ELASTOMECHANICAL PROPERTIES OF GLUED LAMINATED TIMBER MADE OF STRENGTH GRADED OIL PALM LUMBER

Katja Fruehwald-Koenig[1]

ABSTRACT: The wood from oil palm trunks exhibits significant variations in distribution of structural tissue, density and elastomechanical properties across and along the trunk. Its reliable, safe, and economic usage for load-bearing purposes, such as glued laminated timber (GLT), requires a precise definition of its elastomechanical properties through appropriate strength grading procedures. Oil palm lumber is strength graded according to its density using an X-ray technique in which 50 % of the lamellas are ripped, graded, edge glued and therefore density homogenized, and 50 % are cut only according to their geometry. Lamellas are tested in tension parallel to the vascular bundles; combined GLT is produced from strength-graded lamellas and tested in bending parallel and compression parallel and perpendicular to the vascular bundles. The characteristic strength values for C10 and C14 according to EN 338 are achieved. A correlation between density and elastomechanical properties is established. GLT from density-homogenized lamellas achieve higher bending properties than from lamellas with a "natural" density gradient across the width.

KEYWORDS: Oil palm lumber, glue laminated timber, GLT, strength grading, elastomechanical properties

1 INTRODUCTION

Oil palm trees (*Elaeis guineensis* Jacq.) are mainly cultivated in large plantations for palm oil production to be used for food, chemicals, pharmaceuticals and bioenergy. The palms' oil productivity decreases after 20 years of age. Therefore, plantations are renewed after 25 to 30 years. Each year, there is a large supply of oil palm trunks (approximately 200 Mio. m³ per year, of which over 80 % are in SE-Asia) traditionally considered as waste. Recent research, however, has explored the potential commercial uses of oil palm wood [1]. In many cases, the wood can substitute tropical hardwoods, e.g. as panels (blockboards, flash doors multi-layer solid wood panels) and softwoods in construction timber (glued laminated timber, GLT; cross laminated timber, CLT). In the past 35 years, the macro-mechanical properties of oil palm trunk wood have been widely studied. Because of the property gradients within the cross-section and within the height of the trunk [2,3], all investigations on elastomechanical properties of oil palm wood were performed using small, defect-free test specimens (e.g. [4]) and describe strength and stiffness variations over the cross-section and the trunk height and/or depending on the density, the number or the share of vascular bundles. Only a few investigations focus on oil palm wood in construction size. Jumaat et al. [5] tested trussed rafters from oil palm wood, Srivaro [6] and Srivaro et al. [7] tested sandwich panels with oil palm wood core and rubberwood veneer faces in bending, compression and indentation. Srivaro et al. [8] investigated finger-jointed oil palm wood products in bending and compression parallel to the vascular bundles. Srivaro et al. [9] tested cross laminated timber (CLT) in compression, the hygroscopic properties and the rolling shear. Hoffmann [10] dealt with hybrid CLT from bamboo (surface layer) and oil palm wood (core layer) in bending and compression.

The anatomic wood structure of monocotyledonous palms differs from deciduous and coniferous trees. Palms have no secondary thickness growth, due to the absence of a peripheral cambium. Palm wood consists of high density, rather long vascular bundles embedded in soft (low density) parenchymatous ground tissue. Knots, probably the most important grading criteria for common tree species, are not present in palm lumber. Hence, on the macroscopic level, palm wood is in some aspects homogeneous compared to dicotyledonous wood.

Within the context of a research project [11,12], combined GLT from density graded oil palm wood is tested in bending (f_m, E_m) as well as compression parallel ($f_{c,0}$, $E_{c,0}$) and perpendicular ($f_{c,90}$, $E_{c,90}$) to the vascular bundles and glulam lamellas are tested in tension parallel to the vascular bundles ($f_{t,0}$, $E_{t,0}$). Strength, respectively Young's modulus are related to the density and the performance indices for minimum weight design according to Ashby et al. [13] are calculated. The results are compared with those of

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small, defect-free specimens of oil palm wood [4] and with building components from palm wood and common wood species found in the literature.

2 MATERIAL

2.1 LAMELLAS FROM OIL PALM WOOD

The material is taken from 30-year-old oil palms (*Elaeis guineensis* JACQ.) grown near Kluang/Johor, Malaysia. The denser material from the periphery is cut to 30 mm (fresh) and has a thickness after kiln drying of 27 mm, the lower dense material from the centre is cut into 55 mm (fresh) resp. 50 mm (kiln-dried) boards. The kiln-dried material is shipped to Germany. For the GLT production, 70 boards of 27 mm thickness from 20 different logs and two different trunk heights (1 – 4 m and 4 – 7 m above ground) are taken. The mean length of the boards is 2.8 m and mean width 0.22 m.

