Use of northern hardwoods in glued-laminated timber: a study of bondline shear strength and resistance to moisture

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ABSTRACT

The growing demand for engineered wood products in the construction sector has resulted in the diversification of the product offer. Used marginally in structural products in North America, northern hardwoods are now attracting a growing interest from industry and policy makers because of their outstanding strength as well as their high availability and distinctive appearance. Currently, there is no standard in Canada governing the use of hardwoods in the manufacturing of glued-laminated timber. As part of a larger project aiming to assemble the basic knowledge that would lead to such standard, the specific objective of this study was to assess the shear strength in dry and wet conditions of assemblies made from different hardwood species and structural adhesives. Results suggest that a mean shear strength as high as 20.5 MPa for white oak, 18.8 MPa for white ash and respectively 18.2 MPa and 17.4 MPa for yellow birch and paper birch can be obtained in dry conditions. The choice of adhesive did not affect the dry shear strength of our specimens, but differences were observed in wet conditions. Specimens bonded with melamine-formaldehyde adhesive had generally the highest wet shear strength and wood failure values. Our results also highlight the important influence of wood density on the percentage of failure that occurs in wood and, to a lesser extent, on shear strength. Further investigations on finger joint strength and full-size bending tests will allow confirming the potential for the investigated species to be used in glued-laminated timber.

1 INTRODUCTION

The current growing demand for engineered wood products in the construction sector is largely attributable to their outstanding ecological performance. The substitution of materials having a larger ecological footprint, such as steel and concrete, by structural engineered wood products like glued-laminated timber have proven to be effective in minimizing the environmental impacts of the building sector (Thormark 2006). In addition to sustainability-related arguments, building designers also tend to choose wood products because of their aesthetics (Gaston 2014; Gosselin et al. 2016; Laguarda Mallo and Espinoza 2015; Markström et al. 2018). Aware of the market opportunities as well as of the lack of high value-added opportunities for some wood species, industry and policy makers from several jurisdictions have recently joined forces to develop products made from non-conventional species, especially with hardwoods. In addition to the possibility of creating products with a noble and distinctive appearance, the high mechanical properties of some hardwood species offers the opportunity to create engineered products of outstanding strength. Several glued-laminated timber products (DIBt 2009, 2013; ETA-13/0642-02646 2013) made from various hardwood species have been approved in the European union, which are largely exceeding the strength of their softwood counterparts. Hardwood glulam products are also available in the United states for over two decades. Work undertaken in this country in the early 1990s with red maple and red oak (Janowiak et al. 1995; Manbeck et al. 1993; Shedlauskas et al. 1996) led to the development of structural products now used in timber bridge design (Manbeck et al. 1996).

As the laminating effect in glued-laminated timber beams stems from the fact that laminations are bonded (Falk and Colling 1995), the integrity of the cross-section is a key factor in the overall product strength (Dietsch and Tannert 2015). For hardwood, the bonding quality and resistance to moisture remain issues that cannot be neglected. The thick cell walls and small lumens of hardwood species often lead to a limited penetration of the adhesive, and consequently to weakened bondlines (Frihart and Hunt 2010; Selbo 1975). Results from the work of Aicher et al. (2018), Konnerth et al. (2016), Jiang et al. (2014), Knorz (2014) and Lehmann (2018) with several European and Tropical hardwoods revealed that bond strength may greatly vary depending on the adhesive system and wood species. The low dimensional stability of hardwoods also induces important stresses on the bondlines when the moisture content fluctuates (Frihart and Hunt 2010). Several gluing tests (Ammann et al. 2016; Knorz et al. 2015; Konnerth et al. 2016; Vick and Okkonen 1998) conducted with dense hardwoods in wet conditions or after repeated moisture content

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variations confirmed the importance of this effect. Considering the inherent difficulties of bonding hardwoods, the achievable bondline strength of a given species and adhesive system must be carefully assessed in order to confirm the relevance of their use in a structural engineered wood product such as glued-laminated timber (GLT).

In Canada, no structural GLT products made from hardwood species are currently available on the market. The CSA O122 (2016) standard, governing the manufacturing and quality control testing of structural glued-laminated timber, does not include any provision regarding the use of hardwood species. Moreover, the resource is largely available. Each year in the province of Quebec, half of the annual allowable cut of deciduous trees remains unharvested (Durocher et al. 2019). As part of a project seeking to develop new opportunities for these species and promote the production of high value-added products such as GLT, the objective of this study was to assess the shear strength in dry and wet conditions of assemblies made from different hardwood species and structural adhesives.

2 Materials and method

A preliminary test campaign was conducted prior to the main campaign. At the end of this first series of tests, species and adhesives that would be submitted to further investigations were selected and potential improvements in the experimental protocol were identified and integrated in the main test campaign.

2.1 Materials

White oak (*Quercus alba* Linn.), white ash (*Fraxinus americana* Linn.), yellow birch (*Betula alleghaniensis* Britt.) and paper birch (*Betula papyrifera* Marsh.) lumber was purchased from various local merchants and sawmills. Birch trees were harvested in Duchesnay, near Quebec City, Canada, but the exact provenance of the white oak and white ash lumber is unknown.

All pieces used in this experiment showed a maximum slope of grain of 1 in 15, were free of knots and any other defects. Growth rings were making an angle of less than 45° with the wider face of the pieces. Lumber was conditioned at 20°C and 65% relative humidity until constant mass was reached. Density was measured by the volumetric method described in ASTM D2395 (2017). Mean values and standard deviation (SD) are presented in Table 1.

Two adhesive systems were used, approved both for interior and exterior exposure in structural applications. Names and specifications are shown in Table 2. Melamine-formaldehyde (MF) and two-component polyurethane (2C-PUR) adhesives were chosen amongst other products after preliminary trials.

Table 1 Mean density (p_{12}) values from preliminary trials and main test campaign

Species	Preliminary trials		Main campaign	
	Mean density p_{12} (kg/m^3)	**SD**	**Mean density p_{12} (kg/m^3)**	**SD**
Paper birch	634.6	30.6	613.3	13.7
Yellow birch	664.0	15.6	667.6	30.7
White ash	659.0	85.5	731.8	22.9
White oak	739.4	39.4	766.2	87.4

Table 2 Adhesives and gluing parameters

Adhesive type	Resin	Hardener	Glue spread (g/m^2)	Mixing ratio	Pressure (psi)	Press time (h)
Melamine-Formaldehyde (MF)	Cascomel™ 4720	Wonderbond™ 5025A	390	4:1	150	15
Two-component Polyurethane (2C-PUR)	Purbond® GT20	Purbond® GT205	340	100:15	200	2.3

2.2 Block shear tests

In glued-laminated timber quality-control process, block shear tests are widely used to assess the shear strength and wood failure of gluelines. In the United States, AINSI A190.1 (2017), the standard establishing performance requirements for GLT products, relies on the block shear test method described in ASTM D905 (2013). Its counterpart in the European union, EN 14080 (2013), also relies on a block shear test method, described earlier in former standard EN 392 (1995). Block shear test is also the testing method prescribed by international standards ISO 6238 (2018) and ISO 12579 (2007) for determining the glueline shear strength in glued-engineered wood products.

In Canada, block shear tests are an integral part of the quality control testing of glulam as specified in CSA O122 (2016), the standard governing the manufacturing of softwood GLT in Canada. Standard CSA O112.9 (2010) «*evaluation of adhesives for structural wood products (exterior exposure)*» is also largely based on block shear tests. In accordance with this standard, tests must be conducted in dry condition and in wet conditions, after the specimens are subjected to a vacuum-pressure cycle. Wet tests are used because they allow discriminating easily between performing and non-performing adhesives-species combinations in wet conditions.

2.2.1 Preparation of test specimens

Lumber from the four species was cut into billets of 21 mm thick, 65 mm wide and 350 mm along the grain. All billets were planed to a final thickness of 19 mm on the same day when they were bonded, using a planer with a rotary cylindrical cutter. Knives were sharpened just before processing the pieces from the preliminary trial. In the main test campaign, it was decided not to do so, to make the surface preparation process more representative of a factory production.

For each combination of wood species and adhesive, six billets were grouped by pairs of similar density and assembled with the growth rings concave from the bondline. Adhesives application rates, assembly times, pressures and pressing times were specified after consulting the technical data sheets and the manufacturers (Table 2). After bonding, assemblies were placed in a conditioning room at 20°C and 65% relative humidity for at least two days before the preparation of test specimens. Five blocks of approximately 50 x 50 mm were cut from each assembly, as specified in standard CSA O112.9 (2010) and ASTM D905 (2013). A 5-mm notch extending to without going beyond the bondline was cut on each side of the test specimens. The bondline area was approximately 2000 mm^2. Figure 1 shows the configuration and measurements of test specimens. Specimens were returned in the conditioning chamber until tested. The exact contact surface was measured to the nearest 0.01 mm immediately before testing.

