Influence of slope of grain on the mechanical properties of hardwoods and the consequences for grading

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Abstract

The main parameter that influences the bending strength of timber from tropical hardwood is the slope of grain. Although in the grading rules a specific threshold value is given, in these hardwoods the global slope of grain is very difficult to quantify by a visual assessment. The slope of grain measured after testing gives a better indication, but still it can only poorly describe the Hankinson relations. By rewriting the Hankinson relations, the slope of grain can be determined from the bending strength test values and from the MOE test value, both in combination with the density values and constants derived by non-linear regression analysis. These two values correlate very well and the average value is designated as the theoretical slope of grain. With the theoretical slope of grain 5 test samples of tropical wood species were evaluated and slope of grain values of 0.3 were observed where 0.1 is the limit value. Because all pieces passed the normal visual grading method in practice, slope of grain values should be incorporated in the strength class assignment test program, when these qualities cannot be ruled out for coming on the market. The (dynamic) modulus of elasticity can be used to evaluate the occurrence of desired range of slope of grain values in the test samples.

1. INTRODUCTION

To assign a timber beam to a strength class, this beam has to be graded. With visual grading, the grader assesses the most important strength reducing characteristics and designates the visual grade of the beam. In a previously performed laboratory research the relationship between the visual characteristics and the strength is determined, and based on that the strength class connected to that specific visual grade was established. This is documented in grading reports and for a number of species there is a European standard (EN 1912) that provides information of strength classes that can be assigned to visual grades of a number of species from different growth areas. In Europe there is a harmonised standard (EN 14081) that provides guidance how strength assignments should be performed, to ensure that the same method is followed over Europe. The harmonised standard is referring to the standard EN 384 that gives guidelines on sampling in connection with visual grading. This paper discusses the influence of the strength reducing characteristic slope of grain in combination with visual grading.

EN 384 states how the characteristic value of for instance the bending strength can be determined based on the number of samples and specimen within a sample for a visual grade. That means that before the laboratory testing is performed, the material has to be subdivided in visual grades, that are defined in visual grading standards. For softwoods, the knot ratio (the size of the knots related to the width of the beam) is the most governing strength reducing parameter. It is possible to distinguish between different values of knot ratios during grading in practice, therefore it is possible to divide softwood in 2 or 3 visual grades. For tropical hardwoods however, the slope of grain (the deviation of the grain angle with the longitudinal beam axis) is the most important strength reducing characteristic (since in most cases, no knots are present). Because the value of the slope of grain is more difficult to determine in practice, for tropical hardwoods only one visual grade defined is for a species. For instance in the Europeans standard EN 16737 or in the Dutch standard EN 5493. For these visual grades the slope of grain is limited to a value of 1:10. Beams with higher slope of grain should be rejected. Figure 1 shows the definition of slope of grain according to EN 1310. The slope of grain is the tangent of the angle of the grain to the beam axis. Sometimes multiplied by 100 to express it as a percentage. In this paper slope of grain (SoG) is given as the tangent of the angle of the grain to the beam axis (x/y in figure 1).

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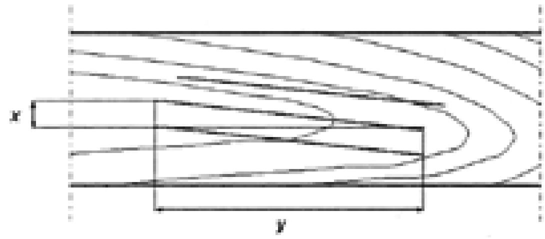


Figure 1: Definition of slope of grain according to EN 1310.

However, related to the requirements for visual grading of tropical hardwoods for slope of grain there are two assumptions that are important in this process. The visual grading for slope of grain is assumed to be correctly performed in practice and related to that: the sampling for the laboratory research for the strength class assignment is representative . These two assumptions will be investigated in this paper.

