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DETERMINATION OF THE SHEAR STRENGTH OF TROPICAL HARDWOOD TIMBER

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ABSTRACT: The current shear strength values for high density tropical hardwoods are very low compared to the values for softwoods, according to European strength class tables. The reason for this is that standardized tests according to European standard EN 408 have not been performed yet for tropical hardwoods. In this research, tropical hardwood species massaranduba was investigated according to EN 408. The test results give a 5%-value for the shear strength of massaranduba that is twice as high as the standardized value for strength class D70. No relation was found between the density and the shear strength for massaranduba. Shear strength was proportional to the density when compared to spruce.

KEYWORDS: shear strength, tropical hardwood, massaranduba, spruce.

1 INTRODUCTION

The shear strength values of structural timber have to be determined according to EN 408 [1] in Europe. These values can be compared to those listed in EN 338 [2]. However, only the shear values for softwoods in EN 338 are based on shear tests according to EN 408, based on research by Denzler and Glos [3]. The shear strength values of tropical hardwoods are not based on shear tests according to EN 408. Basically this value was topped-off by the CEN standardization committee. A previous version of EN 338 contained values based on the following relationship:

$$f_{v,k} = 0.2 f_{m,k}^{0.8} \tag{1}$$

leading to an increase in shear strength for higher strength classes. The shear strength ratio between D70 and C24 is about 2.35 on the basis of equation (1).

Currently however, the characteristic shear strength value of C24 is 4.0 N/mm^2, where the characteristic shear strength value of D70 is 5.0 N/mm^2, only a slight difference. In addition, 5 point bending tests performed at the Delft University of Technology [4], indicated much higher shear strengths for both spruce and tropical hardwoods than currently specified. These tests were performed to have a more practice-oriented result, for instance for beams spanning over more supports. The results of the shear strength tests of azobé and the test set-up can be found in [7].

Because much higher shear strength is expected, the test set-up according to EN 408 has to be evaluated for tropical hardwoods. This paper gives the results of research performed at the Delft University [5], where this is investigated on the hardwood species massaranduba with reference tests on spruce.

2 MATERIAL AND METHODS

2.1 MATERIALS

Two timber species were tested according to the EN 408 test method:

- 62 specimen from the wood species massaranduba originating from Brazil.
- 11 specimen from spruce originating from Germany

Test pieces of l x b x h = 300 mm x 32 mm x 55 mm were cut from remaining pieces from bending tests. The length l is the length along the grain. The cutting borders were parallel to the beam edges, meaning that any grain angle deviation in the beams are also present in the shear test specimen.

Two glue types were used in the experimental program:

- Griffon combi: This is a 2 component epoxy glue. This glue is intended to glue metals to each other but also to glue metal in combination

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with wood, concrete and plastics. The glue should be applied as thin layer.

- Sikadur 30: This is a 2 component epoxy glue. This glue is the strongest glue in the product range of Sika, for instance used for gluing carbon lamellas to concrete. The glue layer is 2-3 mm thick and can be applied without external pressure. The shear strength values given by the producer are in the range of 15-18 N/mm^2 after hardening and for the adhesive strength on a steel surface a minimum value of 21 N/mm^2 is given.
- Steel plates of normal structural steel (S235) were used to glue the timber on.

2.2 METHODS

The test set-up according to EN 408 is used for the experiments. The intention is to determine the "pure" shear strength with as little interaction with other stresses as possible. Tapered glued steel plates of 10 mm thickness are glued on both sides. See figure 1. The test piece is positioned at an angle of 14 degrees with the loading direction in the test set-up. See figure 2.

