Species independent machine stress grading of hardwoods

G.J.P. Ravenshorst*, J.W.G. van de Kuilen,**, M. Brunetti, A. Crivellaro ***,
* Delft University of Technology, Delft, the Netherlands
g.j.p.ravenshorst@tudelft.nl
** Delft University of Technology, Delft, the Netherlands, CNR-Ivalsa, Italy,
j.w.g.vandekuilen@tudelft.nl
*** CNR-Ivalsa, Italy
brunetti@ivalsa.cnr.it, crivellaro@ivalsa.cnr.it

Summary

Machine strength grading has traditionally been focussed on softwoods. With the introduction of many 'new' (hard)wood species from all around the world on the market, especially from sustainable managed forests, there is a need for strength grading of 'unknown' species and assign them into strength classes. In this project, over 2000 beams from 35 different species covering the whole range of strength, stiffness and density profiles and originating from South-America, Africa, Asia and Europe have been tested using both non-destructive and destructive testing techniques. The dataset was used to develop a species independent strength grading model in order to classify timber without the need of extensive and expensive laboratory testing. Since optimisation of the yield of a hardwood species with visual grading is hardly possible, non-destructive measurements on hardwood allows it to be assigned to higher strength classes, greatly improving the yield. The main research goal was to determine a common ground on which hardwood beams can be graded using stress waves. On the basis of the different species tested, a species independent strength grading model was developed. With the derived model, timber can be assigned to strength classes without destructive testing. This method can be used to economically determine the strength class for use with visual grading of 'new' hardwood species that are commonly introduced on the market in rather small amounts. Now, even in remote areas, hardwood timber can be machine graded into strength classes as used in the Pacific, Africa, America and Europe improving their possibilities to sell timber to these high end markets. The aspects on grading and design of hardwood are relevant because presently many unknown timber species are introduced on the market as a result of the demand for timber from forests that are managed in a sustainable, environmentally friendly manner.

1. Introduction

To use timber in structures two steps have to be taken. The first step is to grade the timber. This means that beams from a timber species that fulfil some predefined visual or machine measured characteristics are assigned (graded) into an accompanying strength class for use in practice. The second step is to use the design values of the mechanical properties of that strength class to calculate the resistance of the timber structure with design rules that are laid down in standards.

However, the present grading rules and design rules are mainly based on softwood, with the implicit assumption that these are also valid for hardwood. For the grading of (tropical) hardwood the problem arises that there are very little distinct visual characteristics such as knots. This means that only one visual grade for a hardwood species can be derived. Secondly, the correlation with the modulus of elasticity and the bending strength is not as clear for individual species as for softwood species. In this paper an approach for machine grading of (tropical) hardwood timber is presented. The aspects on grading and design of hardwood are relevant because presently many unknown timber species are introduced into the market as a result of the demand for timber from forests that are managed in a sustainable, environmentally friendly manner. To make economic use of them grading and design has to be accurate.

2. Strength grading of softwood and hardwood

In general, for the design of timber structures the strength properties of the species that is used have to be known. To determine these properties a representative sample of the timber species has to be tested. Based on the tested sample, beams of a timber species that fulfil the requirements for the characteristics can be assigned to a strength class.
A basic principle is that the strength class can be determined by three main properties: the bending strength, the modulus of elasticity and the density. For the bending strength and the density the 5%-lower fractile has to be determined and for the modulus of elasticity the mean value. For visual strength grading of softwoods, characteristics as knot size, knot ratio and grain deviation are the main parameters that have a reasonable correlation with the (bending) strength. The limit values for these characteristics are laid down in grades, published in standards. A grade of a timber species can be connected to a strength class. For machine grading, parameters as modulus of elasticity and density are generally used, sometimes based or extended with X-ray profiles. The grading parameters are used to predict the strength properties of the beams. After grading, not more than 5% of the beams may incorrectly be graded too high.
In softwood knots are clearly visible and this is used to grade beams from a softwood species in more than one grade. However, the correlation of the modulus of elasticity with the bending strength is more accurate than the correlation of the knot ratio with the bending strength. As a result, using the modulus of elasticity as a grading property makes it possible to grade beams in a higher strength class. In contradiction with softwood, for hardwoods it is generally not possible to distinct more than one economic interesting grade based on both the knot ratio and the modulus of elasticity. For the knot ratio this can be explained by the fact that most tropical hardwood species have no clear visual characteristics such as knots. During this research the question arose if it is necessary to observe every hardwood species individually. In this research project it is studied what the effect is on the prediction of the bending strength for individual hardwood species having little distinct visual characteristics, when the material properties of these species are regarded as coming from one population. The reason for this approach is that a timber species is defined only by its distinct botanical characteristics and the assumption is that judging the whole population of timber on material properties as knots, density and stiffness, will give better strength predictions to subpopulations or species-combinations.

