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Development of Arc-laminated Bamboo Lumber

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This study was conducted to develop arc-laminated bamboo lumber (ALBL) from bamboo splits using middle portions of the culms of *Kauayan-tinik* (*Bambusa blumeana* Schult.f.) and *Bolo* [*Gigantochloa levis* (Blanco) Merr.]. Arc lamination of quarter split culm was employed instead of the rectangular machined bamboo slats. Polyvinyl acetate (PVAc) and polyurethane (PUR) adhesives with glue spreads of 80, 120, and 160 g/m² were used. Mechanical press with an arc mold was used in the lamination. Conditioned laminated samples were tested following ASTM and PNS procedures. In general, the arc-laminated *B. blumeana* had better physical properties than *G. levis* as shown by the former's lower radial and tangential swelling in both PVAc and PUR adhesives regardless of glue spread. The mechanical properties and delamination tests showed that best glue spread is 80 g/m² for both bamboo species. This implies that glue spread can be lowered up to 80 g/m² for ALBL to reduce glue consumption.

Keywords: arc-segment lamination, delamination, E-bamboo, physico-mechanical properties, PUR, PVAc

INTRODUCTION

Bamboo is known as the "poor man's timber." This is due to its ready availability in the rural areas and its diverse traditional uses for structural and non-structural applications. Round poles can be used for housing or building components such as columns, posts, and beams. When cut lengthwise into half, it can be used to create doors, walls, windows, shelves, or counters. Cut into slats, it is useful for flooring. It can also be woven into mats for walls and ceilings. Likewise, the poles in round, halved, crushed, slat, and strip forms can be used for making furniture and handicrafts (Espiloy *et al.* 2007, Razal and Palijon 2009).

In the last two decades, revolutionary processing systems and equipment have been developed for the industrial utilization of bamboo. These include machines for producing composite panels, which are collectively known as engineered bamboo (E-bamboo) products. Several innovative types of E-bamboo boards have received worldwide acknowledgement as alternative for wood-based panels (Chaowana 2013). These include laminated bamboo veneer, laminated bamboo slats, bamboo mat board, particleboard, and medium density fiberboard. (Marsh and Smith 2006; DOST-PCAARRD 2011, 2017).

E-bamboo products made locally involve glue-lamination of slats into planks and panels for flooring, walling, and furniture. Local manufacturers typically rely on imported adhesives such as polyvinyl acetate (PVAc) and polyurethane (PUR) – the most widely used adhesives in the furniture and construction industries (Stoeckel *et al.* 2013). The cheapest and most popular among these is Rakoll, a PVAc adhesive (Cabangon 2009, Alipon and Cabangon 2013).

In the Philippines, according to Alipon and Cabangon (2013), most E-bamboo are made from glue-laminated rectangular slats from the butt portion of thick-culmed bamboo species such as *Kauayan-tinik* (*Bambusa blumeana* Schult.f) and

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giant bamboo [*Dendrocalamus asper* (Schult.) Backer]. The slats are sawn from round poles using a twin rip saw to produce uniform width. After drying, the sawn slats are planed to the desired thickness then glue-laminated into planks or panels either horizontally or vertically (Alipon *et al.* 2011, Alipon and Cabangon 2013). This process is laborious and wasteful because the four sides of the slats undergo machining and the glue-laminated panels are further planed and trimmed to final dimensions. The processing system also requires various equipment that are too expensive for micro, cottage, and small bamboo enterprises.

Natividad and Jimenez (2015) developed a different gluing method by arc- laminating quarter-split *buho* [*Schizostachyum lumampao* (Blanco) Merr.] culms. Results of the static bending test showed higher modulus of elasticity (MOE) and modulus of rupture (MOR) for PUR-glued specimens at 120 g/m² glue spread compared to raw *buho* slat. The MOE and MOR for PUR-glued arc-laminated bamboo lumber (ALBL) averaged 8 GPa and 42 MPa, respectively. In contrast, the raw *buho* slat averaged 6 GPa for MOE and 31 MPa for MOR (Espiloy *et al.* 2007). For the *buho* ALBL, horizontal shear type of failure along the glue lines was commonly observed during the static bending test. This implies the need to scrape or roughen the cutin layer of *buho* to improve glue adhesion and consequently increase the bending strength. This may be done by sanding using a very rough sand paper *i.e.*, grit number 60 or by completely removing the waxy cutin layer through a mechanical scraper.