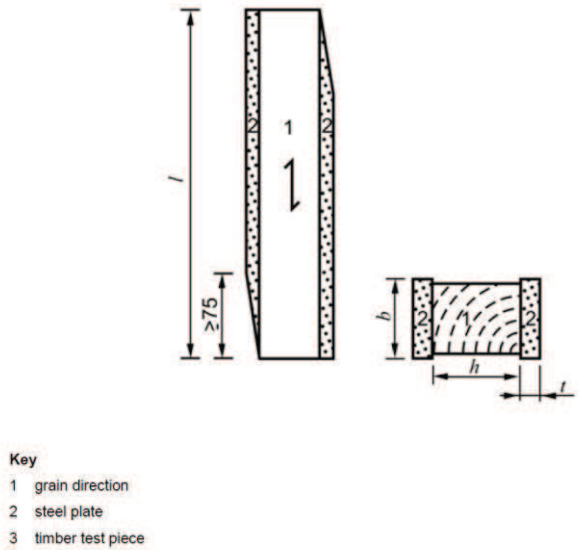

Figure 1: *Timber test piece with glued on steel plates according to EN 408.*

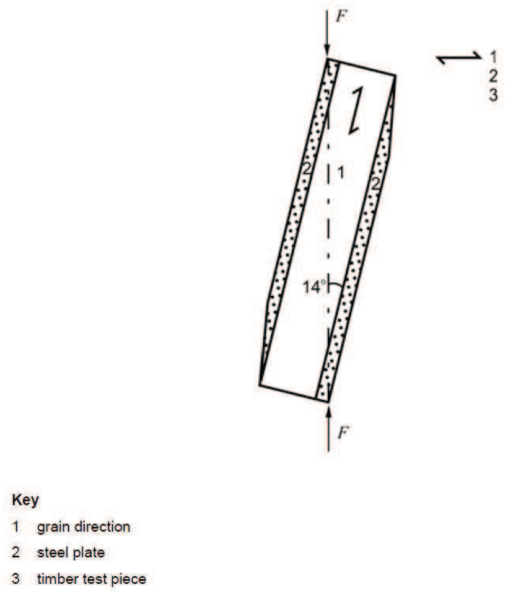

Figure 2: *Loading arrangement of the test piece according to EN 408.*

The shear strength f_v of a test piece is calculated according to equation (2).

$$f_v = \frac{F_{max} \cos 14°}{l\, b} \tag{2}$$

Where F_{max} is the maximum recorded force in N, l is length of the specimen parallel to the grain and b is the thickness of the specimen.

Because no previous tests on tropical hardwoods are reported in literature for this test set-up, an evaluation of this set-up based on numerical analysis was performed. Based on that analysis the configurations for the test set-up was defined.
A pre-test was performed on a small number of specimen to determine the most suitable glue for the rest of the specimen.
The rest of all specimen were tested with the most suitable glue. The objective of the testing of the spruce specimen was to compare the applied testing approach with results from literature.
For all specimen the maximum force, the failure patterns and the density were recorded.

3 EVALUATION OF THE SUITABILITY OF THE TEST SET-UP FOR TROPICAL HARDWOODS

3.1 Introduction

EN 408 gives as a provision that the test result is only valid when the failure area in the timber test piece/steel plate interface is less than 20% of the total bonding area. The intention is that the failure will occur in the middle of the specimen. To prevent failure at the interface peak stresses have to be avoided. In [3] 260 specimens were tested, and for 7.5% of these specimens a failure area larger than 20% of the total bonding area was found. When the failure is in the interface the shear strength of the timber is higher and cannot be determined. The 20%-requirement therefore is a requirement to determine the correct timber shear strength, and to prevent low values.
To prevent peak stresses in the interface the following options were investigated:

- Influence of the thickness of the steel plates: 10 mm and 20 mm respectively.
- Influence of the taper of the steel plates with 3°(taper over the whole length of the steel plate), 8° (the minimum value according to EN 408) , 14° and 90° (no tapering).

3.2 Numerical analysis

The combinations of the different configurations were investigated by linear 3D FEM-analyses in ANSYS Workbench 2015. Because the configuration of EN 408 has proven itself for spruce, this was used as a benchmark to evaluate the results of hardwood. For spruce the mean values of the properties of C24 were used and for hardwood the mean values of the properties of D70. The glue is modelled as a fixed connection between timber and steel plates with no thickness. In table 1 the relevant material properties assigned to the 3D elements are listed. The steel is modelled as an isotropic material and the timber as transverse isotropic (different material properties parallel and perpendicular to the grain, but no distinction between radial and tangential direction).
The load is introduced as a line load over the top surface of the steel plate, the bottom support is modelled as a hinged line support. For the spruce a load of 30 kN is applied, for the massaranduba a load of 100 kN. The aim is not to evaluate the magnitude of the stress values, but the distribution of the stresses.

