Feasibility of glued laminated timber beams with tropical hardwoods

Damien Bourreau, Yamina Aimene, Jacques Beauchêne, Bernard Thibaut

Feasibility of glued laminated timber beams with tropical hardwoods

D. Bourreau[1]✉, Y. Aimene[1], J. Beauchêne[1], B. Thibaut[2]

(1) UAG-UMR Ecofog, Pôle Universitaire Guyanais, 97337 Cayenne Cedex, FRENCH GUIANA.

(2) CNRS-LMGC, Université de Montpellier2, 34095 Montpellier, FRANCE

✉ **Damien BOURREAU**

Phone: +33 (0)6 33 37 16 95

Email:dbourreau@nancy.inra.fr

Abstract:

A feasibility study of glulam was carried out in French Guiana using local wood species. The aim was to determine gluing parameters affording satisfactory behaviour to manufactured glulam in a tropical climate.

Three abundant wood species, with special properties, were selected for the study and Resorcinol-Phenol-Formaldehyde resin was used for bonding. Three industrial parameters were considered: adhesive spread rate, closed assembly time and gluing pressure. Delamination and shearing tests were carried outin accordance with European Standards.

The tests revealed the influence of wood properties and manufacturing parameters on joint resistance. In fact, the results showed that specific gravity and the shrinkage coefficientgreatly influenced the gluing step. Indeed, wood with a medium specific gravity needed more adhesive and more pressure than wood with a high specific gravity. In addition, planning and lamella thicknesswere found to affect glue joint resistance.

Keywords*: tropical hardwoods, glulam, delamination, shear strength*

1 Introduction

Nowadays, glued laminated timber is acknowledgedto be a high-performance composite material used in construction. Indeed, this wood product enjoys high mechanical properties, compared to solid wood (Guitard 1994). It is also an economical and ecological material, comparing to concrete or steel, using a renewable resource provided by a sustainable forest management. Despite increasing glulam imports into French Guiana, these wood products need to meet some specific requirements for use in a tropical climate. However, some local wood species from the Amazon forest could be used for glulam manufacturing, avoiding risks of degradation due to the abundance of fungi and termites.
The assembling of wood products by gluing depends on many interlinked factors to achieve a single glued assembly. While glulam manufacturing in temperate countries has been mastered, the adhesive bonding of wood components in a tropical climate raises numerous problems. One of the main problems is high temperatures and humidity, which weaken the adhesive and its adhesion (EN 301 2006). Consequently, the gluing process is a critical step that can greatly affect adhesion and the mechanical properties of glulam beams manufactured in French Guiana. This step can be defined by various industrial parameters: glue basis weight which is related to the glue spread rate, assembly time which indicates glue polymerization status and the pressure applied to hold lamellae together (Elbez and Bentz 1991). Moreover, tropical hardwood properties, such as a high specific gravity, high shrinkage coefficient, or the presence of resins, are another major bonding problem (Gérard 1999). In order to avoid these problems, the right match has to be established between the gluing parameters, appropriate wood properties and moisture content under tropical conditions (Guiscafre and Sales 1980 intern report). Based on the glulam manufacturing of African hardwoods, past studies (Bedel and Gautier 1972; Guiscafre and Sales 1975, 1980 intern report; Gérard 1999) have shown that closed assembly times need to be shorter than those recommended by the adhesive manufacturer, due to high temperatures in the tropics, which increase resin curing (Bedel and Gautier 1972). A high pressure is not beneficial when gluing wood with a high specific gravity (Guiscafre and Sales 1975, 1980 intern report). Furthermore, careful surface preparation of the lamellae before gluing and a uniform glue joint thickness are required to manufacture a timber beam. Moreover, it appears that a sanded surface does not increase delamination results (Guiscafre and Sales 1980 intern report; Gérard 1999). Lastly, working on hardwoods, Hwang et al. (1993) showed that bonding-strength (evaluated by shearing tests) increases with an increase in the specific gravity of the wood, whereas retention of Resorcinol Phenol Formaldehyde (RPF) adhesive in the wood decreases (Hwang et al. 1993).

As there is no standard on the use of hardwood glulam for structural purposes, this innovative structural wood gluing assembly has to be validated by two standardized tests designed for softwood species. The delamination test assesses the resistance of the assembly to shearing and tension perpendicular to the grain induced by cyclical variations in wood moisture content. It is defined as an ageing test. The block shear test characterizes mechanical resistance of the joint to shearing.

In this study, the bondability of hardwoods for glued laminated timber beams was assessed in French Guiana using local wood species. The aim was to establish gluing parameters affording good mechanical properties to glued laminated beams manufactured in a tropical climate.

2 Materials and methods

The study of the feasibility of glulam with new wood species needs to choose the adequate wood species and adhesive producing the best association wood-adhesive-preservation. The present study focused mostly on the analysis of the combination specie-adhesive. To avoid risks of degradation due to the virulence of fungi and termites, species with natural durability were considered and recommendations in use were provided to enhance the preservation (Bourreau 2011).