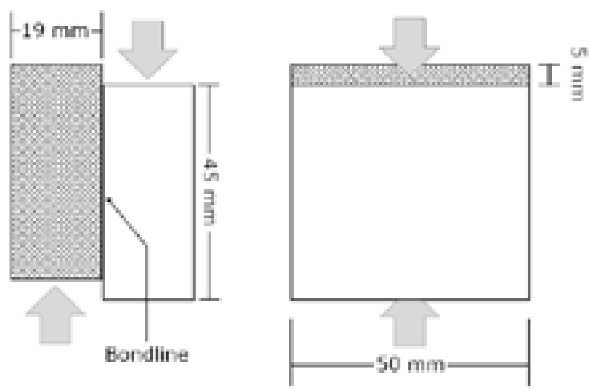

Fig. 1 Geometry and measurements of block shear test specimens from CSA O112.9 (2010)

2.2.2 Testing procedure

Thirty test specimens were obtained for each species-adhesive combination. Fifteen specimens were randomly selected and subjected to a vacuum-pressure cycle as specified in CSA O112.9 (2010) standard before being tested. The cycle consisted of submerging specimens in water, holding a vacuum of 75 kPa ± 10 kPa for thirty minutes and then applying a pressure of 540 kPa ± 20 kPa for two hours. These specimens were tested in wet conditions, while the remaining fifteen specimens were tested in dry conditions.

Block shear tests were conducted on an MTS QTest load frame (Eden Prairie, USA) fitted with a 50 kN load cell and a compression shearing tool. The load was applied parallel to the grain direction in a continuous motion rate of 5 mm/minute. Wood failure percentage was visually estimated to the nearest 5%. The test apparatus and shearing tool shown in Figure 2 complied with ASTM D905 (2008). The maximum load was used to calculate the bondline shear strength with the following equation:

$f_v = \frac{F_{max}}{A}$ in N/mm^2

where

f_v: Shear strength (MPa), F_{max}: Maximum load applied (N) and A: Bondline area (mm^2)

Fig. 2 Block shear testing device

2.3 Data analysis

From the shear strength data, the mean value and standard deviation for each species-adhesive combination were calculated. A mixed-effects analysis of variance was conducted to compare means, using adhesive and wood species as fixed effects and the assembly from which specimens were cut out as a random effect. Assumptions were verified and confirmed. When a significant effect of one of the explanatory variables was detected, multiple comparisons were conducted using Tukey's test. Analyses were made using the *lme4* (Bates et al. 2015) and *emmeans* (Lenth et al. 2018) packages in the R software, version 3.5.2 (R Core Team 2018). Median and mean wood failure percentages were computed for each group as standards rely on either one or the other.

3 Results and discussion

3.1 Results from the preliminary test campaign

Table 3 shows the results of the preliminary test campaign. The highest dry shear strength was achieved by yellow birch specimens glued with 2C-PUR adhesive (22.4 MPa) and was significantly higher ($p = 0.0095$) than the lowest strength value, which was observed with white ash specimens bonded with the MF adhesive (15.8 MPa). Strength of yellow birch specimens was also significantly higher ($p = 0.0416$) than that of paper birch specimens glued with MF adhesive. The differences between all other species-adhesive combinations were not statistically significant ($p > 0.05$).

In tests realized after the vacuum-pressure cycle, white oak specimens bonded with MF adhesive and white ash specimens bonded with 2C-PUR adhesive attained an equivalent strength of 10.0 MPa, which was significantly higher (p = 0.0271, 0.0287) than the strength of white oak specimens bonded with 2C-PUR (6.2 MPa). Specimens from the birch species and white ash specimens bonded with MF adhesive attained an intermediate strength varying between 8.1 and 9.5 MPa. Tukey's test did not reveal other statistically significant differences. In the dry test, the mean level of wood failure ranged from 59 to 98 % while it ranged from 2 to 99 % in the wet test. In both tests, the lowest wood failure percentage was observed on white oak specimens bonded with the 2C-PUR adhesive. In the wet test, wood failure of specimens bonded with 2C-PUR adhesive was always lower than those glued with the MF adhesive.

Table 3 Shear strength (MPa), mean density (kg/m^3), median and mean wood failure percentage from the preliminary trials

Test	Species	Adhesive	n	Mean density (kg/m3)	Mean f_v (MPa)	SD	Median WF (%)	Mean WF (%)
Dry	Paper birch	MF	15	615.4	16.9	0.9	80	81
		2C-PUR	15	653.2	19.5	1.7	100	97
	Yellow birch	MF	15	653.6	20.6	1.0	100	89
		2C-PUR	15	675.9	22.4	1.1	90	79
	White oak	MF	15	756.8	18.7	2.4	90	75
		2C-PUR	15	722.0	17.2	1.4	55	59
	White ash	MF	15	633.0	15.8	4.2	100	95
		2C-PUR	15	684.9	19.9	2.4	100	98
Wet	Paper birch	MF	5	626.8	8.3	0.3	90	93
		2C-PUR	5	644.0	9.3	0.4	75	78
	Yellow birch	MF	5	649.8	8.1	0.5	100	99
		2C-PUR	5	673.8	9.5	0.8	25	31
	White oak	MF	5	774.7	10.0	1.0	85	75
		2C-PUR	5	730.1	6.2	2.5	0	2
	White ash	MF	5	651.3	9.0	2.6	100	81
		2C-PUR	5	672.3	10.0	0.3	50	62

Consecutively to these tests, as density of the wood material between subsamples varied substantially and was most of the time lower than values stated in literature (Jessome 1977), it was decided to better control this parameter in the main test campaign. It was also decided to increase the number of repetitions for specimens tested after the vacuum-pressure cycle from five to fifteen to account for the variability observed in the first tests.

3.2 RESULTS FROM THE MAIN TEST CAMPAIGN

Figure 3 shows the mean dry bondline shear strength from the main test campaign for paper birch, yellow birch, white ash and white oak specimens, glued with MF and 2C-PUR adhesives. White oak specimens glued with MF adhesive exhibited the highest shear strength (20.5 MPa), followed by white oak specimens glued with 2C-PUR adhesive (19.3 MPa). White ash specimens had very similar values regardless of the adhesive used (18.6-18.8 MPa). Paper birch specimens glued with the MF adhesive attained the lowest strength (16.4 MPa). This value was significantly lower than the strength of MF ($p = 0.0001$) and 2C-PUR ($p = 0.0078$) bonded white oak specimens as well as that of white ash specimens bonded with the MF adhesive ($p = 0.0376$). Paper birch and yellow birch specimens bonded with the polyurethane adhesive (17.4-17.5 MPa) also achieved a significantly lower shear strength ($p = 0.0057$, 0.0059) than white oak specimens bonded with the melamine adhesive. Yellow birch specimens glued with the MF adhesive achieved the higher mean shear strength amongst birch samples, with 18.2 MPa, but this value was not significantly different from any other group ($p > 0.05$). No other statistically significant differences were unveiled by Tukey's multiple comparison test.

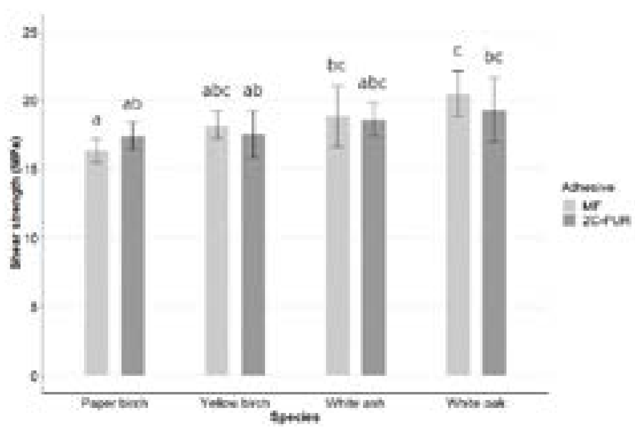

Fig. 3 Bondline shear strength (MPa) in dry conditions of paper birch, yellow birch, white oak and white ash specimens bonded with two adhesives

Figure 4 shows the mean bondline shear strength obtained from the wet test in the main test campaign. The shear strength achieved by the birches specimens was not significantly impacted by the adhesive choice ($p > 0.05$). Paper birch specimens attained a shear strength of 7,6 MPa with MF and 2C-PUR adhesives, corresponding to reductions of respectively 53.7 and 56.3 % compared to strength values from the dry test. Yellow birch specimens achieved slightly higher but not statistically different strengths ($p > 0.05$), with a mean value of 8.6 MPa for specimens glued with MF adhesive, and 7.8 MPa for specimens glued with 2C-PUR adhesive. The corresponding reductions from the dry shear strengths are respectively 52.8 and 55.4 %.

