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Ravenshorst, Geert; Van De Kuilen, Jan Willem G

Publication date
2016

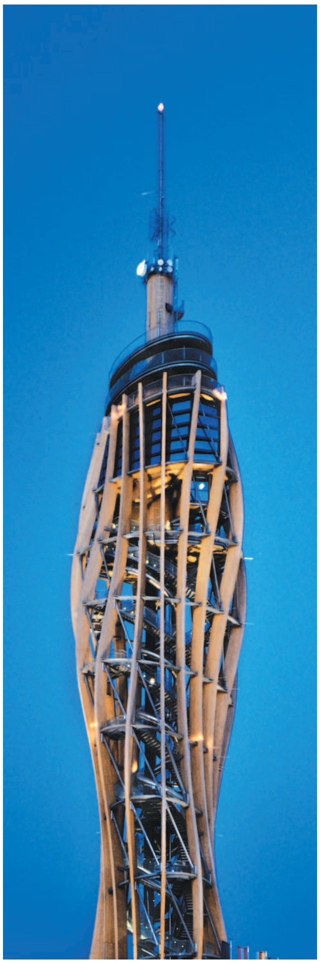
Document Version
Final published version

Published in
WCTE 2016 - World Conference on Timber Engineering

WCTE 2016

World Conference on Timber Engineering

August 22-25, 2016 | Vienna, Austria



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WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

WCTE 2016 e-book
containing all full papers submitted to the World Conference on Timber Engineering (WCTE 2016), August 22-25, 2016, Vienna, Austria

Editors:
Josef Eberhardsteiner, Wolfgang Winter, Alireza Fadai, Martina Pöll

TUVerlag
an der Technischen Universität Wien

Editor:
TU-MV Media Verlag GmbH
Wiedner Hauptstraße 8-10
A-1040 Wien
www.tuverlag.at
office@tuverlag.at

Bibliografische Information der Deutschen Bibliothek:

Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über
http://dnb.d-nb.de abrufbar

www.tuverlag.at
ISBN 978-3-903024-35-9
ISBN 978-3-903024-35-9

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Timber Engineering
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SPECIES INDEPENDENT STRENGTH MODELING OF STRUCTURAL TIMBER FOR MACHINE GRADING

Geert Ravenshorst[1] and Jan-Willem van de Kuilen[2]

ABSTRACT: The current methods for the determination of the strength properties for wood species for grading purposes require extensive testing. Species independent grading might be a solution for this problem, in particular for tropical hardwoods. The strength reducing characteristics such as knots and slope of grain require two groups for which species independent machine grading is possible. Theoretical strength models are formulated and verified with data from a large database of soft- and hardwoods.

KEYWORDS: strength grading, tropical hardwoods, temperate hardwoods, softwoods, dynamic modulus of elasticity,

1 INTRODUCTION

The current methods for the determination of the strength properties for wood species require extensive testing. The requirement in EN 14081 [1] is practically that strength properties need to be determined for each single wood species separately. The destructive test results have to be related to visual grading rules or to limit values ("settings") to be used in machine grading. Due to sustainable forest management, a large amount of species is coming on the market in relative small batch sizes. This is in particular true for tropical hardwoods. The problem with tropical hardwoods is that the main strength influencing parameter, the grain angle deviation, is very difficult to measure both in the laboratory as well as during the grading operations. As a result, with visual grading only a single visual grade and connected strength class can be defined for a tropical hardwood species. At present, there is no hardwood species accepted to be used in machine grading under the current European standards. A species independent strength grading approach might be a solution to apply machine strength grading, in particular for tropical hardwoods. In this paper, the theoretical backgrounds for species independent strength grading for both softwoods and hardwood is investigated, by formulating strength predicting models. The models are validated on a large database containing bending tests on softwoods and hardwoods.

[1] Geert Ravenshorst, Delft University of Technology, Delft,P.O. Box 5048 2600 GA Delft, g.j.p.ravenshorst@tudelft.nl
[2] Jan-Willem van de Kuilen, Delft University of Technology, Delft and Technical University of Munich, Munich.

2 MATERIALS AND METHODS

2.1 MATERIALS

A large database of tropical hardwoods, European softwoods and European temperate hardwoods was built up during the last 15 years consisting of:
- 2218 specimens of structural sizes of 24 tropical hardwood species. See table 1.
- 2271 specimens of structural sizes of 6 European softwoods and European temperate hardwood species. Table 2