2. Influence of the slope of grain on the bending strength

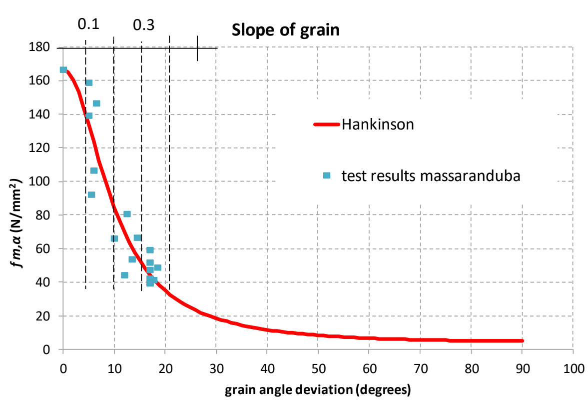
The influence of the grain angle on the strength is described in EC 5 (EN 1995-1-1) by the so called Hankinson equation. However, in EC 5 this is used for a stress verification as the result of a force acting under an angle with the longitudinal beam axis, thereby assuming that the grain direction is parallel to the longitudinal beam axis.

Hankinson (1932) based his equation on compression tests. From a theoretical point of view the Hankinson equation describes the interaction between stresses parallel and perpendicular to the grain. This has proven to be also valid for tension under an angle with the grain, and also for bending properties with varying slope of grain. Equation (1) gives Hankinson equation for the bending strength and equation (2) for the Modulus of Elasticity.

$$f_{m,\alpha} = \frac{f_{m,0}}{\left(\frac{f_{m,0}}{f_{m,90}}\right)*sin^2(\alpha)+cos^2(\alpha)} \tag{1}$$

$$MOE_{\alpha} = \frac{MOE_0}{\left(\frac{MOE_0}{MOE_{90}}\right)*sin^2(\alpha)+cos^2(\alpha)} \tag{2}$$

Figures 2 show results of tests performed on specifically prepared specimens of the tropical hardwood species massaranduba with a depth of 50 mm as described in Ravenshorst (2015). These graphs show that the effect of increasing slope of grain is not linear with bending strength. Through a non-linear regression analysis the values for $f_{m,0}$ and $f_{m,90}$ were determined (And also MOE_0 and MOE_{90}) and inserted in equation (1) and (2). The lines of equation (1) and (2) are shown in the figures together with the original data. The graphs shows the limit value of 1:10 that is used for the visual grade of tropical hardwood. This shows that the reduction in bending strength when the slope of grain increases from SoG =0 to 0.1 is 85% % and when the slope of grain increases from 0 to 0.2 the reduction in bending strength is 50 % . That shows the importance of limiting the slope of grain.



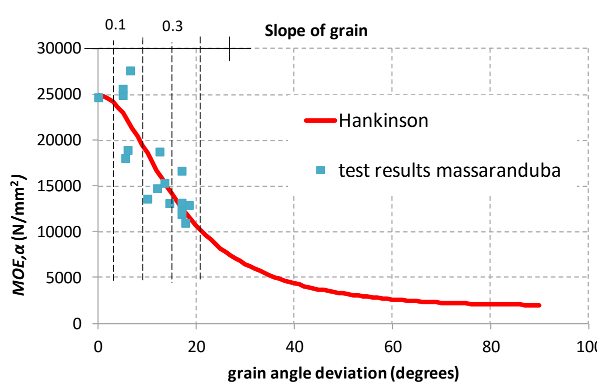


Figure 2: Influence of slope of grain on bending strength (left) and Modulus of Elasticity (right) of specimens of massaranduba according to Ravenshorst (2015)

3. MEASURING OF SLOPE OF GRAIN

3.1. INTRODUCTION

The slope of grain is evaluated in the grading process but can also be studied in the laboratory. Figure 3 shows on the left the measurement of the slope of grain on a timber beam before testing and after a bending test. On the right two beams of tropical hardwood species okan are shown that have to be graded.