Due to the anatomical structure of monocotyledons (rotationally symmetrical around the stem axis), it is assumed that opposite boards have comparable elastomechanical properties. For the pairwise comparison in this investigation, two outer and two inner 27 mm boards placed opposite to each other are selected by visual inspection. Boards with cracks or cell collapse are not used. The edges of the boards are trimmed along the cortex using a table saw. Due to the natural taper of the oil palm trunks (some 0.8 cm per meter trunk length), the boards have different widths at each end (approx. 2–3 cm difference). The rough-cut lamellas are calibrated using a two-side planer with HeliPlan tools from Leitz, Germany, one board of each pair to a thickness of 20 mm, the other to 17 mm. Details on the material preparation are given in Heister and Fruehwald-Koenig [11]. Some of the 17 mm lamellas are used for the tension test parallel to the vascular bundles (Table 1).

2.2 CALCULATION OF LAMELLA STRENGTH CLASS LIMITS

No strength grading standard exists for oil palm wood. Because of the small dimensions of the GLT specimens produced within this investigation, the strength grading of the oil palm lumber is based on the European strength class system for coniferous lumber (C-classes) according to EN 338 [14] and EN 14081-2 [15]. Fruehwald-Koenig and Heister [4] showed that most elastomechanical properties of oil palm wood depend on the density. Therefore, the statistic calculation model of EN 14081-2 attachment B [15] is used in modified form to calculate the density limits for the strength classes. The calculations are based on the relationships between density (indicating property (IP)) and tensile strength ($f_{t,0}$) resp. compression strength ($f_{c,0}$) parallel to the vascular bundles for MOR determined in preliminary investigations on small test specimens, published in Fruehwald-Koenig and Heister [4] and linearized by the natural logarithm. Details on the calculation of lamella strength class limits are described in Heister and Fruehwald-Koenig [11].

For strength class C14, the characteristic tensile strength value parallel to the vascular bundles ($f_{t,0,k}$ = 7.2 MPa) leads to a density limit value of >427 kg/m^3 and the characteristic compression strength ($f_{c,0,k}$ = 16 MPa) to a density range of 363 – 427 kg/m^3. Because of the high share of oil palm wood material with densities below 350 kg/m^3, property values for an assumed strength class C10 are extrapolated with 290 – 335 kg/m^3 for the compression lamellas and 335 – 363 kg/m^3 for the tension lamellas. The density limit value for the shear lamellas is <290 kg/m^3 for both beam setups.

2.3 STRENGTH GRADING OF THE BOARDS

When grading oil palm boards according to their density, the average density of the board must not be assumed because of the density gradient over the trunk's cross-section (which is higher than the gradient along the trunk height) [3]. Figure 1 shows the density profile across the 140 mm width of a board from the outer area of the trunk.

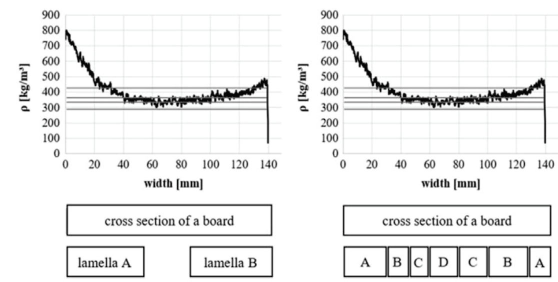

Figure 1: *Density profile of a board from the outer area of an oil palm trunk with a high density gradient over the board width. Cutting of "full size" lamellas according to their geometry with inhomogeneous density (left) and cutting strips with individual width and homogeneous density (right)*

The 17 mm thick board of each pair is used to "conventionally" cut the boards according to their geometry in two 55 mm wide and 2200 mm long lamellas from each side of the board, which results in "full size" cross-section (= non-ripped) lamellas (Figure 1, left) with a density gradient over the cross-section from approximately 800 – 350 kg/m^3. The mean density of each non-ripped lamella is determined from mass and volume.

The 20 mm thick board of each pair is density measured over the board width using X-ray. Therefore, 5 cm long specimens are cut from both ends of the boards. The specimens are planed, rectangular cut and conditioned at a standard climate of 20 °C/65% rh [16]. The X-ray measurements are performed using DENSE-LAB X from Electronic Wood Systems (EWS), Hameln. Measurements are taken at every 0.1 mm of the specimen. Based on the measured density profile from the end with the lower density (according to Koelli [3], it is assumed that this is the upper end), the cutting positions of each board are calculated from the smoothed density profile with a specially developed software. The minimum strip width is 10 mm. The boards are ripped lengthwise from the upper end to strips with individual width (Figure 1, right). The grade assigned to each strip is verified by determining the mean density of each strip from mass and volume. Due to the longitudinal density distribution, the density is higher at