2.1 Wood and adhesive properties

In French Guiana there are almost 1,500 species listed, but wood properties and industrial constraints impose a strict choice of species for glulam manufacture. The most important physical wood properties are specific gravity, wood shrinkage, anisotropy and satisfactory natural durability. The chosen species were logged according to a sustainable forest management provided by the French Forestry Organisation (ONF) pending PEFC and FSC certifications for French-Guiana area.
Three abundant wood species were selected: *Qualea rosea*, *Dicorynia guianensis* and *Peltogyne venosa*. *P. venosa* and *D. guianensis* have both sufficient natural durability when not used in ground contact, whereas the *Q. rosea* needs a soak treatment when used in exterior condition. However, working on the gluing of treated hardwoods, Janowiack et al (1992) and Paes et al (2009) show good bonding results between RPF adhesive and CCA treatment. In this study, a softwood specie, *Larix decidua*, commonly used in temperate countries was considered as a reference species (CIRAD 2008).
Some wood properties can be found in technical documents for Guianese wood species (CTFT 1999, EN 335-2 2006) and they are summed up in table 1.

A wide variety of adhesives is available on the market, but depending on end-uses, requirements are different and are regulated by European standards. Thus, given the structural purposes under tropical conditions, the choice of adhesives is limited to two types, a Melamine-Urea-Formaldehyde (MUF) and a Resorcinol Phenol Formaldehyde (RPF) (EN 301 2006). However, bonding tests on the selected tropical species (Bourreau 2011) showed that the MUF is sensitive to the surrounding environmental conditions of high temperatures and high humidity and is not recommended to be used in a manufacturing process under tropical conditions. This observation was also reported by Custodio et al.(2008).

2.2 Bonding durability tests

To assess bonding efficiency, delamination and block shear tests were used in this study in accordance with European standards EN 391: 2002 and EN 392: 1995 respectively.

2.2.1 Delamination

The delamination test is used to assess the resistance of the glue joint after ageing cycles including strong variations in wood moisture content. As wood dimensions vary during use depending on changes in ambient humidity, delamination assesses the resistance of the glued assembly under those variations. Depending on the service classes for which the end-product is to be used, different delamination test procedures exist relative to the risk levels assessed for the wood product (EN 391 2002). Thus, for glulams used in service class 3, outdoor conditions, delamination tests were carried out according to procedure A, described in EN 391: 2002 standard. This involved three cycles of water immersion with a pressure of 6 bars, then drying between 60 and 70 degrees Celsius until the specimen reached its initial weight (around 22 hours).

Measurements were taken along the glue lines on each cross-section of the specimen. The total delamination of a specimen (D_s) was calculated, which expresses the proportion of the delamination length of all glue lines (l_{DS}) compared to the total length of all the glue lines of a specimen (l_s), as illustrated in the next equation.

$$D_s(\%) = \frac{l_{DS}}{l_s} \times 100$$

Delamination was measured to an accuracy of 0.1 mm. This value was compared to the upper limit allowed by the European standards, i.e. 10% for tropical hardwoods.

2.2.2 Block shear strength and wood failure.

The block shear test is used to assess the shear mechanical resistance parallel to the grain of the glued assembly (EN 392 1995). Indeed during glulam beams loading, the shear is a major failure mode of the interfaces of the lamellae. At the end of the shearing test, the adherence of the glue joint is also assessed on the faces of the sheared samples in order to determine the weakened part of the composite, either the adhesive or the wood.

Shear tests were carried out on specimens with square areas in accordance with EN 392: 1995. Shear-strength testing was conducted using an MTS machine with a constant crosshead displacement rate. During the tests, most failures occurred within 20secondes. The wood failure percentage was estimated to the nearest 5 % of explored shear area. The requirement, according to EN 386: 2002 is a combination between maximum shear strength (f_v) and wood failure percentage (WFP), which is the percentage of wood on the sheared surface. Requirements for individual and average values are given in table 2. However, past studies on the bondability of African hardwoods considered that block shear testing is successful when glue line shear-strength reaches at least 80% of solid wood shear resistance (Guiscafre and Sales 1975).

2.3 Experimental data plan

In order to evaluate the effect of bonding conditions on glued assembly durability for glulam manufacturing under the climatic conditions in French Guiana (average temperature: 30°C, relative humidity: 85%), three industrial parameters were considered: spread rate (g/m²), Closed Assembly Time (CAT in min), defined as the time from assembly until the application of pressure, and clamping pressure (MPa).

2.3.1 Experimental procedure

In this study, 92 glulam beams composed from three wooden slats were manufactured and tested. Depending on the lamellae thickness (*e*), the size of the beams was 3*e*x100x700 mm³. Beams were manufactured from boards, air-dried in the local atmosphere until they had reached a balanced moisture content MC. The balanced MC observed on the guianensis species was 14, 16 and 17% (± 2%) for *P. venosa*, *D. guianensis* and *Q. rosea* respectively. This difference could be explained by an experimental fluctuation induced by the season when the test, and so the MC measures, were done. Because boards were air-stabilized, moisture content recorded during the dry season will be lower than the MC recorded at the wet season.

The clamping pressure was applied by a traditional screw press. The pressure was controlled by a torque wrench. After at least 8 hours' pressurization to ensure almost full bonding strength, all the glulam beams were conditioned in the ambient climate for at least 2 weeks before any handling. Afterwards, beams are planned and full cross-sectional slats were cut from each beam, alternating one specimen for the delamination test and one for the shear test. A total of 5 samples of dimension 3ex90x75mm^3 for the delamination test and 4 samples of dimension 3ex45x45 mm^3 for the shear tests were produced per beam to ensure good

representativeness of bonding. No loading (bending, etc.) has been applied on the beams before delamination or shear tests.
Before testing, the joint thickness of each beam was measured under an electronic microscope on samples reserved for the shear test, in order to determine the actual amount of glue present at the bonding interface. In fact, the actual glue spread rate depends on the squeeze-out of adhesive during the pressing steps, table 3 and the part of the adhesive absorbed by lamellae(Bourreau2011). According to the standards, the samples used for shear tests are stabilized around a moisture content (MC) of 12% and cut in standard dimensions just before performing the tests. This avoids sample shrinkage.