In Europe a division is made in strength classes for softwoods (C-classes) and hardwoods (D-classes). The strength classes are published in European standard EN 338. Where D-classes used to start from D30, with 30 being the value for the characteristic bending strength, recently proposal were developed to have additional D18 and D24 classes added to the system.

3. Experimental research on grading of (tropical) hardwood species

The research had a number of goals. For use with visual grading the intention was to determine the strength classes of hardwood species new on the market. For machine grading a method to grade beams of (tropical) hardwood with little visual distinctions is needed so hardwood can be graded into more than one strength class. And when this question could be answered positively, also a practical solution for machine grading of hardwoods was demanded.

To achieve the research goals, several testing programmes with many destructive and non-destructive tests were performed.

The test programme covered a great number of timber species, for which the bending strength, modulus of elasticity and density were determined. The species were selected in such a way that the expected values of the material properties would cover the relevant range of values for timber. During several years a large number of timber species were tested [1].The timber species that were tested in these research programmes are listed in table 1. The goal for the separate research programmes was to determine the strength class of the tested timber species. Besides the species mentioned in table 1 also a test sample of the species azobé was incorporated in the analysis part of the research. The species azobe (*lophira alata*) was already investigated in previous research [2]. From all timber species, samples were taken with a minimum of 40 test pieces. The test pieces were beams with dimensions that are used in construction, for example 50 x 150 mm^2.

On every test piece the following data was established:

Visual characteristics: Knot sizes, g rain angle and other imperfections

- The mass of the test piece
- The moisture content measured with an electronic moisture meter.
- The moisture content derived with the oven dry method.
- The modulus of elasticity determined through measurement with the Timber Grader MTG (dynamic modulus of elasticity E_{dyn}). See section “practical application for hardwood grading with the Timber Grader MTG” for an explanation of this device.
- The modulus of elasticity determined through a 4-point-bending test according to EN 408 (static modulus of elasticity E_{stat})
- The bending strength determined through a 4-point-bending test according to EN 408.

The test values were adjusted to the reference conditions according to European and Dutch standards. The test results according to EN 408 are presented in table 1. The average bending strength, the coefficient of variation of the bending strength, the mean static modulus of elasticity and the mean density are given. All data has been adjusted to the reference conditions at moisture content of 12%.

*Table 1. Results of test according to EN 384 and EN 408 for tropical hardwoods*Species	Origin	Mean MoR (N/mm^2)	COV-MoR	Mean Static MoE (N/mm^2)	Mean Density kg/m^3)
Angelim vermelho	Brazil	82.9	0.21	16816	1045
Bangkirai	Indonesia	96.3	0.23	20851	930
Basralocus	Surinam	70.5	0.33	21484	725
Cumaru	Brazil	115.5	0.21	20710	1017
Denya	Ghana	84.2	0.16	17727	947
Karri (South-Africa)	South-Africa	77.4	0.20	19302	706
Massaranduba	Brazil	124.5	0.14	24796	1034
Nargusta	Bolivia	77.7	0.22	18349	723
Piquia	Brazil	76.6	0.22	21018	792
Vitex	Solomon islands	69.8	0.19	16339	731

4. A species independent grading model

The correlations between non-destructive measurements and the bending strength (and modulus of elasticity) according to the standardized laboratory methods were studied. Test results of the timber species were studied as an individual species being a population and as all timber species together being a population [3]