The idea of developing ALBL from the middle part of thicker-culm bamboo species was based on a study by Natividad and Jimenez (2015). The goal is to increase pole's utilization for making E-bamboo. Most E-bamboo are produced from sawing and planing to produce rectangular slats for gluing. The slats are obtained only from the thick bottom part of the pole – never from the middle and top.

In the present study, the middle of the bamboo pole was cross-cut in between the internodes to remove the unwanted nodes, as the node bulge hinders the close fitting of the arc laminates during pressing. In addition, nodes reduce the strength of laminated bamboo due to its low density and irregular vascular bundle arrangements (Anokye *et al.* 2016). After cutting of the internode, the culm was split quarterly using a bolo knife. The four-pieces split culm were the ones glued in arc-lamination. Thus, culm wall was almost equal in thickness and fit closely upon pressing.

The four sides of the ALBL are trimmed to the desired size only once, thus minimizing raw materials waste. In a similar study on arc-segment lamination, Zhou *et al.* (2016) showed a very detailed mathematical derivation of the formula and calculation of the utilization rate of recombined arc-segment bamboo lumber (RABL). They showed that RABL has 1.8 times higher bamboo utilization rate and used less adhesive by 0.56 times than rectangular slat laminated bamboo.

The present study developed a process for the arc-lamination of bamboo splits from middle part of *B. blumeana* and *G. levis* culms. The culms were sanded to remove the waxy cutin layer for better glue adhesion compared to Natividad and Jimenez's (2015) previous study, which used a rasp. Also, a lower glue spread was studied to reduce glue consumption. Effects of glue type (PVAc and PUR) and glue spread (80, 120, and 160 g/m^2) on the physical and mechanical properties of the ALBL from the two bamboo species were investigated.

METHODOLOGY

Raw Materials

Culms of *B. blumeana* and *G. levis* bamboo of unknown age were bought from Cavinti, Laguna, Philippines. The middle portion of these were air-dried for three months prior to processing.

Preparation of Specimens. The dried bamboo parts were cross-cut based on length of internode with a mechanized pole cutter that had a blade diameter of 350 mm with two teeth per inch and kerf size of 3 mm. Cross-cutting was done per species. Each internode obtained was immediately quarter-split using a bolo knife, with the splits were tied together to avoid mixing with other samples. The bolo knife was used to quarter-split manually the bamboo internode so that splitting can be adjusted to obtain the arc that would closely fit with one another, as some internode had uneven thickness of the culm wall. Sharpness of the bolo knife was ensured by slicing a piece of folded paper such that if during slicing no fibrous edge were produced, then the knife was considered reasonably sharp and ready for splitting/cutting. The four splits of each internode were sanded per group to ensure that each quarter-split piece that belong together would not be mixed with other quarter-split internodes. A grit number 60 sandpaper was used to remove both the bamboo's inner and outer skin. This grit number is for heavy sanding and stripping, which is the one needed to remove the waxy cutin layer of bamboo. Sanded samples for each treatment group were dusted off and coded for easy distinction.

Gluing of Specimens. The sanded samples were stored in an air-conditioned room at 23 ºC for two weeks with an RH of 65 ± 5%. The two-weeks storage duration was made to ensure that the samples to be arc laminated had an almost similar moisture content based on established standards such as ASTM D143-94 (ASTM 2000a). The arc splits were applied with the required amount of glue per laminate. The quantity of glue was measured using a top loading balance. The split laminate was placed on the balance pan then tared to zero. The glue in a bottle dispenser was poured slowly until the required amount per unit area was attained. It was then spread manually using a piece of rubber tire interior. Four laminates were assembled and pressed mechanically with an arc mold steel pipe. The specific pressing pressure used in arc lamination was 10 kg/cm^2. The main critical factor in arc lamination pressing is the close fitting of the arc laminates to avoid gap in the glue line. The laminated bamboo splits were allowed to cure in the press for 6 hours (minimum duration before removal of the pressure on the adherends). This is based on the established practice in the FPRDI gluing laboratory for the cold setting adhesive like PUR and PVAc to have cured sufficiently before the pressure is removed. Then, the arc laminated samples were conditioned in a room at 23 ± 2 ºC and relative humidity of 65 ± 5% for two weeks prior to machining to produce samples for testing of various properties. The two-week waiting time prior to machining of the material was made, as it served as the conditioning period of the samples before actual physical and mechanical property tests. In actual production say in shop works to fabricate products like furniture, there is no need to wait that long before the samples can be machined. A day is long enough already.

