An economic method to determine the strength class of wood species

Geert Ravenshorst[1], Mario van der Linden[1], Ton Vrouwenvelder[1] and Jan-Willem van de Kuilen[2, 3]

[1] TNO Building and Construction Research, Delft, The Netherlands

[2]. Delft University of Technology, Delft, The Netherlands

[3] CNR-Ivalsa, Italy

As a result of the demand for wood from forests that are managed in an environmentally sustainable manner, many unknown wood species are introduced into the market at the moment. To classify a wood species into a strength class and determine the accompanying grading parameters for visual grading in practice, the strength characteristics are traditionally determined by destructive tests, with a minimum of 40 test pieces. To support a quick introduction of unknown wood species a method has been developed in which only 25% of the test sample that is investigated has to be tested destructively, and 75% can be tested non-destructively. This approach is more economic and faster than the present traditional method. This method has been developed by obtaining general correlations that are species-independent between non-destructive measured timber characteristics and the timber strength.

Keywords: timber strength, non-destructive measurements, timber strength modelling

1 Introduction

Different wood species have different strength characteristics, and also within a species these characteristics may vary. Therefore, in practice, a classification system of strength classes is used. Beams from a wood species that fulfil some predefined visual or machine measured characteristics are assigned (graded) into an accompanying strength class for practical application.

In figure 1 a scheme is given of the different steps necessary before grading of beams from a new, unknown species is possible. The procedure is as follows: one or more representative samples of the species are selected. The number of samples depends on the number of grades one wishes to use for the species in practice. When visual grading is intended, the different grades are characterised by visual characteristics such as knot sizes. Different visual grades then have different limitations for the allowable knot sizes: the higher the grade, the smaller the knots sizes that are allowed. The strength properties (bending strength, modulus of elasticity and density) of the beams of the samples are determined by testing. Traditionally, the bending strength is determined by destructive testing. Based on the test results the characteristic values of the strength properties have to be determined for a test sample. For the bending strength the characteristic value is the 5%-lower limit. The characteristic values are compared with those of the European strength class system [2]. When the characteristic values are higher than those of a specific strength class, than that strength class is assigned to the grade of the test sample. For use in practice it is documented to which strength class a specific visual grade is connected.

For machine grading the procedure is basically the same; the only difference is that the properties of a grade like the density or the modulus of elasticity of the beams are measured by a machine. After the testing and classification the grading rules are incorporated in the settings of the machine for its use in practice.

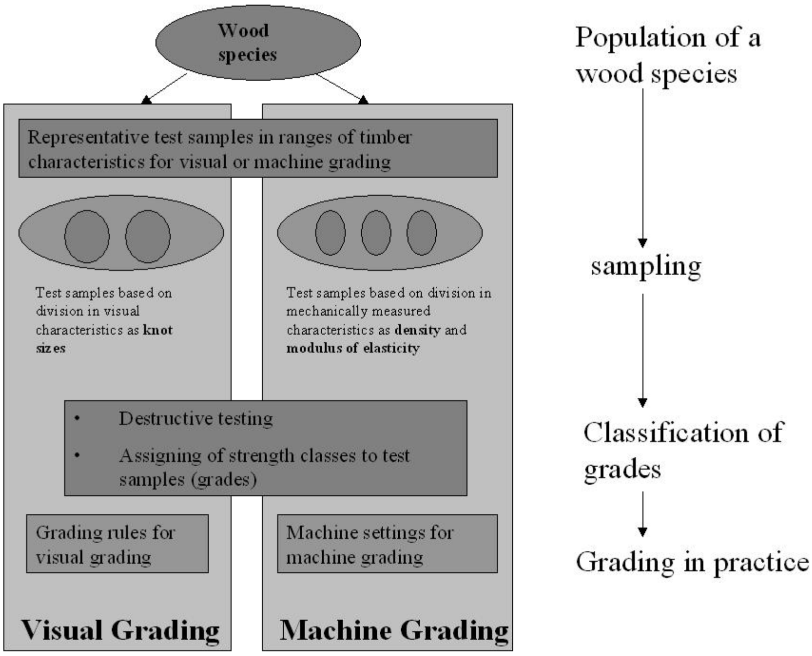

Figure 1: Scheme for necessary testing to determine grading rules for visual or machine grading of beams from a wood species

Presently many unknown wood 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 be able to use them in building structures the strength has to be known. To classify a wood species into a strength class, the strength characteristics are traditionally determined by destructive tests, as is pointed out in figure 1 in the box “classification of grades”. This procedure is time-consuming and expensive. For that reason, it has been investigated, if, using historical data, general relations could be found between certain non-destructive measured timber properties and timber strength for different wood species. As a result the number of destructive tests needed for new wood species could be limited.

To achieve this goal, it is necessary to formulate models through which, after the processing of the non-destructive and destructive test results, the 5%-lower limit strength can be calculated. In this paper a model is being presented and illustrated by test results. With the presented model, visual grades of a new unknown (hardwood) species can be classified into a strength class using less destructive tests than is necessary when using the traditional method.

As will be explained later, for most hardwood timber only one visual grade can be distinguished. Machine grading however, is more accurate and offers the possibility of having more grades. For this reason TNO developed a mobile strength grading device that makes this possible in practice. This will be outlined shortly in section 7, future developments.

Figure 2: A lot of 'new' wood species are introduced onto the market today

2 Backgrounds regarding the determination of the strength-properties of timber

2.1 General

To design timber structures it is necessary to know the strength properties of the species to be used. To determine these properties a representative sample of the wood species has to be tested. To assign the derived properties to individual beams of these species the characteristics

of the tested sample have to be set up. In Europe a system of strength classes is adopted, whereby a complete set of property-values is represented by one mark [2]. Based on the tested sample, beams of a wood species that fulfil the requirements for the characteristics can be connected 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.

2.2 Grading of timber. Material predicting properties. Visual/machine grading

In practice, the timber beams of a species are graded according to the characteristics that have been set up during an initial testing procedure. The grading procedure prescribes the growth characteristics that are used. For visual grading, characteristics as knot size and knot ratio are the main parameters. The limit values for these characteristics are laid down in grades, published in standards. A grade of a wood species can be connected to a strength class. For machine grading, parameters as modulus of elasticity and density are used to select the beams. The grading parameters are used for both methods, visual and machine grading, to predict the strength properties of the sorted beams. As a result of the grading process no more than 5% of the beams may incorrectly be graded too high.
The principle of predicting the bending strength by visual and machine grading is illustrated in figures 3 and 4. These figures are representative for a softwood species. In figure 3 a typical correlation diagram for the knot ratio and the bending strength is presented. The limits on the horizontal axes indicate the different grades. Using the requirement that no more than 5% of the beams in a grade class may incorrectly be upgraded, the exact limits for these grades can be established depending on the classification values for the bending strength on the vertical axis. The 5% incorrectly upgraded beams are marked by the black triangles in the figure. In figure 4 a typical correlation between the modulus of elasticity and the bending strength is shown. This property is often used in machine grading, where the modulus of elasticity is determined either by leading the beams through a bending machine or by means of a longitudinal stress wave analysis. Figures 3 and 4 show that the modulus of elasticity is a more accurate grading property for the bending strength than the knot ratio. As a result, using the modulus of elasticity as a grading property makes it possible to grade beams in a higher strength class.