Oak and ash specimens glued with MF adhesive showed significantly higher shear strength than specimens from the same species glued with 2C-PUR adhesive, with values of 10.6 and 10.1 MPa for white oak ($p = 0.0001$) and white ash ($p = 0.0097$), which corresponded to reductions of 49.8 and 46.3 % from the dry shear strength, respectively. The strength of the oak and ash specimens glued with 2C-PUR was substantially lower with values of 7.3 MPa for white oak and 7.8 MPa for white ash, which corresponded to reductions of 62.2 and 58.1 %, respectively, compared to the dry test values. For specimens glued with the 2C-PUR adhesive system, differences between species were not significant according to Tukey's test ($p > 0.05$). However, strength of white oak and white ash specimens bonded with the MF adhesive was significantly higher than the strength of paper birch specimens bonded with the same adhesive ($p = 0.0009$, 0.003).

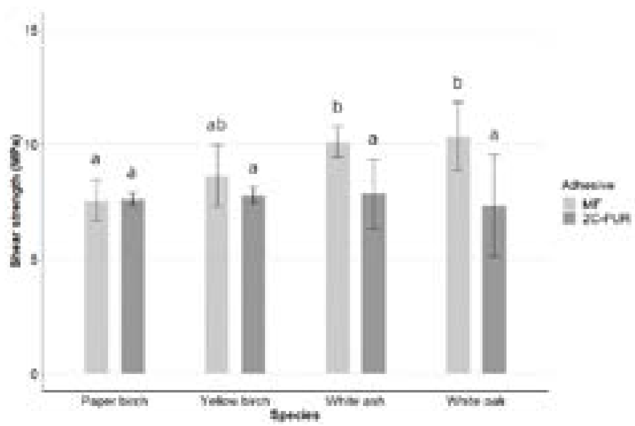

Fig. 4 Bondline shear strength (MPa) in wet conditions of white oak and white ash specimens bonded with two adhesives

Table 4 presents the detailed density values as well as mean and median wood failure percentages for every group from the main test campaign. In dry conditions, the mean wood failure levels of paper birch specimens were the highest amongst all species. Yellow birch specimens showed slightly lower levels, especially those bonded with the 2C-PUR adhesive. White ash and white oak groups followed in order and showed, for a given species, comparable wood failure levels irrespectively of the adhesive used, although 2C-PUR adhesive achieved slightly better results with white ash.

Compared to wood failure levels in dry conditions, wood failure in wet conditions was lower for all species-adhesive combination, exception made of the paper birch specimens bonded with the polyurethane adhesive and of the white ash specimens bonded with the melamine adhesive. Yellow birch, white oak and white ash specimens bonded with the 2C-PUR adhesive exhibited considerably lower wood failure levels in the wet test than their counterpart bonded with the MF adhesive, but this was not the case with paper birch specimens, for which the opposite trend was observed.

Table 4 Density and wood failure (WF) percentages of species-adhesive groups tested in dry and wet conditions

Test	Species	Adhesive	n	Mean density (kg/m3)	Density SD	Median WF (%)	Mean WF (%)	WF SD
Dry	Paper birch	MF	15	617.7	13.9	95	94	7.0
		PUR2	15	614.4	11.0	100	95	8.3
	Yellow birch	MF	15	645.7	29.3	100	88	15.7

		PUR2	15	660.1	23.2	80	76	24.9
	White ash	MF	15	736.5	23.5	70	60	34.7
		PUR2	15	729.3	23.0	75	78	17.3
	White oak	MF	15	783.0	91.1	60	56	38.3
		PUR2	15	756.2	87.7	60	54	28.4
Wet	Paper birch	MF	15	609.4	16.1	75	69	22.5
		PUR2	15	611.7	13.1	95	94	10.2
	Yellow birch	MF	15	691.9	30.5	70	53	32.6
		PUR2	15	672.5	20.1	30	32	31.7
	White ash	MF	15	734.2	23.3	80	76	26.8
		PUR2	15	727.4	23.0	15	29	27.0
	White oak	MF	15	777.9	94.0	50	47	32.5
		PUR2	15	747.8	80.0	10	17	19.1

3.3 Comparison of results with requirements from GLT standards and comparable studies

Various standards issued in different countries comprise shear strength and wood failure requirements for glued-laminated timber products. However, it is sometimes hazardous to use requirements of standards from other countries or that are not designed specifically for the investigated species. Indeed, it has been demonstrated that different block shear test methods can lead to discrepancies of up to 60 % in the results (Okkonen and River 1989). The testing device alone could cause significant differences (Steiger et al. 2010). For example, European standard EN 14080 (2013) relies on a different testing procedure and test apparatus and requirements for shear strength as well as wood failure are exclusively differentiated between softwoods and hardwoods by means of thresholds for the lowest single values.

In Canada, since no standards regulate the use of hardwoods in GLT, threshold values for shear strength and wood failure percentage are only available for softwood GLT in CSA O122 (2016). However, standard CSA O112.9 (2010) provides qualification requirements for adhesives used in products made from hardwoods and softwoods and intended for load-bearing applications in exterior conditions. However, requirements for hardwoods are based on tests conducted exclusively on hard maple (*Acer saccharum* Marsh., *Acer nigrum* Michx. f.). The minimum bondline shear strength requirements of 19 MPa in dry conditions and 11 MPa in wet conditions set out in this standard can therefore not be compared directly with our results.

In the United States, standard ANSI A190.1 (2017) defines the bond shear strength requirement as a ratio of the clear wood shear strength. In dry conditions, bonded specimens must reach at least 90 % of the strength of clear wood specimens as defined in ASTM D2555 (2006). In this study, all groups reached a shear strength considerably higher than the required 90 % of clear wood strength from ASTM D2555 (2006). However, the significance of this criterion should be interpreted with caution because values from this standard do not account for variation within species. As suggested by River et al. (1991) and Aicher (2018), comparing the bondline shear strength with a clear wood strength value obtained from the same sample of wood material would be more meaningful. Moreover, the shear strength should always be interpreted in conjunction with the level of wood failure. Shear strength values are a good indicator of the product's strength only if wood failure levels are sufficiently high (Frihart and Hunt 2010).

Any comparison of our results with reference values from other studies is difficult since very little literature on bonding of northern hardwood species is available. In a study of the impact of block shear test method on shear strength values, Okkonen and River (1989) conducted tests with bonded and clear wood white oak specimens using a phenol-resorcinol-formaldehyde (PRF) resin as adhesive. Amongst others, they used testing method ASTM D905 (2008) and a testing device comparable to that used in this study. White oak lumber had a mean density of 740 kg/m^3 and clear wood specimens achieved a mean shear strength of 18 MPa, while bonded specimens reached 17 MPa. In addition to the difference in the adhesive used, the higher mean density of the white oak used in our study may explain why our bonded specimens reached higher strength than the clear wood specimens from Okkonen and River (1989). Unlike what we observed in our tests, almost all failures occurred entirely at the bondline in the case of their glued specimens. Our review of the literature did not lead to any results on the bondline shear strength of North American white ash. Even if shear strength values cannot be compared directly because of the different testing procedures and apparatus, experiments conducted in Europe with species related to those investigated in this study, namely common ash (*Fraxinus excelsior* L.), common oak (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) provide the best available basis for comparison. In that way, findings of the current study are not consistent with those of Aicher et al. (2018). In block shear tests conducted on specimens originating from industrially manufactured hardwood glued-laminated timber beams, common ash attained higher wood and bondline shear strengths than common/sessile oak with density of 695 kg/m^3 and 752 kg/m^3, respectively. No reference to shear strength of glued assemblies made from the investigated or related birch species was found in literature.

However, our results are consistent with the mechanical properties of the investigated species, as white oak is known to be slightly stronger in longitudinal shear than white ash, followed in decreasing order by yellow and paper birch (Jessome 1977). It must be noted, however, that mechanical properties from the work of Jessome (1977) were obtained from block shear tests conducted following standard ASTM D143, which involves a different specimen geometry and test apparatus to that used in this study.

In wet conditions, shear strength values were considerably lower. However, all species-adhesive combinations did not suffer an equivalent loss in strength. The observed loss ranged from 46,3 to 62,2 % depending on the adhesive and species. In comparison, the deemed-acceptable reduction in median shear strength for hard maple bonded specimens in CSA O112.9 (2010), when submitted to the vacuum-pressure cycle, is 42,1 % (i.e. 19 MPa to 11 MPa). The higher loss of strength observed in our experiment could be explained partially by the occurrence of bondline failures, mostly in the case of higher density specimens. Furthermore, the wet shear strength that was reached in paper birch specimens was similar to that of the yellow birch specimens bonded with the 2C-PUR adhesive. The lower wood failure level observed for the latter and the difference in density between the two species are the most likely factors explaining this result.