Physical and mechanical property tests. Samples per treatment combination were comparatively tested based on ASTM D 143-94 (ASTM 2000a) and ASTM D 1037-99 (ASTM 2000b) standards. Slight modification on the procedures and specimens sizes was made.

The physical properties tested were moisture content (MC), relative density (RD), water absorption (WA), and thickness swelling – radial (TSR) and thickness swelling – tangential (TST). Specimen size for the MC and RD was 25 mm x 25 mm x 25 mm. The sample's initial weight (Wi) was obtained using a digital top loading balance while volume (Vm) was determined by water immersion. After obtaining the volume, the samples were dried in an oven at 103 ± 2 ºC until constant mass/oven dry weight (Wo) was attained. MC was computed as the loss in mass expressed in percent of the Wo. RD was obtained as the ratio of Wo over Vm divided by the density of water. For the WA, TSR, and TST, specimen size was 25 mm x 25 mm x 100 mm. WA, TSR, and TST were determined by submerging specimens horizontally in water for 24 hours. The samples were drained of excess water, wiped dry, and measured for change in thickness and amount of water absorbed. TSR and TST were measured at three marked points along the length of each sample with a digital micrometer. WA, TSR, and TST were expressed as percentage of the original weight and thickness, respectively.

For the mechanical properties, specimen size was 25 mm x 25 mm x 305 mm. The number of layers of the specimens tested were made of either three or four layers each. ALBL made from thick arc laminates when machined to flexural samples were reduced to three layers with two glue lines. The thin arc laminates when machined still had four layers and three glue lines. MOR and MOE were determined for each specimen using a Shimadzu universal testing machine. Loading rate was 1.3 mm/min applied at the center of 255 mm span of the specimen.

The bond test followed the PNS 196 (DTI-BPS 2000) procedure for delamination test of the laminates. Specimens measuring 25 mm x 25 mm x 100 mm were submerged in water at 24 ± 2 ºC for four hours. These were then removed and dried in an oven at 49 ± 2 ºC for 19 hours. This procedure was repeated until three cycles. Delaminated specimens in each glue line were counted and expressed as percentage based on the samples' total glue line.

Using a Phenom XL desktop scanning electron microscope (Phenom-World BV, The Netherlands) mapping at 10 kV, a 3-D reconstruction of the surface images of the unsanded and sanded *G. levis* and *B. blumeana* were taken to determine the rind's surface roughness.

Experimental design. A three-factor factorial in completely randomized design (CRD) was used. The three factors were bamboo species (*B. blumeana* and *G. levis*); glue type (PVAc and PUR); and glue spread (80, 120, and 160 g/m^2). Four replicates of samples per treatment combination were made for testing. Analysis of variance (ANOVA) per property tested was made and means were separated by Duncan's multiple range test (DMRT). Glue spread was correlated with the properties tested.

Prototype products. Additional samples of arc-laminated bamboo splits were made from *G. levis.* These were used in producing furniture parts as they were easier to process and had longer internodes than *B. blumeana.* Prototypes were made to highlight the various decorative geometrical patterns that can be created from the figures of the arc laminates, which resemble the prominent annual growth ring of temperate wood species when viewed at cross-section.

RESULTS AND DISCUSSION

Physical Properties

Moisture content (MC). For both species, the samples had basically the same MC of about 13% (Figure 1). Hence, any variability in other properties tested could not be accounted to it.

Water absorption (WA). WA varied across specimens. ANOVA shows that among the three main factors, only glue spread ($p = 0.021$) contributed to the variability of the WA (Table 1). Among the interaction effects, glue type x glue spread (*p* = 0.014), species x glue spread (*p* = 0.007) and the interaction of the three main factors (*p* = 0.045) contributed to the variability of the mean WA.

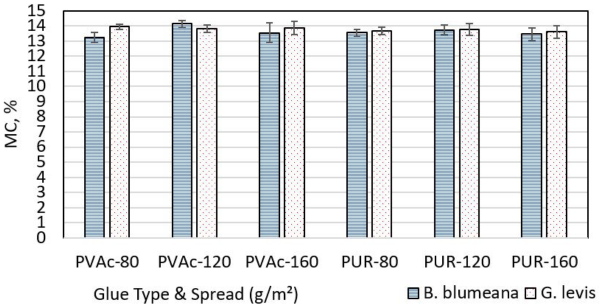


Figure 1. Moisture content of ALBL.