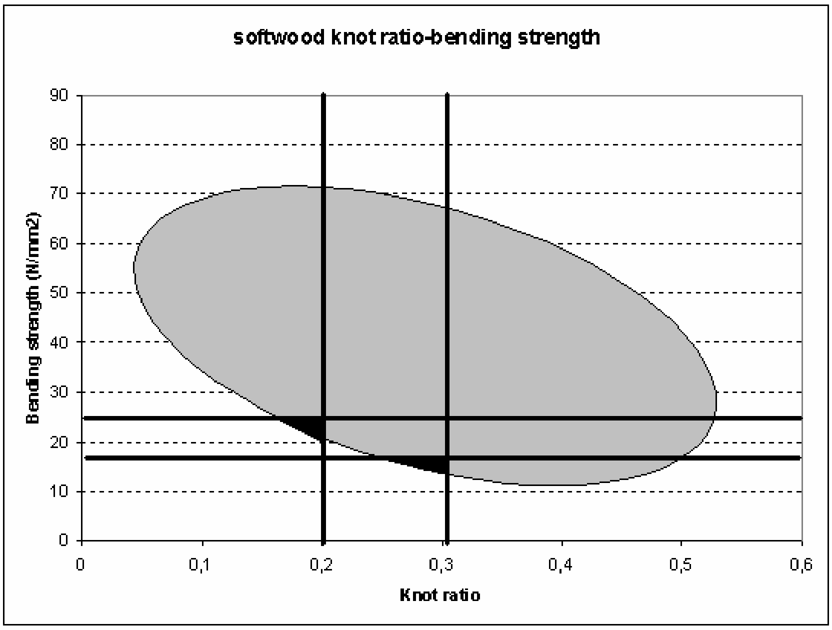

Figure 3: Typical correlation diagram for a softwood species between knot ratio and bending strength

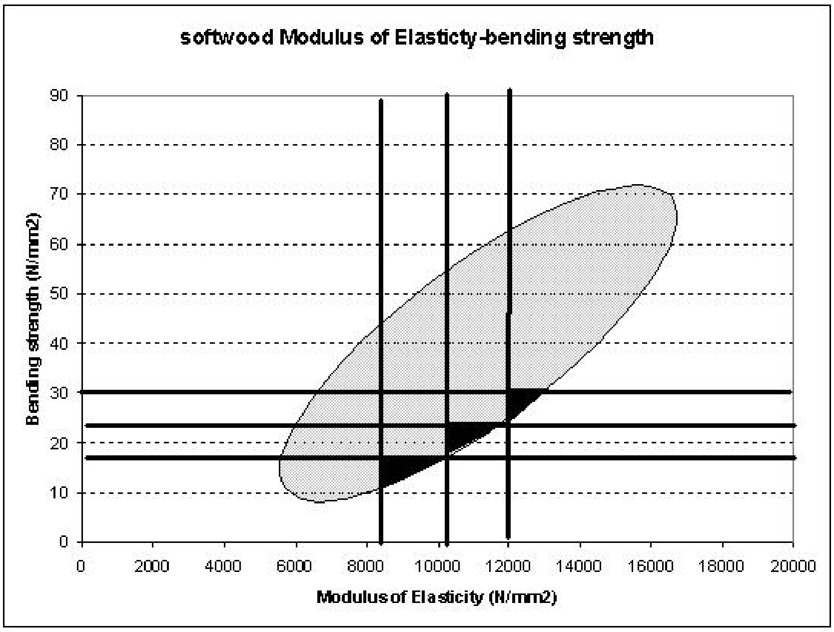

Figure 4: Typical correlation diagram for a softwood species between Modulus of Elasticity and bending strength

2.3 Classification methods. Number of tests. Use of Non-parametric distribution

The strength properties for a population (a grade or a species/ grade combination) are derived from a representative sample from this population. In the European standards a population is defined as a material for which the characteristic values are relevant. The population can be defined by parameters such as species, species grouping or source. According to the European standards prEN14081-1 [1] and EN 384 [3] a minimum of 40 representative beams have to be tested for each sorting grade of the population. Traditionally all 40 beams are tested destructively in a four-point bending test according to EN 408 [4].

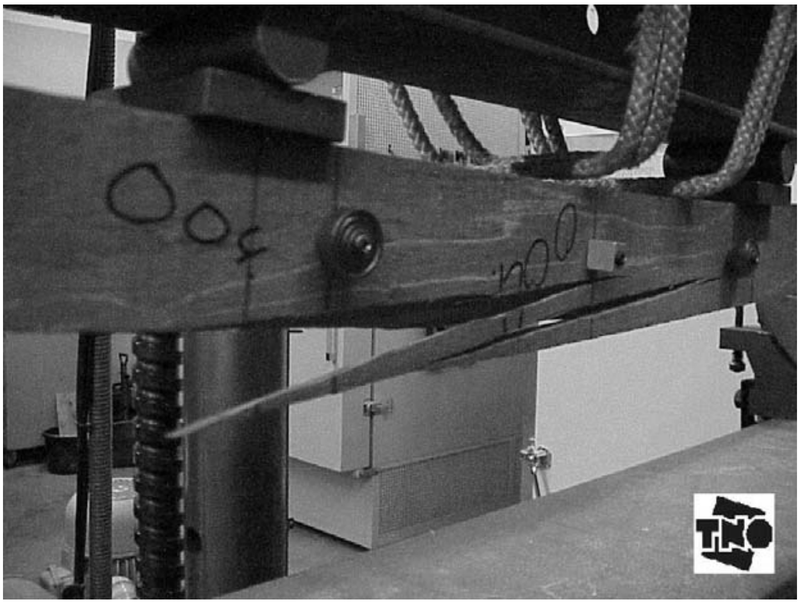

Figure 5: Four-point bending test according to EN 408

The 5%-fractile of the bending strength has to be determined by a non-parametric evaluation of the test results. This means that test results are ranked in order of their value. The 5%-fractile value indicates that 5% of the tests give lower values. For example, after ranking the test values of a sample size of 100, the fifth test value is the 5%-fractile value of the sample.
In general, the first reason for using non-parametric tests is that the actual distribution of the test results may be unknown. The second reason is that by performing extensive tests (say more than 300), it has been proven that a 5%-fractile of both the non-parametric distribution and the normal distribution is almost the same. For a smaller number of tests, like 40 as required for a new species, the reliability of the prediction can be improved if the distribution is known and a parametric method is used. This approach has been followed in this research.

2.4 Testing methods. Standardized methods and alternative methods.

To perform tests for bending strength, modulus of elasticity and density, standardized methods are described in the European standards EN 384 [3] and EN 408 [4], respectively. When other test methods are used they have to be adjusted to the reference conditions described in the standards mentioned. The standardized test methods for both the determination of the bending strength and the modulus of elasticity are described in section 2.4.1 Alternative methods are described in section 2.4.2.

2.4.1 Determination of the bending strength and modulus of elasticity by standardized tests.

The bending strength and the modulus of elasticity are determined by a four-point bending test. The modulus of elasticity is calculated out of the measured deflection at a force between 10% and 40% of the failure force. The modulus of elasticity derived in this way is called the static modulus of elasticity.

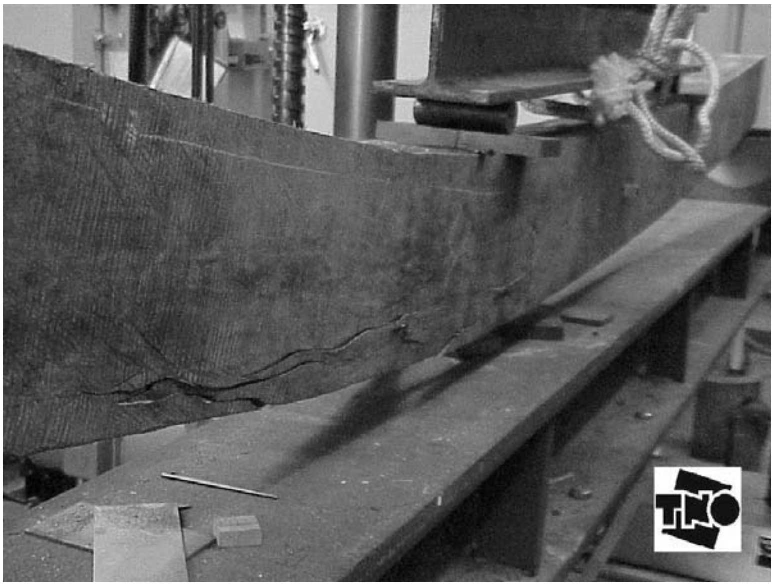

Figure 6: The static modulus of elasticity is calculated out of the deflections measured in a four-point bending test according to EN 408.