Table 1: *Material properties for FEM modelling.*

Material	Steel plates S235	Massa-randuba D70	Spruce C24
MOE_0 (N/mm^2)	210000	20000	11000
MOE_{90} (N/mm^2)	210000	1250	370
$G_{0,90}$ (N/mm^2)	80000	1250	690
$G_{90,90}$ (N/mm^2)	80000	480	142
Poisson ratio $\nu_{0,90}$	0.3	0.3	0.3
Poisson ratio $\nu_{90,0} = \nu_{90,90}$	0.3	0.01	0.01

The results will be shown for the difference between spruce and hardwood, for a steel plate thickness of 10 mm and a taper of 8° and 90°. The thickness of the steel plate did not make the difference in the occurring stresses.

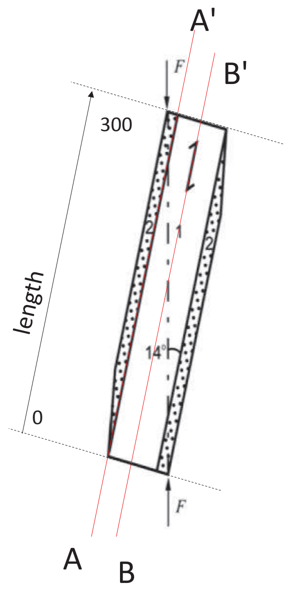

Figure 3: *Indication of cross sections AA' and BB' for which the stresses are shown in figures 4 to 9.*

Figure 3 shows the cross sections for which the stresses are shown in figures 4 to 9. The shear stresses in the glue line in cross section AA' of figure 3 are shown in figure 4 for softwood and figure 7 for hardwood. The normal stresses perpendicular to the grain in cross section AA' of figure 3 are shown in figure 5 for softwood and figure 8 for hardwood. The shear stresses in the middle of the timber pieces in cross section BB' of figure 4 is shown in figure 6 for softwood and figure 8 for hardwood

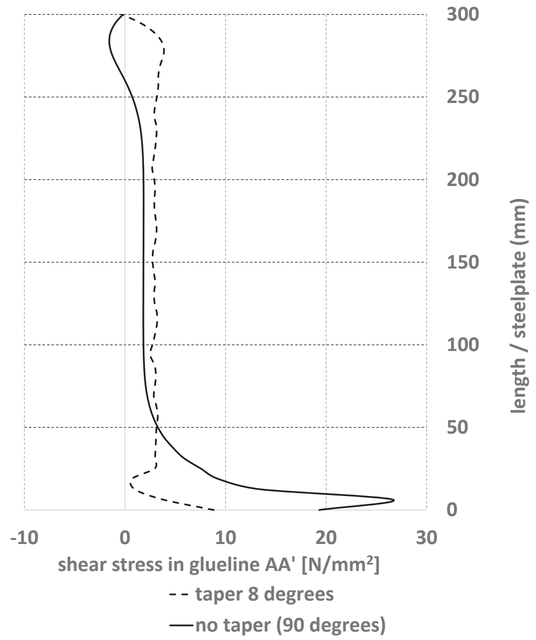

Figure 4: *Shear stress in the glueline AA' for softwood.*

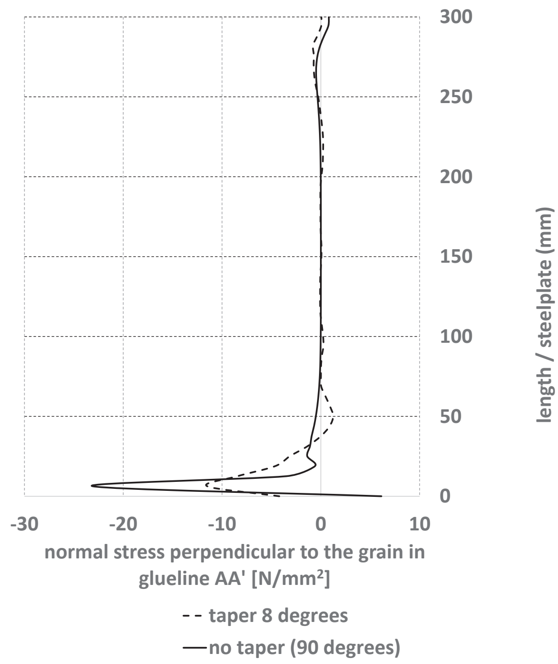

Figure 5: *Normal stresses perpendicular to the grain in the glueline AA' for spruce.*