Table 1.*Tested tropical hardwood species*

Trade name	Botanical name
angelim vermelho	*Diniza excelsa*
cumaru	*Dypterix spp*
massaranduba	*Manilkara bidentata*
azobé	*Lophira alata*
greenheart	*Ocotea rodiaei*
okan /denya	*Cylicodiscus gabunensis*
karri	*Eucalyptus diversicolor*
nargusta	*Terminalia amazonia*
piquia	*Caryocar spp*
vitex	*Vitex spp.*
basralocus	*Dicorynia guianensisAmsh*
Bangkirai	*Shorea spp.*
sucupira vermelho	*Andira spp*
castana rosa	*Pouteria oppsitifolia*
louroa amarela	*Ocotea spp*
louro faia	*Euplassa spp.*
purpleheart	*Peltygone spp.*
tauari vermelho	*Cariniana spp.*
favinha	*Entorolobium spp.*
sapupira	*Hymenolobium spp*
favinha prunelha	*Pseudopiptadenia spp*
bilinga	*Nauclea diderrichii*
eveuss	*Klainedoxa gabonenis*
tali	*Erythrophleum ivorense*

Table 2 .Tested European softwood species and European hardwood species

Trade name	Botanical name
spruce	*Picea abies*
douglas	*Pseudegotsi menzisii*
larch	*Larix spp.*),
oak	*Quercus robur*
robinia	*Robinia pseudoacacia L*
chestnut	*Castanea sativa*

2.2 METHODS

2.2.1 Theoretical derivations

This paper will present theoretical derivations of strength models based on basic relationships. The derived strength models are intended to be used by machine grading. The properties that are suited for machine grading to be measured and to be used to predict the strength are the density and the Modulus of Elasticity. The Modulus of Elasticity can be determined by vibration measurements. In [4] was shown that there is relationship for the Modulus of Elasticity determined by vibration measurements (MOE_{dyn}) and by standardised static laboratory measurements (MOE_{stat}) which is practically species independent. For strength class assignments according to the European harmonised standards the density, the modulus of elasticity and the bending strength are the grade determining parameters. The density and the MOE can be determined with relatively simple devices during the grading process. The bending strength has to be predicted based on models derived in testing programs. From these models settings (limit model values) have to be derived that can be implemented in strength grading machines´ software.

First basic relationships and expected scatter for clear wood will be formulated. After that relationships and scatter for timber with features that reduce the clear wood strength are formulated. Finally, strength predicting models for machine grading based on the measurable properties density and MOE are derived.

2.2.2 Experimental verification

The derived models will be verified with the available data. This will be done by performing regression analyses on the test data and compare them with simulated data based on constants derived from the data.

3 MODELING OF THE BENDING STRENGTH OF STRUCTURAL TIMBER

3.1 BENDING STRENGTH OF CLEAR WOOD

There are several databases containing bending test data of small clear wood specimens. In the Houtvademecum [2] a table is included that is a collection of literature results on the mechanical and physical properties of 192 softwood and hardwood species. In [3] this data was analysed. A linear relationship can be observed between the density and the strength and also between the density and the stiffness. See figures 1 and 2. The magnitudes of the values should not be compared to test results on full size specimen, because they are highly influenced by their size and by the test method. The relationship is however useful to discover trends.

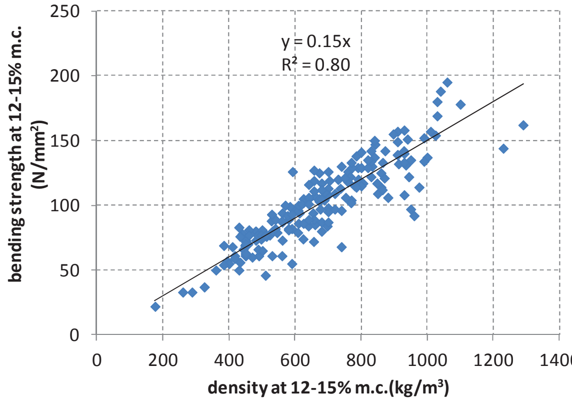

Figure 1: *Mean bending strength values plotted against mean density values for clear wood for 192 softwood and hardwood species.*

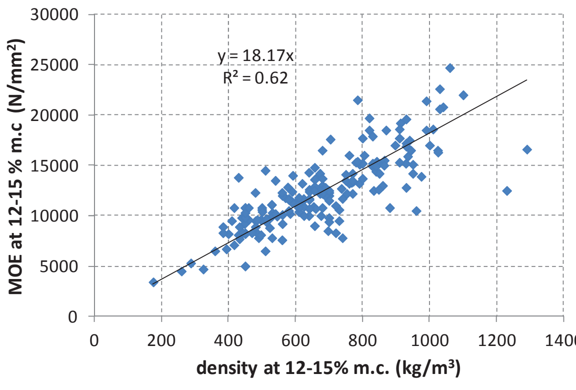

Figure 2: *Mean Modulus of Elasticity values plotted against mean density values for clear wood for 192 softwood and hardwood species.*

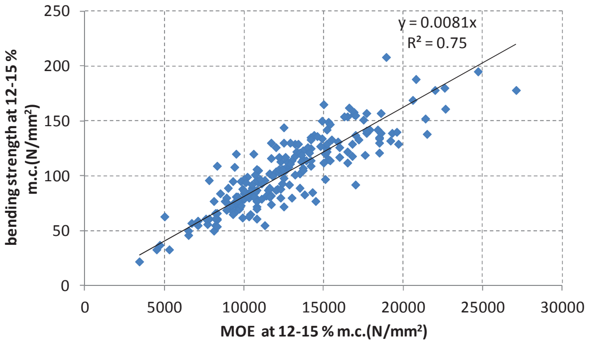

Figure 3: *Mean bending strength values plotted against mean Modulus of Elasticity values for clear wood for 192 softwood and hardwood species.*

Figure 3 shows the relationship between the modulus of elasticity and the bending strength. The regression equations in the graphs in figures 1,2 and 3 are forced through the origin.