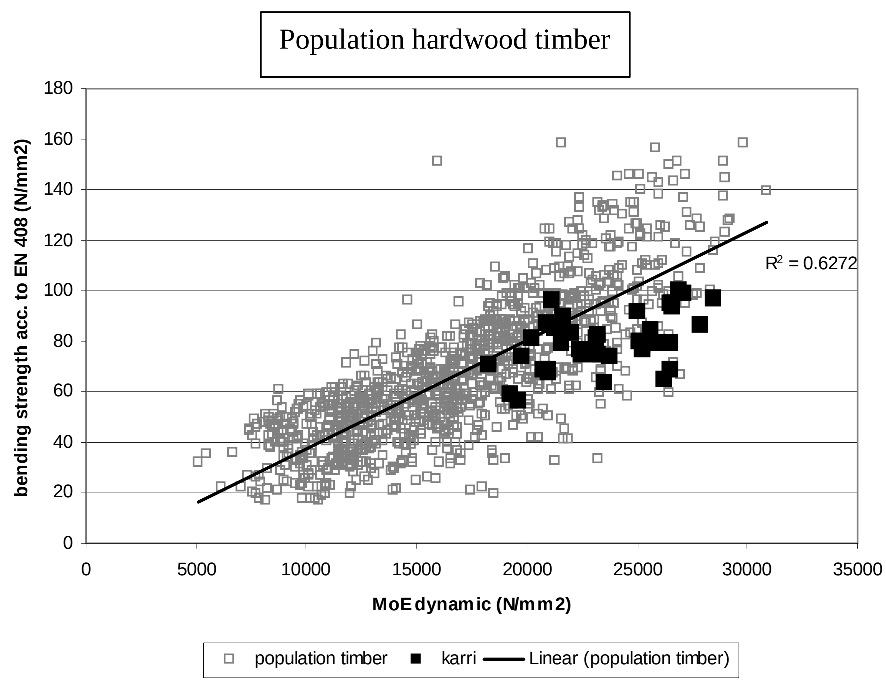

Figure 1. Test results for Karri and for all hardwood species together of the destructive bending strength according to EN 408 plotted against the dynamic modulus of elasticity

According to the expectations formulated previously, the analysis showed that it is not possible to make reliable predicting models for all hardwood pieces individually, contrary to softwood species as pine and spruce. An example is given in Figure 1 for the hardwood species Karri. What can be noticed is that the range of the bending strength values of this individual hardwood species does not start close to zero (this in contrast to softwood species, whereas the minimum strength values for the bending strength are very close to zero). Furthermore, the figure shows poor correlation between the modulus of elasticity and the bending strength. A possible explanation could be that test samples from individual species do not have clear distinct characteristics enough to regard them as a specific subpopulation. The division in botanical species does not seem to be the appropriate way to determine the strength predicting phenomena.

When the hardwood species are not considered as individual populations, but are merged together to form one large population “timber”,
it shows that there are good correlations between non-destructive measured properties and the bending strength. These correlations apply to the entire range of values of the bending strength, as shown in Figure 1. Then the data of the species karri fit into the entire data set values of the population. In that case there is a prediction line that gives reliable predictions and can be used for optimisation.

The main conclusion is that the bending strength of hardwood timber can be predicted for a specific timber species, when the behaviour of the material properties of the entire population of “timber” is taken into account. This opens the possibility to make models for hardwood timber that can predict the bending strength of beams of hardwood species with the required reliability. With these predictions hardwood beams can be classified into more than one strength class in an economic way when they are machine graded. The best predicting model for the bending strength turns out to be a model where the predicting material properties are the dynamic modulus of elasticity and the density. A correlation coefficient r = 0.82 can then be achieved. The static modulus of elasticity has