Wood failure percentage provides much information as it allows knowing if bonding took full advantage of the wood material's strength. In the dry test, wood failure percentages suggest that the maximum strength potential of the wood material was not always reached, particularly in the case of white ash and white oak specimens. With respect to wood failure requirements, ANSI A190.1 (2017) defines a specific category for dense hardwoods and different thresholds for Initial Type Testing (ITT) and Factory Production Control (FPC). Mean wood failure percentages in dry conditions must be at least 60 % for ITT and 50 % for FPC. Every combination of adhesive and wood species tested in the main test campaign reached the mean wood failure requirement in FPC for dense hardwoods from AINSI A190.1 (2017). For ITT however, white oak specimens bonded with MF and 2C-PUR adhesives did not reach the required mean wood failure percentage. Although requirements from CSA O112.9 (2010) apply to different species, our results in dry conditions are close to the minimum median wood failure requirement of 60 % set out in this standard, but only paper birch specimens glued with 2C-PUR adhesive and white oak specimens glued with MF adhesive fulfilled the threshold value of 80 % for the test in wet conditions. Since CSA O112.9 (2010) expects higher wood failure percentage in the wet test than in the dry test, our results are not entirely satisfactory. Only the white ash specimens bonded with the MF adhesive have met this criterion.

In comparable studies, Aicher et al. (2018) obtained higher mean wood failure percentages, with 89 % for the common/sessile oak sample bonded with melamine-urea-formaldehyde (MUF) and 79 % for the common ash sample bonded with a PRF adhesive. In block shear tests on bonded common ash specimens (661 kg/m^3), Knorz et al. (2014) obtained a mean wood failure percentage of 63 % with a one-component polyurethane (1C-PUR) adhesive and 99 % with a MUF adhesive. In tensile shear tests with common ash (638 kg/m^3) specimens bonded with MUF, PRF, 1C-PUR and emulsion polymer isocyanate adhesives, Jiang et al. (2014) obtained mean wood failure values of at least 70 % with all four adhesives tested. No reference to wood failure levels from shear strength tests on glued assemblies of paper birch or yellow birch was found in the literature. The difference between our results and comparable studies might be due to the adhesive system used, but also to the density of the wood material.

3.4 Impact of wood density on bondline strength and wood failure

Differences observed in wood failure between the preliminary trials, the main test campaign and comparable studies tend to confirm the impact of wood density on the adhesive performance. For both white oak and white ash, the species showing the highest specific gravity, specimens made of higher density material showed most of the time lower wood failure percentage. In the first series of tests, average densities of white oak and white ash were lower. Some ash specimens had density as low as 522 kg/m^3, which is far from the mean value of 690 kg/m^3 stated in literature (Jessome 1977). Therefore, it was decided to increase the minimal density of the white oak and white ash sample to obtain more representative results. As a result, dry shear strengths for these species were higher in the main test campaign than in preliminary trials, even if for three of the four species-adhesive combinations, mean wood failure was considerably lower. The significant increase in the white ash sample density resulted in a 30 % reduction of mean wood failure percentage. The same effect is visible within the white oak sample from the main test campaign, where few specimens showed an extremely high density (i.e. 897-902 kg/m^3) and very low wood failure. If those specimens were excluded from the analysis, mean and median wood failure percentages would have been considerably higher, and thus closer to values obtained in preliminary trials.

When comparing all four species, the density of the wood material seemed to have a direct influence on the wood failure levels observed in the dry test, although other anatomical and chemical factors could also be responsible for the differences. Contrarily to white oak and white ash specimens, paper birch and yellow birch specimens had, except for a few exceptions, consistently high wood failure levels. Above a certain density value located somewhere between that of our yellow birch and white ash samples, the adhesive performance in dry conditions appears to be affected by an increase in the density of the adherent. This observation is in line with the threshold zone proposed by Frihart and Hunt (2010) of 700 to 800 kg/m^3. In the wet test, the same general trend could be observed, especially for specimens bonded with the polyurethane adhesive.

These results show the interactions occurring between material density, shear strength and wood failure. To facilitate the use of hardwood species in structural glued-engineered wood products, it is important to consider the hardwoods intraspecies variability in the establishment of standardized shear strength and wood failure requirements. Grading requirements for lumber to be used in the manufacture of this type of product might also include provisions related to density. Nevertheless, if bonded satisfactorily, denser wood offers the possibility to increase the strength of the product.

3.5 Impact of adhesive on wet conditions resistance

In dry conditions, no statistically significant differences between adhesive performance were detected for a given species. In wet conditions, wood failure percentage was particularly low for yellow birch, white ash and white oak specimens bonded with the 2C-PUR adhesive. The loss of strength induced by the vacuum-pressure cycle was also greater for specimens of these species bonded with the same adhesive. However, paper birch specimens showed higher wood failure levels when bonded with the 2C-PUR adhesive rather than with the MF adhesive. This inconsistent result coincides with the fact that paper birch is the least dense amongst all tested species. The magnitude of the stress induced on the gluelines by wood swelling is thought to increase proportionally to the density of the material (Selbo 1975, River et al. 1991, Frihart and Hunt 2010). For paper birch specimens, this stress may have been contained under a certain threshold that is within the limits of the 2C-PUR performance. This could explain why despite showing similar wood failure levels in the dry test, yellow birch and paper birch performed differently in the wet test.

Thus, our findings are globally consistent with studies conducted in the past years on moisture resistance of several adhesive systems used to bond hardwood species. Work from Ammann et al. (2016) with common ash of a density of approximately 650 kg/m^3 glued with six adhesive systems revealed that the two-component polyurethane adhesive was one of the least efficient in wet tensile shear tests and in resistance to delamination tests. In studies of structural bonding in common ash, Knorz et al. (2015, 2014) stated that polyurethane adhesives showed the highest delamination rates amongst multiple adhesive systems when submitted to repeated moisture content variations. In these studies, melamine-urea-formaldehyde (MUF) adhesives, which are recognized to have a lower moisture resistance than MF adhesives (Frihart and Hunt 2010), still offered a higher performance than polyurethane based adhesives. Melamine-formaldehyde adhesive therefore appears to be suitable for structural products exposed to weather. However, results in wet conditions with white oak and MF might have been better in regard to the results obtained with white ash. In the main test campaign, the fact that knives were not perfectly sharpened before planing may have limited adhesive penetration, as shown by Knorz et al. (2015). This effect could have been added to that of density, explaining the low wood failure percentage observed in some specimens. However, these conditions are more realistic in the context of an industrial production, since it is unlikely that knives would be sharpened as frequently as they were in our preliminary test campaign.

5 Conclusion

In this study, white oak and white ash specimens bonded with MF and 2C-PUR adhesives were submitted to block shear tests in dry and wet conditions. Results suggest that a mean shear strength as high as 20.5 MPa for white oak, 18.8 MPa for white ash and respectively 18.2 MPa and 17.4 MPa for yellow birch and white birch can be obtained in dry conditions. For a given species, results from the dry test were similar, regardless of the adhesive. The loss of strength induced by the vacuum-pressure cycle was considerable, especially for high-density specimens bonded with 2C-PUR adhesive. Therefore, the MF adhesive appears more suitable for such products exposed to weather. However, since the products investigated in this study are more likely to be used in a weather-protected environment, 2C-PUR adhesive may also be adequate.

The results also highlight the major influence of wood density on wood failure percentage and, to a lesser extent, on shear strength. In both test conditions, several bondline failures occurred in specimens of higher density. In this sense, it is important to account for extreme density values in the selection of lumber destined to the manufacture of structural glued engineered wood products made from hardwoods. A microscopic examination of the gluelines could be carried out to better understand the impact of material density and specific anatomical features on the adhesive penetration.

Additional tests are required to confirm the potential use of the investigated species and adhesives in commercial glued-laminated timber production. For example, previous work with related species in Europe has pointed out the challenge that represents the fulfillment of delamination tests requirements. Such tests will be performed with the species and adhesives investigated in this study. Also in line with the aim of this project to assess the potential use of the investigated species in glued-laminated timber production, the next experiments will focus on determining the finger-joint strength and the bending strength of full-size beams.