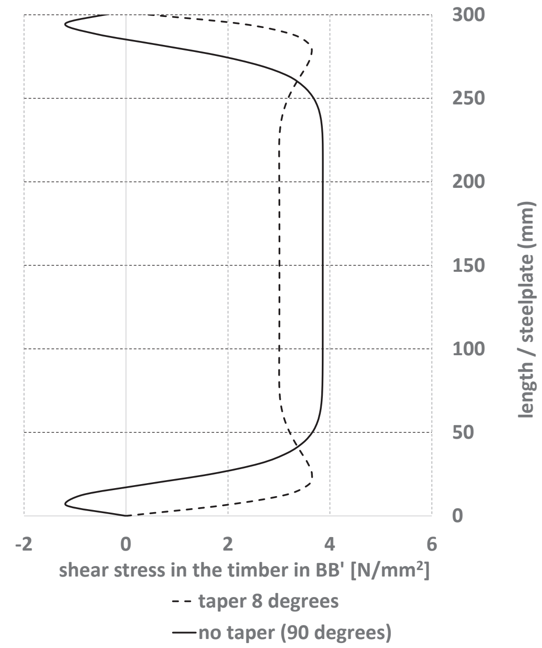

Figure 6: *Shear in the timber in BB' for softwood.*

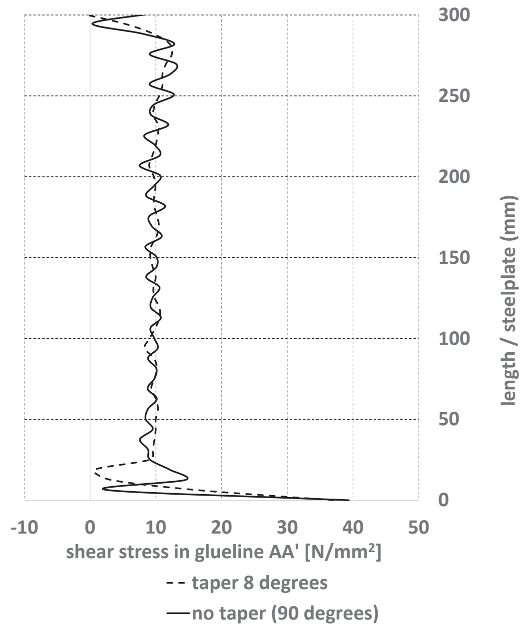

Figure 7: *Shear stress in the glueline AA' for hardwood*

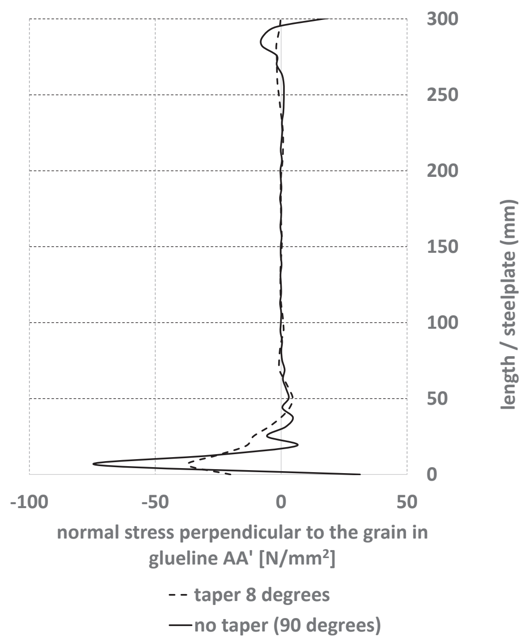

Figure 8: *Normal stresses perpendicular to the grain in the glueline AA' for hardwood.*