WA for all PVAc and PUR samples, regardless of species, decreased as the amount of glue spread increased as evidenced by their negative correlation (Table 2). This behavior might have something to do with the adhesive layer in the glue joint that served as barrier to water during soaking. Thus, in general, the higher the amount of glue spread, the thicker the glue barrier against WA.

In other studies (Zhou *et al.* 2016, Li *et al.* 2016), this trend was not observed because no correlation was made between glue spread and WA. In Natividad and Jimenez's (2015) study, WA did not increase with inceasing PUR glue spread (60, 120, and 240 g/m²) on arc-laminated *buho*. This may be due to the different anatomical characteristics of *buho*, lower RD, and the greater number of laminated layers compared to species used in the present study.

Thickness swelling (TS). TS of all treatment combinations was very varied (Table 2). For both species and for all treatment combinations, radial swelling was higher than tangential swelling for the glue-laminated split bamboo. In a study by Espiloy *et al.* (2007), the shrinkage of six commercial species of bamboo was illustrated. It showed that radial shrinkage is higher than tangential shrinkage by an average of 80%. Similar findings were also showed by Anokye *et al.* (2014) in their study, wherein mean shrinkage of internode strips of *Gigantochloa scortechinii* and *Bambusa vulgaris* showed higher shrinkage in radial when compared to tangential. The opposite of shrinkage is swelling. Thus, in this study, it would be obvious that even if the bamboo laminates were glued together, it would still follow the behavior of individual laminates. This finding supports the previous study of Natividad and Jimenez (2015) on glue-laminated *buho* (*S. lumampao*) lumber where TSR was found greater than TST by about 42%.

The shrinkage or swelling behavior of bamboo and laminated bamboo is different from wood. The apparent shrinkage of bamboo in radial is equal or slightly greater than the tangential direction whereas in wood, tangential shrinkage almost double the radial shrinkage. The absence of traversing radial parenchymatous ray cells in bamboo, which in wood act as structural components restraining shrinkage in the radial section, makes the radial shrinkage of bamboo slightly higher than tangential shrinkage (Liese and Tang 2015).

Table 1. ANOVA on WA, TSR, and TST of glue-laminated bamboo lumber as a function of species, glue type, glue spread, and interaction of species, glue type, and glue spread.

Source of Variation		WA (%)		TSR (%)		TST (%)	
	DF	*F*-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Species	1	0.50	0.486^{ns}	7.90	0.008**	3.18	0.082^{ns}
Glue Type	1	0.22	0.645^{ns}	4.26	0.046*	4.38	0.043*
Species x Glue Type	1	2.83	0.101^{ns}	0.18	0.672^{ns}	0.33	0.572^{ns}
Glue Spread	2	4.33	0.021*	2.23	0.123^{ns}	5.55	0.008**
Species x Glue Spread	2	5.82	0.007**	3.78	0.032*	0.81	0.455^{ns}
Glue Type x Glue Spread	2	4.85	0.014*	1.94	0.158^{ns}	1.22	0.306^{ns}
Species x Glue Type x Glue Spread	2	3.39	0.045*	1.72	0.194^{ns}	4.85	0.014*
Error	36						
Total	47						
R-square (%)		52.82		46.80		47.63	
Coeff. Var.		22.30		45.55		29.27	

Notes:
** – significant at 1% level of probability
* – significant at 5% level of probability
ns – not significant

Table 2. Mean physical properties of ALBL and their correlation with glue spread.