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REFERENCES

Aicher S, Ahmad Z, Hirsch M (2018) Bondline shear strength and wood failure of European and tropical hardwood glulams. European Journal of Wood and Wood Products 76(4):1205–1222. doi:10.1007/s00107-018-1305-0

AINSI (2017) Standard for wood products—structural glued laminated timber. ANSI A190.1. APA—The Engineered Wood Association. https://www.apawood.org/ansi-a190-1. Accessed 12 January 2019

Ammann S, Schlegel S, Beyer M, Aehlig K, Lehmann M, Jung H, Niemz P (2016) Quality assessment of glued ash wood for construction engineering. European Journal of Wood and Wood Products 74(1):67–74

ASTM (2006). Standard Practice for Establishing Clear Wood Strength Values. ASTM D2555. ASTM International. https://www.astm.org/Standards/D2555.htm. Accessed 20 March 2019

ASTM (2013). Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading ASTM D905. https://www.astm.org/Standards/D905.htm. Accessed 16 March 2019

ASTM (2017). Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials ASTM D2395. https://www.astm.org/Standards/D2395.htm. Accessed 25 Februrary 2019

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1):1-48

CSA (2010) Evaluation of adhesives for structural wood products (exterior exposure) CAN/CSA O112.9-10. Etobicoke, Ontario: Canadian Standards Association

CSA (2016) Structural glued-laminated timber CAN/CSA 0122-16. Etobicoke, Ontario: Canadian Standards Association

DIBt (2009) General technical approval Z-9.1-679. BS-Holz Glulam from beech and glulam from beech-hybrid. Wuppertal, Germany: Approval holder: BS-Holz

DIBt (2013) German Technical Approval Z-9.1-821. Holz Schiller oak post and beam glulam. Germany: Approval holder: Holz Schiller GmbH

Dietsch P, and Tannert T (2015) Assessing the integrity of glued-laminated timber elements. Construction and Building Materials 101:1259–1270

Durocher C, Thiffault E, Achim A, Auty D, Barrette J (2019) Untapped volume of surplus forest growth as feedstock for bioenergy. Biomass and Bioenergy 120:376–386. doi:10.1016/j.biombioe.2018.11.024

EN 392 (1995) Glued laminated timber — shear test of glue lines. European Committee for standardization (CEN). Brussels

EN 14080 (2013) Timber structures — glued laminated timber — requirements. European Committee for standardization (CEN). Brussels

ETA-13/0642 (2013) European Technical Approval, "VIGAM-Glued laminated timber of oak". Issued by Österreichisches Institut für Bautechnik (OIB). Vienna: Approval holder: Sierolam SA

ETA-13/0646 (2013) European Technical Approval, "SIEROLAM— Glued laminated timber of chestnut". Issued by Österreichisches Institut für Bautechnik (OIB). Vienna: Approval holder: Grupo Gamiz SA

Falk RH, Colling F (1995) Laminating Effects in Glued-Laminated Timber Beams. Journal of Structural Engineering 121(12):1857–1863. doi:10.1061/(ASCE)0733-9445(1995)121:12(1857)

Frihart CR, Hunt CG (2010) Chapter 10: Adhesives with Wood Materials- Bond Formation and Performance. in : Wood Handbook : Wood as an engineering material. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, Wisconsin, pp 10-1 - 10-24

Gaston CW (2014) Visual Wood Product Trends in North American Nonresidential Buildings. Forest Products Journal, 64(3–4):107–115. doi:10.13073/FPJ-D-13-00077

Gosselin A, Blanchet P, Lehoux N, Cimon Y (2016) Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects. BioResources 12(1). doi:10.15376/biores.12.1.546-570

ISO Standard 12579 (2007) Timber structures—glued laminated timber—method of test for shear strength of glue lines. International Organization for Standardization ISO. Geneva

ISO Standard 6238 (2018) Adhesives - Wood-to-wood adhesive bonds - Determination of shear strength by compressive loading. International Organization for Standardization ISO. Geneva

Janowiak JJ, Manbeck HB, Hernandez R, Moody RC, Blankenhorn PR, Labosky P (1995) Efficient Utilization of Red Maple Lumber in Glued-Laminated Timber Beams. Res. Pap. FPL–RP–541. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, Wisconsin

Jessome AP (1977) Resistance and Related Properties of Native Wood Species in Canada. Eastern Forest Products Laboratory. Ottawa, Canada

Jiang Y, Schaffrath J, Knorz M, Winter S, van de Kuilen J-W (2014) Applicability of various wood species in glued laminated timber - Parameter study on delamination resistance and shear strength. Proceedings of the World Conference on Timber Engineering, Quebec, Canada, 10-14 August 2014

Knorz M (2014) Investigation of structurally bonded ash (Fraxinus excelsior L.) as influenced by adhesive type and moisture. Thesis submitted for the title of Doctor of Engineering. Technischen Universität München. https://mediatum.ub.tum.de/1274270. Accessed 6 December 2018

Knorz M, Neuhaeuser E, Torno S, van de Kuilen J-W (2015) Influence of surface preparation methods on moisture-related performance of structural hardwood–adhesive bonds. International Journal of Adhesion and Adhesives 57:40–48. doi:10.1016/j.ijadhadh.2014.10.003

Knorz M, Schmidt M, Torno S, and van de Kuilen J-W (2014) Structural bonding of ash (Fraxinus excelsior L.): resistance to delamination and performance in shearing tests. European Journal of Wood and Wood Products 72(3):297–309. doi:10.1007/s00107-014-0778-8

Konnerth J, Kluge M, Schweizer G, Miljković M, Gindl-Altmutter W (2016) Survey of selected adhesive bonding properties of nine European softwood and hardwood species. European Journal of Wood and Wood Products 74(6):809–819. doi:10.1007/s00107-016-1087-1

Laguarda Mallo MF, Espinoza O (2015) Awareness, perceptions and willingness to adopt Cross-Laminated Timber by the architecture community in the United States. Journal of Cleaner Production 94:198–210. doi:10.1016/j.jclepro.2015.01.090

Lehmann M, Clerc G, Lehringer C, Strahm T, and Volkmer T (2018) Investigation of the bond quality and the finger joint strength of beech glulam. Proceedings of the World Conference on Timber Engineering, Seoul, Republic of Korea, 20-23 August 2018

Lenth R, Singmann H, Love J, Buerkner P, Herve M (2018) Emmeans: Estimated marginal means, aka least-squares means. Henrik Singmann [ctb], Jonathon. https://CRAN.R-project.org/package=emmeans. Accessed 10 March 2019

Manbeck HB, Janowiak JJ, Blankenhorn PR, Labosky P Jr (1996) Standard Designs for Hardwood Glued-laminated Highway Bridges. Ritter MA, Duwadi SR, Lee PDH, ed(s). Madison, Wisconsin. pp. 351–360

Manbeck HB, Janowlak JJ, Blankenhorn PR, Labosky P. Jr, Moody RC, Hernandez R (1993) Performance of Red Maple Glulam Timber Beams. Res. Pap. FPL–RP–519. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, Wisconsin

Markström E, Kuzman MK, Bystedt A, Sandberg D, Fredriksson M (2018) Swedish architects view of engineered wood products in buildings. Journal of Cleaner Production181:33–41. doi:10.1016/j.jclepro.2018.01.216

Okkonen EA, River BH (1989) Factors affecting the strength of block-shear specimens. Forest Products Journal, 39(1):43-50

R Core Team (2018) R: A language and environment for statistical computing. http://www.R-project.org/. Accessed 3 December 2018

River BH, Vick CB, Gillespie RH (1991) Wood as an adherend. Treatise on adhesion and adhesives. Vol 7. Marcel Dekker Inc., New York. 230 p.

Selbo ML (1975) Adhesive bonding of wood. Tech. Bull. No. 1512. U.S. Department of Agriculture, Forest Service. Washington D.C.

Shedlauskas JP, Manbeck HB, Janowiak JJ, Hernandez R, Moody RC, Labosky P Jr, Blankenhorn PR (1996) Efficient Use of Red Oak for Glued-laminated Beams. Transactions of the ASAE, 39(1):203–209. doi:10.13031/2013.27499

Blue gum: Assessment of its potential for load bearing structures

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ABSTRACT

Portuguese Forest is mainly composed of hardwoods which represented 69% of the forest area in 2010, being Blue gum (Eucalyptus globulus Labill.*) the most abundant species (26%) (INCF 2013). The suitability of Blue gum species for structural application was demonstrated in previous studies. However, the most common uses are still related to pulp and paper industry as well as energy applications. The present paper describes a preliminary study on the potential application of non-destructive tests and analytical methods to predict the most important mechanical properties of glued laminated timber (glulam) beams made of Blue gum. The potential of mixed beams made of Blue gum and Poplar (mix of Hybrid Poplar, White Poplar and Black Poplar) was also analysed. Longitudinal vibration method (LVM) and the transformed section method (TSM) were considered. A total of 7 full-scale glulam beams (4 of Blue gum and 3 mixed) were manufactured in laboratory and tested for determination of modulus of elasticity and bending strength. After the bending tests their density and moisture content were determined, and the bonding performance was checked by delamination and shear strength tests. Correlation coefficients were established between the predicted values (LVM and TSM) and the mechanical properties, indicating a huge potential. The determined mechanical properties were above the typical values found in the literature for the most common hardwoods available in European Forest.*

1. INTRODUCTION

Blue gum is a fast growing hardwood species that presents interesting physical and mechanical properties. Besides, this is the dominant species in the Portuguese forest, occupying 26% of the Forest area (ICNF 2013). The most common uses are the pulp and paper industry as well as energy applications, being largely unknown its potential for other valuable application, like furniture, floors or load bearing structures. The little use of Blue gum as structural material is typically associated with difficulties regarding sawing and drying processes (Franke and Marto 2014).