2.3.2 Bonding tests

To conduct this study, 3 sets of experiments were carried out. They are summarized in table 3. The 1stset examined the influence of surface preparation before bonding. The 2nd set, the main one in this study, focused on the effect of the industrial parameters described previously on the bonding of each wood species studied (*Q. rosea, P. venosa, D. guianensis* and *L. decidua*). In this set of tests, the glue was spread on both sides of the boards. The values of the tested gluing parameters used in the first two sets were selected on the basis of the adhesive manufacturer recommendations, that advised to glue with 750g/m² per face with a clamping pressure of the 1 MPa and a CAT of 20 minutes at 30°C. Finally, a set of validation tests was carried out on the species with good delamination results established in the 2ndset of tests. In addition, the effect of lamella thickness on delamination was investigated, in order to improve bonding.

3 Results and discussion

In this part, the results of the delamination and the block shear tests are presented. They are followed by a discussion that explains the influence of the considered parameters (Glue spread rate, CAT and Pressure) on the bonding of the glulam.

3.1 Delamination results

3.1.1 Planning influence

Firstly, the influence of surface preparation was examined by means of the 1st set of delamination tests. Table 4 shows the delamination results for 3 gluing conditions obtained on specimens planned more than a day before gluing and glued a maximum of 8h after planning.

This table shows that the delamination factor was greatly affected by surface preparation. The results show that a surface glued more than 24hours after planning interfered with the adhesion of the resin. It appears that the wood surface needed to be refreshed just before the gluing step to avoid contamination of the surface by wood chemicals, which are very present in hardwoods and migrate to the surface (Nussbaum and Sterley 2002). This step therefore prepares the wood support, to give good anchorage of the adhesive to its surface and also enhances the physical and chemical links between its surface and the glue (Nussbaum and Sterley 2002; Gindl et al. 2004). In temperate countries, when gluing softwood species, it is recommended to spread the adhesive within a day (Nussbaum and Sterley 2002). In our case it seemed that gluing within 8 hours after planning was very beneficial.

3.1.2 Glue spread rate influence

The effect of the glue spread rate on delamination was examined in the 2nd set of tests. The results are given in figure 1 for the three wood species used. In this figure, one point represents the average delamination recorded on the 5 samples obtained from the same beam.

On this graph, the first observation is that the amount of adhesive measured on the glue joint of the samples was much lower than the quantity applied. Despite some good results for samples with a thin glue joint, delamination results greatly varied and were well over the 10% limit allowed by the European standard. Moreover, the reference softwood species, *L. Decidua*, gave very good results. In fact, when glued under the same conditions, the samples of the reference species had a significantly greater glue joint thickness and therefore resisted cracking and joint opening during the severe moisture variations.

We also found that higher delamination results (D_s = 80%) were achieved with wood species displaying higher swelling coefficients (*Q.rosea*: R_B= 14.44%), whereas the wood displaying lower swelling coefficients (*P. venosa*) showed less delamination (D_s = 40%) and low variability in the results. Indeed, the higher the swelling coefficient of the bonded wood, the higher was the delamination risk, due to greater tensile and shearing stresses at the gluing interface, induced by the moisture variations.

Lastly, figure 1 illustrates that, for *P. venosa* and *D. guianensis*, the specimens with a glue spread rate over 180 g/m²at the joint interface had delamination results under the standard limit of 10%.

In order to analyse the effect of the glue spread rate on delamination resistance for the three species, a generalized additive model (GAM) was used (figure 2).

Figure 2 shows the general trends of dependence of the bonding of the three species on the glue spread-rate. The black line represents the mean effect of glue spread rate on delamination and the dotted lines represent its 95% confidence interval. When these three lines become positive or negative, it means that the influence of glue spread rate parameter is meaningful. Thus, Figure 2 shows no significant dependence for *Q. rosea* (a) within the range of 80g/m² - 135 g/m². In fact, the recorded quantity of glue on the bonding interface was very small, and cannot identify any dependence. For *P. venosa* (b) and *D. guianensis* (c), the plot shows a high dependence and give a general trend. It appeared that the larger the amount of adhesive was on the bond, the lower was the delamination factor. Lastly, this analysis identified the lower limit needed to obtain acceptable delamination results for structural bonding. The amounts were respectively 175g/m2 and 220g/m2 for *P. venosa* and *D.guianensis* determined graphically when the mean effect and its confidence interval become negative on the figure.

3.1.3 CAT and Pressure influences

In order to analyse the effect of the other gluing parameters on delamination resistance, statistical analyses of variance (ANOVA) were performed using the CAT and the pressure level P as variables and the interaction between them (table 5).And figure 3 presents graphically the influence of pressure (1) and CAT (2) on delamination results of the three Guianese wood species. Black lines on this figure represent the maximal delamination according to the standard.

