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Van De Kuilen, J. W.; Ravenshorst, Geert

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Relationships between non-destructive measurements and mechanical properties of tropical hardwoods

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

ABSTRACT: There are more than 1000 wood species worldwide available that have the potential to be used in structural applications. Many of these species are tropical hardwood species. In this paper, the mechanical and physical properties of a large number of tropical hardwoods are presented. They are investigated for relationships that are valid for all tropical hardwood species based on non-destructive measurable parameters. It is found that slope of grain and density can be used to describe the relationship between the mechanical properties of the entire dataset. However, slope of grain is difficult to identify and measure in practice. The dynamic modulus of elasticity in combination with density can be used as grading parameters on the basis of which a species can be assigned to multiple strength classes.

KEYWORDS: Tropical hardwoods, slope of grain, density, dynamic modulus of elasticity,

1 INTRODUCTION

Due to the increasing amount of sustainable managed forests, the number of different tropical wood species to be used for structural applications also increases. To be able to use them structurally, the mechanical and physical properties have to be known with sufficient accuracy. In order to open up the market for lesser known species, a large database was built up over the last fifteen years in the Netherlands. The data is presented in this paper and analyzed to investigate the existence of some generally applicable relationships between non-destructive and destructive parameters, primarily bending strength. In addition, also effects of sampling and the influence of moisture content on the strength values are presented.

2 MATERIALS AND METHODS

2.1 MATERIALS

A large database of with mechanical properties of tropical hardwoods was set-up over the last 20 years consisting of 2314 specimens of structural sizes of 24 different tropical hardwood species. The species were sampled from countries in South-America, Africa and Asia, practically the central green belt around the equator. For some species there were more samples tested from different locations. Typical samples contain approximately 50 specimens, in accordance with the minimum of 40 specimens required by European standard EN 384. The size of the cross sections of the specimens varied, with the most common size being 60 mm x 150 mm. See table 1 for the overview of tested species

[1] Geert Ravenshorst, Delft University of Technology, Delft, g.j.p.ravenshorst@tudelft.nl
[2] Jan-Willem van de Kuilen, Deflft University of Technology and Technical University of Munich, Munich, vandekuilen@hfm.tum.de

2.2 METHODS

2.2.1 Destructive measurements

All specimens were test according to the European standard EN 408 [1]. According to EN 408 a four point bending test is required with third point loading and a span between the supports of 18 times the height. During the destructive bending test the MOE_{local} (the pure MOE, based on the deflection measurements in the area with a constant bending moment) was determined.
After the test, a cross section of 25 mm length was cut out and with the oven-dry method the moisture content was determined. A large variety in moisture contents was recorded between different wood species.

2.2.2 Non-Destructive measurements

Non-destructive measurements are used in either visual or machine grading. Through laboratory research the relationships between the non-destructive and destructive measurements can be derived. For practical use, limits for non-destructive measurements can then be defined for grading in practice. In the next section a description of non-destructive measurements by visual or machine recordings are shortly explained.
<u>Non-destructive visual measurements.</u>
The most important characteristics that influence the strength are the density, presence of knots, slope of grain, fissures and compression failures. Compression failures (also known as brittleheart) are not allowed, so when these are detected the pieces have to be rejected for structural use. Detection however is difficult and remains a challenge for the industry [2]. Fissures are allowed for certain limits. For knots and slope of grain, the magnitude of the measurement is related to the reduction of the strength. The knot sizes and slope of grain were visually measured according to Dutch standard EN 5493 [3], the core of which dealing with strength grading is also available as a European standard for tropical