2.4.2 Determination of the bending strength and modulus of elasticity by alternative testing methods.

The modulus of elasticity may be derived by measuring the frequency response. This principle is described in [5]. The modulus of elasticity determined this way is called the dynamic modulus of elasticity. The dynamic modulus of elasticity has shown to have a strong correlation

with the static modulus of elasticity. In this research, a device developed by TNO, the Mobile Timber Grader was used to derive the dynamic modulus of elasticity.
The bending strength can also be calculated on the basis of non-destructive measurements, when models to predict the bending strength are formulated. This will be presented in section 4 of this paper.

3 Research programme

3.1 Scope of the research

Nowadays "new" hardwood wood species are introduced into the market as a result of the demand for timber from forests that are managed in an environmentally sustainable manner. The strength properties of these "new" species are not known and have to be determined. Therefore the demand rose for an economic method to determine the strength class of these "new" wood species. The research programme included two goals:

- The first goal was to develop an economic method with combined destructive and non-destructive tests for the classification of "new" wood species in a strength class, in combination with visual grading.
- The second goal was to study the possibility of optimising the grading of beams of a hardwood species into more than one strength class, when the beams are machine graded.

To illustrate the second goal figures 7 and 8 will be discussed. These figures can be compared with figures 3 and 4 for softwood species. The knot ratio and the bending strength for a tropical hardwood species with less visual distinct characteristics as knots, is presented as a typical correlation diagram in figure 7. Figure 8 shows a typical correlation pattern of the modulus of elasticity and the bending strength of this tropical hardwood species. For both figures the black fills mark the 5% incorrectly upgraded beams. These figures show that, in contradiction with the softwood example, it is 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.

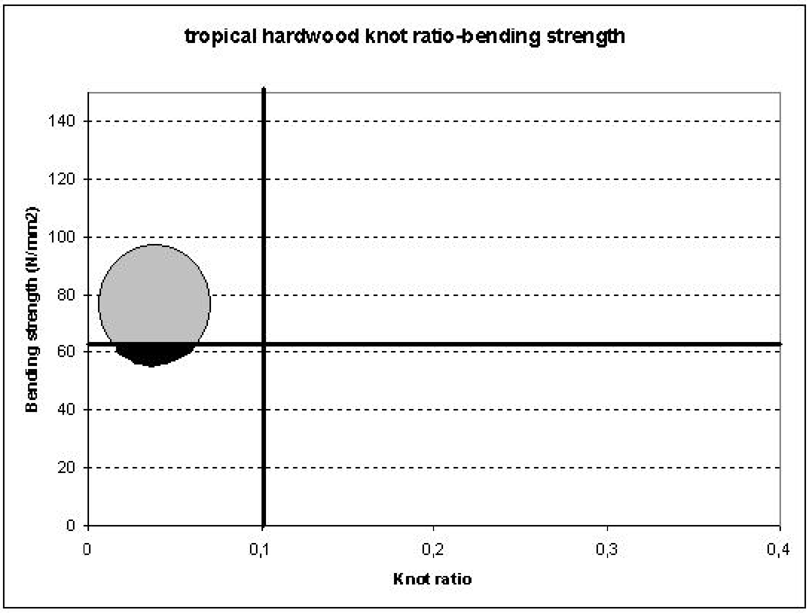

Figure 7: Typical correlation diagram for a hardwood species between knot ratio and bending strength

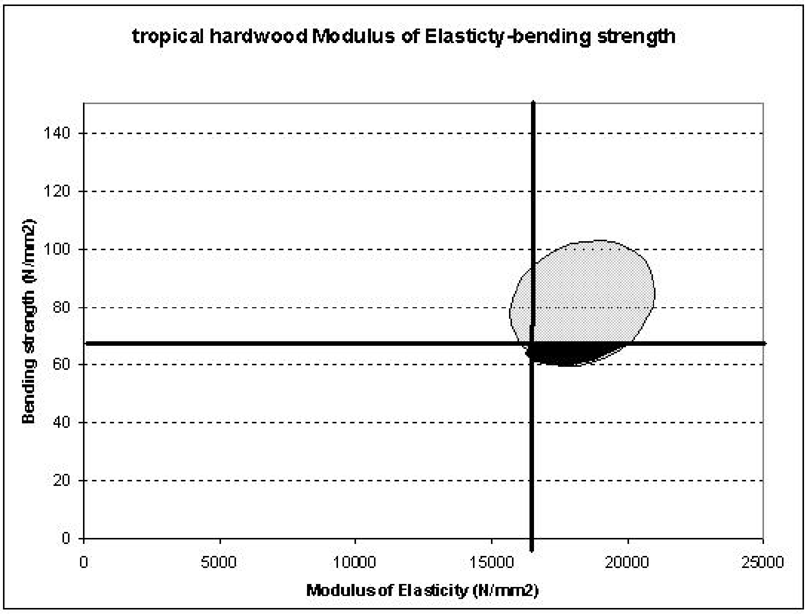

Figure 8: Typical correlation diagram for a hardwood species between Modulus of Elasticity and bending strength

Figure 8 shows that there is no profit in using the modulus of elasticity as a grading criterion since no more than one class can be distinguished. However, this is detected when hardwood species are observed on an individual basis. During this research the question arose if it is necessary to observe every hardwood species individually. Observing figures 7 and 8 it is not clear if a sample from each hardwood species is sufficiently representative to gain insight into the correlation of material properties with the bending strength. 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 wood 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.
To achieve the research goals, several testing programmes with many destructive and non-destructive tests were performed. Based on these data, formulas have been developed that can predict the characteristic timber strength given a small number of destructive tests. These models should describe the properties of the population to such a degree that the strength class of a new wood species can be determined with a sufficient level of reliability.

3.2 Test programme

The test programme covered a great number of wood 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 wood species were tested [7], [8],[8],[10]. The wood 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 wood species.
Besides the species mentioned in table 1 also a test sample of the species azobe was incorporated in the analysis part of the research. The species azobe (*lophira alata*) was already classified in a strength class in previous research. An overview regarding the mechanical properties of azobe has been described and accepted for publication [11]. Data out of softwood research on spruce, pine, douglas and larix, in which also non-destructive data was available, is used in the study to the correlation between part non-destructive and destructive measurements.

Table 1: Species that were tested in the research programme

Species	Origin	Latin name
Angelim vermelho	Brazil	*Dinizia excelsa*
Bangkirai	Indonesia	*Shorea leavis*
Basralocus	Surinam	*Dicorynia guianensis*
Cumaru	Brazil	*Dipteryx odorata*
Denya	Ghana	*Cylicodiscus gabunensis*
European oak	Poland	*Quercus robur*
European oak	Middle- and Central Europe	*Quercus robur*
Karri	South-Africa	*Eucalyptus diversicolor*
Massaranduba	Brazil	*Manilkara bidentata*
Nargusta	Bolivia	*Terminalia amazonia*
Piquia	Brazil	*Caryocar villosum*
Robinia	Hungary	*Robinia pseudoacacia*
Vitex	Solomon islands	*Vitex cofassus (spp)*

From all wood 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:
  a. Knots sizes
  b. Grain angle
  c. 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 Mobile Timber Grader (dynamic modulus of elasticity E_{dyn})
- 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 destructive 4-point-bending test according to EN 408.

The test values were adjusted to the reference conditions according to European and Dutch standards [4], [6].

The test results have been processed for the following purposes:

- To determine the characteristic properties of the wood species according to EN 384 [3] and to classify the wood species into strength classes according to EN 338 [2].
- To investigate the correlations between non-destructive measurements and the standardized measurements according to EN 408 [4] for bending strength and modulus of elasticity.

The test results according to EN 408 are presented in table 2. 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 a moisture content of 12%. In the last column the strength class according to EN 338 is presented. These strength classes are determined using the method described in EN 384, with the non-parametric method for the characteristic bending strength.
Species that could not be classified into a D-strength class for hardwood were classified into a C-strength class.

Table 2: Results of tests according to EN 384 and EN 408.