The scatter around the mean regression line of strength against density is assumed to be the natural variation in properties as species have different microstructural features that cannot be explained at the macroscopic clear wood level. The scatter increases with increasing density, the coefficient of variation being constant. The same phenomenon is observed for the stiffness and the density.

The bending strength and MOE can be described as stochastic variables according to equations (1) and (2)

$$f_{m,0} = \rho C_1 + \varepsilon_f \quad (1)$$
$$MOE_0 = \rho C_2 + \varepsilon_M \quad (2)$$

Where:

$f_{m,0}$ is the bending strength for clear wood, the zero indicates no grain angle deviation.

ρ is the density of clear wood.

MOE_0 is the modulus of elasticity for clear wood, with no grain angle deviation.

C_1 is the ratio between the clear wood strength and the density.

C_2 is the ratio between the clear wood stiffness and the density.

ε_f and ε_M describe the scatter around the mean regression lines for respectively the bending strength and the MOE and are considered to be normally distributed with a mean value of zero for a certain density:

$$\varepsilon_f = X_2 v_F\, \rho C_1 \quad (3)$$
$$\varepsilon_M = X_1 v_M\, \rho C_2 \quad (4)$$

Where

X_1 and X_2 are stochastic variables following the standard normal distribution $N(0,1)$.

v_F is the coefficient of variation for the error for the bending strength for a certain density value with the mean bending strength value for this density.

v_M is the coefficient of variation for the error for the Modulus of Elasticity for a certain density value with the mean Modulus of Elasticity value for this density.

Equations (3) and (4) show an increasing error for increasing density, as the coefficient of variation is constant over the density range.

From equations (1) and (2) the relationship between the MOE and the bending strength for clear wood can be expressed as:

$$f_{m,0} = \frac{C_1}{C_2} MOE_0 - \frac{C_1}{C_2}\varepsilon_M + \varepsilon_f \quad (5)$$

The clear wood bending strength is related to the Modulus of Elasticity.

Figure 3 shows the relationship between the bending strength and the MOE for the data from figures 1 and 2.

The model values for the bending strength (which are the values on the regression line) are then described by equation (6)

$$f_{m,0,mod} = \frac{C_1}{C_2} MOE_0 \quad (6)$$

The scatter around the regression line is then described by equation (7):

$$\varepsilon_{f_{m,0}} = -\frac{C_1}{C_2}\varepsilon_M + \varepsilon_f \quad (7)$$

The magnitude of the scatter $\varepsilon_{fm,0}$ depends on the correlation between ε_f and ε_M. When they are perfectly correlated ($r^2 = 1.0$), the scatter in equation (5) becomes zero. It is shown in [3] that the coefficient of determination between ε_f and ε_M for the data in figure 3 is approximately $r^2 = 0.25$. This explains that the MOE is a good predictor for the bending strength of clear wood. That is because both MOE and bending strength are dependent of the density, and the natural variations for these dependencies for the MOE and bending strength are correlated.

The model coefficient C_1/C_2 in (6) can be calculated from the values found in figures 1 and 2, but can also directly be determined by regression analysis. Also the scatter around the model line can be determined by regression analysis.

3.2 STRENGTH REDUCING CHARACTERISTICS

3.2.1 Introduction

In section 3.1 was explained that the prediction of the bending strength from the MOE of clear wood can be explained by the fact that both properties are correlated to the density. That means that the prediction of the bending strength of clear wood is not related to the species, but to the property density (and by that also to the MOE), and therefore species independent.

To extend this theory to structural sized specimens it has to be investigated which features in structural size specimen cause that the bending strength of the piece is reduced compared to clear wood strength.

For this purpose the concept of the weak zone model proposed in [5] is used. This model regards structural timber as clear wood connected by weak zones that affect both strength and stiffness. The weak zones then initiate the failure of structural timber. For structural timber there are two main features that initiate the failure under bending:

- knots
- global slope of grain

Figure 4 shows the bending failure of a beam initiated by the presence of a knot and figure 5 shows the bending failure of a beam initiated by the presence of global slope of grain.