Table 5 shows the effect of gluing parameters on the delamination resistance of the three Guianese wood species used. The results showed that the CAT greatly affected *D. guianensis* but not *Q. rosea* and *P. venosa.* On figure 3 (a2 and c2),it appeared that best results were obtained when the CAT was shortest (5 minutes), and maximum delamination occurred when the CAT was 10 minutes long. Likewise, the pressure level was only significant for *P. venosa*. Indeed, the results showed that a low pressure level was needed to prevent delamination (figure 3b1). For *Q.rosea,* table 5 reveals a significant effect of the coupling agent P and CAT. For this species, it appeared that the higher the applied pressure level was, the longer the CAT needed to be in order to obtain sufficient bonding.

3.2 Block shear results

As well as the delamination tests, the 27 gluing conditions given for the 2nd set of tests (table 3) were also tested, in accordance with the European standard, to assess glue joint shear resistance. Figure 4 gives the block shear results for the 2nd set of tests, as a function of the maximum shear resistance, f_v, and the wood failure percentage (WFP) of the assembly. Figure 4a shows all individual values and Figure 4b the mean values of the 54 beams tested per species. On each graph, black line represents the WFP minimum value to reach according to EN386: 2002. Dotted lines represent the requirements proposals made by Aicher and Ohnesorge(2011) when tested beech glulam.
The block shear test gave an average strength $f_{v, mean}$ per species of around 13.5, 14.7 and 13.5MPa for *Q. rosea, P. venosa* and *D. guianensis* respectively.
Despite some minor differences between wood species, the block shear strength of the individual specimens ranged between 4.3 and 21.7 MPa and the wood failure percentage from 15 to 100%. It appeared that 4% of all the specimens tested displayed low shear strength (from 4 to 6 MPa), 11% had medium shear strength (from 6 to 11 MPa) and 85% showed high shear resistance (over 11 MPa). This

last resistance class presents results close to the shear strength recorded for solid wood samples($f_{v,\text{-mean-solid}}$ = 13.3, 15.0 and 13.8MPa for *Q. rosea*, *P. venosa* and *D. guianensis* respectively). Indeed, the shear resistance ratios between glulam, at its glue joint, and solid wood, recorded on each specimen, were from 80% to 125%. Moreover, each specimen with a low shear strength f_v presented a major lack of adherence, characterized by low wood failure percentages. Thus, 16 specimens and 1 beam failed the block shear test. It is important to note that the beams which failed the shearing test also failed the delamination test, whereas the beams that failed the delamination test could pass the block shear one. In accordance with Aicher and Ohnesorge (2011), requirements made on the block shear test standard (EN 386: 2002) is set too low when using hardwoods. And requirements proposed by these authors (dotted lines) are rather rigorous and permit to identify more beams which failed the delamination test (30 specimens and 8 beams here).

Lastly, these results on tropical hardwoods did not show any specific gravity effects on bond shear strength, as reported by Hwang et al. (1993).

3.3 General Discussion

The above delamination and shearing results showed that gluing parameters were interdependent and needed to be matched to each wood species. Indeed, dense wood was greatly affected by the pressure level (case of *P. venosa*). On the other hand, the relation between CAT and pressure had a major effect on glue joint resistance for a softer wood (*Q. rosea*). Obviously, the amount of glue spread on the surface needs to be sufficient to ensure good adhesion and to be resistant to lamella swelling and shrinkage during delamination tests, especially in the case of wood with a high shrinkage coefficient. High pressure can squeeze out the adhesive from the interface or lead to excessive penetration into the substrate, especially when the glue has not already hardened. In the case of *D. guianensis*, the CAT greatly influenced the delamination resistance of the bonds, especially due to the tropical climatic conditions observed during the gluing step despite the good wettability of this species (Bourreau 2011). When the assembly time was very long, the ambient temperature increased resin cure, preventing its penetration into vessel and cell walls, leading to weak joint anchorage.

As regards block shear resistance, the results arising from this study showed that 86% of the samples passed the block shear test, despite the unsatisfactory delamination results on the samples with the same gluing conditions. This tallies with the results reported by Aicher and Ohnesorge (2011) on beech glulam, highlighting that the standard shear test requirements are set too low to validate a structural glued assembly made from hardwoods. It appears that the block shear test identifies glue joints displaying a major lack of adherence and can easily assess if the strength of the glued assembly is similar to that of solid wood.

Lastly, these two standard tests complement each other, but the delamination test is the strictest, involving joint opening by both tension and shearing perpendicular to the grain due to rapid and severe humidity variations.

3.4 Validation of gluing parameters

The above results seemed to qualify *D. guianensis* for glulam manufacturing in French Guiana, other species need more investigations. Consequently, the 3rd set of tests was carried out on this species with the gluing parameters fixed in table 3. For industrial purposes, the time to assemble beams before applying pressure needed to be longer than 20 minutes, so the CAT was extended to 40 minutes. In this set of tests, glue was spread on one face. The delamination results for these tests were in accordance with the European standard, with an average delamination of 5.9%. However, 12% of the samples recorded delamination over 10% (a maximum of 12.7%).

The results for the block shear test are given in table 6. Based on the European standards, all the samples successfully passed the block shear test and the strength ratio between glulam joints and the solid wood exceeded 80%.

In order to improve the resistance of the samples to delamination, the effect of lamella thickness on delamination risks was investigated in this set of tests, making it possible to determine an adequate thickness that reconciles the cost of glulam production with the resistance of the bond to severe moisture variations. Figure 4 shows delamination results for each lamella thickness group considered in table 3.
The results show that the thinner the bonded lamella thickness was, the better was the glulam resistance to delamination. It appeared that at around 28 mm, average delamination was below the limit set by the European standard. However, the thinner the lamella thickness was, the higher was the cost of glulam production. This was mostly due to more adhesive use and also to greater wood wastage during manufacturing. Consequently, a thickness of 28 mm appears to be the optimum lamella thickness for manufacturing *D.guianensis* glued laminated timber in French Guiana (Bourreau 2011).