Table 1.*Tested tropical hardwood species*

Species ID	Species trade name	Botanical name	Origin	Number of samples
AV	angelim vermelho	*Diniza excelsa*	Brazil	5
CUM	cumaru	*Dypterix spp.*	Brazil	5
MAS	massaranduba	*Manilkara bidentata*	Brazil	5
AZ	azobé	*Lophira alata*	West Africa	3
GR	greenheart	*Ocotea rodiaei*	Surinam/Guyana	4
OK	okan /denya	*Cylicodiscus*	Ghana/Cameroon/Gabon	5
KA	karri	*Eucalyptus diversicolor*	South africa	1
NA	nargusta	*Terminalia amazonia*	Honduras	1
PI	piquia	*Caryocar spp.*	Brazilie	1
VI	vitex	*Vitex spp.*	Solomon Islands	1
BAS	basralocus	*Dicorynia*	Suriname	1
BAN	Bangkirai	*Shorea spp.*	Indonesia	1
SV	sucupira vermelho	*Andira spp.*	Brazil	1
CR	castana rosa	*Pouteria oppsitifolia*	Brazil	1
LA	louroa marela	*Ocotea spp.*	Brazil	1
LF	louro faia	*Euplassa spp.*	Brazil	1
PU	purpleheart	*Peltygone spp.*	Brazil	1
TV	tauari vermelho	*Cariniana spp.*	Brazil	1
FA	favinha	*Entorolobium spp.*	Brazil	1
FP	favinha prunelha	*Pseudopiptadenia spp.*	Brazil	1
SA	sapupira	*Hymenolobium spp.*	Brazil	1
BIL	bilinga	*Nauclea diderrichii*	Cameroon	2
EV	evuess	*Klainedoxa gabonenis*	Cameroon	2
TA	tali	*Erythrophleum*	Cameroon	2

hardwoods: EN 16737:2016 Structural timber. Visual strength grading of tropical hardwood [4].
In tropical hardwoods knots are much more rare then in softwoods and their presence is mostly restricted to 0.2 defined as the ratio of the knot size in the direction of the depth of the beam divided by the depth size.
For softwoods relationships between growth ring width and density can be determined. For tropical hardwoods this is not the case.
The most important characteristic is the slope of grain.
In figure 1 the principle of measuring the slope of grain is explained. For this research for a number of pieces the slope of grain was measured before the bending test, (at time of grading), and after the bending test (where the slope of grain is measured at the crack line). The slope of grain is defined as the tangent of the angle of the grain with the longitudinal beam axis.

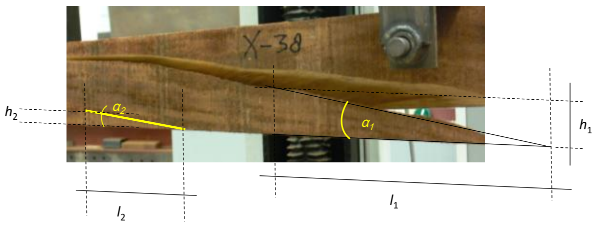

Figure 1: *Angle of the grain and associated slope of grain measured before (α_2) and after (α_1) the bending test*

<u>Non-destructive measurements by machine readings.</u>
The density of the specimens was determined by dividing the weight of the whole beam by its volume.
The dynamic Modulus of Elasticity was calculated using the measured first natural frequency, the density and the length of the specimen. In the test data presented in this paper the first natural frequency was measured using a Brookhuis handheld timbergrader MTG 960 [5]

3 RESULTS

In section 4 the relationships between the non-destructive measurements and mechanical properties are presented and analyzed. . The strength class system according to EN 338 [6] gives the values for the strength and stiffness properties at 12% m.c. The mean moisture content of the tested samples varied between 15% and 50%. Therefore, the properties for the bending strength, stiffness and density of each specimen were adjusted to 12% m.c. according to equations (1), (2) and (3):

$$\rho_{12\%} = \rho_{mc} \frac{(1 + 0{,}01 * \beta_v * (mc_{FSP} - mc_{12}))}{(1 + 0{,}01 * (mc - mc_{12}))} \tag{1}$$

$$MOE_{12\%} = MOE_{mc}/(1 - k_{mc}\frac{(m.c.) - 12)}{13} \tag{2}$$

$$f_{m;mc12} = \frac{f_{m;mc}}{\left[\left(1 - 0.15\ \frac{(m.c.) - 12}{13}\right)\right]} \tag{3}$$

In Rijsdijk and Laming (1994) [7] the fiber saturation points and the shrinkage coefficients are given for 145 softwood and hardwood species. As a mean approximation for all wood species, a fiber saturation point of 25% m.c. is used. As an average value for β_v a value of 0.5% per percent moisture content change is used as approximation for all species for moisture contents between 12% and 25%. Equations (2) and (3) are only valid until fiber saturation point (assumed at 25% for all wood species). Above 25% m.c. no further adjustment for strength and stiffness is applied, and the value at 25% m.c. is applied.

For most samples, the specimens´ the slope of grain was investigated before testing according to figure 1. The specimens that fulfilled the maximum limit of 0.1 were included in the results. For species massaranduba, greenheart, okan, bilinga, evuess and tali also the slope of grain after testing was measured for every specimen. These measurements are used to analyse the relationships of the mechanical properties with the slope of grain in the next section.