Species	**Treatment**	**WA, % *(SD)***	**TSR, % *(SD)***	**TST, % *(SD)***
B. blumeana	PVAc-80	24.19 *(2.95)*	2.45 *(0.34)*	1.36 *(0.17)*
	PVAc-120	17.44 *(3.38)*	2.73 *(1.48)*	1.32 *(0.37)*
	PVAc-160	16.37 *(5.79)*	2.90 *(2.00)*	1.43 *(0.68)*
Correlation (*r*)		**–0.63**	**0.14**	**0.07**
B. blumeana	PUR-80	21.11 *(6.58)*	1.76 *(0.47)*	1.40 *(0.29)*
	PUR-120	16.37 *(2.17)*	2.14 *(0.32)*	1.04 *(0.16)*
	PUR-160	12.86 *(1.12)*	2.30 *(0.52)*	0.78 *(0.15)*
Correlation (*r*)		**–0.69**	**0.49**	**–0.81**
G. levis	PVAc-80	21.70 *(4.71)*	5.37 *(2.74)*	2.17 *(0.88)*
	PVAc-120	17.22 *(2.02)*	4.41 *(1.98)*	1.21 *(0.30)*
	PVAc-160	15.59 *(4.17)*	2.02 *(0.62)*	1.13 *(0.22)*
Correlation (*r*)		**–0.59**	**–0.62**	**–0.63**
G. levis	PUR-80	25.40 *(5.25)*	4.22 *(0.71)*	1.51 *(0.24)*
	PUR-120	19.53 *(3.67)*	2.35 *(0.60)*	1.15 *(0.07)*
	PUR-160	13.93 *(4.01)*	2.37 *(1.28)*	1.35 *(0.24)*
Correlation (*r*)		**–0.78**	**–0.64**	**–0.29**

Thickness swelling – radial (TSR). TSR varied across samples. From the three main factors, species (*p* = 0.008) and glue type (*p* = 0.046) contributed to the TSR variability (Table 1). Among the interaction effects, only the species x glue spread (*p* = 0.032) contributed to the variability of the mean TSR.

On the effect of the main factors, *B. blumeana* in general had lower TSR than *G. levis* (Table 2). Although arc-laminated *B. blumeana* had higher RD than arc- laminated *G. levis* (Table 5), its TSR was lower for both glue types. This was consistent with Sulastiningsih and Nurwati's (2009) findings where *Gigantochloa apus* (density = 0.750) and *G. robusta* (density = 0.715) had a TS of 2.74% and 3.92%, respectively. *G. apus* had a higher density but its TS was lower than *G. rubusta*.

A study of Espiloy *et al.* (2007) on six species of bamboo showed a similar negative correlation between RD and TSR for raw bamboo. For instance, *S. lumampao* had an RD of 0.461 and TSR of 18.7%. In contrast, *B. blumeana* had an RD of 0.644 and TSR of 12.0%.

This finding is again different from wood. For wood, in general, the higher the sample's density, the higher is the shrinkage or swelling (Haygreen and Bowyer 1996). Thus, as mentioned previously, the anatomical traits of the species could be said to greatly influence its thickness swelling.

On the effect of glue, PUR resulted in lower TSR than PVAc (Table 2). This is expected as PVAc is just water-resistant while PUR is water-proof once cured (Pizzi and Mittal 2003). Hence, the glue line of the laminates with PUR glue would resist the swelling of the bamboo fibers in the radial direction.

TSR due to the interaction effect of species x glue spread differed between the two species (Table 2). For *B. blumeana*, a positive correlation was obtained *i.e.*, as the glue spread increased, TSR also increased. However, for *G. levis*, the correlation was negative – as glue spread increased, TSR decreased. The differences may be due to variations in the species' anatomical traits and bonding behavior with the adhesive. Further research is needed to fully explain the phenomenon.

Thickness swelling – tangential (TST). ANOVA (Table 1) shows that of the three main factors, glue type (*p* = 0.043) and glue spread (*p* = 0.008) contributed to the variability of the TST. Among the interaction effects, only the interaction of the three main factors (*p* = 0.014) contributed to the variability of the mean TST.

Table 2 shows that like in TSR, the TST due to the effect of glue type is similar. PVAc in general gave higher TST than PUR. As previously mentioned, this is because PVAc is water-resistant while PUR is water-proof once cured.

As to the effect of glue spread on TST, Table 2 shows a trend similar to the effect on WA. Generally, as the glue spread increased, the TST decreased as shown by their negative correlation. This may be explained by the thicker layer of glue line that prevents the fibers' water absorption especially for the PUR glue, which is water-proof. As to the interaction of the three main factors, *B.*

blumeana-PUR-160 and *G. levis*-PVAc-80 gave notable results *i.e.*, the lowest (0.78%) and the highest (2.17%) TST, respectively.

Mechanical Properties – Flexural Test

Modulus of rupture (MOR). MOR differed across specimens (Table 5). Of the three main factors, only glue type ($p = 0.009$) notably contributed to the variability of the MOR values (Table 3). The mean MOR of PUR is higher than PVAc by 22% or 16 MPa (Table 4).