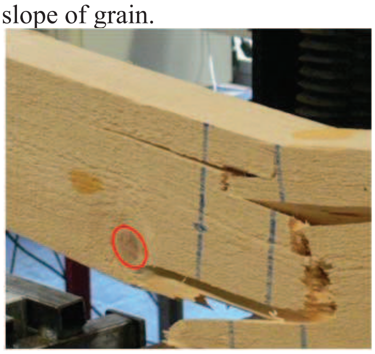

Figure 4: *Bending failure of a softwood beam initiated by the presence of a knot.*

Figure 5: *Bending failure of a tropical hardwood beam initiated by the presence of global slope of grain.*

For knots it could be argued that failure is also caused by slope of grain, but in this case it is considered as *local* slope of grain. Global slope of grain may be present independent of the presence of knots, which is quite common for tropical hardwoods.
In the next sections the reduction of the bending strength due to knots and global slope of grain are further elaborated in two separate models.

3.2.2 Reduction of the bending strength and MOE due to the presence of knots

Figure 6 shows how the dimensions of a knot can be schematized.

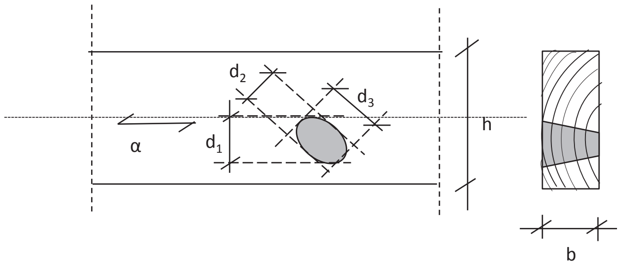

Figure 6: *Representation of knot dimensions.*

Knots are often quantified as a knot ratio, that can be defined as the knot dimension divided by the beam side dimension. Which dimension of the knot is used differs between national visual grading standards, equation (8) gives an example for the knot ratio defined as the knot dimension d_1 perpendicular to the beam axis divided by the beam width h perpendicular to the beam axis(see figure 6):

$$KR = \frac{d_1}{h} \tag{8}$$

In visual grading standards the reduction of strength is implemented by a stepwise reduction of the strength grade with reducing knot ratio. The exact physical explanation is more complex [6], but this approach gives reasonably good correlations for the most common cross sections, as for instance is shown in [7].
The bending strength and the MOE can be described as a reduction of the clear wood strength by equations (9) and (10):

$$f_{KR} = \left(\rho C_1 + \varepsilon_f\right)(1 - C_6 KR) + C_7 \tag{9}$$

$$MOE_{KR} = (\rho C_2 + \varepsilon_M)(1 - C_8 KR) \tag{10}$$

Where:

f_{KR} is the bending strength for timber with knot initiated failure

MOE_{KR} is the MOE for timber with knots.

C_6 describes magnitude of the influence of the knot ratio on the reduction of the bending strength.

C_8 describes the magnitude of the influence of the knot ratio on the reduction of the MOE.

Factor C_7 brings the systematic effects into account that can be caused by for instance the load configuration or size effects. The term $(1 - C_6 KR)$ assumes a linear reduction of the bending strength with increasing KR-value and the term $(1 - C_8 KR)$ a linear reduction of the MOE.

Equations (9) and (10) assume that the reduction of strength is deterministic and the scatter is caused by the natural variation of clear wood.

3.2.3 Reduction of the bending strength and MOE due to the presence of global slope of grain

Figure 7 shows how global slope of grain is defined as the tangent of the angle α of the grain with the beam axis.

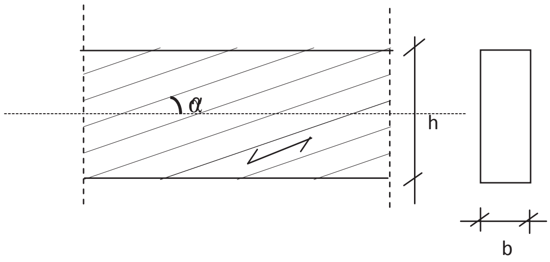

Figure 7: *Representation of global slope of grain.*

The reduction of the bending strength and MOE can be described by the Hankinson equation. For the bending strength this relation is given in equation (11):

$$f_{m,\alpha} = \frac{f_{m,0}}{C_3 sin^2(\alpha) + cos^2(\alpha)} \qquad (11)$$

Where
$f_{m,\alpha}$ is the bending strength for timber with failures initiated by the slope of grain.
$f_{m,0}$ is the bending strength for clear wood with zero slope of grain.
$C_3 = \frac{f_{m,0}}{f_{m,90}}$ describes the ratio between the bending strength parallel and perpendicular to the grain.
Inserting equation (1) in equation (11) and rewriting the denominator in equation (11) gives equation (12):

$$f_{m,\alpha} = \frac{(\rho C_1 + \varepsilon_f)C_1}{(C_3 - 1)sin^2(\alpha) + 1} + C_5 \qquad (12)$$

Where C_5 brings the systematic effects into account.
The same procedure for the MOE gives equation (13)

$$MOE_\alpha = \frac{(\rho C_2 + \varepsilon_M)C_2}{(C_4 - 1)sin^2(\alpha) + 1} \qquad (13)$$

Where
$C_4 = \frac{MOE_0}{MOE_{90}}$ describes the ratio between the MOE parallel and perpendicular to the grain.