4 ANALYSIS

4.1 GENERAL RELATIONSHIPS BETWEEN NON-DESTRUCTIVE MEASUREMENTS AND MECHANICAL PORPERTIES

The relationships between the following non-destructive measurements and mechanical properties are analyzed:

- Between density and bending strength, figure 2
- Between the ratio bending strength/density and density, figure 3
- Between density and MOE_{local}, figure 4
- Between density and MOE_{dyn}, figure 5
- Between MOE_{dyn} and MOE_{local}, figure 6
- Between the ratio MOE_{dyn}/density and density, figure 7
- Between slope of grain and bending strength, figure 8
- Between slope of grain and MOE_{dyn}, figure 9
- Between MOE_{dyn} and bending strength, figure 10

The adjusted properties to 12% moisture content are used in the analysis. In the plots of figure 2 to figure 10 the datapoints of all specimens are shown to investigate if there are general relationships that are species independent. From figure 2 and 3 it seems that there is a constant ratio between the bending strength and the density. A regression of all data gives a constant of approximately 0.1 between bending strength and density. However, in [8] a constant for clear wood at structural level for massaranduba of 0.13 was found.

In figures 6 and 7 only the species for which the slope of grain values were measured after failure are plotted. Knots were only very few and almost never causing specimenfailure, so no scatterplots with the knot ratio are included.

In figure 4 and 6 some individual high values for the MOE_{local} can be seen. These were among the oldest test data and it might be possible that these are caused by measuring errors, but there is no certainty. The connected MOE_{dyn} values show normal values. The MOE_{dyn} measurements are more stable and can be easily repeated.

From figures 5 and 7 a constant ratio between MOE_{dyn} and density seems visible. A regression of all data gives a constant of approximately 23 between MOE_{dyn} and density, which is close to the value for massaranduba for which a value of 24.1 was found in [8] for clear wood with structural size

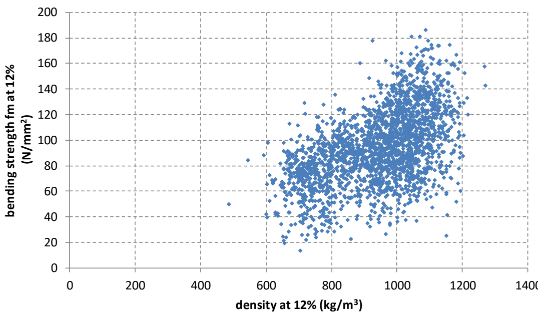

Figure 2: *Scatterplot of the bending strength at 12% m.c. against the density at 12% m.c.*

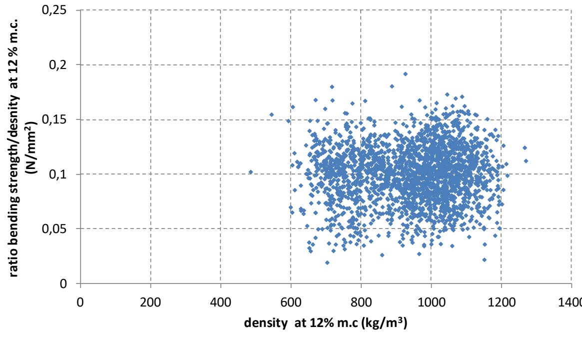

Figure 3: *Scatterplot of the ratio bending strength/density at 12% m.c. against the density at 12% m.c.*

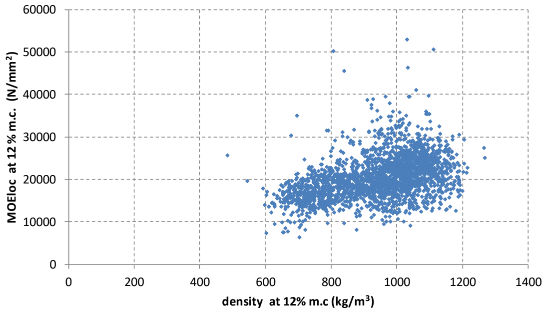

Figure 4: *Scatterplot of the MOE_{loc} at 12% m.c. against the density at 12% m.c.*