Species	**Mean bending strength (N/mm2)**	**Coefficient of variation of the bending strength**	**Mean Static modulus of elasticity (N/mm2)**	**Mean Density (kg/m3)**	**Strength class according to EN 338**
Angelim vermelho	82.9	0.21	16816	1045	D35
Bangkirai	96.3	0.23	20851	930	D50
Basralocus	70.5	0.33	21484	725	C22
Cumaru	115.5	0.21	20710	1017	D60
Denya	84.2	0.16	17727	947	D40
European oak, Polish	51.2	0.16	11596	616	C24
European oak, M+C. Europe	45.6	0.30	10358	684	C20
Karri	77.4	0.20	19302	706	D35
Massaranduba	124.5	0.14	24796	1034	D60
Nargusta	77.7	0.22	18349	723	C24
Piquia	76.6	0.22	21018	792	D35
Robinia	75.6	0.22	17704	699	D30
Vitex	69.8	0.19	16339	731	D30

3.3 Correlations between non-destructive measurements and standardized measurements according to EN 408.

3.31 General

The correlations between non-destructive measurements and the bending strength (and modulus of elasticity) according to the standardized methods of EN 408 were studied as a basis for the two research goals, mentioned in section 3.1. Therefore test results of the wood species are studied as an individual species being a population and as all wood species together being a population. This is discussed in the next sections.

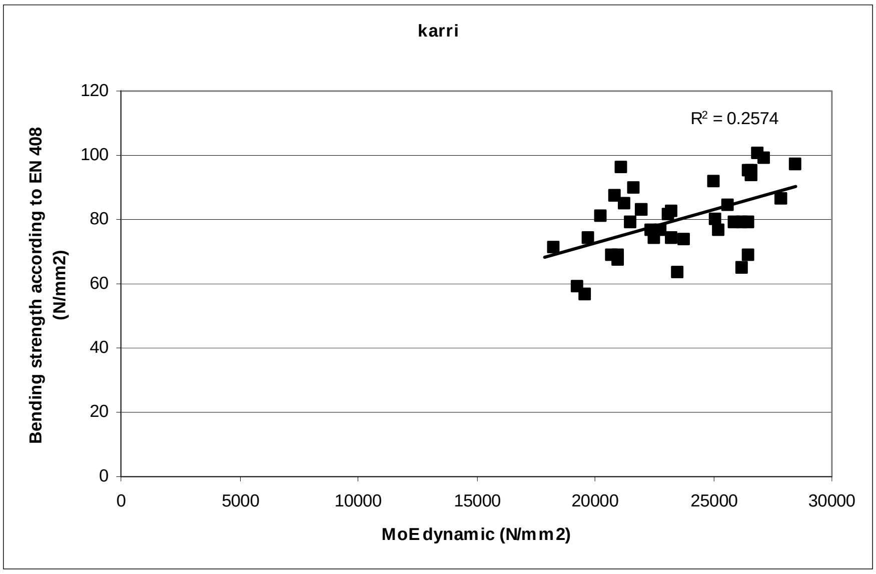

Figure 9: Test results of the species karri for the bending strength according to EN 408 plotted against the dynamic modulus of elasticity.

3.3.2 Predicting models based on test results of individual hardwood species.

According to the expectations formulated in section 3.1 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 9 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, of which 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 enough clear, distinct characteristics to be regarded as a specific subpopulation. The division in botanical species does not seem an appropriate way to determine strength predicting phenomena.

3.3.3 Prediction models based on test results regarding all hardwood species as one population.

When the hardwood species are not considered as individual populations, but are merged together to form one large population "timber", correlations between non-destructive measured properties and the bending strength appear to be good. This population has a sorting criterion that the beams (from all hardwood species) have restricted visual characteristics as knots. For now useful correlations between these properties and the bending strength can be found. These correlations apply to the entire range of values of the bending strength, from zero to the highest values, as shown in figure 10. Now the data of the species karri fit into the entire data set values of the population. So there is a prediction line that gives reliable predictions and can be used for optimisation.

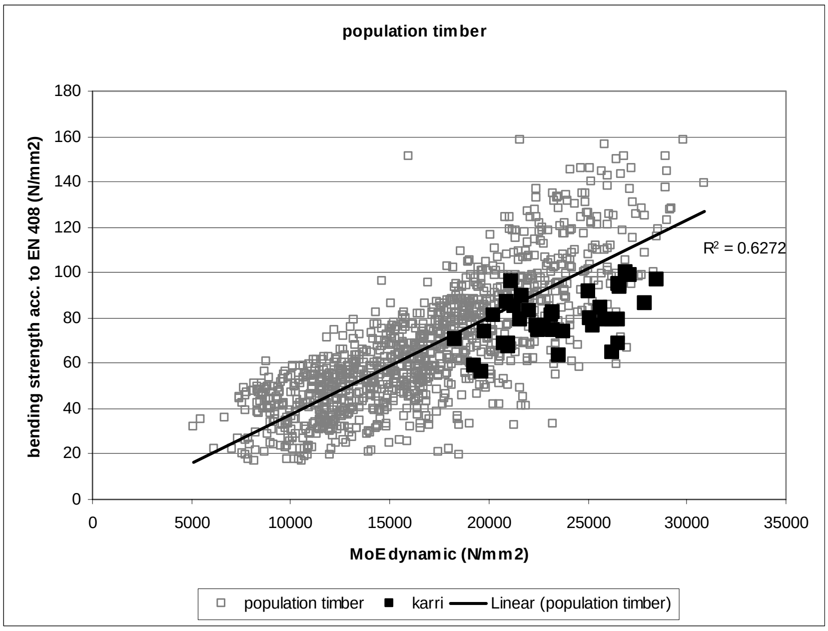

Figure 10: Test results for karri and for all species together of the destructive bending strength according to EN 408 plotted against the dynamic modulus of elasticity.

The main conclusion is that the bending strength of hardwood timber can be predicted for a specific wood species, when the behaviour of the material properties of the entire population of “timber” is taken into account. This opens the possibility to develop models for hardwood timber that can predict the bending strength of subpopulations as an individual species with the required reliability. With these predictions individual wood species can be classified into a strength class for visual grading in an economic way.

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, as illustrated in figure 11.

In figure 12 is shown that the static modulus of elasticity has a strong correlation with the dynamic modulus of elasticity. For these properties a correlation coefficient of r = 0,85 was found.

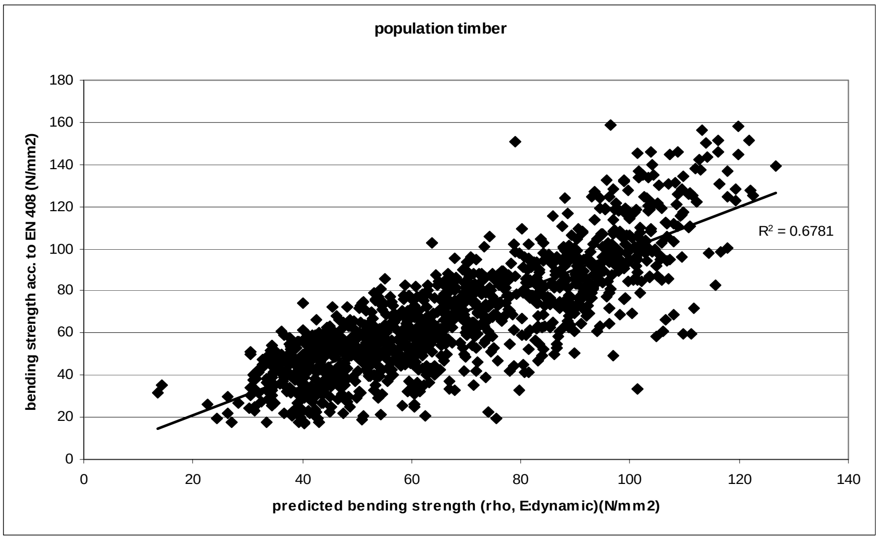

Figure 11: Test results of the bending strength according to EN 408 plotted against the predicted bending strength, using data of all species, based on a model with the density and the dynamic modulus of elasticity as predicting parameters.