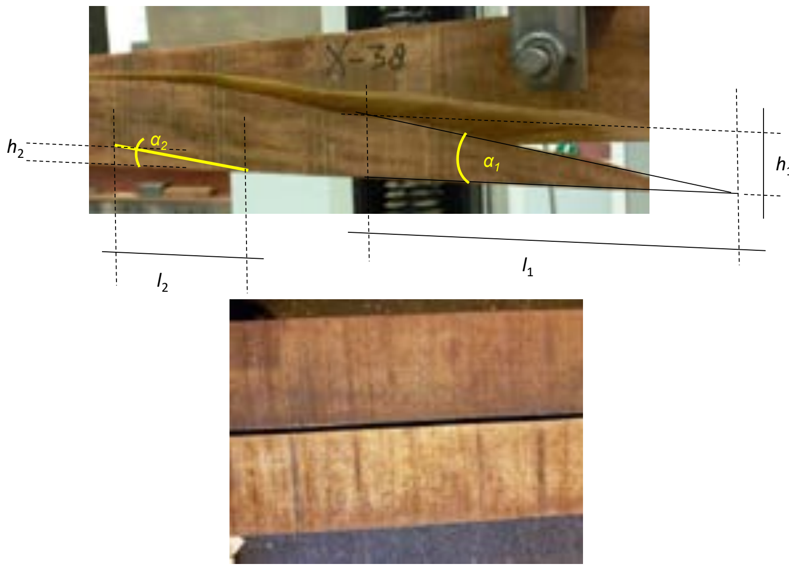


Figure 3: Angle of the grain and associated slope of grain measured before (α_2) and after (α_1) the bending test (left) and two okan beams that have to be graded (right)

3.2. MEASURING THE SLOPE OF GRAIN IN THE GRADING PROCESS

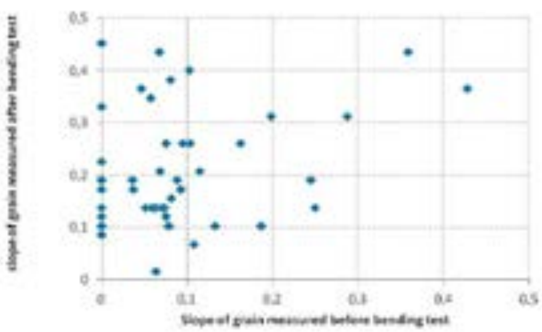
For tropical hardwoods there is only one visual class with the requirement to limit to the slope of grain of 1:10 according to grading standards NEN 5493 or EN 16737. In contrast with visual grading on the basis of knots, to determine the exact slope of grain in practice is very difficult. Therefore in practice, graders will judge the slope of grain as within our without the required limits. When the slope of grain is assessed to be out of the limits, the beam will be rejected. The right picture in figure 3 shows how difficult the determination of the slope of grain in practice can be.

3.2. MEASURING THE SLOPE OF GRAIN AFTER TESTING

After testing in the laboratory the slope of grain can be measured based on the failure cracks that follow the grain (although this also sometimes is difficult). See figure 3 on the left. EN 384 states that in the report for visual grading assignments histograms showing samples distributions of knot size measurements, rate of growth and density. This is clearly focused on softwoods, and in practice, in reports dealing with tropical hardwoods, distributions of the slope of grain are required, to give insight in the distribution in the strength reducing characteristics. EN 384 does not state if these distributions should be measured before or after testing. However, to get insight in the actual influence it is more valuable to give the slope of grain values after testing. In Ravenshorst (2015) was shown that when beams from a large number of species are evaluated the influence of the slope of grain is visible, but with much more scatter than when specimens are specifically prepared as was described in section 2.

3.3. COMPARISON OF SLOPE OF GRAIN MEASUREMENTS BEFORE AND AFTER TESTING

To evaluate the predicting capability of the slope of grain after failure on measurements before testing two samples of hardwood timber species were investigated. All pieces were visually graded as in practice with the result that the slope of grain was acceptable and the piece did not have to be rejected. Then the slope of grain was measured in the laboratory before and after testing according to figure 3 (left). Figure 4 (left) shows the results for a sample of okan and figure 4 (right) shows the results for a sample of greenheart. Figure 4 shows that is very difficult to predict the slope of grain after failure before testing with measurements before testing, that there is a large scatter, and that it also depends on the species or sample. For the okan sample (left) is was much more difficult than for the greenheart sample. The slope of grain often exceeds the maximum value of 0.1 according to the visual grading standards. Once again,all pieces passed the normal visual grading process.