The effect of lamella thickness is in keeping with the results reported by Ohnesorge et al. (2010) who analysed beech wood beams with lamella thicknesses of 29, 35 and 38 mm. The high delamination rates observed may have been related to the increase in wood swelling under moisture variation. This was also observed when using a wood species with a high shrinkage coefficient (*Q. rosea*). In order to prevent high swelling stress during the delamination test, the lamella thickness could be reduced and the same sawing pattern needs to be used for the beam assembly.

4 Conclusions and recommendations

Depending on the wood species used, the delamination results showed significant gluing parameter effects. Prior to being bonded, the board needed to be planned just before adhesive application and it appeared that the glue joint needed a minimum thickness to provide a satisfactory assembly that could resist severe moisture variations. Consequently, gluing parameters need to be adjusted to the wood species, especially in a tropical climate. Moreover, the current delamination test seemed to be too strict and may not be easy to use or adapt to validate a structural glued assembly using tropical hardwoods.

Lastly, to prevent cracks along the glue joint, due to moisture variations, the board thickness can be decreased. An optimum of 28 cm was adopted for *D. guianensis* glulam manufacturing in French Guiana. As regards the block shear test, it was successfully passed by almost all the glulam specimens despite a lack of adhesive observed in a large number of samples.

Despite some gluing conditions validated by European standards for *D.guianensis* glulam manufacturing more research is needed to determine gluing conditions for the other two wood species. In the case of *Q. rosea*, the amount of glue needs to be increased and, in order to avoid high shrinkage constraints, the lamella thickness should be decreased. For the densest wood, *P. venosa*, the pressure level needs to be decreased in order to prevent glue from being squeezed out of the joint. The validation of some gluing conditions needs to focus on the delamination test, and the block shear test should be used to characterize joint resistance.

In the future, prior to industrializing Guianese glulam, the resistance of finger jointing assembly has to be tested in order to validate the use of these tropical species for glulam industry.

References

Aicher S and Ohnesorge D (2011) Shear strength of glued laminated timber made from European beech timber. Eur. J. Wood. Prod. 69: 143-154

Bedel J and Gautier R (1972) Glued laminated structures from tropical hardwoods. Bois et Forêts des Tropiques 141: 51-72

Bourreau D (2011) Etude de faisabilité de lamellé-collé endémique en Guyane Française. Thesis, Université des Antilles et de la Guyane, Cayenne,pp164

Centre International de Recherche Agronomique pour le Développement (2008) Mélèze. Technical data sheet, pp 2

Centre Technique Forestier Tropical (1999) Bois de Guyane : Gonfolo, Angélique, Amarante. Technical data sheet, Euroimpressions,pp4

Custodio J, Broughton J and Cruz H (2008) A review of factors influencing the durability of structural bonded timber joints.International Journal of Adhesion&Adhesives 5(2): 1-13

Elbez G and Bentz D (1991) Le collage du bois. La technologie du bois.CTBA Paris

EN 392 (1995) Glued laminated timber - Shear test of glue lines

EN 391 (2002) Glued laminated timber - Delamination test of glue lines

EN 386 (2002) Glued laminated timber - Performance requirements and minimum production requirements.

EN 301 (2006) Adhesives, phenolic and aminoplastic, for load-bearing timber structures- Classification and performance requirements

EN 335-2 (2006) Durability of wood and wood-based products – Definition of use classes – Part 2: Application to solid wood

Gérard J (1999) Les spécificités du collage des bois tropicaux : valorisation des essences secondaires et collage multi-essences. Annales Génie Civil Bois numéro spécial Collage Structurel, 15-30

Gindl M, Reiterer A, Sinn G and Stanzl-Tschegg SE (2004) Effects of surface ageing on wettability, surface chemistry and adhesion wood. Holz RohWerkst 62: 273-280

Guiscafre J and Sales C, (1975) Etude de l'aptitude du Movingui (*Disthemonanthus benthamianus*) à l'utilisation en lamellé-collé. Bois et Forêts des Tropiques161 : 35-40

Guiscafre J and Sales C, (1980) Etude de l'aptitude au collage du bois d'Azobé (*Lophira alata*) à partir de résine Résorcine-Formaldéhyde, Centre Technique Forestier Tropical, Intern report, Nogent-Sur-Marne, pp 19

Guitard D (1994) Comportement mécanique du bois. In: ARBOLOR (ed) Le bois matériau d'ingénierie, Nancy, pp 91-125

Hwang GS et al(1993)Gluing properties of high-density hardwoods. Mokuzai Gakkaishi 39(3): 363-367

Janowiak JJ, Manbeck HB, Blankenhorn PR and Kessler KR (1992) Strength properties of exterior adhesives on preservative-treated hardwoods. For Prod J 42 (10): 68-76

Nussbaum RM and Sterley M (2002)The effect of wood extractive content on glue adhesion and surface wettability of wood. Wood and Fiber Science 34(1): 57-71

Ohnesorge D, Richter K and Becker G(2010) Influence of wood properties and bonding parameters on bond durability of European Beech (*Fagus sylvatica*L.) glulams. Ann. For. Sci., 67: 601