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the lower end of the board. This leads to a deviation between the calculated X-ray density class and the measured mean density of the strip. The strips are grouped according to their grade and randomly (within the grading class) edge-glued into boards. Two to six strips are required to achieve a board width of 175 mm. A fibre-reinforced, one-component polyurethane adhesive (Jowapur® 686.60) is used for the edge-gluing. After curing and conditioning, the edge-glued timber boards are calibrated to the final thickness of 17 mm. Three ripped lamellas are cut in width (55 mm) and length (2200 mm) from each edge-glued board. After lamella preparation, the average density is determined from mass and volume. Ultimately, the ripped lamellas show a more uniform density over their width compared to the non-ripped lamellas.

2.4 PRODUCTION OF GLT FOR BENDING AND COMPRESSION TESTS PARALLEL

Six strength-graded lamellas are arranged within the combined GLT beam according to Figure 2. Due to the low number of ripped and non-ripped lamellas of grading class <290 kg/m³, additional non-ripped lamellas are produced from the low density boards from the center of the same trunk sections. The boards are processed in accordance with the manufacturing steps of the non-ripped lamellas described in Sect. 2.3.

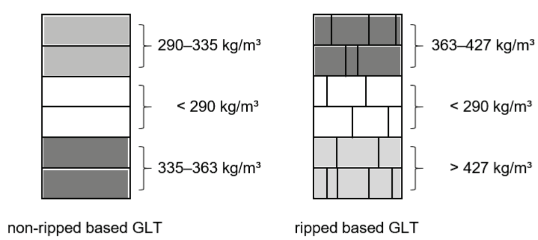

Figure 2: *Examples for lamella arrangement in the 6-lamella GLT test specimens for bending and compression test parallel produced from non-ripped (left) and ripped (right) lamellas, dimensions cf. table 1*

The same resin is used for gluing the GLT as for the edge-gluing (Jowapur® 686.60). The mean adhesive application rate is approx. 350 g/m². Pressing the GLT is done with a specific pressure of 0.75 MPa for a minimum of 240 min on a modified press, TimberPress X 300, commonly used to produce CLT at MINDA Industrieanlagen in Minden, Germany. After storing the beams in a standard climate [16], they are calibrated to the final width of 50 mm and stored again in the standard climate until testing. In summary, 20 beams with different beam setups and from different lamella strength classes are produced, which are used for the bending tests (cf. Sect. 3.2). After the bending test, two specimen sizes are cut from ends of the bending specimens for the compression tests parallel to the vascular bundles. Large specimens are taken over the entire cross-section of the GLT beams with a dimension of 100 x 50 x 300 mm³ (height x width x length) according to EN 408+A1 [17] (= 6 lamellas). Small specimens are taken from the compression and tension zones with a dimension of 34 x 50 x 205 mm³ (= 2 lamellas) (table 1).

2.5 PRODUCTION OF GLT FOR COMPRESSION TESTS PERPENDICULAR

For the compression tests perpendicular to the vascular bundles, test specimens with dimensions of 250 x 204 x 100 mm³ (length x height x width) according to EN 408+A1 [17] are produced out of twelve lamellas each. The arrangement of the lamellas over the cross-section of the specimens is comparable to that of the test specimens for the bending and compression test parallel to the vascular bundles. Figure 3 shows the arrangement of six lamellas as taken for the GLT beams, which are arranged mirror inverted. The two outer lamellas (top and bottom) have the highest densities, the four core lamellas medium density and the two intermediate lamellas are of low density. For the high and medium density lamellas, the 17 mm material described in Sect. 2.1 and 2.3 is used. The low density lamellas are produced from oil palm wood scantlings with dimensions of approximately 1300 x 75 x 45 mm³ (length x width x height), treated with about 2 % of boron by using the vacuum-pressure method. The scantlings are imported to Germany in dry state and visually graded. Due to the width of the scantlings (75 mm), two scantlings are edge-glued together after planning and trimming. For gluing one-component PUR adhesive (Jowapur® 686.60) is used.

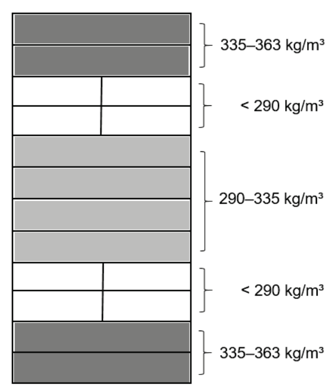

Figure 3: *Compression test specimen perpendicular to the vascular bundles, dimensions cf. table 1*

2.6 OVERVIEW TEST SPECIMENS

Before testing all specimens are stored in a climate chamber at a climate of 20 °C and 65 % relative humidity according to DIN 50014 [16]. An overview on all test specimens is given in Table 1.