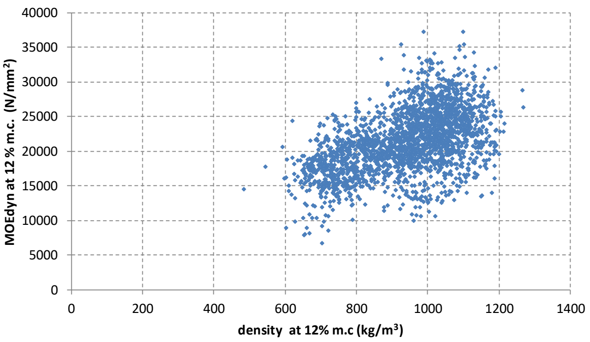

Figure 5: *Scatterplot of the MOE_{dyn} at 12% m.c. against the density at 12% m.c.*

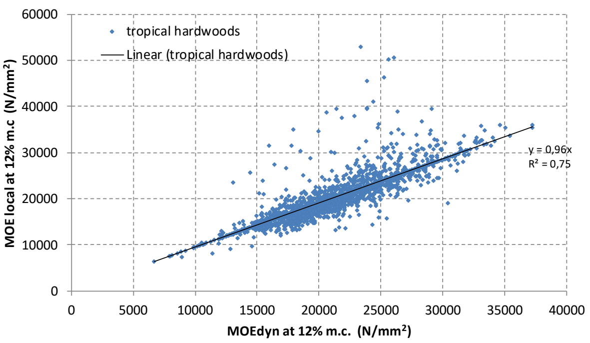

Figure 6: *Scatterplot of the MOE_{loc} at 12% m.c. against the MOE_{dyn} at 12% m.c.*

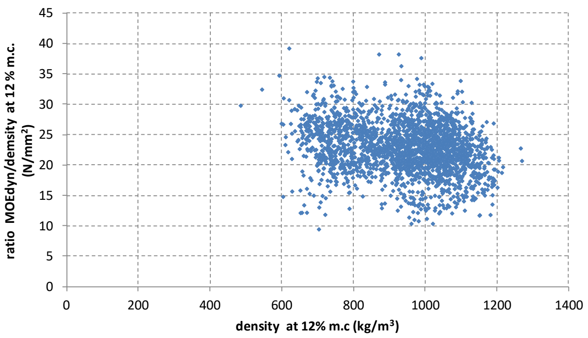

Figure 7: *Scatterplot of the ratio MOE_{dyn}/density at 12% m.c. against the density at 12% m.c.*

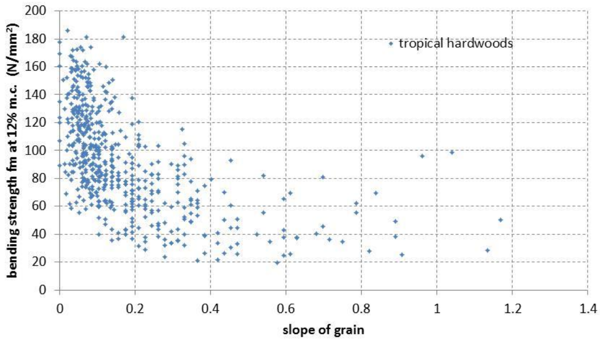

Figure 8: *Scatterplot of the bending strength at 12% m.c. against the slope of grain.*

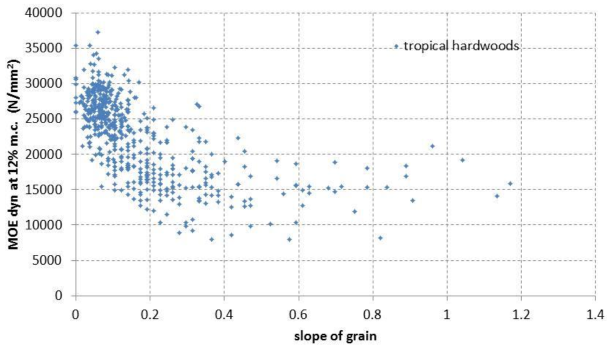

Figure 9: *Scatterplot of the MOE_{dyn} at 12% m.c. against the slope of grain*

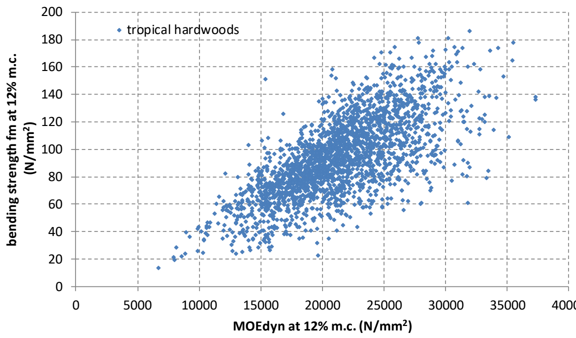

Figure 10: *Scatterplot of the bending strength at 12% m.c. against the MOE_{dyn} at 12% m.c.*