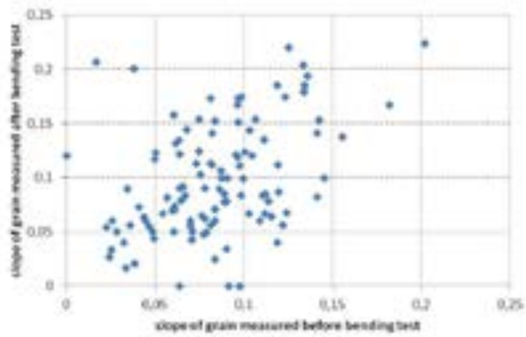


Figure 4: Slope of grain measured before and after testing for a sample of okan (left) and a sample of greenheart (right)

4.THEORETICAL DERIVATION OF THE SLOPE OF GRAIN.

According to section 2 the slope of grain has an effect on both the bending strength and the Modulus of Elasticity. That explains why the Modulus of Elasticity and the bending strength are well correlated. In Ravenshorst (2015) the Hankinson equations were rewritten according to equations (3) and (4).

$$f_{m,\alpha} = \frac{(\rho C_1)}{(C_3-1)sin^2(\alpha)+1} \quad (3)$$

$$MOE_\alpha = \frac{(\rho C_2)}{(C_4-1)sin^2(\alpha)+1} \quad (4)$$

Where ρ is the density, α the grain angle and C_1, C_2,C_3 and C_4 are constants. Equations (12) and (13) can be rewritten to respectively equations (5) and (6) to calculate $sin^2(\alpha)$ when the actual values of the density, the bending strength and MOE are known.

$$sin^2(\alpha) = [\frac{(\rho C_1)}{f_{m,\alpha}} - 1]\frac{1}{(C_3-1)} \quad (5)$$

$$sin^2(\alpha) = [\frac{(\rho C_2)}{MOE_\alpha} - 1]\frac{1}{(C_4-1)} \quad (6)$$

For this paper a dataset of 5 samples of timber species okan as described in Ravenshorst and van de Kuilen (2018) was studied. The constants C1, C2, C3 and C4 were determined through a non-linear regression analysis with the precondition that the slope of the regression line of the values of sin2(α) calculated with equation (5) and (6) should be 1. The correlation graph is show in figure 6. The found values of the constants were C1 =0.12, C2 =25.9, C3=27.8 and C4=15.0. From the calculated values of sin2(α) the square root is taken to calculate sin(α). For negative values of sin2(α) the value of sin(α) is taken as 0. From the values of sin(α) derived from equation (5) and (6) in this way the average was taken. Then the angle was calculated from this average sin(α). The tangent of angle α was calculated and this value was designated as the theoretical slope of grain.

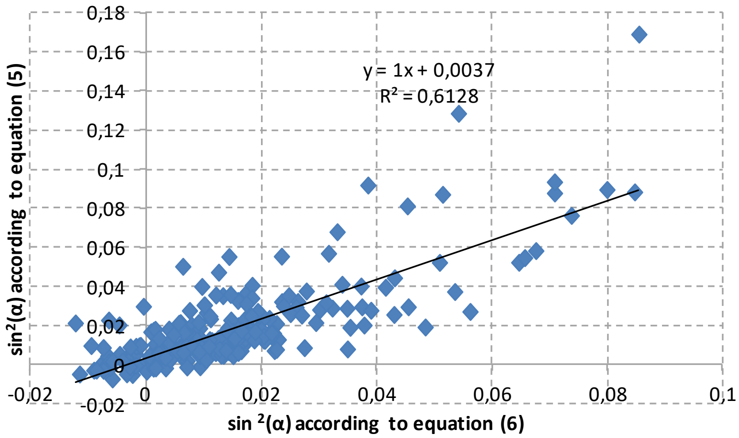


Figure 6: Relationship between $\sin^2(\alpha)$ calculated with equations (5) and (6).