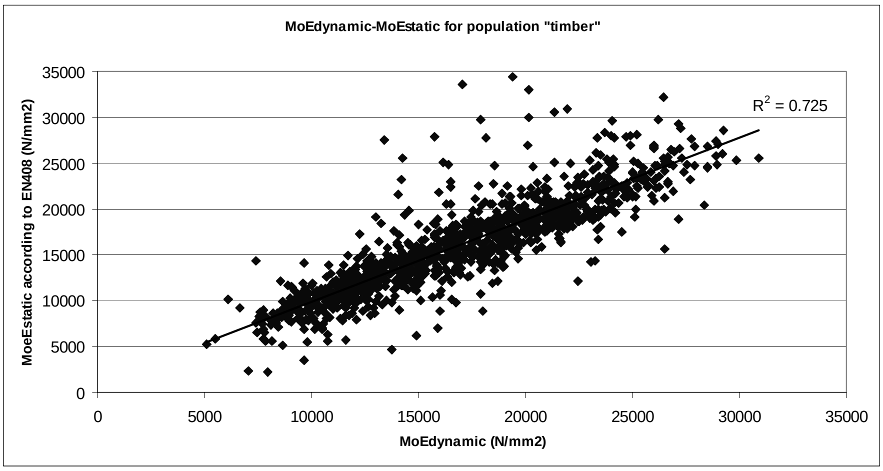

Figure 12: Test results of the static modulus of elasticity according to EN 408 plotted against the dynamic modulus of elasticity, using data of all species.

3.4 Analysing the distributions of the bending strengths of the tested wood species

3.4.1 The distributions of timber bending strength data.

As mentioned in section 2, traditionally non-parametric tests are used for determining the 5%-fractile strength value of wood species. However, according to Eurocode 1 parametric methods are preferred. But for timber, non-parametric tests are used as in that case knowing the actual statistical distribution and type of the test results is not necessary. The second reason is that by performing extensive tests (more than 300) it has been proven that a 5%-fractile of both the non-parametric distribution and the normal distribution is almost the same. For the classification of timber a minimum of 40 beams is allowed. For that reason the following questions were considered:

- Can the test values of the individual hardwood wood species be regarded as a sample from a normally distributed population? (see section 3.4.2)
- When the hardwood species are regarded as one population “timber”, do subsets generated with species-independent classification rules show normal behaviour? (see section 3.4.3)

If both assumptions are correct, the knowledge of the entire timber population can be used to classify a subset of this population by a parametric method.

3.4.2 Verification of the normal distribution of the test results of individual species

The distributions of the bending strengths of the tested wood species were investigated. It is often presumed that timber strength data can be described by a Weibull distribution. In [12] a large amount of softwood data sets were analysed and it was concluded that the normal distribution also gives a good description of the data for softwood. To verify this for hardwood all test data of individual species are considered to judge whether they can be seen as part of normal distributions [13]. Two plots of the data of all individual species are made. The first plot shows the normal probability of the dataset (when all data points are on the straight line the dataset is completely normal), as shown in figure 13a. Because the data is only a relatively small sample of a total population, it is possible that the sample is not quite normally distributed although the entire population is. To test if the sample is part of a normal distributed population a large number of samples are randomly taken from the normal distribution, represented by the straight line (Fig 13a). These are plotted together with the data of a specific species data set. This plot shows the range of datasets that can be expected when they are taken from a completely normal distribution. See figure 13 for the normal probability plot of the observed data of massaranduba (13a) and the range where the data is expected when they are taken from a population that is normally distributed (13b). This shows for the species massaranduba that the observed data could be a sample from a normal distributed population.

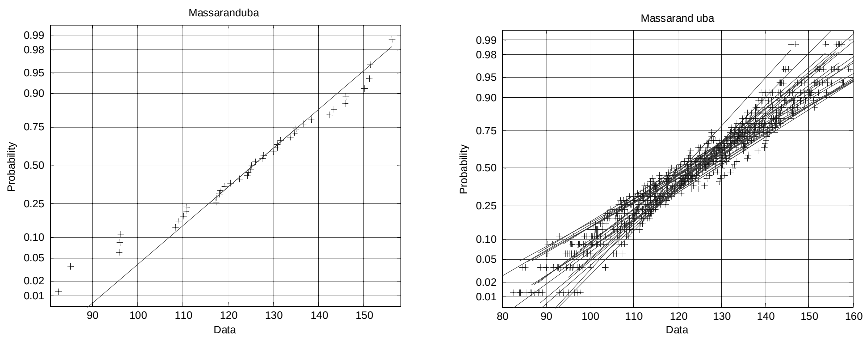

Figure 13: Normal probability plot of the test data of massaranduba (a) and a number of test samples from a normal distribution plotted together with the test data of massaranduba (b).

However, one restriction has to be made. For species with a lot of defects as knots and grain angle, a sample can fit on the normal distribution, but can have a deviation from the expected normal probability line that is not random (as for species with limited visual defects), but follows a pattern. When the sample is restricted on the visual defect that may occur, the sample fits better on the normal distribution. As an example the test data of Middle and Central European oak is plotted. In figure 14a no restrictions to the visual characteristics as knot sizes were made; all timber was considered to be useful for structural purposes, although in practice this is not true. Although this sample could be part of a normal distributed population, the deviation in the tail does not seem to be random, but has a systematic pattern. When restrictions are made to the knot sizes, see figure 14b, the test sample fits very well on the normal distribution and the deviations in the tail occur randomly.

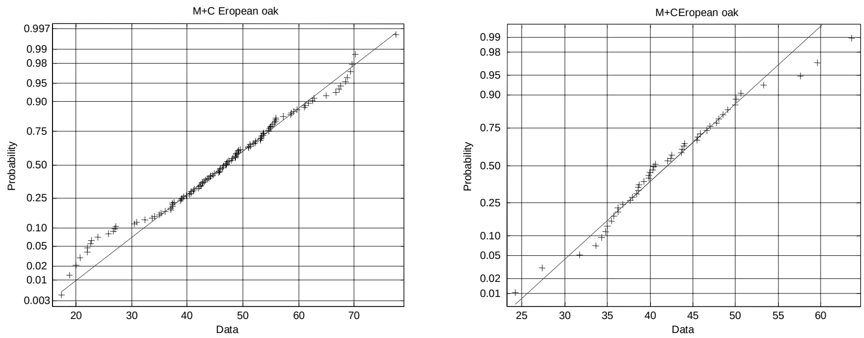

Figure 14: Normal probability plots of Middle and Central European oak with no restrictions to knot sizes (a) and with limited knot sizes (b).

The plots show that hardwood species can be considered to be normally distributed, when they are restricted to defects as knots and grain angle. In practice, these restrictions will be used to visually sort out the beams of a species, to which the determined strength class may be assigned. The beams that do not pass these restrictions should not be used for construction.

3.4.3 Normal behaviour of classified subsets of the entire population "timber"

In section 3.3.3 correlations are found between the bending strength and non-destructive measurements, when all species are regarded as belonging to one population "timber". These correlations can be used to make predictions. In chapter 4 these models will be explained. The bending strength of every beam, regardless the species, can be predicted with a certain safety level. Then, every beam can be classified in the D-classes available from D35 to D70. Because the beams are classified with a certain safety level that is both reliable (only 5% is allowed to be incorrectly upgraded) and economic (which depends on the accuracy of the model), many of the actual values derived by destructive tests, will be higher. However, the distribution of these actual values that are predicted to be in the same D-class, can be analysed. In figure 15a a probability plot for normal behaviour of the beams classified to be in strength class D40 is shown and in figure 15b the same for strength class D60.

Figures 15a and 15b show normal behaviour. This means that when the entire set of hardwood data is regarded as one population “timber”, models can be formulated which can classify the population into subsets that are normally distributed.

