k}$ ratio of 0.6 with tension strength estimated on the safe side, similar to softwoods. However, as Burger & Glos (1997) and Steiger & Arnold (2009) have shown that a higher ratio may apply for higher grades of spruce. Recently, for softwood bending strength classes the higher $f_{t,0,k}/f_{m,k}$ ratio of 0.73 was introduced (EN 338 2016, FprEN 384 2015).

For the softwood T-Classes, the tension strength is determined by tests and bending strength is given from a ratio. In this case, bending strength is taken on the safe side by assuming higher $f_{t,0,k}/f_{m,k}$ ratio of 0.8 (Bacher & Krzosek 2014). To determine the characteristic bending strength of a sample tested in tension is used:

$$f_{m,k} = 3.66 + 1.213 \cdot f_{t,0,k} \quad (1)$$

In ASTMD 1990 (2000) standard, a tension/bending strength ratio of 0.83 for the tension test values is used.

For the compression strength parallel to the grain the following relationship is assumed in FprEN 384 (2015):

$$f_{c,0,k} = 4.3\, f_{m,k}^{\,0.5} \quad (2)$$

For softwood T-Classes the Eq. 2 was adopted to Eq. 3 under the assumption of 0.6 ratio between $f_{m,k}$ and $f_{t,0,k}$ (Bacher & Krzosek 2014).

$$f_{c,0,k} = 5.5 \cdot f_{t,0,k}^{\,0.5} \quad (3)$$

2.4 Characteristic properties perpendicular to the grain direction

EN 338 (2016) lists one characteristic tension strength value perpendicular to the grain for all strength classes, distinct for softwoods (0.4 N/mm²) and hardwoods (0.6 N/mm²). The characteristic compression strength perpendicular to the grain is given in FprEN 384 (2015) as a ratio of compression strength to the characteristic density, for both softwoods and hardwoods. For medium dense hardwoods ($\rho_k < 700$ kg/m³) the Eq. 3 is used, while the higher ratio 0.015 $\cdot\, \rho_k$ is assumed for denser hardwoods.

$$f_{c,90,k} = 0.01 \cdot \rho_k \quad (4)$$

The modulus of elasticity perpendicular to the grain is given as a ratio to the E parallel to the grain by the following equation:

$$E_{90,mean} = E_{0,mean} / 15 \quad (5)$$

The standard does not distinguish between $E_{t,90}$ and $E_{c,90}$.

3 Materials and methods

3.1 Destructive test data

In this paper, the properties of medium dense hardwoods ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*) and maple (*Acer sp.*) are analysed with regard to the tensile strength, modulus of elasticity in tension and density. The data sets of different projects on hardwoods carried out at the TU Munich over the past years are used. Table 2 gives an overview of the available data grouped by testing type, cross sections, and free testing length. All specimens, unless otherwise specified, have been tested according to EN 408 (2010) and EN 384 (2010).

Out of 1560 hardwoods tested in tension, 300 beech and 466 ash specimens were tested with the free testing length of 200 mm. The beech specimens were initially used to develop the models for the glulam out of beech by KIT (Blass et al. 2004). The ash specimens were tested in a project of the TU Munich on the mechanical properties of ash for the glulam production (van de Kuilen & Torno 2014). The intention of the small ash specimens was to make them compatible with the Karlsruhe model for glued laminated timber simulations. For those calculations, two test pieces - one for the tension test and the other for the compression test - were cut out of a single beech lamella. Both test pieces are included in the current analysis. The tension strength of the data tested over 200 mm was adjusted to the testing length of 9h using a separate factor for each strength value and is introduced in section 3.3.

To estimate the bending strength to tensile strength ratio, samples with similar cross-section are desirable. Therefore, out of the entire dataset, only one ash sample tested in bending with cross-sections 50×100 mm, 50×150 mm was selected for the determination of this ratio. Although the selected cross-section exceeds the dimensions of the lamellas typically used for the glulam, the 50 mm thickness matches the dimensions of unplaned boards with a final thickness of 36 mm.

Table 2: General overview of data sets, grouped by test type and species

Type of test	Species	Cross sections *b*×*h* (×*l*) [mm]	Free length/test span	N
Tension parallel	ash	25×85, 30×100, 35×160, 50×100, 50×150	765 – 1440 mm (9h)	519
	ash	25×110, 25×110, 30×150, 25×160, 35×160	200 mm (1.2h – 1.8h)*	466
	beech	30×120, 30×160	1080 – 1440 mm (9h)	218
	beech	25×100, 35×100 25×150, 35×150	200 mm (1.2h – 1.8h)*	300
	maple	30×100	900 (9h)	57
Bending	ash	50×100,50×150	1800, 2700 mm (18h)	324
Compression parallel	ash	25×110, 25×110, 30×150, 25×160, 35×160	200 mm (5.7b – 8b)	457
	beech	25×100, 35×100 25×150, 35×150	200 mm (5.7b – 8b)	383
Tension perpendicular	ash	45×180×70	180 mm (h)	56
	beech	45×180×70	180 mm (h)	32
Compression perpendicular	ash	45×90×70	90 mm (h)	70
	beech	45×90×70	90 mm (h)	54

* below the required free length of 9h

The compression and tensile test tested perpendicular to the grain originate from a project on the strength profiles of middle European hardwoods by Hunger & van de Kuilen (2015) and Westermayr (2014).