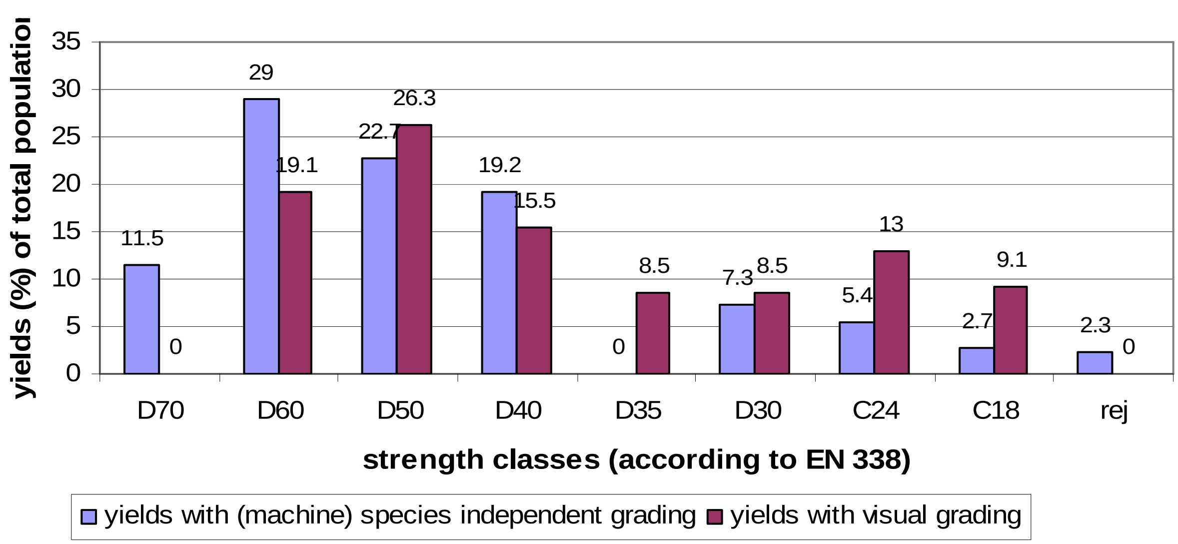

Figure 2.Comparison of grading yields for (machine) species independent grading with visual grading

a strong correlation with the dynamic modulus of elasticity. For these properties a correlation coefficient of r = 0.85 was found.

With the species independent grading model settings were derived to grade individual beams in D-classes (C-classes below D30). These are compared with the grading results for visual grading. With visual grading all the beams of one species have the same strength class, because there is no visual distinction to be made between them. With the (machine) grading model individual beams within one species can be assigned to different strength classes. [4] Figure 2 shows that with the species independent grading model based on non-destructive measurements the yields are much higher than with visual grading. More than 50 % of the beams are assigned to a higher strength class then with visual grading.

5. Application of the models for European oak and chestnut

European Oak was sampled from Poland, France and Germany. The same test programme for destructive and non-destructive tests was followed as for the tropical hardwoods. The results are shown in table 2. European chestnut was sampled from Italy. The same test programme for destructive and non-destructive tests was followed as for the tropical hardwoods. The results are shown in table 3.

Table 2. Results of test according to EN 384 and EN 408 for European oak

Species	Origin	Mean MoR (N/mm^2)	COV-MoR	Mean Static MoE (N/mm^2)	Mean Density kg/m^3)
European oak, Poland	Poland	51.2	0.16	11596	616
European oak, Middle- and Central Europe	France and Germany	45.6	0.30	10358	684

Table 3. Results of test according to EN 384 and EN 408 for Italian chestnut.

Species	Origin	Mean MoR (N/mm^2)	COV-MoR	Mean Static MoE (N/mm^2)	Mean Density kg/m^3)
Chestnut	Italy	54.9	0.26	12790	587

The beams of European oak and chestnut were also predicted with the species independent grading model. The result is shown in Figure 3. Figure 3 shows that the strength of oak and chestnut is lower than for most tropical hardwoods, but that it is possible to make predicting models that include both tropical and European hardwoods. With visual grading it is not possible to grade beams above D30.

Using the species independent grading model based on non-destructive measurements, it is possible to grade 30% of the amount of the beams in D35.