4 STRENGTH PREDICTING MODELS FOR MACHINE GRADING

4.1 SPECIES INDEPENDENT STRENGTH MODELS

In section 3 is shown that the basic strength and stiffness of timber is related to the density and is not related to the species. However, for structural timber this basic strength is reduced by features that occur in structural timber but not in clear wood. The most important features that cause this reduction are knots and slope of grain. These features can also be quantified by measuring the size of knots and the slope of grain.
That means that also species independent strength modelling is possible, but that the density is required as a parameter that has to be measured. For that reason machine grading is the most suitable grading method for species independent strength grading. With machine grading also the MOE can be determined easily with for instance vibration measurements. With equations (10) and (13) the effect of respectively knots and slope of grain on the MOE is described, which means that the MOE can be used to incorporate the effect of knot and slope of grain without measuring these parameters, but only measuring the MOE. This will be further elaborated in the next sections. However, the MOE cannot incorporate the effect of both parameters knots and slope of grain at the same time, because then there is an variable too much.
That means that for species independent strength grading a division has to be made between structural timber with failures induced by knots and failures induced by slope of grain. In practice this division is represented by softwoods and some European hardwoods (failures initiated by knots) and tropical hardwoods (failures initiated by slope of grain, and brought on the market with very limited amounts of knots). European hardwoods may show knots, but the mechanical properties may also be mainly governed by slope of grain.

4.2 SPECIES INDEPENDENT STRENGTH MODEL FOR FAILURES INITIATED BY KNOTS

The parameters to be measured in machine grading are the density and the MOE. Equation (10) can be rewritten to describe the knot ratio *KR* in terms of the density and the MOE:

$$KR = \frac{(\rho C_2 + \varepsilon_M) - MOE_{KR}}{(\rho C_2 + \varepsilon_M)C_8} \qquad (14)$$

Equation (15) describes the strength distribution that can be expected for timber with knots and with zero slope of grain for which the density and the MOE are measured by inserting (14) in (9).

$$f_{KR} = \left(\rho C_1 + \varepsilon_f\right)\left(1 - C_6 \frac{(\rho C_2 + \varepsilon_M) - MOE_{KR}}{(\rho C_2 + \varepsilon_M)C_8}\right) \qquad (15)$$

The prediction of the strength will give the mean value of this distribution for this density and MOE, so with zero scatter:

$$f_{KR,mod} = \rho C_1 \left(1 - C_6 \frac{\rho C_2 - MOE_{KR}}{\rho C_2 C_8}\right) + C_7 \qquad (16)$$

Equation (15) can be rearranged as:

$$f_{KR,mod} = \rho C_1\left(1-\frac{C_6}{C_8}\right)+\frac{C_1C_6}{C_2C_8}MOE_{KR}+C_7 \quad (17)$$

And by combining the constants (17) can be further rewritten as:

$$f_{KR,mod} = D_4\rho + D_5 MOE_{KR} + D_6 \quad (18)$$

With

$D_4 = C_1\left(1-\frac{C_6}{C_8}\right)$

$D_5 = \frac{C_1C_6}{C_2C_8}$

$D_6 = C_7$

In principle, when all C_i - constants are known, the D_i - constants can be calculated. However, when a prediction model is built for a specific dataset there are two problems that have to be addressed:

1. When a certain dataset in studied, only the bending strength, density and MOE of each piece are known, and not the values of all C_i - constants. They have to be derived in a separate investigation.
2. When the C_i - constants are known, from previous investigations, then the values of the D_i - constants can be calculated, but this will only give a good correlation between the model values according to equation (17) and the measured bending strength values when all test pieces have the same density. This means that the regression plot of the model values and the test values are dependent on the distribution of the density values of the timber used.

To overcome these two problems the D_i - constants can be derived directly from a regression analysis for a certain input distribution. That means that one must be aware that the values of the D_i - constants will change when the input distribution changes. However, when simulations are run on different input distributions then the expected scatter around the model line can be studied.

The values of the C_i - constants can be regarded as "fixed properties" of the timber which are constant for , and the values of the D_i - constants as "dynamic properties", dependent on the input distribution of the dataset studied. Therefore, the *C*-constants can be used to simulate the data, and by varying the input density the effect on the D-values can be studied.