5. Analysis

In figures 7 and 8 the slope of grain measured after the bending test and the theoretical slope of grain, determined according to section 4 are compared with the theoretical Hankinson equations according to equations (3) and (4) with the average density of all 5 samples of okan as input value, and the C-factors determined in section 4.

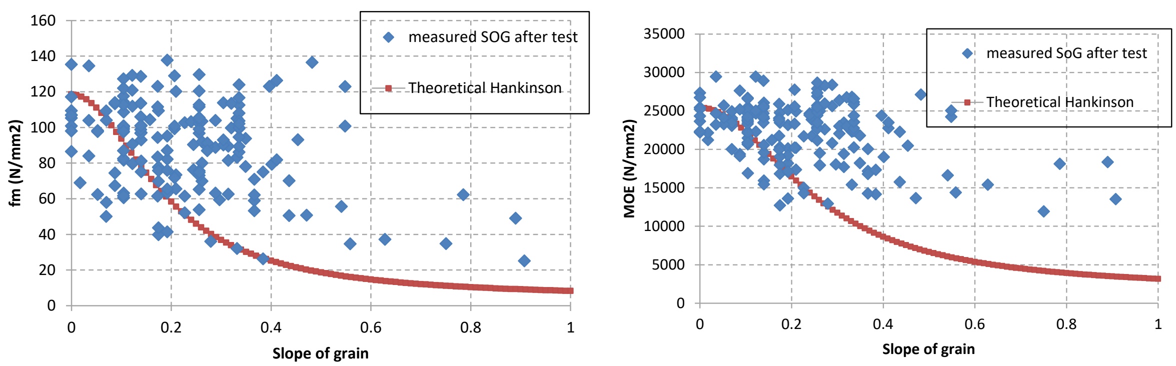


Figure 7: Bending strength (left) and MOE (right) against for slope of grain measured after testing and theoretical Hankinson line 5 samples of okan

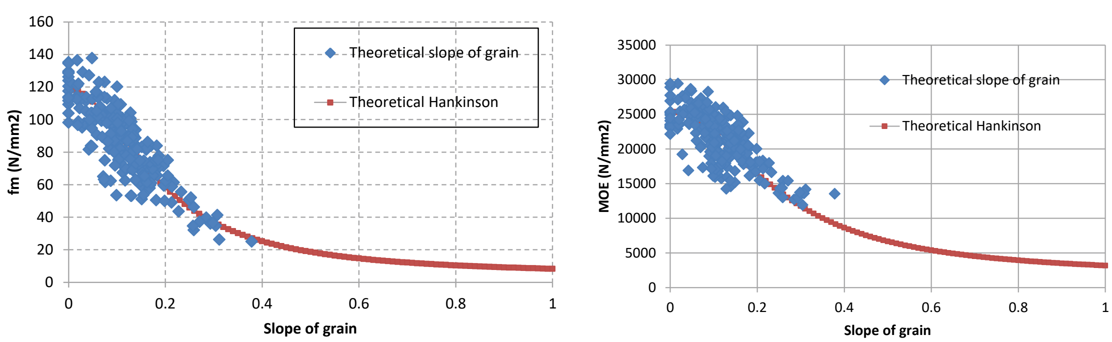
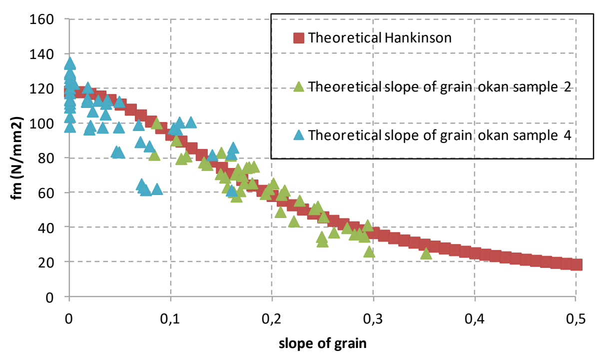


Figure 8: Bending strength (left) and MOE (right) against theoretical slope of grain and theoretical Hankinson line for 5 samples of okan

Figures 7 and 8 show that the theoretically determined slope of grain follows the theoretical Hankinson lines much better for both bending strength and MOE than the slope of grain measured after the test. This can be explained by two things. Firstly, also after the bending test the slope of grain is not always very clear to measure. Secondly, it is difficult to capture the 3D effect that is present in timber beams. These two effects show different in test results of full size compared to the specifically prepared specimens described in section 2. Figure 8 shows that the theoretical slope of grain values can capture the 3D effect for bending strength and MOE.