3.2 Non-destructive measurements and strength modelling

The non-destructive methods are used to assess timber quality, assign timber to the strength classes and analyse the profiles. Therefore, for all timber pieces both visual and machine grading parameters were measured. The dynamic modulus of elasticity was measured using longitudinal vibration method.

The visible grading criteria listed in the German visual grading standard DIN 4074-5 (2008), rules for boards, were measured. In overall the visual standards contains ten visual criteria to assign timber into the visual grading classes. In the current study, to assign specimens to the visual grades the criteria single knot and knot cluster and the presence of the pith were considered. The single knot (*SK*) is the size of the single knot related to the width and calculated using equation:

$$SK = \frac{\sum a_i}{2w} \tag{6}$$

where a_i is the size of the knot area i measured parallel to the edge of the board. The Knot Cluster (*KC*) is a multiple knot criterion that sums up all *SK* over a length of 150 mm. The edge knot criterion (the penetration depth of the knot) was not considered for the visual grading, as for the glulam lamellas the use of this criterion is optional.

To calculate ratios of tensile strength to both bending and compression strength, the best possible model for the tensile strength prediction was selected. The model included the *SK* – the best single predictor of the tensile strength - and E_{dyn} – the best predictor for the tensile E. Eq. 7 represents the created model.

$$IP\, f_t = a + b \cdot SK + c \cdot E_{dyn} \tag{7}$$

3.3 Adjusting the tensile strength to the free length of 9h

The tension strength of the specimens tested with the free length of 200 mm was adjusted to the free length of 9h using a separate factor for each strength value. Therefore, we assumed that the specimens tested over the free length of 200 mm if tested with the free length of 9h, would observe the same probability distribution the ash and beech specimens tested under the reference conditions. For the ash and beech specimens, the tensile strength was described using a log-normal distribution, as especially in the lower 40 % of the CDF this proved to be the best fit.

To generate a sample of tensile strength tested over the free length of 9h the inverse transformation method is used. This method allows transforming uniform deviates drawn from U (0, 1) into samples drawn from a specified distribution.

In the following $x \sim \ln N(\mu,\sigma^2)$ is the strength of the specimens tested with the free length 9h. The corresponding CDF is described using the Eq. 8:

$$F_x(x) = p \tag{8}$$

For the strength of the specimens (y) tested with the free length of 200 mm the CDF is described as follows:

$$F_y(y) = u \tag{9}$$

with probability $u \sim U(0,1)$.

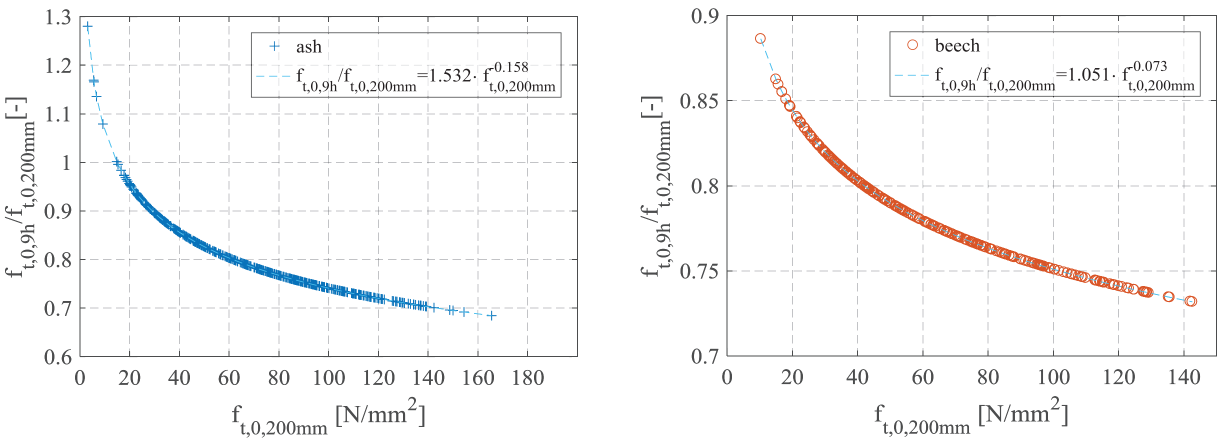
By applying the inverse CDF to the probability u the sample with the tensile strength tested over 9h is generated:

$$F_x^{-1}(u) = x \tag{10}$$

The ratio $\frac{f_{t,9h,est}}{f_{t,200mm}}$ was calculated for each $f_{t,200mm}$. Figure 1 shows the estimated ratio dependent on tensile strength tested over 200 mm for ash and beech separately.