Nevertheless, some studies have been performed in the last two decades to promote the use of Blue gum in structural applications. Touza Vásquez and P. Saavedra (2002) presented a proposal for drying Blue gum down to 12% moisture content based on two phases, ensuring good quality of the material in terms of absence of cross section collapse. Also Franke and Marto (2014) studied the drying process of Blue gum suggesting radio-frequency pre-treatments for the improvement of the permeability of the wood.

The study of physical and mechanical properties of Blue gum grown in Spain was reported in Alvite et al. (2002) both for sawn wood and glued laminated timber. Average values of 760 kg/m^3, 20580 MPa and 130 MPa were presented respectively for density, modulus of elasticity and bending strength for sawn wood, while for glued laminated timber the average values obtained were 20300 MPa and 125 MPa, for modulus of elasticity and bending strength respectively. A recent study carried out by Martins (2015) on Blue gum grown in Portuguese forest revealed lower mechanical properties for sawn wood (75x75 mm^2): average values of 18150 MPa for modulus of elasticity and 75 MPa for bending strength, yet reasonable bending properties. Previous test results obtained from clear wood specimens are presented in M6 sheet (LNEC 1997) with average values of 127 MPa for bending strength and 17500 MPa for modulus of elasticity.

The study of innovative applications, such as glued laminated timber, was performed by Lopez-Suevos (2009). This study focused on the use of primers to enhance the bond durability of Blue gum, through delamination and shear strength tests, being observed a significant improvement of the bonding performance in the case of the PUR adhesive. Another genus of Eucalyptus, Eucalyptus grandis, was considered for glued laminated timber production, considering also the combination with Poplar (*Populus* x *euramericana*, 'Neva' Clone) (Castro and Paganini 2003).

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The present research focuses on the use of Blue gum and its combination with Poplar (both grown in Portuguese forest) for glued laminated timber. The use of non-destructive methods (longitudinal vibration method and transformed section method) was considered for the prediction of static bending properties, since previous studies have demonstrated high accuracy of both methods (Hodousek et al. 2017 and Martins et al. 2018). A total of 7 glulam beams were produced in laboratory, non-destructively tested through longitudinal vibration method and destructively tested following EN 408 requirements (CEN 2012). Finally, the bonding performance of the PUR adhesive was evaluated through delamination and shear strength tests according to EN 14080 (CEN 2013).

2. Materials and Methods

2.1. Characterization of Raw Material and Assembly Process of Glulam Beams

A total of 35 timber boards, 26 of Blue gum (BG) and 9 of Poplar (BP) were chosen from larger samples. The selected boards were measured to determine their cross sectional dimensions, length, weight and moisture content (using a moisture meter device) resulting in average dimensions of 36 x 125 x 2479 mm^3 and 38 x 118 x 2573 mm^3 for BG and BP samples, respectively. The average value and standard deviation of density and moisture content were 905±55 kg/m^3 and 13.9±0.6% and 417±25 kg/m^3 and 14.2±1.9%, for BG and BP samples, respectively.

In a first step, all boards were non-destructively assessed through the longitudinal vibration method (LVM). A rubber mat between the steel plate and the board was used to ensure minimal attenuation of passing waves. Average values of 20450 MPa (COV = 13.4%) and 10100 MPa (COV = 4.9%) were determined, for BG and BP respectively.

2.2. Assembly Process of Glulam Beams

Each glulam beam was composed of five lamellas. Boards were sorted to place the lowest E_{dyn_b} in the central lamella then increasing stiffness towards the external layers, ensuring similar values between tension and compression sides. For the mixed glulam beams of Blue gum and Poplar (HBGBP), Poplar was used in the 3 central layers, to maximize the density reduction of the cross section.

Before assembly the boards were planed to the final thickness of 24 mm and trimmed to 100 mm wide and to the shortest length of each group of five lamellas (between 2300 mm and 2500 mm). Each lamella in its final dimensions was non-destructively assessed through LVM, providing a new value of dynamic modulus of elasticity (E_{dyn_l}). Re-arrangement of the lamellas was made when necessary. Figure 1 presents the distribution of E_{dyn_l} values of all 7 glulam beams, the respective average value, $E_{dyn\_l\_av}$ and the density of each beam. From each group of five columns the left one corresponds to the compression layer and the right one to the tension layer.

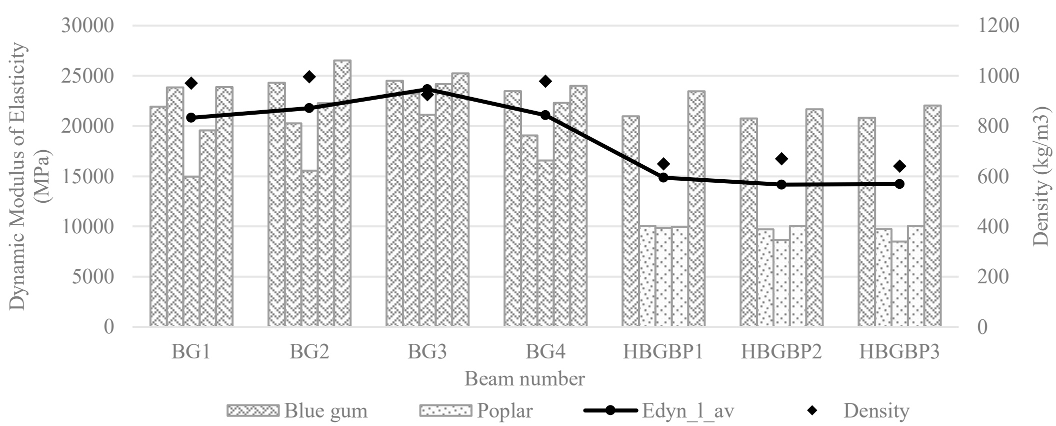

Figure 1: Summary of E_{dyn_l} values and their distribution within each glulam beam.

The assembly of lamellas was made with a one component polyurethane adhesive, commercially available for load bearing structures. Previous studies on Maritime pine (Martins 2018) and Poplar (Martins et al. 2017) with the reference Purbond HB S 709, showed the need of a primer. PR 3105 primer especially developed for bonding Blue gum was used. Based on those results an amount of adhesive of 180 g/m^2 was considered and 20 g/m^2 of primer. The adhesive was applied with a manual roller spreader and primer was sprayed. Both amounts were controlled by weighing.

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The clamping pressure was 1.2 MPa (maximum recommended at the adhesive TDS) applied by a series of hydraulic jacks spaced by 500 mm and with a maximum load capacity of 5 tons each, under controlled conditions of temperature (20±2ºC) and relative humidity (65±5%). After the pressing process (7 hours), beams stayed in controlled conditions for a minimum curing period of 7 days. Later on the beams were planed to final dimensions of 92 mm x 120 mm x 2300 mm (width x height x length).

2.3. Mechanical Properties: non-destructive and destructive characterization

Non-destructive prediction of mechanical properties

Prediction of mechanical properties of glulam beams is essential to ensure the quality of the material. In the present paper two methods were considered: i) LVM and ii) Transformed Section Method (TSM).

The LVM method was applied to all glulam beams, following the same procedure adopted for boards/lamellas. Each glulam beam was measured (width, height, length) and weighted. The moisture content of each glulam beam was determined based on average value of the respective lamellas. From the application of LVM it was determined the dynamic modulus of elasticity (E_{dyn_LVM}).

The TSM is a simple analytical method fully described in annex A4 of ASTM D 3737 (ASTM 2005), used to predict the static modulus of elasticity and bending strength properties. It is based on the conversion of a section with three well defined stiffness zones (symmetrically displayed) into a section with homogeneous properties through a transformed section factor. The predicted values of modulus of elasticity (E_{dyn_TSM}) were determined through the multiplication of the transformed section factor by the average modulus of elasticity of the outer stiffness zone.

Static tests

Modulus of elasticity (local E_{local} and global E_{global}) and bending strength (f_m) were determined through four-point bending tests of full scale glulam beams according to EN 408 (CEN 2012). Both tests were performed with a total span of 2.16 m and 0.72 m of load span. Both supports and loading points had a piece of timber between glulam beam and steel elements to minimize local indentation on the glulam beams.