From the scatterplots the following observations can be made:

- The bending strength shows a clear positive correlation with the density, but with a considerable scatter (and increasing COV with increasing density). With scatter is meant the standard deviation of the datapoints around the regression line. The density therefore is not an efficient sole grading parameter. This is different for clear wood, as is shown in [9], where there is a good relationship between bending strength and density. The presence of deviations from clear wood like deviating slope of grain with the beam axis is causing part of the scatter, but also the fact that the material has been sampled over a long time frame and originates from large growth areas. The presence of differences in slope of grain is indicated by the difference in the ratio bending strength/density for structural size clear wood and those found for the dataset.

- The same is valid for the MOE_{loc} and MOE_{dyn} for the relationship with the density. There is an increasing trend with the density, but with scatter around the regression line, with the same reason as for the bending strength, influenced by the presence of slope of grain.
- The MOE_{loc} has a good correlation with the MOE_{dyn}. That means that the MOE_{dyn} can be used as a grading parameter for the MOE_{loc}, independent of the species.
- The presence of differences in slope of grain is indicated by the difference in the ratio MOE_{dyn} /density for structural clear wood and those found for the dataset.
- Figures 8 and 9 show clearly that the slope of grain of individual specimens is an important factor for both the bending strength and MOE. For both properties, the relation indicates that the strength drops with an increased slope of grain. The slope of grain is therefore an important grading parameter, which is addressed in rules for visual grading like [3, 4]. The large scatter in datapoints for a certain slope of grain value can be explained by the fact that the specimens with different densities are plotted in figures 8 and 9, and by the difficulty of measuring the slope of grain, as will be discussed in the next section.
- Figure 10 shows that there is an increasing trend of the bending strength with the MOE_{dyn}, with an increasing scatter for higher values.

At present, tropical hardwoods are only assigned to strength classes in Europe that can be used in relation with visual grading. The property that determines the basic (clear wood) strength of a timber pieces is addressed in most visual grading rules by the growth ring width. For tropical hardwoods this is not a measurable feature because the growth rings cannot be distinguished.
For the second important feature, the slope of grain, there is a relation with the strength, but it has to be investigated how good this can be measured in practice. Even with the measurements after failure, a large scatter in the relationship with the bending strength is found.

4.2 RELATIONSHIPS BETWEEN NON-DESTRUCTIVE MEASUREMENTS AND MECHANICAL PROPERTIES FOR WOOD SPECIES OKAN

To investigate the applicability of visual grading for tropical hardwoods the case of wood species okan is studied more precisely. For visual grading according to [3] and [4] there is only one visual grade for tropical hardwoods, and therefore a wood species can only be assigned to one strength class. The current strength classification of okan according to EN 1912 [10] is D40, according to the strength class system of EN 338 [6]. 5 different samples of okan were tested. In figure 11 the variation in the mean values of the bending strength is shown.

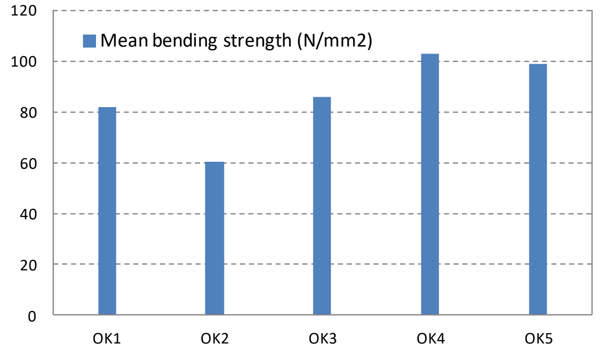

Figure 11: *Mean values of the bending strength at 12% m.c. of okan samples OK1 to and OK5*

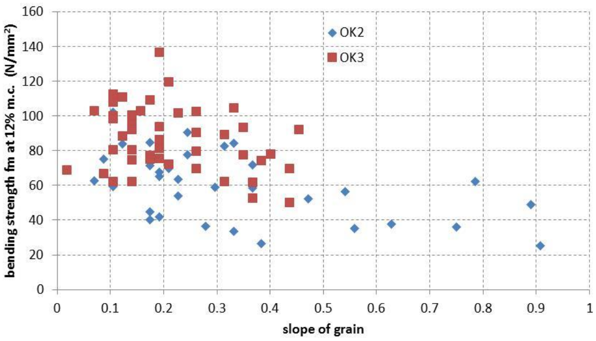

Figure 12: *Scatterplot of the bending strength at 12% m.c. against the slope of grain for okan samples OK2 and OK3*