3.4 Data analysis

The aim of the current analysis is to create optimised profiles for the strength classes with the certain tensile strength to E ratio. To conduct the study, the specimens were grouped two times in equal sized groups of 100 specimens each; one time by the tensile E and one time by the tensile strength. An ideal grading machine able to determine with 100 % accuracy the tensile E in one case and tensile strength in the other case is assumed. The 5th percentile of the tensile strength and density of the grouped specimens are calculated using the ranking method. The calculated values of characteristic tensile strength ($f_{t,0,k}$), $E_{t,0,mean}$ and characteristic density are plotted against each other and compared to the values of T-Classes, listed in EN 338 (2016).



(a) *(b)*

Figure 1: Ratio of tensile strength tested over 9h to tensile strength tested over 200 mm as a function of tensile strength tested over 200 mm for (a) ash and (b) beech

Additionally, the material property profiles based on tension E and tensile strength are compared to the actual grading results. Therefore, beech, ash, and maple specimens were virtually strength graded. Visual grading was applied according to German visual grading standard DIN 4074-5 with visual grades LS10 and LS13. Machine grading was applied using the indicating property (*IP* f_t) calculated using the Eq. 7. Although the regression model is used here, the model parameters are comparable to the combined visual and machine strength grading introduced by Frese & Blass (2005). Whereas two predictors can compensate each other in the regression model, the combined visual and machine grading does not allow for such interactions by defining separate boundary values for both parameters. Currently, no machine capable to detect knots in hardwoods is industrially available.

The boundaries for the combined visual and machine strength prediction are determined for grading to a single class. The class boundaries were increased stepwise by 10 N/mm² of *IP* f_t and all specimens matching or exceeding those threshold values were assigned to the class. For each group of specimens, the relationship between the material properties has been determined.

The relationship between tension strength and compression strength, as well as tension strength and bending strength, is determined as grouped data. Therefore, first, the tension test data are arranged by the *IP* f_t into equal sized groups of 80 specimens each. In the next step, the compression strength and bending strength data are split using determined *IP* f_t boundaries.

4 Results and discussion

4.1 Tensile strength, tensile E parallel to the grain and density

First, the tensile strength to tensile *E* ratio is analysed in groups of 100 specimens with tensile *E* as indicating property. Compared to the tension classes specified in EN 338, the relationship between tensile strength and $E_{t,0,mean}$ for ash and beech is steeper (Figure 2a). Both species show lower $E_{t,0,mean}$ values compared to the required $E_{t,0,mean}$ of the T-Classes if the same characteristic strength is achieved.

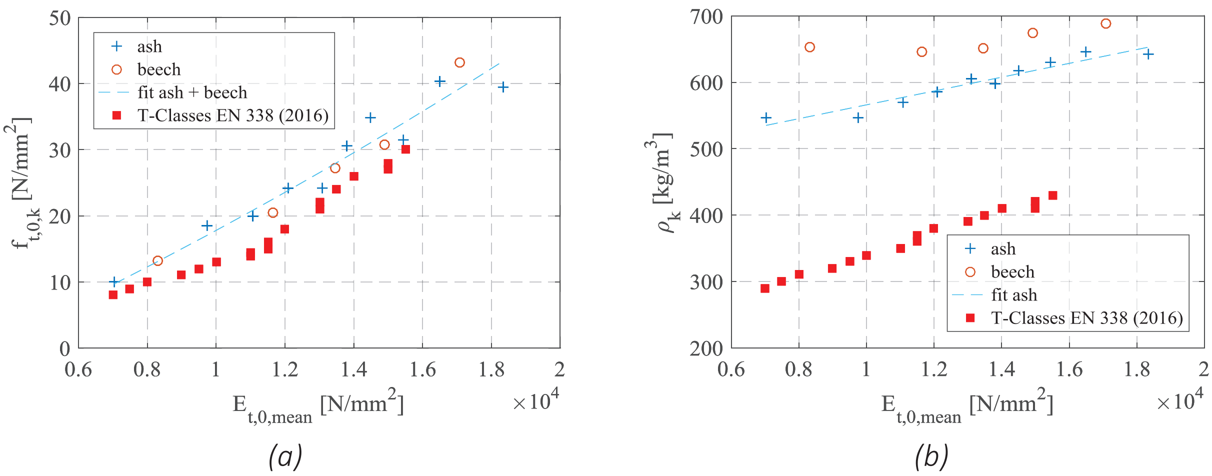
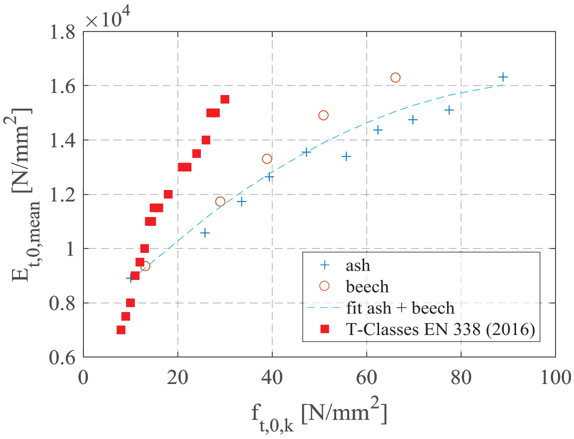