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Table 1: *Number and dimensions of test specimens, 2l = 2 lamellas, 6 l = 6 lamellas*

test	# specimens	dimension (length x height x width) [mm³]
f_m E_m	20	2,200 x 102 x 50
$f_{c,0,2l}$ $E_{c,0,2l}$	150 48	205 x 50 x 34
$f_{c,0,6l}$ $E_{c,0,6l}$	41	300 x 102 x 50
$f_{c,90}$ $E_{c,90}$	15 22	250 x 204 x 100
$f_{t,0}$ $E_{t,0}$	88	610 x 17 x 50

3 METHODS

3.1 DETERMINATION OF DENSITY

Contrary to EN 408+A1 [17], for all test specimens the density is not determined on a section from the immediate vicinity of the fracture after destructive testing, but as an average from the mass and volume of the entire specimen before testing.

3.2 BENDING TEST

Modulus of rupture (MOR) and local and global modulus of elasticity (MOE) are determined in a four-point bending test according to EN 408+A1 [17]. A 20 kN testing machine is used for the C10 and a 100 kN testing machine for the C14 beams. For measuring the local and global MOE of the C10 beams, three inductive displacement transducers are used (two of type WA50 and one of type WA100; Hottinger Baldwin Messtechnik (HBM), Germany). Plywood and oil palm wood supports of various dimensions are used to protect against support roller imprints when testing the C10 beams, plywood supports are used for the C14 beams (length of all supports three times the specimen width). Specimen geometry and test setup are corrected with k_h and k_l according to EN 384 [18] and the calculation of the characteristic values is done according to EN 14358 [19] (parametric approach for calculation of characteristic density (ρ_k) and strength ($f_{m,k}$) values). Instead of the reduction factor k_s (n), which depends on the number of specimens, the value of the 5 % quantile for a standard normal distribution (p0.05=1.645) is used in all calculations of the characteristic values in addition to the calculation according to the normalized reduction value for k_s (n). Details on the bending test and the calculation of the results are described in Heister and Fruehwald-Koenig [11].

3.3 COMPRESSION TEST

The compression tests parallel and perpendicular to the vascular bundles are carried out according to EN 408+A1 [17] using a 200 kN universal testing machine (FORM+TEST Seidner&Co. GmbH). In deviation to EN 408+A1 [17], the force used to calculate the compression strength perpendicular ($f_{c,90}$) is determined at 1 % plastic strain of the specimen height and the strain measurement for the Young's modulus is carried out by means of digital image correlation (DIC) with a camera system (type GOM Aramis 5M, Carl Zeiss GOM Metrology GmbH). The strain measurements are evaluated with GOM Correlate 2019 (Carl Zeiss GOM Metrology GmbH). Details on the compression test and the DIC strain measurement are described in Fruehwald-Koenig and Heister [12].

3.4 TENSION TEST

The tension test on glulam lamellas parallel to the vascular bundles is carried out according to EN 408+A1 [17] on the FORM + TEST universal testing machine with a clamping length of 80 mm (resulting in a free test length of 9 x width = 450 mm). The elongation is measured with a long-travel extensometer up to approximately 50 % of the tensile strength ($f_{t,0}$) of small, defect-free specimens according to Fruehwald-Koenig and Heister [4]. In deviation to EN 408+A1 [17], the measuring distance of the sensors is 200 mm. To avoid compression failure in the clamping area, the specimens are reinforced with birch plywood on both face sides.

4 RESULTS AND DISCUSSION

4.1 INFLUENCE OF THE DENSITY ON THE PROPERTIES

Figure 4 shows the tensile properties parallel, compressive properties parallel and perpendicular and bending properties of oil palm wood as a function of density for full-size and small, defect-free test specimens. Independent of the specimen size, they show a higher correlation to the density compared to dicotyledons. This is caused by the much larger density range of the oil palm wood and the resulting large range of property values. All strength and stiffness values of the full-size specimens parallel to the vascular bundles increase with the density by power law relationship with similar exponents, except the higher exponent for the bending properties ($f_{m,0}$ and $E_{m,0,global}$), which might be due to the lower number of test specimens in a much lower density range. Properties from compression test perpendicular to the vascular bundles ($f_{c,90}$ and $E_{c,90}$) on full-size test specimen are constant, which might be due to the low number of test specimen and the very low density range. The exponents correspond to the results for oil palm wood on small test specimens according to Fruehwald-Koenig and Heister [4], Srivaro et al. [20] and Srivaro et al. [21] and for other palm species according to Rich [22]. But the determined exponents are very different from those of softwood and hardwood species from modelling [23-25] or from experimental results [26-28], which might be due to the different anatomical structures. The concentration of vascular bundles, as well as the concentration of fibers within the bundles, is greater in the periphery of the trunk than in the central tissue [2,29]. Cell wall thickening is more pronounced in the peripheral tissue than in the central tissue and more in the bottom of the trunk than in the top of the trunk [30], because the bending stresses on the arborescent palm are greatest on the bottom at the periphery of the trunk. Furthermore, the cell wall properties themselves are not constant. Cell wall thickening means that as the palm tissue (vascular bundles and parenchymatous ground tissue)