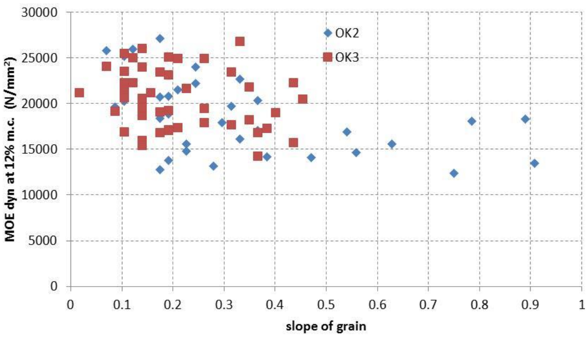

Figure 13: *Scatterplot of the MOE_{dyn} at 12% m.c. against the slope of grain for okan samples OK2 and OK3*

In figures 12 and 13 the bending strength and MOE_{dyn} are plotted against the slope of grain measured after the bending test for okan samples OK2 and OK3. A slope of grain of 0.9 is very high. In that case the slope of grain was locally very high, or the exact slope of grain was also after failure difficult to determine. It can be seen that the reduction of strength due to increasing slope of grain is visible, but less clear than in figures 8 and 9. However, when the bending strength is plotted against the MOE_{dyn}, a clear correlation between the 2 properties which much less scatter is shown. See figure 14. This can be explained by considering that the slope of grain has an influence on both the bending strength and the MOE_{dyn}.

Apparently, the influence of the slope of grain is much better captured by the measurement of the MOE_{dyn} than the visual observation of the slope of grain.

Another aspect of the measurement of the slope of grain is that it has to be performed at the time of grading. The plots in figures 8,9, 12 and 13 show the slope of grain measured after the bending test, which includes valuess much higher than the limit of 1:10 for tropical hardwoods according to [3, 4]. In figure 15 the slope of grain measurements before the bending test and after the bending test measured according to figure 1 are plotted against each other for sample OK3. Figure 15 shows that a large number of slope of grain measurements that seemed to be within the limit of 0.1 before the bending test turned out to be much larger when measured after the bending test. As an example in figure 16 two okan beams are shown on which the visual assessment of the slope of grain has to be performed.

It can be concluded that a visual assessment of the slope of grain during grading is very difficult. However, the difference in magnitude of the slope of grain in different samples of the same species like the 5 okan sample, together with variations in density, can explain the differences in bending strength between these samples. That means that when a strength class is assigned to a species for visual grading, the weak sample becomes governing. Besides that, it can be questioned if the weakest sample that can come onto the market is tested.

Because the variation in the slope of grain also causes variation in the MOE_{dyn} of the various samples, the MOE_{dyn} measurement, together with the density, can be used for machine grading of tropical hardwood species, which will be explained in the next section

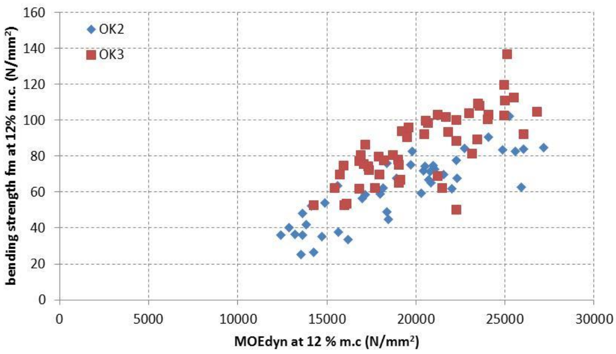

Figure 14: *Scatterplot of the bending strength at 12% m.c. against the MOE_{dyn} at 12% m.c. for okan samples OK2 and OK3.*

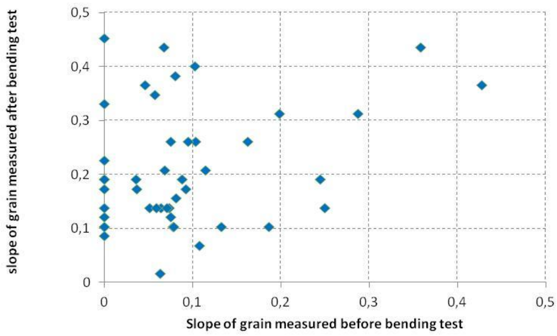

Figure 15: *Slope of grain measured after the bending test plotted against the slope of grain measured before the bending test for sample OK3 of okan .*