There was a negative correlation of MOR values between species and glue type (Table 5). As glue spread increased from 80 to 160 g/m^2, the MOR decreased. The highest MOR was obtained from the thinnest glue line regardless of species. Similarly, Ramazan (2006) showed that shear strength is significantly reduced when glue line thickness increases. Hajdarevic and Sorn (2012) also showed that joint strength decreases with increasing adhesive thickness.

The present study and these previous ones support the theory that thicker glue line does not necessarily produce stronger bond. According to Marra (1992), there is a strong relationship between glue line thickness and loss of joint strength – as glue line thickens, glued joint decreases in strength.

On the effect of glue, bamboo laminates with PUR had higher MOR than those with PVAc (Table 5). In the present study, it appears that PUR was a stronger and more flexible glue than PVAc. This finding, however, differs from Sogutlu's (2017) when he studied the effect of surface roughness on the bonding strength of wooden materials. In his result, PVAc's bond strength was higher than PUR's.

However, in the research of Gasparik *et al.* (2017) using PVAc and PUR for bonding densified and non-densified wood, PUR gave higher shear bond strength. The present study is related to the study of Gasparik *et al.* (2017) as the bamboo laminates were joined in the outer (cutin side) and inner sides of the culm wall with different density due to varying concentration and arrangement of the vascular bundles in the culm's peripheral and inner zones (Liese 1998).

MOR values of *B. blumeana* for PVAc bonded arc laminates show that only the one bonded at 80 g/m^2 with 58 MPa has higher value than the 54 MPa of raw bamboo. However, with PUR, all MOR values are greater. In contrast, *G. levis*' MOR values for both species and all glue spreads were higher than the 24 MPa of raw bamboo. It can thus be concluded that lamination improved the flexural strength of bamboo.

Table 4. Comparative MOR and MOE of the two glue types of ALBL.

Glue Type	Mean MOR ± SD (MPa)	Mean MOE ± SD (GPa)
PVAc	56 ± 8^{a}	7 ± 2^{a}
PUR	72 ± 7^{b}	9 ± 1^{b}

Notes:
± SD is standard deviation
Means with same letter are not significantly different at $\alpha = 0.05$.

Table 3. ANOVA on RD, MOR, and MOE of glue-laminated bamboo lumber as a function of species, glue type, glue spread, and interaction of species, glue type, and glue spread.

Source of Variation		RD (No Unit)		MOR (MPa)		MOE (GPa)	
	DF	*F*-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Species	1	52.40	<0.0001**	0.18	0.673^{ns}	0.84	0.370^{ns}
Glue Type	1	1.02	0.322^{ns}	8.13	0.009**	4.43	0.046*
Species x Glue Type	1	0.55	0.464^{ns}	3.58	0.071^{ns}	2.40	0.134^{ns}
Glue Spread	2	1.43	0.259^{ns}	2.23	0.129^{ns}	1.46	0.253^{ns}
Species x Glue Spread	2	1.42	0.262^{ns}	0.06	0.938^{ns}	0.57	0.573^{ns}
Glue Type x Glue Spread	2	6.03	0.008**	0.01	0.986^{ns}	1.45	0.254^{ns}
Species x Glue Type x Glue Spread	2	4.64	0.020*	0.10	0.902^{ns}	0.11	0.899^{ns}
Error	24						
Total	35						
R-squared (%)		77.14		41.05		38.20	
Coeff Var		8.73		26.34		44.18	

Notes:
** – significant at 1% level of probability
* – significant at 5% level of probability
^{ns} – not significant

Table 5. Mean mechanical properties of ALBL showing correlation with increasing glue spread and comparison with raw bamboo constituents.