Figure 2: Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k grouped by $E_{t,0}$



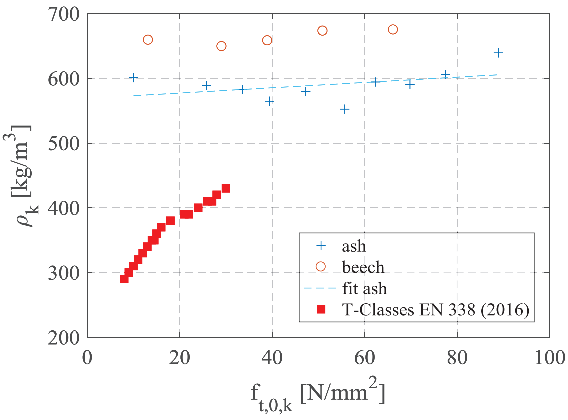


Figure 3: Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k grouped by $f_{t,0}$

Figure 2b shows the relationship between the $E_{t,0,mean}$ and ρ_k. Both ash and beech show higher characteristic density compared to the values stated in EN 338 (2016). The density of ash is level lower compared to the beech. Therefore, the characteristic density should be increased at least to the values of ash, compared to the softwoods.

If the data are grouped with regard to the tensile strength, the property relationship differs more than that assumed in EN 338. Figure 3 illustrates the relationship between the material properties in this case. Compared to the T-Classes the slope of the line between the characteristic strength and tensile *E* is flatter. For the same characteristic strength as assumed for the T-Classes, lower *E* values are observable. For example, for the characteristic tensile strength of 30 N/mm², a tensile *E* of as little as 11700 N/mm² is obtained, compared to 15500 N/mm² listed for T30.

The relationship between density and tensile strength does not increase continuously. For ash, the density remains on the same level of 600 kg/m³ with some decreases down to 550 kg/m³.

For defining the class values the relationship between tensile *E* and strength should be considered, and, whether the strength or the *E* should be most important grading parameter for the hardwoods presented here.

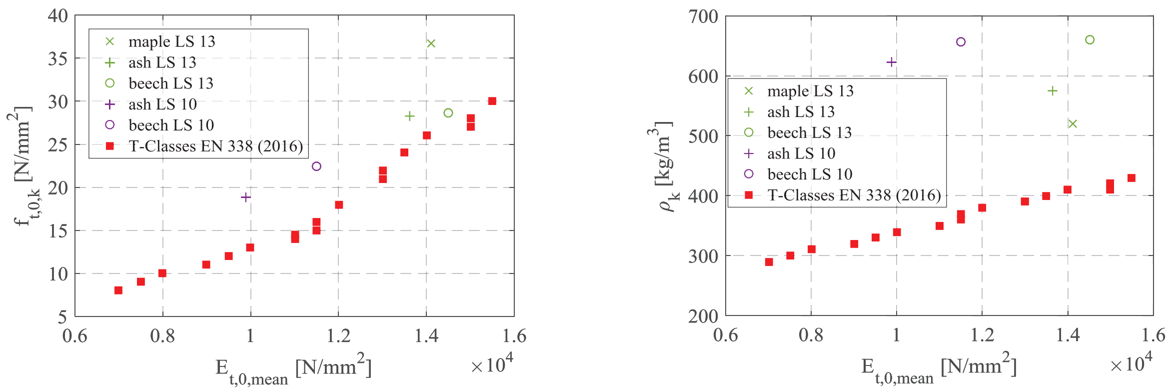
4.2 The effect of grading on the major characteristic properties

For the deviation of strength class profiles, the material properties of both visually and combined visually - machine strength graded timber are analysed. Figure 4 illustrates $E_{t,0,mean}$ to $f_{t,0,k}$ and $E_{t,0,mean}$ to ρ_k for the visually graded hardwoods. $E_{t,0,mean}$ to $f_{t,0,k}$ does not match the ratios for the softwood T-Classes. If the samples are assigned to the T-Classes, the requirements on the $E_{t,0,mean}$ are not met in each case, making E the grade-limiting property. For LS10 timber with lower tensile strength, the difference between the tested $E_{t,0,mean}$ and required E is even higher.