Figure 16: *Examples of okan beams for which the slope of grain has to be determined by visual grading.*

5 MACHINE STRENGTH GRADING FOR TROPICAL HARDWOODS

5.1 SPECIES INDEPENDENT STRENGTH GRADING MODEL FOR TROPICAL HARDWOODS

In [8] the principle of species independent machine grading for tropical hardwood has been presented. It was shown that the density and the MOE_{dyn} are parameters that can be derived from non-destructive measurements and therefore can be used as predictors for the strength. The MOE_{dyn} takes into account the main strength reducing feature for tropical hardwoods, the slope of grain, with higher accuracy than is possible with visual grading. In figure 17, the ratio MOE_{dyn}/density is plotted against the ratio bending strength/density. In the red circle the datapoints are shown that can be considered as clear wood with structural sizes. When the ratio MOE_{dyn}/density goes down, this is probably caused by increased slope of grain, as no other major defects are present in the material. For a ratio of for instance 15, severe slope of grain can be expected.

The same trend is visible for the ratio bending strength/density, which has the same explanation.

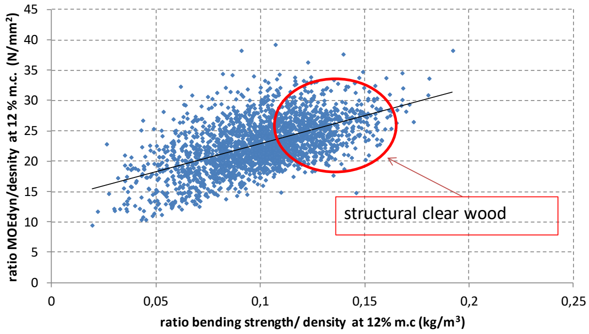

Figure 17: *Ratio MOEdyn/density against ratio bending strength/density for the entire dataset.*

In [9] the following species independent regression model, based on the entire dataset was derived:

$$f_{m,\alpha} = \frac{\rho \cdot \min(MOE_{\alpha};25\rho)}{183.8\ \rho + 0.15 \cdot \min(MOE_{\alpha};25\rho)} - 12.9 \qquad (4)$$

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 and a safe species independent strength model could be determined. The regression graph is shown in figure 18. In figure 18 the bending strength at 12% m.c. is plotted against the model values calculated according to equation (4). For the density (ρ) and the MOE_{dyn} the input values are also those at 12% m.c.

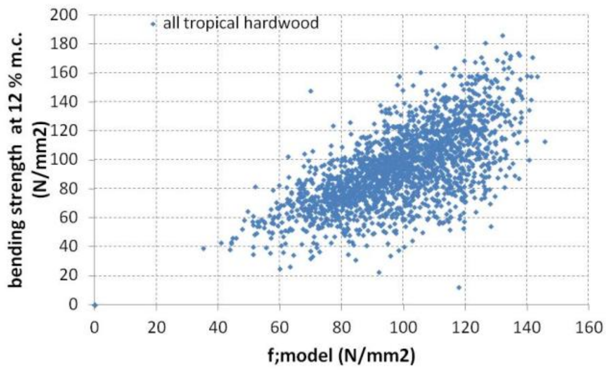

Figure 18: *Scatterplot of the bending strength at 12% m.c. against the model values calculated according to equation (4).*

5.2 APPLICATION ON WOOD SPECIES OKAN

In the previous section was shown that the variation in presence of slope of grain can explain the difference in mechanical properties for different sample of okan. And it was shown that by visual grading this variation in slope of grain is very difficult to detect. By machine grading the slope of grain is indirectly included by the MOE_{dyn} measurement. In this section the application of machine strength grading for the tropical wood species okan is studied. In figure 19 the datapoints for the 5 okan samples are plotted with the model values calculated according to equation (4) over the general model. Figure 19 shows that the difference in bending strength values for the individual okan pieces is captured by the model values. Figure 20 shows that the low ratios of the MOE_{dyn} and bending strength over density caused by severe slope of grain can explain the low bending strength values.