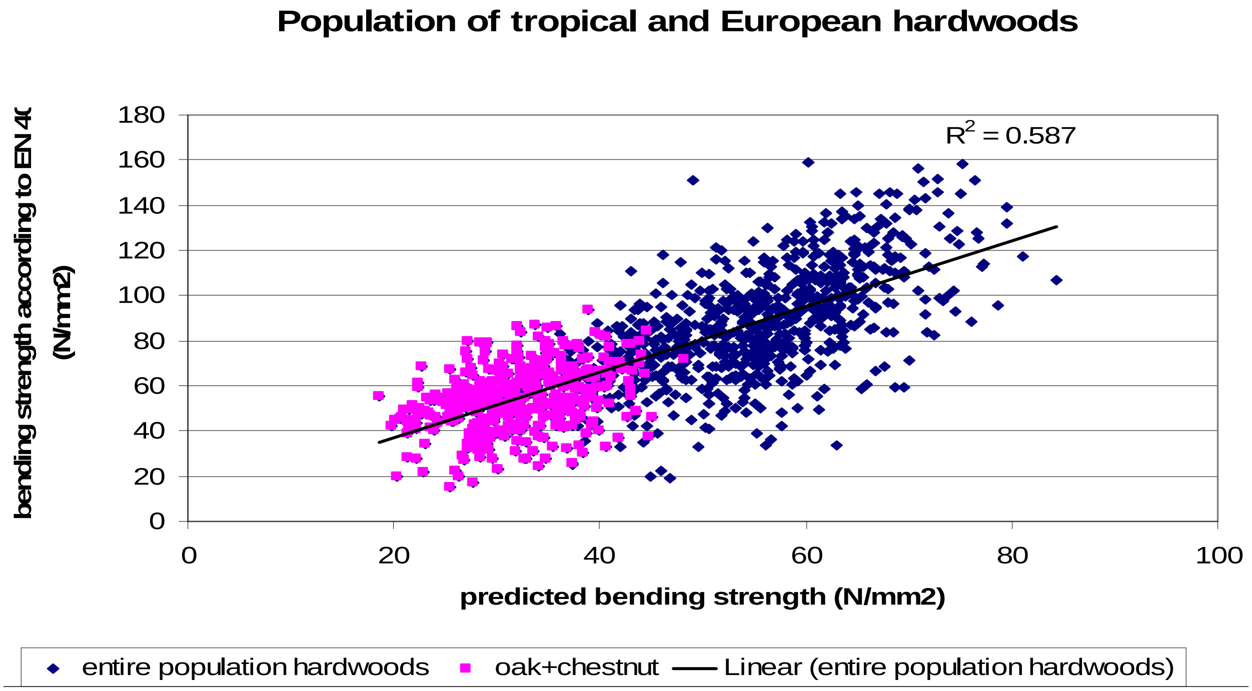

Figure 3. Predicted bending strengths for oak and chestnut plotted in the entire population of hardwoods.

6 Practical application for grading of individual hardwood beams with the Timber Grader MTG

It was explained that hardwood beams can be machine graded, without having the need of very large populations tested as is generally done for softwoods and in-line strength grading machines. For the relatively small amounts and many different sizes of hardwoods that enter the market today, practical and economic reasons prevent that in-line grading machines can be used for hardwoods. That is why TNO has developed the Timber Grader MTG in cooperation with Brookhuis Micro Electronics. At present, this device has a European approval according to EN 14081-4 for Northern and Middle-European spruce.

Figure 4. The Timber Grader MTG. An automatic hammer and sensor are integrated in the front that is placed on the end of the timber beam.

The Timber Grader MTG is a handheld grading machine as shown in Figure 4, based on the principle of frequency response. The stress waves are introduced with an integrated automatic hammer and measured with an also integrated sensor. This makes it an easy-to-use device. The results are stored on a notebook with a bluetooth connection with the handheld. Only a visual override for abnormal growth disturbances is necessary. The Timber Grader MTG can also be used for softwood for small companies for whom in-lines machines are too expensive

7 Conclusions

It is possible to determine a common ground on which hardwood beams can be strength graded based on non-destructive measurements. Hardwood is characterized by few visual defects but it should be able to grade hardwoods in more than one strength class, when they are machine graded. On the basis of the different species tested, a species independent strength grading model was developed. When hardwood species are not considered as individual populations, but are merged together to form one large population “timber”, it shows that there are good correlations between non-destructive measured properties and the bending strength. The model is programmed into a simple handheld machine that can be used under difficult circumstances in sawmills. Even in remote areas, hardwood timber can be machine graded into strength classes as used in the Pacific, North-America and Europe improving their possibilities to sell timber to these high end markets. The aspects on grading and design of hardwood are relevant because presently many unknown timber species are introduced on the market as a result of the demand for timber from forests that are managed in a sustainable, environmentally friendly manner

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