Paes JB, de Oliveira AKF, de Oliveira E, de Lima CR (2009) Physical-mechanical characterization of the glue laminated bamboo (*Dendrocalamus giganteus*). Ciencia Florestal 19 (1-2):41-51

Table legends:

Table 1 Properties of selected wood species

Table 2 Normalized values for a successfulblock shear test (EN 386: 2002)

Table 3 Recap of the bonding tests

Table4 Effect of planning on delamination for 3 different gluing conditions

Table5 Effects of the CAT and P parameters on the delamination factor Ds

Table6 Block shear test results for *D. guianensis* (3rd set of tests)

Table 1 Properties of selected wood species

Wood species	S_G	R_B	R_t	R_r	R_t/R_r	**HC**
Qualea Rosea	0.70	14.44	9.74	5.80	1.68	2
Dicorynia guianensis	0.79	13.50	8.24	5.13	1.61	3
Peltogyne venosa	0.84	11.47	6.80	4.83	1.41	3
Larix decidua	0.60	11.92	8.20	4.20	1.95	3

S_G: Mean specific gravity

R_B, R_t and R_r: total, tangential and radial shrinkage coefficients respectively (%).

HC: Hazard Class (EN 350-2: 2007)

Table 2 Normalized values for a successful block shear test (EN 386: 2002)

	Average			Individual Values		
Shear strength f_v, in MPa	6	8	f_v>11	4< f_v <6	6	f_v>10
Minimum WFP, in%	90	72	45	100	74	20
For values in between linear interpolation shall be used.						

Table 3 Recapitulation of the bonding tests

Specifications	**1st Set**	**2nd Set**	**3rd Set**
Wood species	*Q. rosea*	*Q. rosea* *D. guianensis* *P. venosa* *L. decidua*	*D. guianensis*
Adhesive type	RPF		
Adhesive/hardener(ratio)	100/20		
Lamella thickness	28 mm		16 /22 /28 /34 mm
Maximum time between planning and bonding	>24h / ≤ 8h	≤ 8h	
Adhesive spreading	2 faces		1 face
Adhesive spread rate (g/m²)	750 / 1500	250 / 750 / 1500	300
CAT (min)	10 / 20	5 / 10 / 20	40
Pressure (MPa)	0.7 / 1	0.4 / 0.7 / 1	1
Total beams/delamination specimens/shear specimens (per species)	6/60/0	54/270/216	32/160/0

Table4 Effectof planning on delamination for 3 different gluing conditions

Maximum time between planning and gluing	Delamination results (%) depending on gluing parameters Spread rate (g/m^2)/CAT (min)/Pressure (MPa)					
	1500/10/0.7		750/10/0.7		750/20/1.0	
	Mean	Stdv	Mean	Stdv	Mean	Stdv
>24h	61.4	9.5	35.2	13.0	12.3	6.3
≤ 8h	19.5	11.2	14.6	8.4	6.0	5.3

Stdv: Standard deviation

Table5 Effects of the CAT and P parameters on the delamination factor Ds

Wood species	**Source**	**DOF**	**Sum of squares**	**Mean of squares**	**F-value**	**P**
Q. rosea	P	5	0.033	0.007	0.197	0.964
	CAT	0	0.000			
	P*CAT	12	1.015	0.085	2.543	0.004**
D. guianensis	P	0	0.000			
	CAT	2	3.484	1.742	44.887	<0.0001**
	P*CAT	15	1.278	0.085	2.196	0.007
P. venosa	P	5	0.223	0.045	3.522	0.004**
	CAT	0	0.000			
	P*CAT	12	0.105	0.009	0.694	0.757

DOF: Degrees of freedom

* Coupling agent

** Significant for $p < 0.005$. The smaller p, the more significant the effect

Table6 Block shear test results for *D. guianensis* (3rd set of tests)

	f_v (MPa)	**WFP (%)**
Min	11.67	40
Mean	15.48	79
Max	19.57	100

All figures were provided by R software except for figure 1 which was realized by Excel 2007.

Figure legends:

Fig.1 Influence of measured glue spread rate on delamination results

Fig.2 Influence of glue amount on delamination resistance for *Q. rosea*(**a**), *P. venosa* (**b**) and *D. guianensis* (**c**)

Fig. 3 Influence of Pressure (**1**) and CAT(**2**) on delamination resistance for Q. rosea(**a**), P. venosa (**b**) and D. guianensis (**c**).

Fig.4 Block shear test results (2nd set of tests) for individual values (a) and mean values (b) - current minimum requirements for production control (black lines) and Aicher and Ohnesorge proposals (dotted lines).