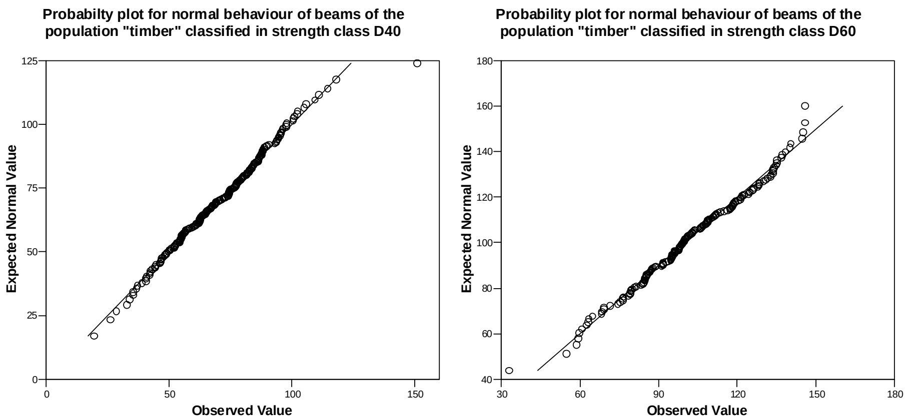

Figure 15: Normal probability plot for the actual values of beams of the population “timber “ that are classified to strength class D40 (a) and D60 (b) with predicting models.

3.5 Conclusions

In section 3.3 correlations have been found between non-destructive measurements on the one hand and the standardized destructive bending strength and the standardized modulus of elasticity on the other. As a result accurate economic predicting models can be made to classify hardwood timber in different strength classes.

Section 3.4 describes that datasets of hardwood species can be regarded as subsets from a normal distribution. When hardwood timber is regarded as one population “timber”, this population can be classified in subsets that show normal behaviour.

An economic method using combined destructive and non-destructive measurements can be developed with these findings. This method makes use of a parametric distribution (the normal distribution) to classify “new” wood species into a strength class. This method is described in section 4.

4 Classification of new wood species with combined destructive and non-destructive tests

4.1 General

In section 3.3 general correlations between material properties independent of the wood species were found. Section 3.4 displays that the normal distribution gives a good description of the bending strength of wood species. Combining these two facts makes it possible to classify new hardwood species in an economic way. When new species are regarded as a subpopulation of the entire timber population, for which we know general properties, it is possible to classify new wood species with a smaller number of destructive tests. In this chapter a model is presented that can predict the 5%-fractile bending strength for a wood species on the basis of combined destructive and non-destructive tests. The basic principle of this method is the following: 75% of the beams will be tested non-destructively and 25% will be tested destructively according to EN 408. So, for the minimum sample size of 40 beams this means 10 destructive tests and 30 non-destructive tests. With this method the 5%-fractile can also be calculated for other ratios of destructive and non-destructive measurements.

The non-destructive measurements are related to:

- Dimensions of the timber beam
- Weight, measured with a balance
- Moisture content, measured with a moisture meter
- Dynamic modulus of elasticity, measured with the TNO Mobile Timber Grader

For 75% of the beams, the bending strength of the beams will be calculated on the basis of the predicting regression lines.

The measurements according to EN 408 are:

- Moisture content with the oven dry method
- Static modulus of elasticity, measured with a bending machine
- Bending strength

In sections 4.2 and 4.5 the models for the bending strength and the modulus of elasticity are described. The methods to calculate the 5%-fractile bending strength and the mean Modulus of Elasticity using the non-destructive and destructive measurements are described in sections 4.4 and 4.6.

4.2 The correlation between non-destructive measured material properties and the bending strength for the population "timber".

A general bending strength model has to be formulated that correlates the bending strength according to EN 408 with the material properties that are measured non-destructively. This model is based on analysis of the non-destructive and destructive test results of all beams in the research programme. All test data are adjusted to the reference moisture content of 12%.
For the bending strength the following model was formulated:

$$f_b = g(\rho, Edyn) + \varepsilon \qquad (1)$$

where

f_b is the model bending strength (N/mm^2).

$g(\rho, E_{dyn})$ is the bending strength regression line with ρ and E_{dyn} as input parameters (N/mm^2).

ρ is the density (kg/m^3).

E_{dyn} is the dynamic modulus of elasticity measured with the Mobile Timber Grader (N/mm^2).

ε is the uncertainty in the prediction model.

$g(\rho, E_{dyn})$ can be a linear, but also a non-linear model. The lineair model is given by:

$$g(\rho, E_{dyn}) = a\rho + bE_{dyn} + c \tag{2}$$

where

$g(\rho, E_{dyn})$ is the predicted bending strength (N/mm^2)

a,b and c are constants.

The distributions of ρ, E_{dyn} and ε are supposed to be normal.

The uncertainty in the prediction model ε is stochastic with $\mu(\varepsilon) = 0$, $\sigma(\varepsilon) = \sigma_\varepsilon$. Investigation of the test results showed that the value of σ_ε varies with the value of $g(\rho, E_{dyn})$. The larger $g(\rho, E_{dyn})$, the larger σ_ε, see the dotted lines in figure 16.

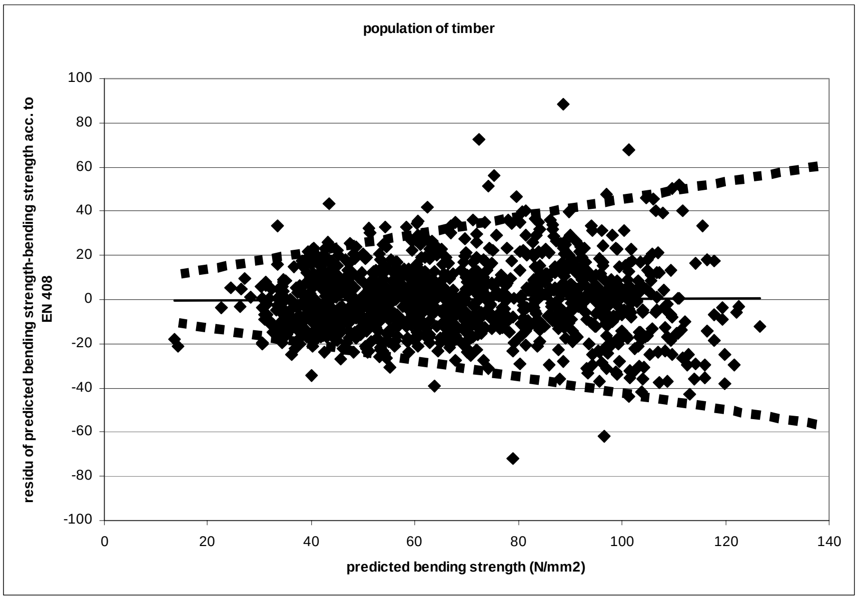

Figure 16: The model standard deviation increases with bigger values of the predicted bending strength

The relation between the predicted value of the bending strength and the value of σ_ε is linear and can be described in the following way:

$$\sigma_i(\varepsilon) = d * g_i(\rho, E_{dyn}) \tag{3}$$

where

$\sigma_i(\varepsilon)$ is the value of $\sigma(\varepsilon)$ in point $g_i(\rho, E_{dyn})$ (N / mm²).

$g_i(\rho, E_{dyn})$ is the predicted value of the bending strength (N / mm²).

d is a constant.

4.3 Calculation method for the 5%-fractile of the bending strength with a computer model based on Bayesian statistics.

The 5%-fractile of the bending strength can now be calculated. For this purpose a computer model based on Bayesian statistics has been developed, which incorporates both destructive and non-destructive measurements. The backgrounds for this computer model will be outlined in a future publication. In the next paragraph a hand calculation method is presented. This method is presented because it is easy to use and gives a good insight into the various uncertainties.

4.4 A hand calculation method to find the 5%-fractile of the bending strength from combined destructive and non-destructive test results.

The 5-fractile of the test samples is calculated with the following equation:

$$f_{0,05} = \mu(f_{i,j}) - 1{,}64 * \sigma(f_{i,j}) \tag{4}$$

In (5) $\mu(f_{i,j})$ and $\sigma(f_{i,j})$ are:

$$\mu(f_{i,j}) = (\mu(g_i) * n_i + \mu(g_{des\,;j}) * n_j) \;/\; (n_i + n_j) \tag{5}$$

$$\sigma(f_{i,j}) = \sqrt{\,(\sigma(g_{des\,;j})^2 + \sigma_{\mu(g_i)}(\varepsilon\,)^2)} \tag{6}$$

where

$\mu(f_{i,j})$ is the average value for the sample of the combined predicted and destructively measured bending strengths (N / mm²).

$\mu(g_i)$ is the average value of the bending strengths predicted by non-destructive measurements (N / mm²).

n_i is the number of beams on which non-destructive measurements are performed.