The $E_{t,0,mean}$ to ρ_k ratio is, as expected, above the values for the T-Classes. Nevertheless, the ratio does not seem to depend on the visual grading procedure. For ash graded to LS13, the density is even lower compared to the specimens assigned to LS10. For beech specimens, the density increases only slightly between LS10 and LS13. These results comply with the fact that density of hardwoods cannot be estimated visually, for instance by growth ring width analysis. Therefore, a single density value for all strength classes, that visually graded hardwoods might be assigned to, is a possible solution.

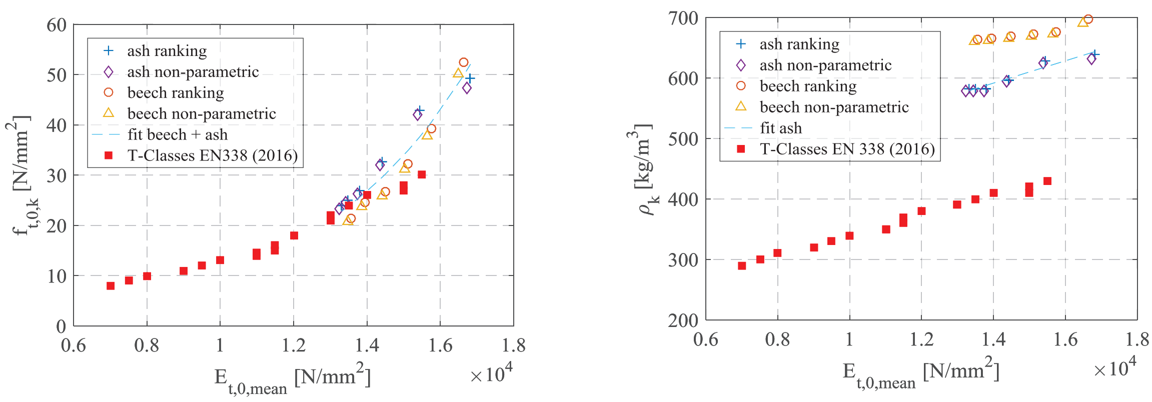
For a combined visual and machine strength prediction, the relationship between tensile strength and tensile *E* is closer to the T-Classes. However, for the higher *E* values, the tensile strength increases with a higher slope. This increase is similar to the behaviour of tensile strength/tensile E ratio obtained for grouping on the tensile strength (Figure 3). As *IP* f_t predicts both tensile strength (R^2 = 56 %) and tensile E with a high accuracy (R^2 = 59 %), the tensile strength /tensile E ratio of the combined visual and machine grading is similar to the ratios derived on tension *E* and tension strength basis.

The characteristic density of the machine graded hardwoods increases with tensile *E*. The used *IP* f_t includes density as one of the inputs for the E_{dyn} calculation. Therefore, for the higher strength classes, feasible for the machine strength grading using the combined approach, an increase in density values should be allowed.



(a) (b)

Figure 4: Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k for the visually graded timber



(a) (b)

Figure 5 Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k for the combined visual and machine strength grading of hardwoods to a single class

4.3 Tension strength to bending strength ratio

In the current study, the tension to bending strength ratio was examined for ash specimens of equal dimensions tested in tension and in bending. Figure 6 shows the tension strength to bending strength ratio for the equal sized timber grouped by the IP f_t. The estimated ratio, shown in the figure, is higher than the one for the T-Classes (value equals 1.213). The underlying ratio is close to one of the D-Classes, determined on the safe side for the bending strength and not for the tension strength.