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ages, more cell wall layers are added on the cell wall towards the lumen of the cells resulting in smaller lumina diameters and thicker cell walls with a higher cellulose content [29]. The density in the peripheral zone at the bottom of the trunk rises over time because the trunk volume increase is lower than the mass increase by added volume of additional cell wall layers. But, the density increase due to cell wall thickening is lower than the increase of the elastomechanical properties, which leads to exponents > 1 of the power law relationship.

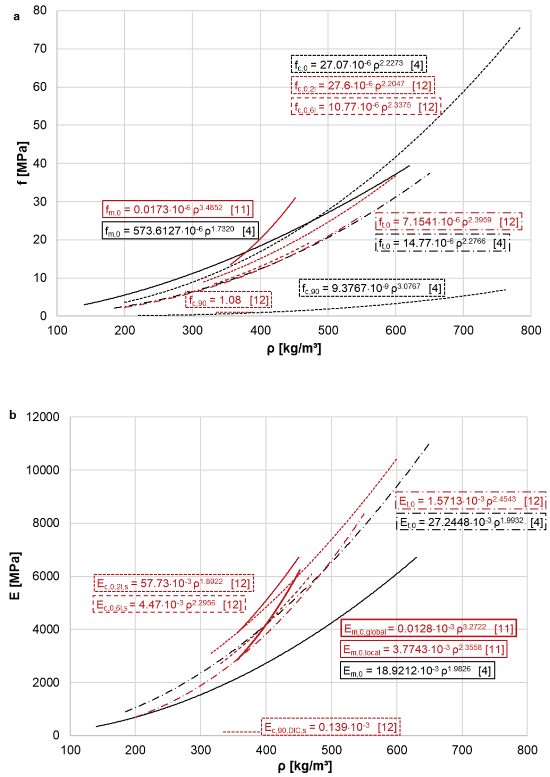

Figure 4: *Elastomechanical properties in relationship to the density (ρ), a strength properties, b stiffness properties (full-size specimens in red, small-size specimens in black)*

4.2 INFLUENCE OF THE TEST SPECIMEN SIZE ON THE PROPERTIES

In contrast to common wood species, the strength of the full-size test specimens is above ($f_{c,90}$), in the same range ($f_{t,0}$, f_m) or only slightly below ($f_{c,0}$) that of small, defect-free test specimens, cf. Figure 4a. Therefore, for oil palm wood specimen size does not influence the strength values.

When testing common wood species a clear distinction must be made between

– "material testing" of small, defect-free specimens that fail on a microscopic level as a result of many small, randomly distributed structural defects in the specimen, and
– "(building) component testing" with macroscopic structural defects due to natural growth characteristics, which mostly fail as a result of these structural defects (especially knots and fiber deviation). For most strength types, the properties of the defect-free wood between the structural defects have no influence on the properties of the building component respectively it´s influence is superimposed by the structural defects.

Both, material and component testing show different failure modes depending on the type and direction of loading and results in significantly different property values.

In contrast to the dicotyledonous common wood species, monocotyledonous palm tissue consists of vascular bundles (having honeycomb-like prismatic cells and dense fibers aligned along the stem) surrounded by parenchymatous ground tissue (made up of thin-walled polyhedral parenchyma like close cell foam-like structure) [31]. From a structural mechanics perspective, if the vascular bundles are considered as reinforcements (fibers) and the ground tissue as the matrix, oil palm wood can be seen as a unidirectional long-fiber-reinforced biocomposite. Therefore, on the microscopic level, palms as monocotyledons have a more heterogeneous structure in comparison to dicotyledons. Since monocotyledons only grow at the top part of the trunk where the apical meristem is located; no radial growth occurs and therefore, palms do not possess radial oriented ray cells or an annual ring structure. The tissue does not contain the typical macroscopic structural defects due to natural growth characteristics (e.g. knots) like dicotyledones. The elastomechanical properties of oil palm wood depend on the anatomical structure at the microscopic level and are therefore not influenced by the specimen size. Main influencing factors on the elastomechanical properties are the density, but also the age of the palm, the location within the trunk (height and cross section) and probably also the oil palm subspecies, differences between individual palms and the plantation sites.