Modulus of elasticity tests were done in displacement control (10 mm/min) recording load-deformation data between 10% and 40% of the predicted failure load at every second. Deflection was measured with linear variable differential transformer (20-50 mm maximum capacity) and loads were measured using a load cell (200 kN maximum capacity).

After failure, moisture content of each glulam beam was determined by the oven-dry method following EN 13183-1 (CEN 2002). At least one specimen (representative of the full cross section) per beam was collected, free from defects and at least 0.3 m away from the ends. The same specimens were used for density calculation. Density and modulus of elasticity were adjusted to a reference moisture content of 12% according to EN 384 (CEN 2004). Bending strength values were multiplied by a factor to account for a reference depth of 600 mm and by a factor to account for a reference lamella thickness of 40 mm as mentioned in EN 14080 (CEN 2013). Test results and the adjusted values are summarized at Table 1.

2.4. Quality Control of Bonding Process

The bonding quality of glue lines was assessed trough delamination and shear strength tests following the procedures described in EN 14080 (CEN 2013). At least one specimen per glulam beam was collected for delamination and one for shear strength test. Delamination tests followed Method A of Annex C, involving the full cross section (92 mm x 120 mm) and 75 mm of length. Shear strength tests followed Annex D considering specimens of 50 x 50 x 120 mm^3 (length x width x height). The test was performed in displacement control with a speed rate of 0.06 mm/s. Table 2 presents the results both for delamination and shear strength tests.

3. Results and Discussion

3.1. Mechanical Properties

Table 1 presents the individual results of non-destructive tests (E_{dyn_LVM} and E_{dyn_TSM}) as well as of static tests (E_{local}, E_{global} and f_m), moisture content (w) and density (ρ) and the adjusted values of density ($\rho_{12\%}$), modulus of elasticity ($E_{12\%}$) and bending strength (f_{m_adj}).

Table 1: Summary of non-destructive and static test results of Blue gum beams (BG) and mixed beams of Blue gum and Poplar (HBGBP)

Beam number	w (%)	ρ (kg/m³)	E_{dyn_LVM} (MPa)	E_{dyn_TSM} (MPa)	E_{local} (MPa)	E_{global} (MPa)	f_m (MPa)	$\rho_{12\%}$ (kg/m³)	$E_{12\%}$ (MPa)	f_{m_adj} (MPa)
BG1	13.2	978	21545	22593	24577	21885	125.8	972	22417	118.8
BG2	13.0	996	22167	24480	28803	24829	130.7	991	25310	123.5
BG3	13.1	938	24062	24605	28394	24805	131.9	933	25367	124.7
BG4	12.6	980	21400	23044	27132	23332	127.6	977	23602	120.6
Average	13.0	973	22294	23680	27226	23713	129.0	968	24174	121.9
Minimum	12.6	938	21400	22593	24577	21885	125.8	933	22417	118.8
Maximum	13.2	996	24062	24605	28803	24829	131.9	991	25367	124.7
COV (%)	2.2	2.5	5.5	4.3	7.0	5.9	2.2	2.6	5.9	2.1
HBGBP1	13.6	654	15304	19615	22638	20010	107.0	649	20663	101.1
HBGBP2	12.8	678	14409	18754	29815	18768	88.9	675	19064	84.0
HBGBP3	13.1	657	14438	18934	27835	18601	93.6	653	19006	88.5
Average	13.2	663	14717	19101	26763	19126	96.5	659	19578	91.2
Minimum	12.8	654	14409	18754	22638	18601	88.9	649	19006	84.0
Maximum	13.6	678	15304	19615	29815	20010	107.0	675	20663	101.1
COV (%)	3.3	2.0	3.5	2.4	13.9	4.0	9.7	2.2	4.8	9.9

Very good mechanical properties were obtained for BG glulam beams. Mean static modulus of elasticity was approximately 16.6% higher compared to the results presented by Alvite et al. (2002) (20300 MPa) whereas for bending strength the results were 2.9% higher in the present study (Alvite et al. (2002) - 125 MPa). A comparison with previous studies on Blue gum sawn wood revealed even higher differences. The technical data sheet M6 published by LNEC (1997) for Blue gum indicates a range of densities between 750 kg/m³ and 850 kg/m³, average modulus of elasticity of 17500 MPa (35.5% lower) and bending strength of 127 MPa (1.2% lower).

The combination of Blue gum with Poplar resulted in a significant decrease of the average density (31.9%). Also the mechanical properties registered a decrease of 19.3% and 25.2% for modulus of elasticity and bending strength, respectively. The comparison of HBGBP results with glulam beams fully made of Poplar tested by Martins et al. (2018) showed an increase of 53.9%, 77.8% and 73.3% for density, modulus of elasticity and bending strength, respectively, based on the adjusted values. Castro and Paganini (2003) studied the combination of Poplar ("Neva" clone) with several clones of *Eucalyptus grandis* ("358", "7", "329" and "330"). The clone "330" provided the highest mechanical properties; therefore, the mixed glulam beams made of Poplar are compared with clone "330" of *Eucalyptus grandis*, being observed higher values with the combination of the present study, namely 35.6%, 31.4% and 61.6% for density, modulus of elasticity and bending strength. This shows the potential of Blue gum species for load bearing structures as glulam beams.

Failure of the glulam beams occurred in the central third span and were triggered by tension failure of the bottom lamination. In all glulam beams it was observed a ductile behavior (Figure 2) associated with the presence of compression folds on the top laminations (Figure 3).

The structural efficiency (relation between a specific mechanical property and the density) was determined for each group of beams. For HBGBP glulam beams the highest values were determined, 29.7 for modulus of elasticity and 0.138 for bending strength. On the other hand, BG glulam beams had 25.0 and 0.125 for modulus of elasticity and bending strength, respectively. The values determined for modulus of elasticity are in line with the ones presented by Castro and Paganini (2003): for mixed glulam beam Poplar/E. grandis "330" the structural efficiency for bending strength was significantly lower (0.129).

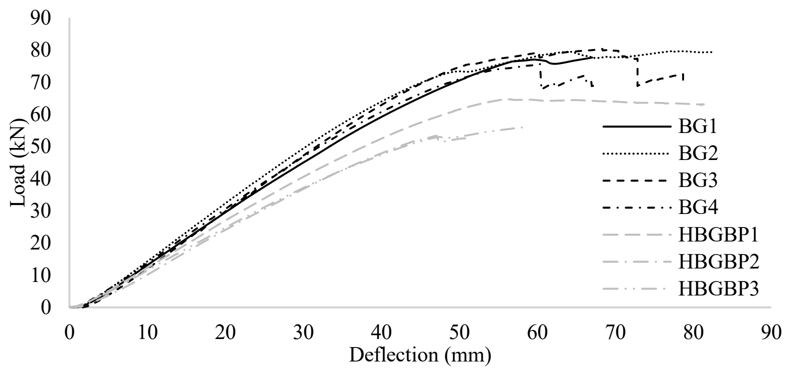

Figure 2: Load-deflection curves of BG and HBGBP glulam beams

Figure 3: Load-deflection curves of BG (left) and HBGBP (right) glulam beams

The analysis of non-destructive values showed a better accuracy of TSM to predict the static values of modulus of elasticity both for BG and HBGBP glulam beams. It could be also mentioned that LVM underestimated static modulus of elasticity especially for HBGBP glulam beams with a difference about 4000 MPa. A linear regression analysis between the non-destructive methods (E_{dyn_TSM} and E_{dyn_LVM}) and static modulus of elasticity ($E_{12\%}$) results was performed (Figure 4). Correlation coefficients close to 1.0 for TSM (both BG and HBGBP glulam beams) and for LVM (HBGBP glulam beams) were determined. The prediction of bending strength through non-destructive methods showed similar values as for static modulus of elasticity. The prediction considering the E_{dyn_LVM} provided a correlation coefficient of 0.83, significantly higher if compared to the prediction of $E_{12\%}$ (0.72). It should be noted that the number of glulam beams tested was and the size of sample should be increased to prove these results.

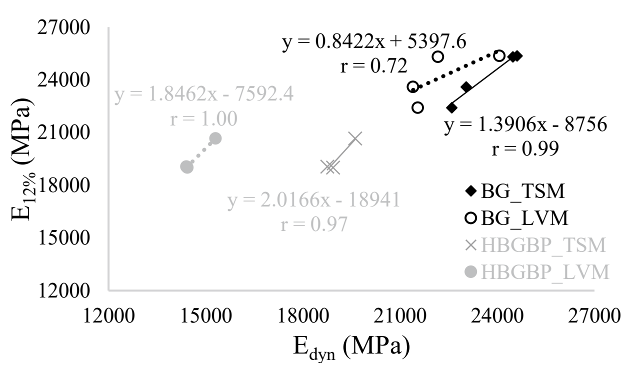

Figure 4: Correlation coefficients between non-destructive tests (E_{dyn_TSM} and E_{dyn_LVM}) and static modulus of elasticity ($E_{12\%}$)

3.2. Quality Control of Glue Lines

Table 2 presents a summary of delamination and shear strength results. Delamination test results (Method A) evidence an inadequate performance of the bonding procedure followed considering the maximum limits defined for softwoods in EN 14080 (CEN 2103) both for 2nd and 3rd test cycles, 5% and 10%, respectively. Even HBGBP beams presented excessive values, with only one specimen showing total delamination below 10%. Figure 5 shows that the inadequate performance was observed at the glue lines between Blue gum lamellas and between Blue gum and Poplar. Glue lines between Poplar lamellas presented a good performance, as previously demonstrated by Martins et al. (2017).