4.3 SPECIES INDEPENDENT STRENGTH MODEL FOR FAILURES INITIATED BY SLOPE OF GRAIN

Again the parameters to be measured are the density and the MOE. Equation (13) can be rewritten as:

$$sin^2(\alpha) = \left(\frac{\rho C_2+\varepsilon_M}{MOE_\alpha}-1\right)\frac{1}{C_4-1} \quad (19)$$

Equation (20) describes the strength distribution that can be expected for timber with slope of grain > 0 and no knots for which the density and the MOE are measured by inserting (19) in (12):

$$f_{m,\alpha} = \frac{\rho C_1+\varepsilon_f}{(C_3-1)\left(\frac{\rho C_2+\varepsilon_M}{MOE_\alpha}-1\right)\frac{1}{C_4-1}+1} \quad (20)$$

Equation (20) can be rearranged as:

$$f_{m,\alpha} = \frac{(\rho * C_1+\varepsilon_f)MOE_\alpha(C_4-1)}{\rho(C_3C_2-C_2)+MOE_\alpha(C_4-C_3)+\varepsilon_M(C_3-1)} \quad (21)$$

The prediction of the strength will give the mean value of this distribution for this density and MOE, so with zero scatter:

$$f_{m,\alpha,mod} = \frac{\rho C_1(C_4-1)MOE_\alpha}{(C_3-1)C_2\rho+(C_4-C_3)MOE_\alpha}+C_5 \quad (22)$$

By combining the constants (22) can be rewritten as:

$$f_{m,\alpha,mod} = \frac{\rho MOE_\alpha}{D_1\rho+D_2MOE_\alpha}+D_3 \quad (23)$$

With

$D_1 = \frac{(C_3-1)C_2}{C_1(C_4-1)}$

$D_2 = \frac{(C_4-C_3)}{C_1(C_4-1)}$

$D_3 = C_5$

Again, when bending strength, MOE and density data is available, the D_i - constants can be directly determined by a non-linear regression analysis. The values of these constants will change depending on the distributions of the density and MOE. With simulations the expected scatter around the model line can be studied. Again, because the *C*-constants are fixed values, they can be used to simulate data, and by varying the input density the effect on the D-values can be studied.

4.4 DISCUSSION

In the previous sections species independent strength models have been derived. The influence of the knots or the slope of grain can be represented by the MOE, but not at the same time. It is therefore necessary to divide the timber not in different species, but in the dominating feature type that initiates failure. Then a division between timber containing knots but very little slope of grain and timber containing slope of grain but almost no knots can be made. In practice this division is represented by softwoods and some temperate hardwoods (knots dominating) and tropical hardwoods (global slope of grain dominating) as it is coming on the market nowadays.

The strength reducing features can be described by constants (C_i-constants in this paper), which are properties of the material itself and therefore fixed values. They are regarded as fixed values because it is

assumed that these constants are the same when different datasets with different densities are studied. In the next paragraphs it is shown that the values for C_1 and C_2 are very close for a dataset of douglas with mean density of 575 kg/m^3 and massaranduba with a mean density of 1010 kg/m^3.
From the relationships of these constants species independent strength models for the two timber types are derived. For the timber containing knots a linear prediction model was derived and for timber with global slope of grain a non-linear prediction model was derived. The D_i - constants derived by regression models depend on the input distribution of the used parameters, the density and the MOE.
By performing simulations, the expected scatter around the model line can be studied. The data can be simulated by the use of the *C*-constants, and the effect on the *D*-constants can be studied.

5 EXPERIMENTAL VERIFICATION

5.1 EUROPEAN SOFTWOODS AND EUROPEAN TEMPERATE HARDWOODS

To be able to uses species independent strength models for grading it is important the shape of the scatter around the model line is known. Therefore, for a dataset of 356 pieces of European softwood species douglas the distribution properties were determined and the C_i - constants were derived. Then by performing simulations to calculate the expected residuals, defined as equation (17)-equation (15) can be compared with the residuals from a direct regression analysis to determine the *D*-values with equation (18).
In table 3 the distribution properties of the density and the knot ratio are given, in table 4 the derived C_i - constants, the values for v_F, v_M and the correlation between the errors of the bending strength and the MOE are given.

Figure 8 shows the bending strength values plotted against the modelled values for the dataset of douglas from a direct regression analysis with equation (18), together with 2500 simulations points based on the distribution properties of table 3 and the constants in table 4 with the *D*-values in equation (18) directly calculated from the *C*-values. This approach is possible because there is only a limited scatter in the density.

Table 3: *Distribution properties derived from the dataset of Douglas.*

Property	mean	Standard	Distribution
Density (kg/m^3)	575	62	normal
KR	α=0.27	β=2.2	weibull
X_1	0	1	normal
X_2	0	1	normal

Table 4: *Constant values derived from the dataset of Douglas.*

Property	Value
C_1	0.11
C_2	26.9
C_6	1.03
C_7	-0.03
C_8	0.37
v_F	0.29
v_M	0.16
r^2 between X_1 and X_2	0.27

Figure 8: *Douglas test data compared with simulated data based on tables 1 and 2.*

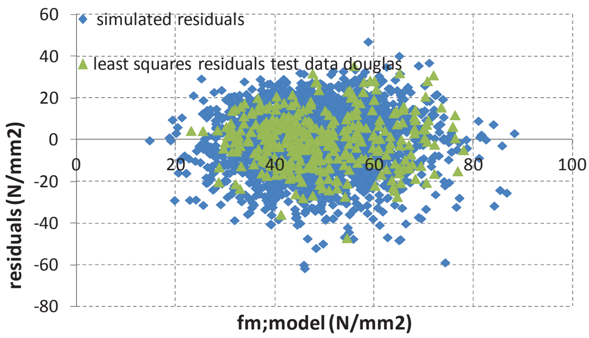

Figure 9: *Residuals based on regression on test data compared with residuals based on simulations.*

Figure 9 shows that the simulated residuals follow the same trend as the residuals from the direct regression analysis. It can be observed that the magnitude of the error around the model line remains practically constant with increasing model values. The aim of the exercise on the douglas data is to show that the appropriateness of the model of equation (18) can be explained from the distribution properties of table 3 and the *C*-constants according to table 4.