4.3 RELATIONS OF THE PROPERTIES

For the full-size test specimens, the compressive strength parallel to the vascular bundles ($f_{c,0}$) is only approx. 1.2 times the tensile strength parallel (($f_{t,0}$) Figure 4a), whereas it is much higher for low grade softwood (e.g. 2.2 for C14 $f_{c,0,k}/f_{t,0,k}$ according to EN 338 [14]). The ratio of bending and tensile strength parallel to the vascular bundles (Figure 4a) rises with the density from 0.8…1.7…2.6 : 1 within the relevant density range of ρ = 200…400…600 kg/m³ and is in the range of low grade softwood (e.g. 1.9 for C14 $f_{m,k}/f_{t,0,k}$ according to EN 338 [14]). Similarly, the ratio of compression strength parallel and perpendicular to the vascular bundles (Figure 4a) rises with the density from 2.7…13.0…32.6 : 1 for ρ = 200…400…600 kg/m³ and is therefore for most densities above that for low grade softwood (e.g. 8.0 for C14 $f_{c,0,k}/f_{c,90,k}$ according to EN 338 [14]). Figure 4b shows that for oil palm wood $E_{m,0,local} : E_{c,0} : E_{t,0} = 1.3 : 1.2 : 1$ for ρ = 400 kg/m³. This is in contrast to common wood species according to Egner [32], who stated that $E_m < E_{t,0}$. and according to Kretschmann [27], who stated that E_m includes an effect of shear deflection and therefore can be increased by 10 %.

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4.4 PERFORMANCE INDICES FOR MINIMUM WEIGHT DESIGN

Because of the power law relationship between strength respectively stiffness and density, the performance indices for minimum weight design by Ashby et al. [13] calculated for oil palm wood rise with the density and are shown in Table 2. They are comparable to that of small size oil palm, coconut palm and date palm wood test specimens. The strength-density performance index M_4 (strength of a tie under uniaxial load) of oil palm wood is comparable to that of structural size softwood, M_5 (strength of a beam in flexure) and M_6 (strength of a plate in flexure) are only slightly lower than that of structural size softwood. However, the modulus-density performance indices ($M_1 – M_3$) of oil palm wood are much lower than that for structural size softwood. The performance index for elastic design M_8 to allow large, recoverable deformation based on tensile tests is above and that based on compression tests in the range of structural size softwood lamellas.

Table 2: *Performance indices for minimum weight design as proposed by Ashby et al. [13] for ρ = 200…600 kg/m³*

	full-size oil palm wood	softwood lamellas T8…T30 [14]
$M_1 = E/\rho$ (GPa (Mg m^{-3})$^{-1}$)	3.5…17.2[a] 4.3…17.8[b]	20.0…30.6[a]
$M_2 = E^{1/2}/\rho$ (GPa$^{1/2}$ (Mg m^{-3})$^{-1}$)	4.2…5.4[a] 5.7…4.6[b]	7.5…7.9[a]
$M_3 = E^{1/3}/\rho$ (GPa$^{1/3}$ (Mg m^{-3})$^{-1}$)	4.4…3.6[a] 5.5…3.6[b]	5.5…4.8[a]
$M_4 = \sigma_f/\rho$ (MPa (Mg m^{-3})$^{-1}$)	11.7…54.0[a] 12.9…61.3[b]	27.6…69.8[ad] 55.2…70.7[bd]
$M_5 = \sigma_f^{2/3}/\rho$ (MPa$^{2/3}$ (Mg m^{-3})$^{-1}$)	8.8…16.9[a] 9.4…18.4[b]	13.8…22.5[ad] 21.9…23.0[bd]
$M_6 = \sigma_f^{1/2}/\rho$ (MPa$^{1/2}$ (Mg m^{-3})$^{-1}$)	7.6…9.5[a] 8.0…10.1[b]	9.8…12.7[ad] 13.8…13.1[bd]
$M_8 = \sigma_f/E$ [-]	0.0033…0.0031[a] 0.0025…0.0035[b]	0.0017…0.0028[acd] 0.0034…0.0028 [bcd]

[a] based on tensile tests
[b] based on compression tests
[c] E based on bending tests
[d] calculation based on the 5th quantile