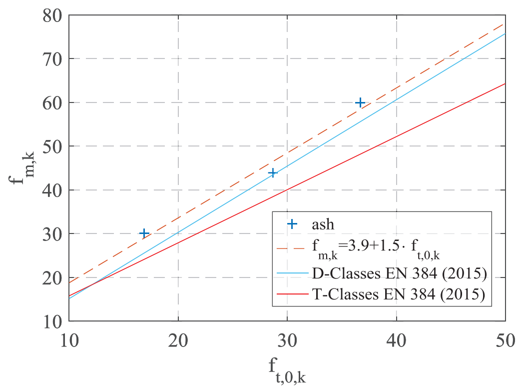
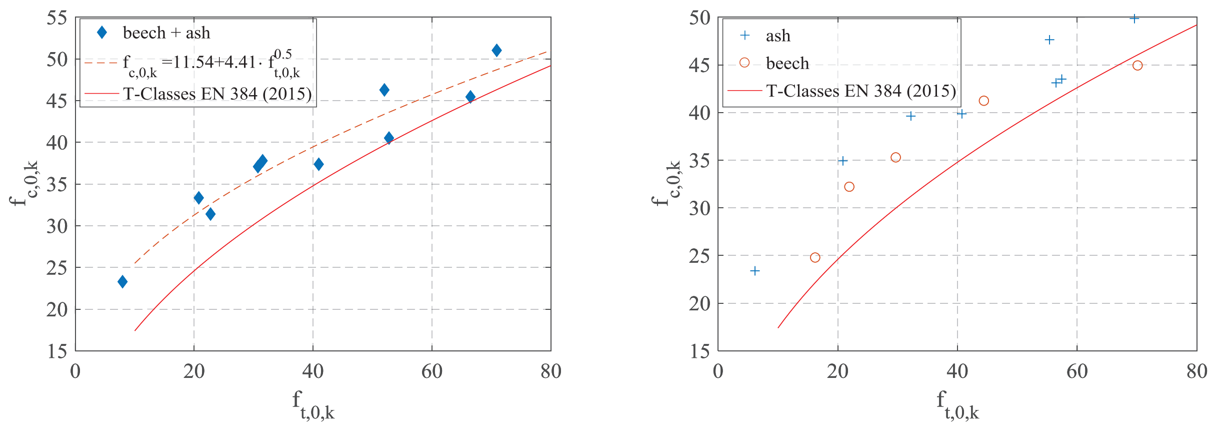


Figure 6: Relationship between tension and bending strength for data grouped by IP f_t

4.4 Tension strength to compression strength ratio

Figure 7 shows the ratio between tension and compression strength obtained for the combined beech and ash data. The estimated equation leads to higher compression strength values compared to the ones listed in EN338 (2016). For the higher strength classes, the fitted equation converges to the one for the softwood T-Classes. If the species are observed separately, both hardwood species tend to behave in a similar way, even though ash seems to have a slightly higher f_c/f_t ratio. For simplicity reasons, it is proposed to apply the equation for softwoods on medium dense hardwoods as well.



(a) (b)

Figure 7: Relationship between characteristic tensile strength and compression strength for a) joint beech and ash data and b) beech and ash separately, grouped by IP f_t

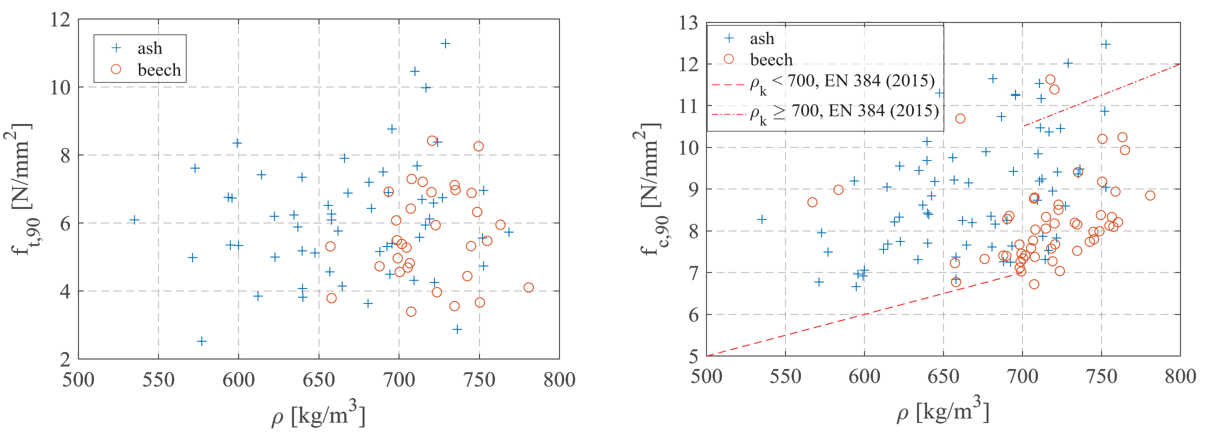
4.5 Properties perpendicular to the grain direction

Figure 8 shows the relationship between density and both tension and compression strength perpendicular to the grain for ash and beech for the data of Hunger & van de Kuilen (2015) and Westermayr (2014). No correlation between tension strength and density, as well as between compression strength and density for a combination of two species could be found. Only for ash, a correlation of 0.462 between compression strength and density, can be reported. The density values for ash show wide variation if compared to the beech.