With the theoretical slope of grain the influence different samples on the classification of samples can be investigated. Figure 8 shows that for pieces that pass the normal grading procedure for visual grading, can have a theoretical slope of grain up to 0.3. Figure 9 shows the bending strength against the theoretical slope of grain values for okan samples 4 and 5 (left) and the bending strength against the MOE (right). When only samples with the quality of sample 4 would be incorporated in the testing program and the strength class assignments would be based on these samples, then when in practice a sample with the quality of sample 2 is used in practice (this would pass the current grading method for visual grading as explained) this would be unsafe.

Therefore, when the presence of samples with higher slope of grain values cannot be ruled out, for strength class assignments the range of slope of grain values should be more than the threshold value of 0.1, a range between 0 and 0.3 seems reasonable. To be sure that these pieces are incorporated the (dynamic) MOE of pieces can be determined and based on these values a selection can be made. The MOE for straight grained pieces (SoG of 0) is expected to be the density (for the okan samples an average value of 980) multiplied by constant C_2 (=25.9) which gives a value around 25400 N/mm^2. Therefore, sample 4 can be regarded as high quality. For a slope of grain of 0.3 a value of 11000 N/mm^2 can be expected.



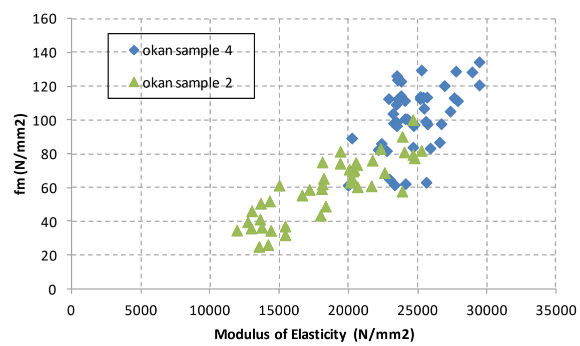


Figure 9: Bending strength against theoretical slope of grain and theoretical Hankinson line for okan samples 2 and 4 (left) and bending strength against MOE for okan samples 2 and 4 (right).

6. CONLUSIONS AND RECOMMENDATIONS CONCERNING THE SLOPE OF GRAIN IN THE STRENGTH CLASS ASSIGNMENT S OF TROPICAL HARDWOODS

For tropical hardwoods the slope of grain is the most important parameter that influence the bending strength and the Modulus of Elasticity. The relation of the slope of grain with these parameters can be described with Hankinson equations. Because the slope of grain is more difficult to assess than the size of knots for softwoods, only one visual grade is possible for tropical hardwoods. In practice it is assessed if the beams complies with the required limit of 1:10 for the slope of grain or not. The actual value of the slope of grain is not measured. However, it is shown that slope of grain values measured after testing can be much higher than the limit of 1:10, but also these values do not follow the Hankinson relations very well. This can be explained by the 3D effect that is difficult to capture visually.

The theoretical slope of grain can be determined with the measurements of the bending strength, the MOE and the density. The theoretical slope of grain follow the Hankinson relations very well. For 5 samples of okan species values for the theoretical slope of grain were found in the range from 0 to 0.3 for pieces that pass the normal visual grading assessment.

It is therefore advised that in the testing program for the strength class assignments specimens with values for the slope of grain up to 0.3 are incorporated in the testing program, when it cannot be ruled out, that these pieces might come on the market. The selection of the specimens can be made of the expected MOE for the range of slope of grains.

The slope of grain should be measured after testing and the theoretical slope of grain can be calculated. These distributions should be incorporated in the strength class assignment reports. For historical data where no slope of grain data are available the theoretical slope of grain can be calculated from the density, bending strength and MOE, to evaluate if the sampling was representative and not consisted of unique high quality samples.

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