$\mu(g_{des;j})$ is the average value of the bending strength, measured by destructive measurements (N / mm²).

n_j is the number of beams on which destructive measurements are performed

The proportion between n_i and n_j is n_i / n_j = 3 and the minimum for $n_i + n_j = 40$.

$\sigma(f_{i,j})$ is the resulting standard deviation

$\sigma(g_{des;j})$ is the standard deviation of the destructive measurements (N / mm^2).

$\sigma_{\mu(g_i)}(\varepsilon)$ is the model uncertainty according to equation (3) in point $\mu(g_i)$ (N / mm^2), multiplied by the factor n_i / $(n_i + n_j)$: $\sigma_{\mu(g_i)}(\varepsilon) = \sigma_i(\varepsilon) * n_i$ / $(n_i + n_j)$

4.5 The correlation between non-destructive measured material properties and the static modulus of elasticity for the population "timber".

A number of models for the static modulus of elasticity have been considered. The linear model has the best fit:

$$E_{stat} = e\, E_{dyn} + f + \varepsilon \tag{7}$$

where

E_{stat} is the predicted value of the modulus of elasticity (N / mm^2).

e and f are constants

ε is the uncertainty of the model, which is a stochastic with $\mu(\varepsilon) = 0$, $\sigma(\varepsilon) = \sigma_\varepsilon$.

The value of σ_ε is constant for the modulus of elasticity, regardless its value.

4.6 A hand calculation method for the 50%-fractile of the modulus of elasticity.

The characteristic value of the modulus of elasticity is equal to the mean value.
The 50%-fractile can be calculated with the following equation.

$$E_{0,50} = \mu(E_{i\,j}) - 0{,}2 * \sigma(E_{i,j}) \tag{8}$$

In (9) $\mu(E_{i\,j})$ and $\sigma(E_{i,j})$ are given by:

$$\mu(E_{i\,j}) = (\mu(E_i) * n_i + \mu(E_{stat\,;j}) * n_j) \;/\; (n_i + n_j) \tag{9}$$

$$\sigma(E_{i,j}) = \sqrt{(\sigma(E_{stat;j})^2 + \sigma_\varepsilon^2)} \tag{10}$$

where

$\mu(E_{i\,j})$ is the average value of the sample of the combined predicted values out of the dynamic modulus of elasticity and the measured modulo of elasticity by static bending tests (N / mm^2).

$\mu(E_i)$ is the average value of the modulus of elasticity predicted by the measurements of the dynamic modulus of elasticity (N / mm^2).

n_i is the number of beams from which the dynamic modulus of elasticity was measured

$\mu(E_{stat;j})$ is the average value of the modulus of elasticity of beams measured by static bending tests (N / mm^2).

n_j is the number of beams from which the modulus of elasticity was measured by static bending tests.

The proportion between n_i and n_j is n_i / n_j = 3 and the minimum for $n_i + n_j = 40$.

$\sigma(E_{i,j})$ is the resulting standard deviation of the modulus of elasticity.

$\sigma(E_{stat,j})$ is the standard deviation of the modulus of elasticity measured by static bending tests (N/mm^2).

σ_ε is the model uncertainty (N/mm^2), multiplied by the factor n_i / ($n_i + n_j$): $\sigma_\varepsilon = \sigma_\varepsilon * n_i / (n_i + n_j)$.

5 Comparison with test results

5.1 General

In this section the 5%-fractiles for the bending strength and the mean values for the modulus of elasticity, calculated out of the test results for all beams according to EN 408, will be compared with the values calculated from the combined destructive and non-destructive tests according to the presented new method of section 4.

5.2 The 5%-fractile of the bending strength

In figure 17 the 5%-fractiles for the bending strength according to the non-parametric method calculated using the standardized measurements according to EN 408 are compared with the values according to the presented model in section 4 based on combined destructive and non-destructive tests. In figure 18 the ratios of these two values are presented. The average ratio is 1,07. This is above 1, which is slightly conservative but low enough to give beneficial results.

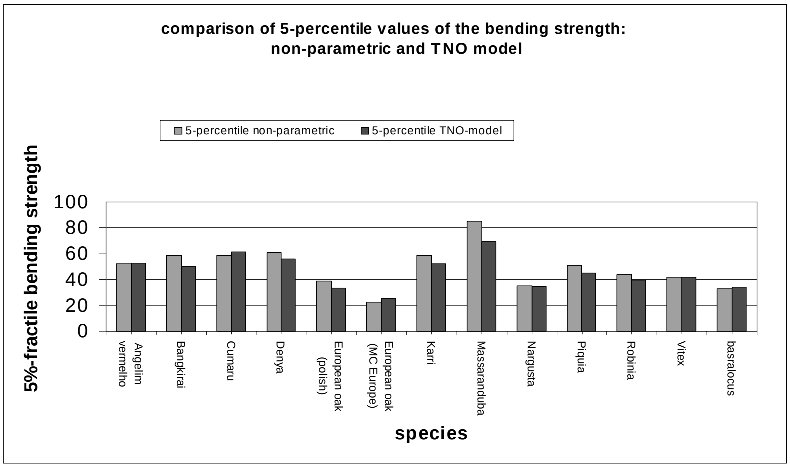

Figure 17: Comparison of 5%-fractile bending strength values determined with the non-parametric method and calculated with the TNO model.

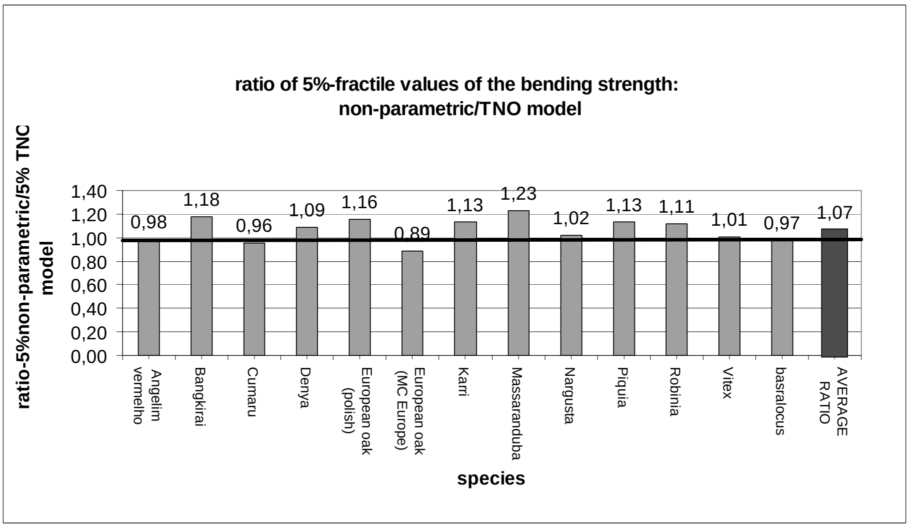

Figure 18: Ratio's of the 5%-fractile bending strength values for the non-parametric method divided by the value calculated with the TNO model

5.3 The mean modulus of elasticity

In figure 19 the mean values for the modulus of elasticity, in accordance with the standardized testing methods according to EN 408, and the modulus of elasticity determined by the presented model of chapter 4 based on combined measurements, are compared. The average value of the ratios is 1,06, which is above 1. This is slightly conservative, but low enough to give beneficial results.