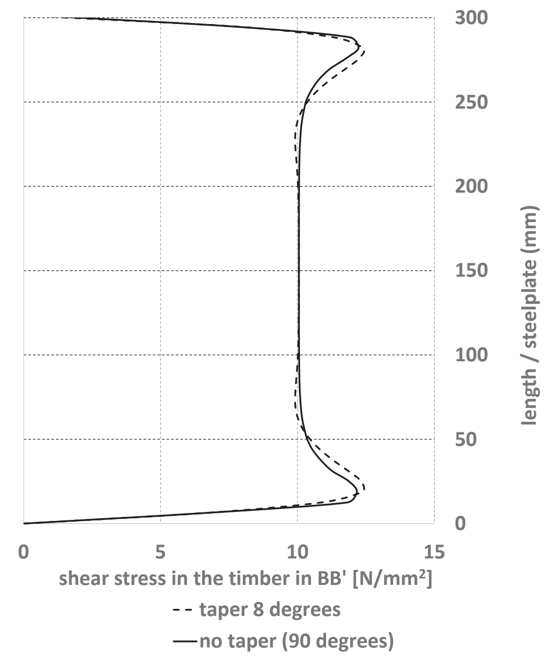

Figure 9: *Shear in the timber in BB' for hardwood.*

3.3 Discussion

From the numerical analysis the following can be concluded for softwood:

- The application of the taper gives an almost evenly distributed shear stress in the glue line with the steel plate over the length of the steel plate, although at the taper the shear stress increases.
- Tension stresses perpendicular to the grain almost not occur, both for the tapered and the non-tapered configuration
- The taper gives a more evenly distributed shear stress in the middle of the timber.

It can be concluded that the main function of the taper is to limit the shear stresses at the interface steel-timber, but that even then some peak stresses dooccur. This is in line with the experiments from Denzler [3] where most of the specimen failed in the timber, but a small portion still failed in the interface.
From the numerical analysis the following can be concluded for hardwood:

- Peak shear stresses occur for both tapered and non-tapered steel plates at the interface.
- For the non-tapered steel plates peak tension stresses perpendicular to the grain may occur.
- For the shear stress in the middle of the timber there is not much difference in the shear stresses between the two configurations.

It can be concluded that for hardwood the effect of the taper is less clear. Peak shear stresses may occur at the interface for both tapered and non-tapered steel plates. However, for the tapered steel plate the tensile stresses perpendicular to the grain appear to be less.

Based on the numerical analysis it was decided that steel plates of 10 mm thickness would be used and that both steel plates with a taper of 8 degrees and non –tapered steel plates would be applied to investigate the effect of the peak stresses..

4 RESULTS

4.1 Pre-test

In the pre-test 3 pieces of massaranduba where glued with Griffon Combi and 4 pieces of massaranduba were glued with Sikadur 30. Non-tapered steel plates were used.
The retrieved shear strength values are listed in table 2.

Table 2: *Pre-test results for massaranduba glued with Griffon Combi and Sikadur 30.*

Glue type	Test no.	f_v (N/mm^2)
Griffon Combi	1	2.3
	2	0.8
	3	1.3
Sikadur 30	1	10.9
	2	10.6
	3	12.8
	4	11.3

The results show that the Griffon Combi with the very thin glue line did not give satisfactory results. The failure occurred 100% at the interface timber-steelplate at one side. The steel plates popped of spontaneously at a low load. The retrieved values are even lower than the values for softwood, indicating that the stiffer hardwood and the absence of the taper introduce peak stresses causing the failure.
For the tests with the Sikadur 30 the failure occurred in the timber itself with values clearly higher than for softwoods. Besides that the glueline itself is very strong, the thickness of the of 3 mm might reduce peak stresses. The stiffness for compression and tension given by the technical sheet for Sikadur 30 is approxiametely 10 000 N/mm^2, much lower than steel and about half of massaranduba, which might be the reason for the reduction in peak stresses.

4.2 Final test

For the final test all specimen were glued with Sikadur 30. In table 3 the test results for all specimen are given.

Table 3: *Test results for massaranduba and spruce*

Wood species	Massa randuba	spruce
N=	62	11
Mean shear strength (N/mm^2)	13.9	5.4
Standard deviation shear strength (N/mm^2)	2.4	0.5
Mean density (kg/m^3)	1070	435
Standard deviation density (kg/m^3)	65	14
Mean moisture content (%)	14.5	13.0
Ratio density / mean shear strength	77	80

In figures 10 to 12 typical failure modes are shown.