Fig.5 Influence of D. guianensis lamellae thickness on delamination

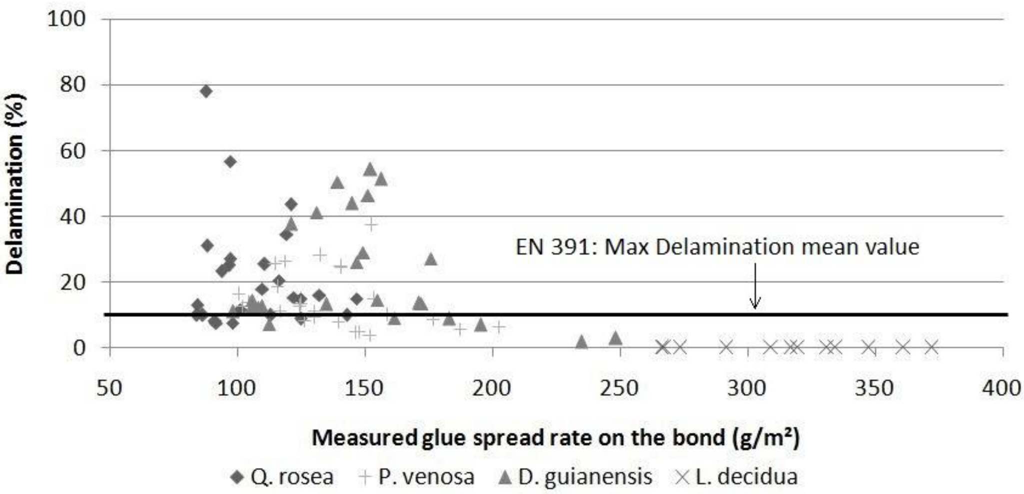

Fig.1 Influence of measured glue spread rate on delamination results

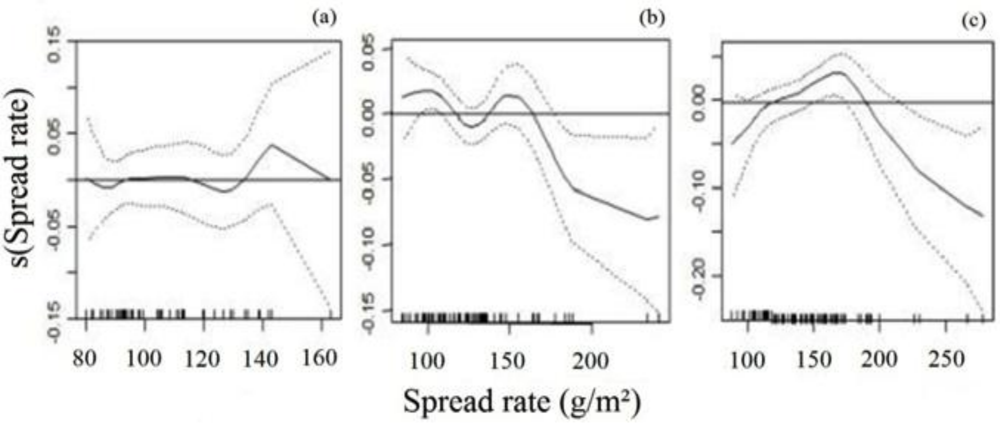

Fig.2 Influence of glue amount on delamination resistance for *Q. rosea*(**a**), *P. venosa* (**b**) and *D. guianensis* (**c**)

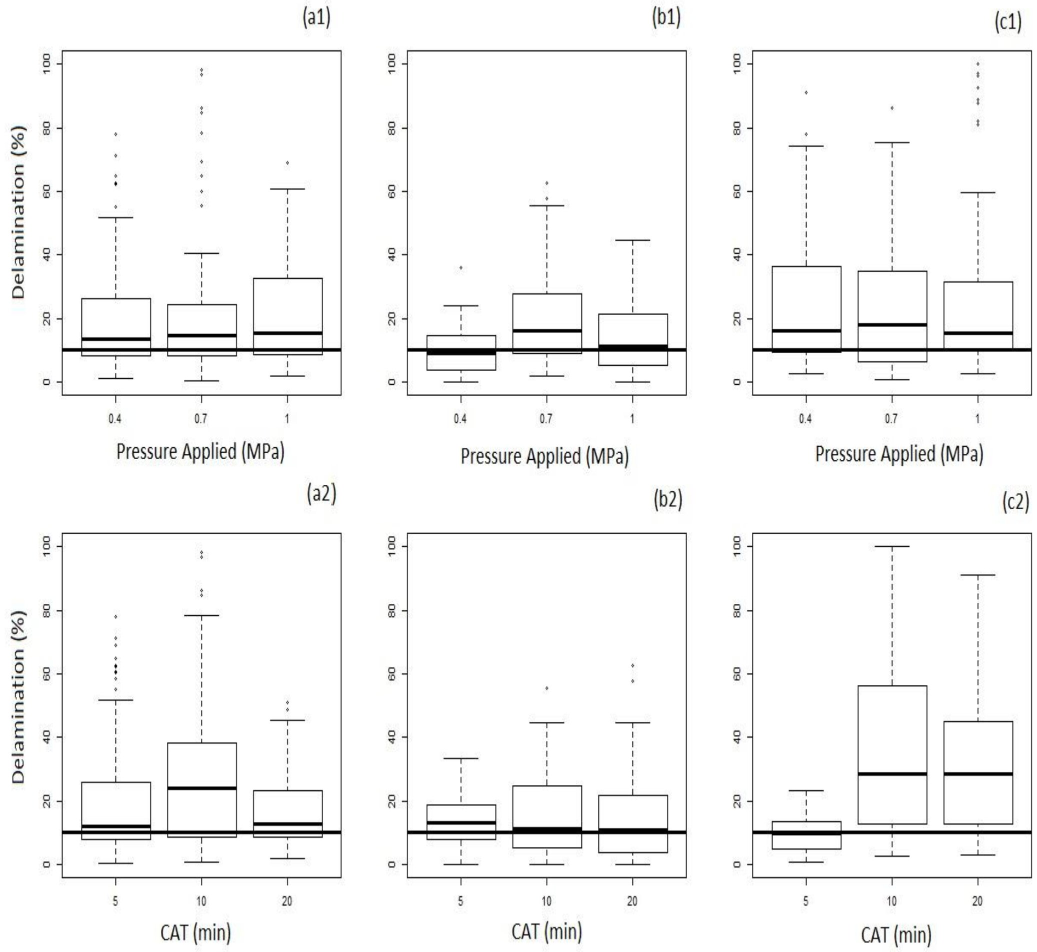

Fig.3 Influence of Pressure (**1**) and CAT (**2**) on delamination resistance for *Q. rosea*(**a**), *P. venosa* (**b**) and *D. guianensis* (**c**)