4.5 INFLUENCE OF RIPPED LAMELLAS ON BENDING PROPERTIES

Figure 5 shows the positive trend between density (ρ) and bending strength ($f_{m,0,rf}$) after taking the reduction factors k_h and k_l into account. The bending strength of the ripped beams ($f_{m,0,rf,r}$) is higher than that of the non-ripped beams at the same density and ranges between 22…27 MPa for the ripped C14 and 17…24.5 MPa for the ripped C10 beams. At a density of 400 kg/m³, the ripped C10 and C14 beams show almost the same bending strength of 22.5…24 MPa. The characteristic bending strength ($f_{m,k}^{0.05}$) of the ripped C14 beams is 21 MPa and comparable to that of the ripped C10 beams with 20 MPa (Table 3). The difference between the characteristic bending strength of the non-ripped C10 (11 MPa) and C14 (16 MPa) beams is higher. The characteristic values $f_{m,k}^{k(s)}$ according to EN 14358 [19] are 2…3 MPa lower than the $f_{m,k}^{0.05}$ values. The coefficient of variation ranges between 9…13 % for the C14 and 7…8 % for the C10 beams. The oil palm wood GLT C10 and C14 achieves the target MOR ($f_{m,k}$) according to EN 338 [14]. Applying the reduction factor for coniferous wood according to EN 14358 [19], the target $f_{m,k}$ is not fulfilled by the non-ripped C10 beams. Therefore, the calculated density limits for achieving a target characteristic strength and the calculation method are reasonable.

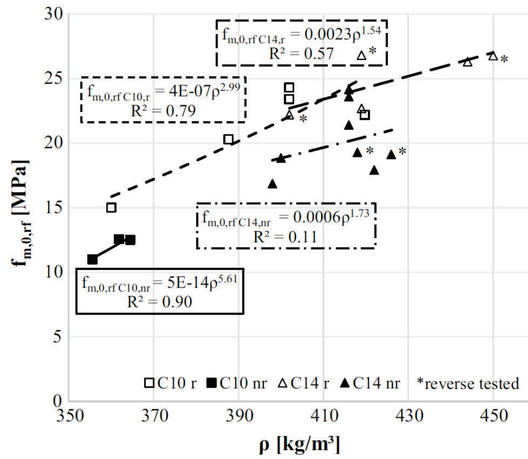

Figure 5: *Relationship between bending strength ($f_{m,0,rf}$) after considering the reduction factors k_h and k_l [18] and the GLT density*

Table 3: *Bending strength properties of GLT beams class C10 and C14*

	C10		C14	
	non-ripped	ripped	non-ripped	ripped
n (-)	3	4	8	5
$f_{m,\bar{x}}$ (MPa)	12	23	20	25
cv (%)	7	8	13	9
$f_{m,k}^{0.05}$ (MPa)	11	20	16	21
$f_{m,k}^{k(s)}$ (MPa)	9	17	14	19
$E_{m,0,l,\bar{x}}$ (GPa)	4.27	5.21	5.64	5.80
cv (%)	14	14	14	19
$E_{m,0,mean,l}^{0.05}$ (GPa)	3.28	4.00	4.32	3.99
$E_{m,0,mean,l}^{k(s)}$ (GPa)	3.99	4.86	5.37	5.44

$f_{m,k}^{0.05}$ = reduction factor k(s) = p(0.05) = 1.645
$f_{m,k}^{k(s)}$ = reduction factor k(s) according to EN 14358 [19]
$E_{m,0,mean,l}^{0.05}$ = reduction factor k(s) = p(0.05) = 1.645
$E_{m,0,mean,l}^{k(s)}$ = reduction factor k(s) according to EN 14358 [19]

Figure 6 shows the local MOE ($E_{m,0,l}$) for the different beam setups and strength classes. The range of the local MOE ($E_{m,0,l}$) of C14, especially the ripped beams, is the highest for all setups and strength classes. The lower values of the C14 are similar to the higher values of C10. The statistical values for the local MOE are shown in Table 3. The ripped beams show a higher mean local MOE ($E_{m,0,l,\bar{x}}$) than the non-ripped beams and the C14 are higher than the C10. $E_{m,0,mean,l}^{0.05}$ of the non-ripped C14 beams is higher (4.32 GPa) than that of the ripped C14 beams (3.99 GPa) (due to one very low MOE value in the C14r group, cf. Figure 5). In contrast, $E_{m,0,mean,l}^{0.05}$ of the ripped C10 beams is higher (4.00 GPa) than that of the non-ripped

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C10 beams (3.28 GPa). $E_{m,0,mean,l}^{0.05}$ for ripped beams of both strength classes is almost similar (3.99 GPa for C14 and 4.00 GPa for C10). The target MOE for C14 according to EN 338 [14] ($E_{m,0,mean}$ = 7 GPa) is far from achieved. In contrast, the target density (ρ_k = 290 kg/m^3) of C14 according to EN 338 [14] is achieved by all oil palm wood beams.