The missing correlation between the tensile strength perpendicular to the grain and density does not allow specifying a distinct value for each class. As a consequence, the same value for all classes is sufficient. For the present data, characteristic values for the ash and beech are 3.40 N/mm² and 3.48 N/mm² respectively and exceed the values for solid wood listed in EN 338. Therefore, for all medium dense hardwoods, a single value of 3.4 N/mm² is proposed.

The weak correlation between the density and compression strength does not allow making a significant conclusion on the relationship between these variables. By keeping in mind the low feasibility of visual grading to distinguish between different density levels, same characteristic strength value for the compression strength perpendicular to the grain is essential. For the data of Hunger & van de Kuilen (2015) the characteristic compression strength values are 6.67 N/mm² and 6.77 N/mm² for ash and beech respectively. The results are comparable to the values reported by Huebner (2013) on beech and ash glulam. For the standard, a single characteristic strength value for all classes - 6.6 N/mm² - is proposed.

For both compression and tensile test perpendicular to the grain, the ratio of $E_{90,mean}$ can be compared to the $E_{t,0,mean}$ values of ungraded timber. The ratio ranges from 14.65 to 16.0 for $E_{t,0,mean}$ to $E_{t,90,mean}$ and 12.4 to 13.8 for $E_{t,0,mean}$ to $E_{c,90,mean}$.



(a) (b)

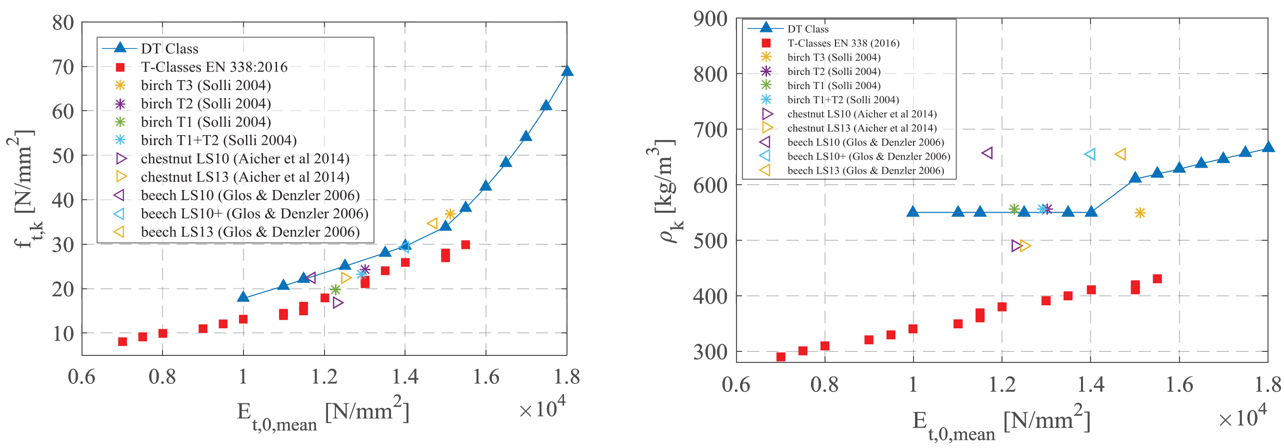
Figure 8: Relationship between (a) $f_{t,90}$ and ρ and (b) $f_{c,90}$ and ρ

4.6 Proposal for tensile strength profiles for hardwoods

Based on the analysed relationships we propose tensile strength classes for hardwoods named DT-Classes, where "D" stands for hardwoods ("deciduous") and "T" for tension. Table 3 lists a selection of new classes, which could be extended in both directions using the derived relationships. The tensile E to strength ratio is defined with regard to the tensile E. However, for the classes with a characteristic tensile strength above 30 N/mm² the $E_{t,0,mean}$ to $f_{t,0,k}$ ratio is defined using the combined visual and machine strength prediction. The prediction model integrates both $E_{t,0,mean}$ to $f_{t,0,k}$ ratios derived on the tensile E and tensile $f_{t,0}$ in the best way, by building an intermediate solution between both ratios. This is also a practical way as the design of glulam will be governed by both stiffness and strength. The resulting $f_{t,0,k}$ increases with a higher slope for characteristic strength above 30 N/mm², as illustrated in Figure 9.