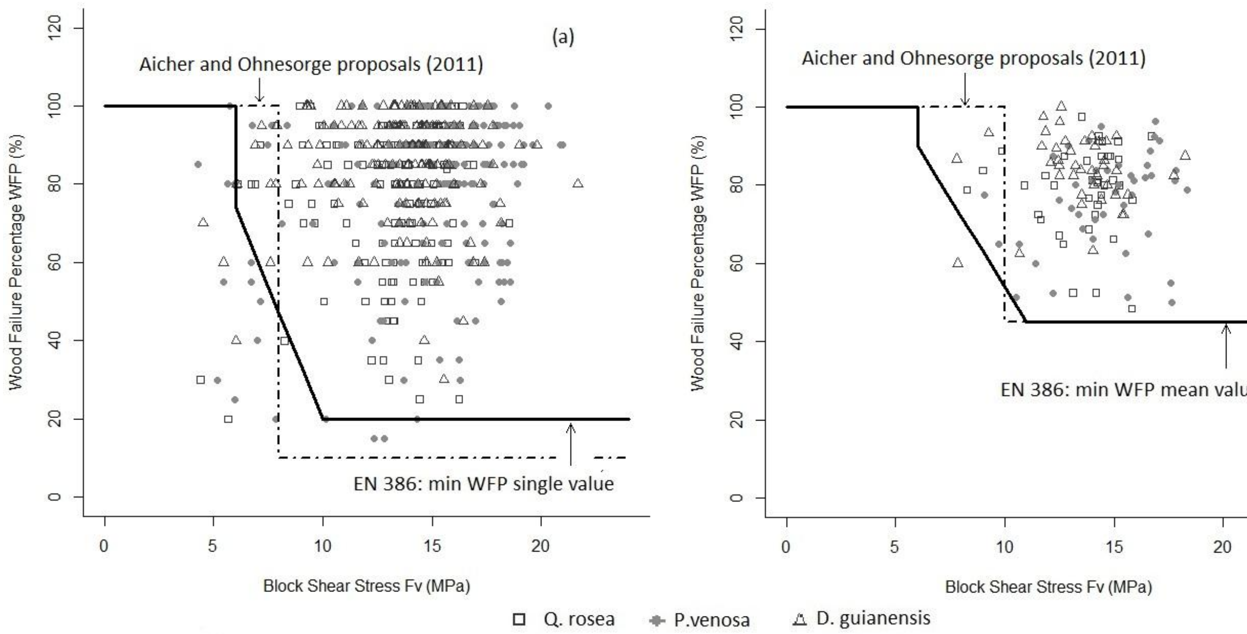

Fig.4 Block shear test results (2nd set of tests) for individual values (a) and mean values (b) - current minimum requirements for production control (black lines) and Aicher and Ohnesorge proposals (dotted lines).

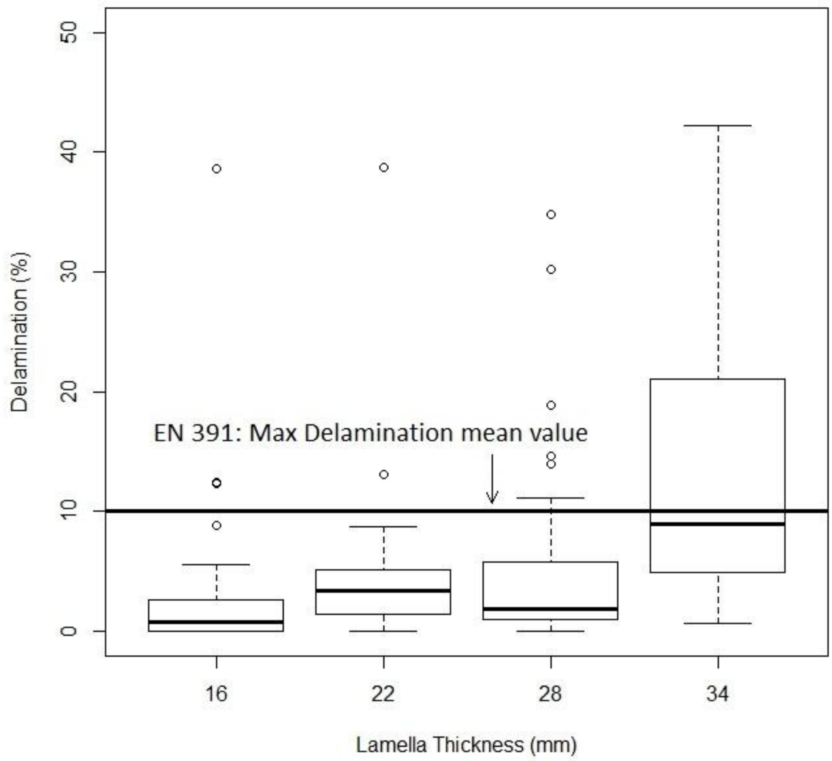

Fig.5 Influence of D. guianensis lamellae thickness on delamination