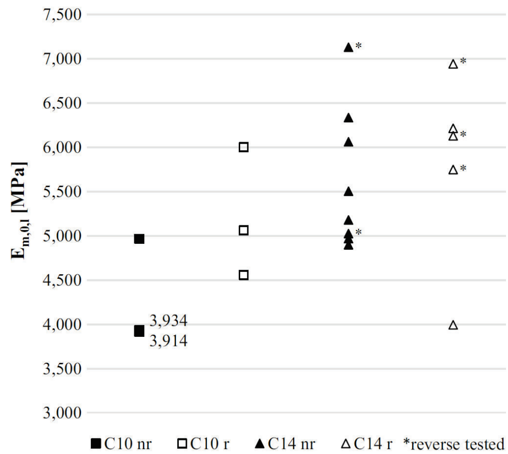

Figure 6: *Local MOE ($E_{m,0,l}$) of the different beam setups and strength classes*

4.6 LOCAL VS. GLOBAL MOE

Figure 7 shows the relationship between the local MOE ($E_{m,0,l}$) and global MOE ($E_{m,0,g}$) for oil palm wood beams with different setups and strength classes and the linear relationship for coniferous wood species according to EN 384 [18]. For all specimens, the local MOE ($E_{m,0,l}$) is above the global MOE ($E_{m,0,g}$). All oil palm wood beams tested showed a positive linear correlation between the global and local MOE, but the linear relationship for softwoods according to EN 384 [18] does not apply to oil palm wood.

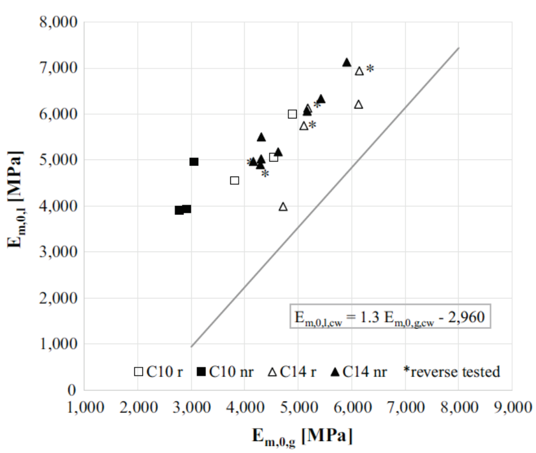

Figure 7: *Relationship between global MOE ($E_{m,0,g}$) and local MOE ($E_{m,0,l}$) for oil palm wood GLT and the linear relationship for coniferous wood species according to EN 384 [18]*

5 CONCLUSIONS

Oil palm wood availability provides good opportunities for supplementing respectively substituting common tropical timber species especially in Asia and timber from pine plantations. Due to its elastomechanical properties, medium and high-density oil palm wood can be used for load bearing products like GLT, but the elastomechanical properties are slightly lower compared to common wood species. The challenge with regard to load-bearing construction products such as GLT and CLT from oil palm wood lies in the comparatively low stiffness of oil palm wood compared to common wood species. The high variation of oil palm wood´s properties compared to common wood species requires grading the oil palm wood, e.g., according to density, because most design values are based on 5th percentiles and high variations result in low product performance. The strength grading according to density and the defined density limits used in this study appear to be reasonable in principle, the targeted strength classes of EN 338 [14] are achieved. Designing beams with lamella positions according to their density has a significant influence on the properties. Ripping boards according to their density into stripes and edge-gluing the stripes to density homogeneous lamellas results in higher MOR and MOE values (no difference is shown for compression properties parallel to the vascular bundles).

As the oil palm wood (similar to other palms) differs in its structure and properties compared to common wood species, special product development (including material respectively product modelling) and process development is necessary to achieve market competitiveness. Hackel [33] modelled the bending properties described in this paper using the finite element method (FEM). For load bearing products, grading and trimming of the lumber, long term durability under load (and wet climate) and design values as well as standardization (matching with building codes) are significant challenges. Standards for common wood species do not automatically fit for oil palm wood. For example, the effect of test specimen size, especially the difference between small-size and construction-size test specimens, is much smaller compared to common wood species; for some properties, the full-size test specimens show higher values than small-size test specimens at the same density (which is likely caused by the complex macroscopic structure of the oil palm wood). The equation between local and global MOE for solid construction timber from softwoods according to EN 384 [18] does not apply for oil palm wood GLT. The relationship between the characteristic values for strength and density of coniferous timber according to EN 338 [14] fits for GLT from oil palm, but not the relationship between the mean MOE and density. The MOE is – in relation to strength and density – much lower for oil palm wood. The correlations between lamella and GLT quality (“GLT model”) and the various properties among themselves, which are well-known for common wood species, do not apply to oil palm wood. Therefore, the building codes need to be adapted for oil palm wood.

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