As a next step the database of 2271 specimens of six European softwood and hardwood species with knots as the main strength reducing parameter are studied. From

this data only the dynamic MOE and the density are available as model parameters for machine grading. For the douglas data was shown that the D-values of equation (18) can be directly derived from a regression analysis.
The multi-linear regression model that was found is:

$$f_{KR,mod} = 0.025\rho + 0.0031MOE_{KR} - 7.3 \quad (24)$$

The regression graph is shown in figure 10. Compared to equation (6) for clear wood the density is now included into the equation. This is because now the influence of the strength reducing feature is now integrated in the MOE, where for clear wood the MOE is only related to the density.
The residuals against the model values are plotted in figure 11.

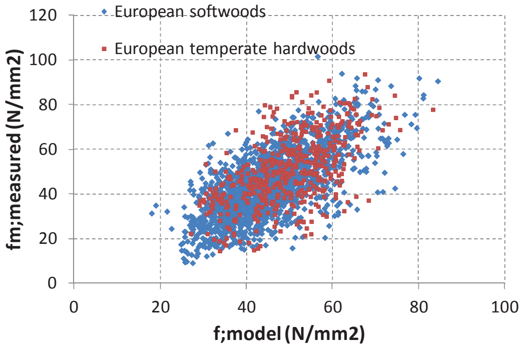

Figure 10: *Bending strength values plotted against the model values according to the model of equation (24)*

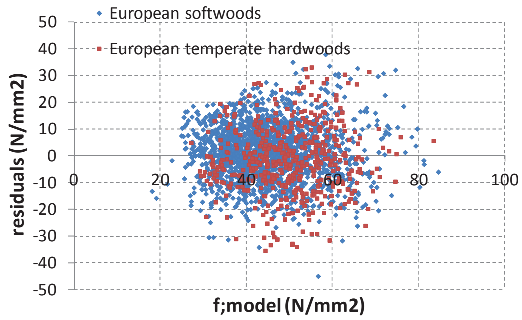

Figure 11: *Residual strength values plotted against the model values according to the model of equation (24)*

Figure 10 shows that the six softwood and temperate hardwood species can be combined in one consistent model. Figure 11 shows that the shape of the residuals around the model line are as expected from the simulations of figure 9. An almost constant magnitude of the error for increasing model values is observed.

5.2 TROPICAL HARDWOODS

To investigate the expected scatter around the model line for tropical hardwood, 74 specimens of the tropical hardwood species massaranduba were analysed. To derive the constants for this dataset, 18 specimens with slope of grain at different levels were specially prepared. In table 5 the distribution properties of the density and the global slope of grain are given, in table 6 the derived C_i - constants, values for v_F, v_M and the correlation between the errors of the bending strength and the MOE are given.

Table 5: *Distribution properties derived from the dataset of Massaranduba.*

Property	mean	Standard	Distribution
Density (kg/m^3)	1010	67	normal
Slope of grain	α=0.12	β=1.5	weibull
X_1	0	1	normal
X_2	0	1	normal

Table 6: *Constant values derived from the dataset of massaranduba.*

Property	value
C_1	0.13
C_2	24.1
C_3	28.2
C_4	9.3
C_5	-8.5
v_F	0.15
v_M	0.09
r^2 between X_1 and X_2	0.18

Figure 12 shows the bending strength values plotted against the modelled values for the dataset of massaranduba from a direct regression analysis with equation (23), together with 2500 simulations points based on the distribution properties of table 5 and the constants in table 6with the D-values in equation (23) directly calculated from the C-values. This approach is possible because there is only a limited scatter in the density

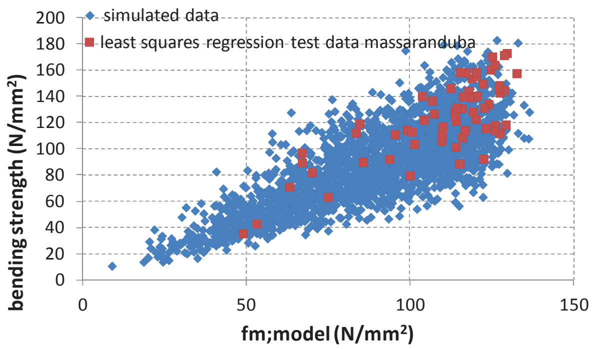

Figure 12: *Residuals based on regression on test data compared with residuals based on simulations.*

Figure 13 shows the residuals against the model values. The residuals from the simulations are defined as equation (22)-equation (21) that are compared with the residuals from a direct regression analysis to determine the *D*-values with equation (23).
Figure 13 shows that the simulated residuals follow the same trend as the residuals from the direct regression analysis. It can be observed that the magnitude of the error around the model line increases with increasing model values.