Figure 10: *Massaranduba specimen: Failure of 100% in the glueline.*

Figure 11: *Massaranduba specimen: Failure of 0% in the glueline.*

Figure 12: *Spruce specimen: Failure of 0% in the glueline.*

5 ANALYSES

5.1 Failure patterns

The spruce specimen all failed in the timber, so with no failure in the glueline or the interface of the glue with either the steel plate or the timber. The values found in table 3 are very much in line with the results of [3] on spruce.

For the massaranduba specimen the failure patterns were clearly different then for spruce. As was mentioned, EN 408 prescribes that a specimen should not have more than 20% failure in the glueline (or the interface) to be taken into account in the analysis.

In table 4 the difference between the shear strength values for the pieces with 20% or less failure in the glueline are compared with the pieces with more than 20% glueline failure. It must be noted that it is very difficult to accurately determine the exact failure percentages.

Table 4: *Test results for massaranduba for different glueline failures*

	<= 20% glueline failure	> 20% glueline failure
N=	23	39
Mean shear strength (N/mm^2)	12.9	14.5
Standard deviation shear strength (N/mm^2)	3.0	1.7
Mean density (kg/m^3)	1050	1077
Standard deviation density (kg/m^3)	61	53
5% shear strength value acc, to FprEN 14358 (N/mm^2)	7.7	11.4

The 5%-values of the shear strength are calculated according to FprEN 14358, assuming a lognormal distribution. It is interesting to see that the 5%-values (and also the mean values) of the pieces with no more than 20% failure in the interface have a lower value than the pieces with more than 20% failure in the glueline.

The 4 pieces with the lowest strength values had 0% failure in the interface (see figure 11), and were all cut from the same massaranduba beam.

The pieces with more than 20% failure in the glueline might have had a higher value when the interface layer was stronger, or it could be that in those pieces the peak stresses at the interface became governing.

Therefore the values for more than 20% failure in the glueline are minimum values for the shear strength of the specimen. Because of that it seems justified to calculate to 5%-value from all 62 pieces from table 3.

That would give a 5%-value, calculated according to FprEN 14358 of 9.8 N/mm^2 for massaranduba. For comparison, for the 11 pieces of spruce from table 3 the 5%-value, calculated according to FprEN 14358 would become 4.2 N/mm^2, in line with the value of 4.0 N/mm^2 for softwood C-classes according to EN 338.

5.2 Influence of the steel plate taper on the massaranduba pieces.

Based on the numerical analysis it is expected that applying a taper will reduce the peak stresses at the interface layer. Therefore it is expected that for the specimens with the taper, the percentage of failure in the interface is less than for the specimens without a taper. In table 5 the results for the test pieces are divided between specimen with tapered and non-tapered steel plates. In figure 13 the individual results of all pieces are plotted.

Table 5: *Test results for massaranduba divided in specimen with and without tapered steel plates.*

	Pieces with tapered steel plates	Pieces without tapered steel plates
N=	29	33
Mean shear strength (N/mm^2)	14.1	13.8
Standard deviation shear strength (N/mm^2)	2.3	2.4
Mean % failure in the interface (%)	30	35
Standard deviation failure in the interface (%)	23	31

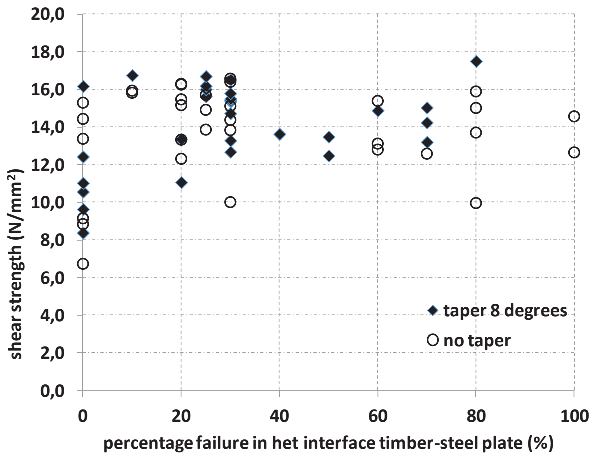

Figure 13: *Shear test results for massaranduba plotted against percentage failure in the interface divided in to specimens with and without tapered steel plates.*