Table 3: Proposed tensile strength classes for hardwoods (DT-Classes)

	Property	DT18	DT22	DT25	DT28	DT30	DT34	DT38
Strength properties [N/mm²]	$f_{m,k}$	31	37	41	46	48	55	61
	$f_{t,0,k}$	18	22	25	28	30	34	38
	$f_{c,0,k}$	30	32	34	35	36	37	39
	$f_{t,90,k}$	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	$f_{c,90,k}$	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Stiffness properties [kN/mm²]	$E_{0,mean}$	10	11.5	12.5	13.5	14	15	15.5
	$E_{90,mean}$	0.67	0.77	0.80	0.90	0.93	1.0	1.03
Density [kg/m³]	ρ_k	550	550	550	550	550	610	620



(a) (b)

Figure 9: Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and(b) between $E_{t,0,mean}$ and ρ_k for the proposed DT classes in comparison to the T-Classes for softwoods and literature values

If the proposed classes are compared to the literature values in Figure 9, for the highest visual grades of birch, beech and chestnut, the derived profiles match the properties better compared to the current T-Classes. Also higher classes than T30 are possible. However, if the existing system of T-Classes is used for hardwoods, $E_{t,0}$ becomes the grade-limiting property, whereas strength is generally fulfilled. In cases where one of the properties is generally fulfilled, the timber properties are utilised inefficiently.

The selected density profile follows the constant characteristic density value for the strength classes below DT30. Above DT30 the density increases, following the relationship for the machine graded timber. This reflects the fact that the visual grading is not able to distinguish between the different density values. The estimated profiles are shown in Figure 9b in comparison to the existing classes and literature values. For tensile strength below 30 N/mm², the defined threshold value for characteristic density matches the values for birch and beech. Whereas for the characteristic density of chestnut, the value is too high.

This also shows clearly, that determining a single density value for all medium-dense hardwood species might not be easy. The characteristic density of timber analysed here shows high variation and ranges between 520 kg/m³ for LS13 maple to 660 kg/m³ for LS13 beech. For LS13 maple tested in bending, characteristic values as high as 590 kg/m³ are reported by Glos & Torno (2008). For chestnut, a characteristic density of 510 kg/m³ was found by Nocetti et al. (2010). As a consequence, a separate declaration of the density for each combination of species and grade could be the best solution. Already Frühwald & Schickhofer (2005) suggested making density an optional, indicative parameter, rather than a mandatory one.

The relationships between the material properties are derived on medium dense hardwoods ash, beech and maple from Central Europe only. The relationship should be checked on other relevant hardwood specimens, such as oak.

5 Conclusion

In this paper, the material properties of the medium dense European hardwoods tested in tension have been analysed. The material property profiles are examined with regard to tensile E, tensile strength, visual grading and combined visual and machine strength prediction. This allows creating profiles fitting the properties of the selected hardwoods in the best way. These profiles are incorporated in the system of tensile strength classes for hardwoods (DT-Classes) presented here.

The presented DT-Classes are tailored to the material properties of hardwoods and allow, in comparison to the T-Classes an efficient utilisation of timber properties. If the T-Classes are used for hardwoods, the tensile E becomes a grade-limiting property.

Setting a characteristic density value remains a challenging task. High variation in density properties between the hardwoods and the fact that the density of hardwoods cannot be estimated using visual grading rules, compromise the use of density as one of the major characteristic properties for hardwoods. The possibility to declare density separately from the strength classes should be checked.

The ratio of bending strength to tension strength and compression strength to tension strength were checked for hardwoods. This ratio is higher than for softwood T-Classes. For the simplicity reasons the relationships listed in T-Classes for softwoods may also be used for hardwoods.

Based on the available data on compression and tension properties perpendicular to the grain, constant values for $f_{t,90,k}$ and $f_{c,90,k}$ all strength classes are proposed.

6 Acknowledgements

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Discussion

The paper was presented by A Kovryga

K Crews commented that no finger joint material was evaluated and in Australia the limiting factor was finger joints with hardwood with delamination and gluing issues. He also commented that in slide 13 there was significant extrapolation and suggested to remove the extrapolation. A Kovryga replied that it was the real data.

G Fink commented that although the values were quite high they could be even higher. He questioned whether testing according to EN 408 was appropriate. A Kovryga agreed as the shorter test span might not be appropriate in terms of location of the weakest parts in the test zone.

K Ranasinghe received clarification that the single knot criterion was not based on UK standards and shear strength had not been analysed. He commented that it would make more sense to declare characteristic density according to species. There were discussions that the tensile strength perpendicular to grain was very high and it was decided to lower the value for design to discourage its use.

A Frangi asked what the coefficient of variation was. A Kovryga replied that the information was in the database.

K Crews commented that one should examine whether too many groups were examined.

F Lam commented that information about yield would be important. A Kovryga replied that each class considered 100 data points and the approach could not provide yield and such information would be obtained in another study on grading.