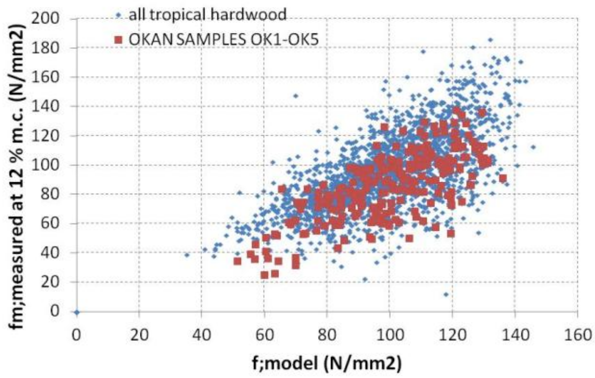

Figure 19: *Scatterplot of the bending strength at 12% m.c. against the model values calculated according to equation (4 for all tropical hardwoods and for the wood species okan.*

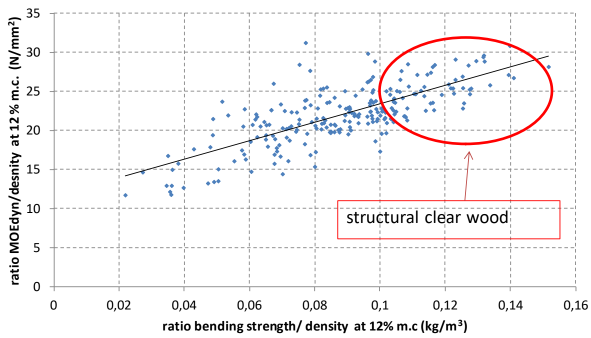

Figure 20: *Ratio MOEdyn/density against ratio bending strength/density for the specimens of the 5 samples of okan.*

In [9] limits for the model values are derived for application for species independent strength grading of tropical hardwoods. These are plotted for the data of the 5 okan samples in figure 21. Figure 21 shows that by applying these limits to the data of okan, okan beams could be assigned to D30, D50 but also D70. The okan data assigned to the mentioned strength classes fulfill the requirements of the characteristic bending strength for that strength class. In this way, okan could be used moreeconomically because beams with higher strength can be distinguished better. The grading process becomes also more reliable because slope of grain is determined with greater accuracy than with visual grading, as it results in a low MoE..

The green dots in figure 20 show the datapoints of sample OK2. This shows that by machine grading a sample containing weak pieces can be determined..

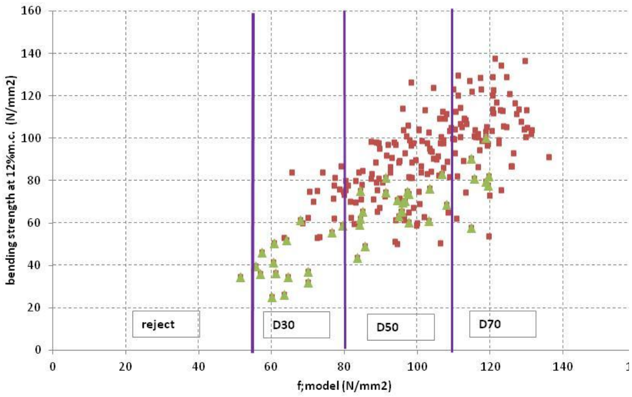

Figure 21: *Scatterplot of the bending strength at 12% m.c. against the model values calculated according to equation (4 for the wood species okan with limit values for D30, D50 and D70.*

6 CONCLUSIONS

The mechanical and physical properties of a large database of tropical hardwoods are analyzed against non-destructive measurements The non-destructive measurements are used in either visual grading (knot ratio and slope of grain) and machine grading (density and MOE_{dyn}).

From the analysis of the dataset of tropical hardwoods the following can be concluded:

- The bending strength shows an increasing trend with the density, but with a large scatter.
- The MOE_{loc} and MOE_{dyn} shows an increasing trend with the density, also with a large scatter.
- The MOE_{loc} has a good correlation with the MOE_{dyn}. That means that the MOE_{dyn} can beused as a grading parameter for the MOE_{loc}, independent of the species.
- Increasing slope of grain of individual specimens is causing a reduction for both the bending strength and MOE.
- There is an increasing trend of the bending strength with the MOE_{dyn}, with an increasing scatter for higher values.

The slope of grain is the most important grading parameter for tropical hardwoods, which is addressed in rules for visual grading.

However, it is very difficult to predict the actual slope of grain before a bending test is performed.

For the tropical wood species okan is was shown that with machine grading individual beams can be graded to different strength classes, making the grading process more efficient and more reliable than with visual grading.

This is because the measurement of the MOE_{dyn} captures the slope of grain with much more accuracy than is possible with visual grading.

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