Table 5 and figure 13 indicate that the application of the taper to the steel plates had no effect on the shear strength values and the percentage failure in the interface. This might be caused by the fact that the glue, the Sikadur 30 is applied with 3 mm thickness, in contrast to the FEM calculations, where a zero thickness was assumed. This thickness of 3mm might reduce the peak stresses in such a way, that the effect of the taper diminishes.

5.3 Comparison to 5-point bending tests

In [4] a series of 5-point bending tests were performed on spruce and a number of tropical hardwoods, among which azobé [7], massaranduba and angelim vermelho, all with a density of 950 kg/m^3 or more. Mean shear strength values were 17.7, 18.7 (20%) and 18.3 (20%) N/mm^2 respectively at moisture content of 30% for azobè and about 20% for massaranduba and angelim vermelho. For spruce at 9% moisture content, a mean shear strength value of 9.1 N/mm^2 was found. So in this case and with these boundary conditions, the ratio between the experimentally found shear strengths for relatively wet hardwoods and dry spruce was between 1.7 and 2.

5.4 Relationship with other material properties.

In the current strength profiles according to EN 338:2012 there is no relationship of the shear strength with another material property given. Based on the results presented, it is clear that the characteristic shear strength value of 5.0 N/mm^2 for hardwood strength class D70 is too low. It can be motivated that the shear strength could be related to the density, because the density gives an indication for the amount of fibers available. The ratio between mean density and mean shear strength is close to 80 for both species, see table 4.
Because in this test program only two wood species at two density levels are tested, only an indication for the relationship between the shear strength and the density can be presented. See figure 14.

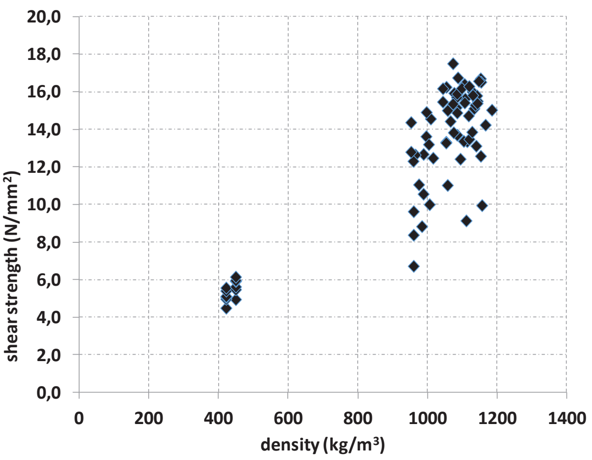

Figure 14: *Relationship between the shear strength and the density for the spruce and massaranduba specimen.*

Figure 14 suggests a constant ratio between the shear strength and the density of the two wood species..

6 CONCLUSIONS

When shear tests are performed on tropical hardwoods with high density according to the configuration of EN 408 high peak shear and tension perpendicular stresses to the grain at the interface steel-timber are expected when a thin glue is used. Experiments have confirmed that in that case, lower test values than for softwood can be observed. The use of a thick-layered (3 mm) two-component epoxy glue like Sikadur 30 overcomes these problems. Then also the effect of tapering of the steel plates does become insignificant.
The test results on massaranduba show that the shear strength value for high density hardwoods is underestimated by the values given in EN 338 by at least a factor of 2. This is also supported by the ratio found in the 5-point bending tests.
The requirement in EN 408 that only test specimens with no more than 20% failure in the interface layer between is not supported by the test results on hardwood species massaranduba. When all tested massaranduba specimen are taken into account a 5%-value of 9.8 N/mm^2 is found. The shear strength values found for the spruce specimen which were tested as a validation of the applied method are in line with previous results from literature.
The ratio of the shear strength with the density ratio seems consistent for the two wood species tested and such a dependency could be introduced in the standard. Alternatively, equation (1) could be used with modified constants, increasing the shear strength for high density hardwoods more than it does now.

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