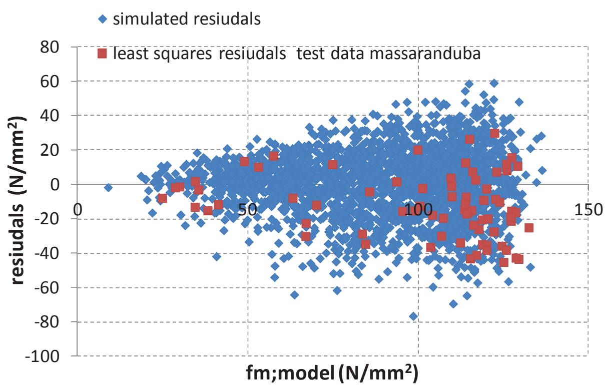

Figure 13: *Residuals based on regression on test data compared with residuals based on simulations.*

The aim of the exercise on the massaranduba data is to show that the appropriateness of the model of equation (23) can be explained from the distribution properties of table 5 and the *C*-constants according to table 6.

Next, the database of 2218 specimens of 24 tropical hardwoods with global slope of grain as the main strength reducing characteristic are studied. From this data only the dynamic MOE and the density are available as model parameters for machine grading. For the massaranduba data was shown that the *D*-values of equation (23) can be directly derived from a regression analysis.

The regression model found was:

$$f_{m,\alpha,model} = \frac{\rho \min(MOE_\alpha;25.0\rho)}{183.8\,\rho + 0.15\min(MOE_\alpha;25.0\rho)} - 12.9 \qquad (25)$$

In this model the maximum value for the MOE was restricted to 25 times the density value, In this way the scatter was more symmetric. The regression graph is shown in figure 14.
The residuals against the model values are plotted in figure 15.

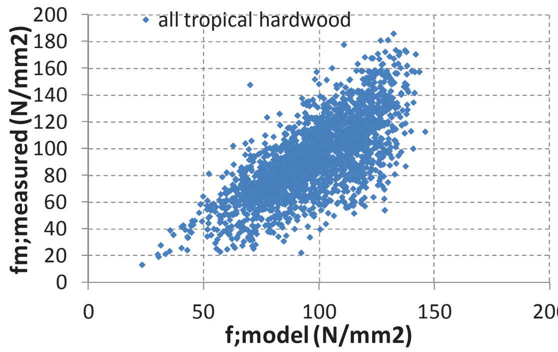

Figure 14: *Bending strength values plotted against the model values according to the model of equation (25)*

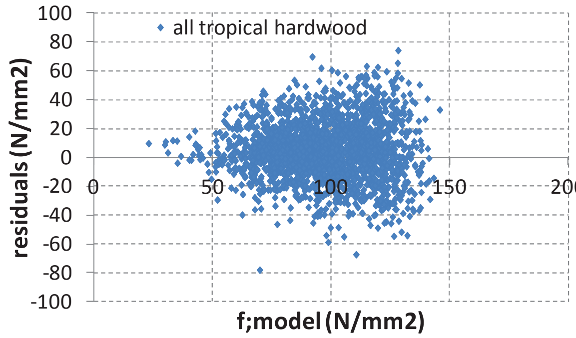

Figure 15: *Residual strength values plotted against the model values according to the model of equation (25)*

Figure 14 shows that the 24 tropical hardwood species can be combined in one consistent model. Figure 15 shows that the shape of the residuals around the model line are as expected from the simulations of figure 13. An increasing magnitude of the error for increasing model values is observed.

6 CONCLUSIONS

The fact that the basic strength and stiffness of clear wood timber is related to the density is considered as applicable on all species. The scatter between species, and in between a single species are both considered to be covered The reduction of strength and stiffness from the clear wood strength for structural timber is mainly caused by the features knots and global slope of grain, and not by species related anatomical features.

The equations to describe these reductions contain constants that can be regarded as timber properties.

The influence of either knots or global slope of grain can be represented by the modulus of elasticity but not both features at the same time. Therefore, to derive models for machine grading, a separation has to be made for timber with knots as the dominating feature and timber with global slope of grain as the dominating feature.

For timber with knots, a linear strength predicting model is derived. The constants in this model depend on the input distribution of the density and the MOE. The expected scatter around the model line can be found by performing simulations, and is almost constant with increasing model values.

For timber with slope of grain a non-linear predicting model is derived. The constants in this model depend on the input distribution of the density and the MOE. The expected scatter around the model line can be found by performing simulations, and is increasing with increasing model values.

Because the global slope of grain is very difficult to measure in practice in particular for tropical hardwoods species independent strength grading opens possibilities for safe and economic use of this type of timber in structures.

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