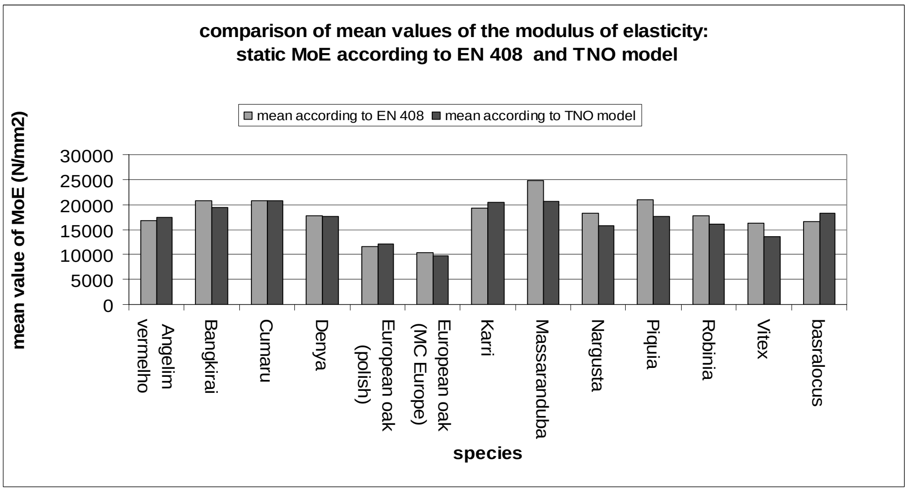

Figure 19: Comparison of the mean values of the modulus of elasticity determined with the static modulus of elasticity according to EN 408 and the modulus of elasticity calculated with the TNO model.

5.4 Conclusions

The verification shows that the presented models for the bending strength and modulus of elasticity correlate good with the traditional method. They are slightly conservative compared to the traditional method for the test samples.

Considering the use of the traditional non-parametric method a remark has to be made: for different test samples coming from the same population there can be significant differences for the 5%-fractiles of the bending strength.

The presented models are based on parametric methods, which create the possibility to take the expected variability between different test samples into account. It can be concluded that the presented methods are a good alternative for the traditional standardized methods.

6 Application of the new method for the classification of new wood species.

In 2003 a project was performed with the classification of 9 new wood species in a strength class using the new method in commission of FSC Netherlands. An overview of the final results is presented in table 3.

Table 3: Strength classes of 9 new wood species, determined using the presented model

Species	**Latin name**	**Origin**	**Strength class according to EN 338, derived by the new model**
Cupiuba	Goupia glabra	Brazil	D35
Louro itauba (itauba)	Mezilaurus itauba	Brazil	D40
Sucupira amarelo	Qualea paraensis D..	Brazil	D40
Sucupira vermelho	Andira spp	Brazil	D30
Uchi torrado (Uxi)	Sacoglottis guianensis, Vantanea parviflora, V. micrantha	Brazil	D40
Muiracatiara (Gonçalo-Alvez)	Astronium graveolens Jacq., A. fraxinifolium Schott, A. lecointei Ducke, A. Urundeuva	Brazil	D40
Jarana	Lecythis spp	Brazil	D40
Sapucaia	Lecythis pisonis	Brazil	D50
Piquia marfim	Aspidospermum desmanthum	Brazil	D50

In table 4 the derivation of the characteristic values of the bending strength and the modulus of elasticity of the test sample are presented for the species Sapucaia. They are calculated according the calculation models of section 4.4 and 4.6. See these sections for the explanation of the symbols.

Table 4: Derivation of the characteristic values of the bending strength and the modulus of elasticity of the test sample of sapucaia.

Derivation of the characteristic value of the bending strength of the test sample of sapucaia according section 4. 4. All values in N/mm² (n_i / n_j = 3)		**Derivation of the characteristic value of the modulus of elasticity of the test sample of sapucaia according to section 4.6. All values in N/mm² (n_i / n_j = 3)**	
$\mu(g_i)$	105,8	$\mu(E_i)$	22568
$\sigma_i(\varepsilon)$	23,3	$\sigma(\varepsilon)$	3550
$\sigma_{\mu(g_i)}(\varepsilon)$	17,5	σ_ε	2662
$\mu(g_{des;j})$	106,7	$\mu(E_{stat;j})$	25892
$\sigma(g_{des;j})$	12,5	$\sigma(E_{stat,j})$	4154
$\mu(f_{i,j})$	106,0	$\mu(E_{i\,j})$	23400
$\sigma(f_{i,j})$	21,5	$\sigma(E_{stat,j})$	4934
$f_{0,05}$	70,6	$E_{0,50}$	22412

The characteristic bending strength of the test sample is 70,6 N / mm². Because there were 40 specimens in the test sample, this value has been reduced with a sample factor of 0,78 according to [3] to a value representative for the population of the species sapucaia. This value of 0,78 * 70,6 = 55,1 N / mm² has been compared with the values of the strength class system of EN 338 [2]. Since this value is higher than 50 N / mm² the strength class that could be assigned to the species sapucaia is D50. The characteristic values for the modulus of elasticity and the density of the test sample were also higher than those of strength class D50 of EN 338 [2].
The strength classes mentioned in table 3 are used in compliance with the requirements for visual grading that are stated in the Dutch guidelines for timber in waterworks.

7 Future developments for machine grading

In this paper it has been explained that for most hardwood species, when using visual inspections, only one visual grade can be distinguished. When the beams do not meet the requirements of the visual characteristics, they cannot be used in construction. However, the research has shown that when grading is not done visually but by mechanically measured properties, such as the dynamic modulus of elasticity, weight and moisture content, it is possible to grade beams of a hardwood species into more than one strength class. To accomplish this TNO has developed the Mobile Timber Grader.

Figure 20: Lab prototype of the Mobile Timber Grader. Beams of different wood species and different sizes can be graded.

In this research the Mobile Timber Grader was used for the determination of the dynamic modulus of elasticity. The device has also been equipped with a software tool for predicting the strength class. The device does not only fill up the gap between expensive in-line grading machines and visual grading, it also makes machine grading possible for beams that cannot be graded by in-line machines, see figure 21

Figure 21. The Mobile Timber Grader makes it possible to machine grade beams of large sizes.

8 Conclusions

A new method to classify new hardwood species has been presented. When this method is used, less destructive bending tests are necessary, compared to traditional methods. The research shows strong correlations between properties predicted from non-destructive measurements on the one hand and the bending strength and the modulus of elasticity derived according to standardized tests on the other. To make these correlations visible all wood species are regarded as belonging to one (super) population. A computer calculation model to determine the 5%-fractile of the bending strength has been developed, together with a hand calculation model. This hand model was verified with the test data from standardized tests. The results are reliable and also very economical, since their values are slightly conservative compared to the traditional method as a reference. For the mean value of the modulus of elasticity also a hand calculation model has been developed.
Applying the method the visual characteristics, such as knots and grain angle, have to be restricted. These restrictions are being used to visually grade the beams.

References

[1] prEN 14081-1 Timber Structures – Strength graded structural timber with rectangular cross section- part 1 : General requirements

[2] EN 338. Structural Timber – Strength classes, 2003

[3] EN 384, Structural timber – Determination of Characteristic values of mechanical properties and density

[4] EN 408, Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties

[5] Goerlacher, Sortierung von Brettschichtholzlamellen nach DIN 4074 duch Messung von Longitudinalschwingungnen. Bauingenieur vol. 65,1990

[6] NEN 6760, TGB 1990 Timbers structures, 2002

[7] Van de Kuilen, J-W.G., Ravenshorst, G.J.P. Bending strength and stress wave grading of (tropical) hardwoods, COST E24 Zurich, 2002

[8] Van de Kuilen, J-W.G. Development of a general determination method for the strength of timber. Phase 1. TNO Reports 1999-LBC-R7027 / R7028/2 / R7029 / R7030/2. (in Dutch)

[9] Van der Linden, M.L.R., Van de Kuilen, J-W.G., Blass, H.J., Application of the Hoffman Yield Criterion for load sharing in timber sheet pile walls. Pacific Timber Engineering Conference pp. 1994

[10] Van de Kuilen, J-W.G., Ravenshorst, G.J.P. Development of a general determination method for the strength of timber Phase 2. TNO Reports 2000-CHT-R101 / R102 / R156 / R157 /R158 / R172 / R173 / R174 / R178 / R179 (in Dutch).

[11] Van de Kuilen, J-W.G., Blass, H.J. Mechanical properties of azobe (lophira alata), Holz als Roh-und Werkstoff . DOI 10.1007/s00107-004-0533-7.,2005.

[12] Sorensen,J.D. and Hoffmeyer, P.,Statistical Analysis of Data for Timber Strengths, Aalborg University, 2001

[13] De Wit, S. and van de Wiel, W., Characteristic timber strength of a timber sample, TNO paper, 2004.