Table 2: Summary of non-destructive and static test results from Blue gum beams (BG) and mixed beams of Blue gum and Poplar (HBGBP)

Beam number	Total delamination (%)			Shear strength tests		
	Specimens	2nd cycle	3rd cycle	Specimens	Shear strength (MPa)	WFP (%)
BG1	D1 / D2	89 / 88	92 / 91	S1 / S2	15.4 / 15.1	63 / 79
BG2	D1 / D2	91 / 93	93 / 94	S1 / S2	16.8 / 15.4	65 / 44
BG3	D1 / D2	64 / 62	68 / 70	S1 / S2	16.8 / 17.0	84 / 84
BG4	D1 / D2	88 / 86	91 / 91	S1 / S2	16.2 / 15.7	78 / 89
HBGBP1	D1 / D2	9 / 6	10 / 6	S1 / S2	9.4 / 9.5	99 / 80
HBGBP2	D1	34	35	S1	9.9	80
HBGBP3	D1	21	22	S1	11.2	88

Figure 5: Delamination specimens after 3rd test cycle (Method A): BG3-D1 specimen (left) and HBGBP2-D1 specimen (right)

The analysis of average values of shear strength showed significant differences between BG and HBGBP glulam beams. According to Vick (1999), shear strength values increased for higher densities (up to a certain point) as it was observed for BG glulam beams compared to HBGBP glulam beams. Figure 6 presents the individual shear strength and wood failure percentage (WFP) values both for BG and for HBGBP glulam beams. HBGBP glulam beams had two different responses of their glue lines, namely BG/BP and BP/BP. From all the tests, three glue lines (2 BG and 1 HBGBP-BG/BP) did not fulfilled the minimum requirements of EN 14080 (CEN 2013). A comparison between HBGBP-BG/BP and HBGBP-BP/BP clearly shows that Poplar species conditioned the shear strength values and Blue gum was responsible for the lowest values of wood failure percentage measured.

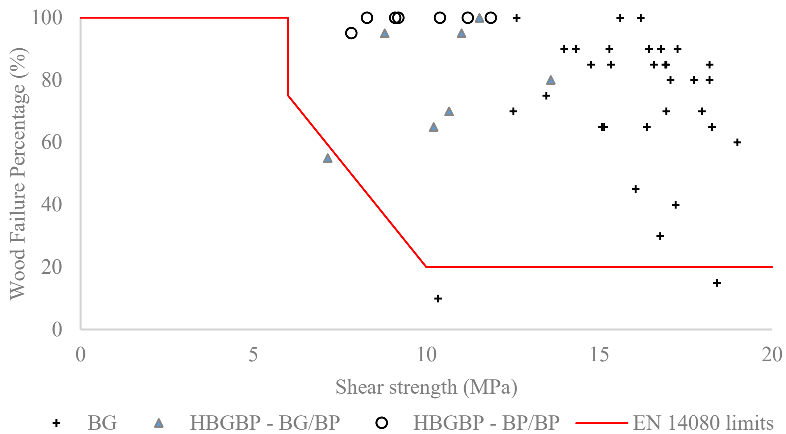

Figure 6: Invidivual values of shear strength and wood failure percentage

4. Conclusions

The research performed had as main goal the assessment of the potential of Blue gum timber for load bearing structures as glulam beams made of a single species or mixed with Poplar. To accomplish the established aims, an experimental campaign was carried out. A total of 7 glulam beams (4 of BG and 3 HBGBP) were produced with five lamellas each of 24 mm of thickness and tested at SerQ laboratory to assess the most important mechanical properties in bending as well as the respective density and the bonding performance (delamination and shear strength). Assembling followed the specifications of EN14080 for softwoods and the technical data sheet from the adhesive used. Two non-destructive methods were considered to predict the mechanical properties, namely: i) longitudinal vibration method (also applied to raw material characterization) and ii) transformed section method. Delamination and shear strength tests were performed to assess the bonding quality of glue lines. The main conclusions from this study are as follows.

- Very high mechanical properties were obtained both for BG and HBGBP glulam beams with average values of 23700 MPa and 19100 MPa for static modulus of elasticity and 121 MPa and 91 MPa for bending strength, respectively.
- The comparison of the present results with similar studies confirm the potential of Blue gum or its combination with Poplar for load bearing structures.
- Transformed section method predicted accurately the mechanical properties of both BG and HBGBP glulam beams (correlation coefficients above 0.97). Longitudinal vibration method also showed potential to be used namely on the non-destructive characterization of the raw material.
- High correlation coefficients were obtained both for static modulus of elasticity and bending strength considering both non-destructive methods applied.
- An inadequate bonding performance was observed in delamination tests, for glue lines between BG lamellas and on the interface between Blue gum and Poplar with the adhesive and bonding procedure adopted.
- Future work should focus on the bonding performance improvement, and the increase of the number of glulam beams tested to validate the present results. Also the finger-joint performance should be considered (tensile and bending tests), namely its influence on bending strength values of glulam beams.

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REFERENCES

Alvite, J. D. B., M. C. Touza Vásquez and F. S. Infante (2002). White Eucalyptus Species manual (in Spanish). Ourense, Fundación para o Fomento da Calidade Industrial e Desenvolvimento Tecnológico de Galicia.

ASTM (2005). ASTM D 3737 - Standard Practice for Establishing Allowable Properties for Structural Glued Laminated Timber (Glulam).

Castro, G. and F. Paganini (2003). "Mixed glued laminated timber of poplar and Eucalyptus grandis clones." Holz Als Roh-Und Werkstoff 61(4): 291-298.

CEN (2002). EN 13183-1 - Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method. Brussels.

CEN (2004). EN 384 - Structural timber - Determination of characteristic values of mechanical properties and density. Brussels.

CEN (2012). EN 408 - Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. Brussels.

CEN (2013). EN 14080 - Timber structures - Glued laminated timber and glued solid timber - Requirements. Brussels.

Franke, S. and J. Marto (2014). Investigation of Eucalyptus globulus wood for the use as an engineered material. WCTE 2014 - World Conference on Timber Engineering. Quebec City, Canada.

Hodousek, M., A. M. P. G. Dias, C. Martins, A. F. S. Marques and M. Bohm (2017). "Comparison of Non-Destructive Methods Based on Natural Frequency for Determining the Modulus of Elasticity of Cupressus lusitanica and Populus x canadensis." Bioresources 12(1): 270-282.

ICNF (2013). IFN6 – Areas land use and forest species in mainland Portugal in 1995, 2005 and 2010 (in Portuguese). I. d. C. d. N. e. d. Florestas. Lisboa: 34.

LNEC (1997). M6 – Common Eucalytpus (in Portuguese). Lisbon, Portugal

Lopez-Suevos, F. and K. Richter (2009). "Hydroxymethylated Resorcinol (HMR) and Novolak-Based HMR (n-HMR) Primers to Enhance Bond Durability of Eucalyptus globulus Glulams." Journal of Adhesion Science and Technology 23(15): 1925-1937.

Martins, C. (2018). Health Assessment of Glued Laminated Timber Elements (in Portuguese). PhD thesis, University of Coimbra.

Martins, C., A. M. P. G. Dias and H. Cruz (2017). Glulam made by Poplar: delamination and shear strength tests. ISCHP 2017 - International Scientific Conference on Hardwood Processing. Lahti, Finland.

Martins, C., A. M. P. G. Dias and H. Cruz (2018). "Using non-destructive testing to predict the mechanical properties of glued laminated poplar." Proceedings of the Institution of Civil Engineers – Structures and Buildings.

Martins, M. (2015). Eucalyptus globulus characterization for structural applications (in Portuguese). MSc, University of Coimbra.

Vick, C. B. (1999). Adhesive Bonding of Wood Materials - Chapter 9. Wood Handbook - Wood as an engineering material. Madison, Forest Products Laboratory.

Touza Vásquez, M. C. and F. Pedras Saavedra (2002). An industrial proposal for drying timber of Eucalyptus white (Eucalyptus globulus) from Galicia (in Spanish). CIS-Madera.