Species	**Treatment**	**RD, Unitless (SD)**	**MOR, MPa (SD)**	**MOE, GPa (SD)**
B. blumeana	PVAc-80	0.71 *(0.07)*	58 *(13)*	10 *(3)*
	PVAc-120	0.70 *(0.11)*	47 *(9)*	5 (2)
	PVAc-160	0.80 *(0.02)*	42 *(4)*	4 *(2)*
Correlation (r)		**0.26**	**–0.64**	**–0.77**
B. blumeana	PUR-80	0.65 *(0.08)*	80 *(17)*	11 *(6)*
	PUR-120	0.82 *(0.04)*	75 *(33)*	12 *(7)*
	PUR-160	0.65 *(0.05)*	72 *(23)*	10 *(6)*
Correlation (r)		**0.20**	**–0.16**	**–0.12**
G. levis	PVAc-80	0.61 *(0.03)*	71 *(9)*	9 *(1)*
	PVAc-120	0.57 *(0.07)*	60 *(10)*	8 *(2)*
	PVAc-160	0.57 *(0.03)*	56 *(11)*	6 *(1)*
Correlation (r)		**–0.33**	**–0.57**	**–0.75**
G. levis	PUR-80	0.55 *(0.02)*	78 *(10)*	7 *(1)*
	PUR-120	0.59 *(0.07)*	65 *(14)*	9 *(2)*
	PUR-160	0.60 *(0.01)*	60 *(24)*	8 *(2)*
Correlation (r)		**0.46**	**–0.47**	**0.27**
B. blumeana raw bamboo		**0.64**[a]	**54**[a]	**10**[a]
G. levis raw bamboo		**0.54**[a]	**24**[a]	**10**[a]

Note: a – Espiloy *et al*. 2007

During the flexural test, there were instances when the deflection of PUR- bonded ALBL was already too high but the laminates were not giving in yet compared to samples with PVAc. Most of the static bending failures observed for both glue types were horizontal shear or separation of the laminates on the glueline/s – similar to results of Natividad and Jimenez's (2015) work on laminated *buho* lumber. Although the MOR values in the present study were almost doubled compared to laminated *buho* lumber, there is still a need to improve the laminates' surface preparation to remove the bamboo culm's cutin layer. This would lead to better adhesion, which is crucial to attaining the 80 MPa minimum MOR requirement for general purpose E-bamboo (DTI-BPS 2015).

Modulus of elasticity (MOE). MOE values across samples were variable (Table 5). Of the three main factors, only the glue type (p-value = 0.046) contributed significantly to the differences (Table 3). The mean MOE of PUR samples was higher than PVAc samples by 22% or 2 GPa (Table 4).

Although not significant in the ANOVA, the lower MOE of *B. blumeana* compared to *G. levis* (Table 5) might be due to the former's poor adhesion with PVAc (Fig. 2). However, with PUR glue which can adhere to both porous or non-porous surfaces, higher MOE values were observed for *B. blumeana* than *G. levis*. Perhaps, being almost equal in the quality of bond formed, the higher RD of *B. blumeana* governed in achieving a higher MOE compared to *G. levis*.

Compared to the MOE of raw bamboo for both species, only those from PUR-bonded arc laminates from *B. blumeana* had values higher than the raw bamboo's MOE. The very high coefficient of variation (44%) as shown in ANOVA (Table 3) for MOE implies that other factors affect its value. This could include the RD of the individual laminates and the number of layers or glue lines in the flexural samples.

Comparison of flexural strength with other E-bamboo. The flexural strength of ALBL with 80 g/m^2 glue spread, though highest in the present study, is lower than most of the commercially produced E-bamboo by eight companies with rectangular slats laminates (Alipon and Cabangon 2013) as shown in Table 6. When compared with other E-bamboo such as those made from crushed bamboo (MOR = 42 MPa and MOE = 5 GPa), flexural strength of ALBL is higher. However, with similar geometry of laminates, as the one made by Zhou *et al.* (2016) for RABL, strength of ALBL in the present study was lower. Compared to the previous work on arc lamination of *S.*

Table 6. Comparative mean mechanical properties of bamboo lumber from rectangular slats, crushed bamboo, and arc segment lamination.

Code / Company	**MOR, MPa**	**MOE, GPa**
Alipon and Cabangon 2013		
Commercial E-bamboo's mean strength from 8 manufacturers[1]	100	13
Commercial E-bamboo from crushed bamboo by one company	42	5
FPRDI E-bamboo *B. blumeana*	122	14
FPRDI E-bamboo *D. asper*	93	14
RABL[2] (Zhou *et al.* 2016)	105	5
PUR-120 *S. lumampao* (Natividad and Jimenez 2015)	42	8
Present study[3]		
PVAc-80 *B. blumeana*	58	10
PVAc-80 *G. levis*	71	9
PUR-80 *B. blumeana*	80	11
PUR-80 *G. levis*	78	7

Notes:
1 – rectangular slats
2 – recombined arc-segment bamboo lumber
3 – highest MOR with corresponding MOE

lumampao, ALBL made from *B. bluemeana* and *G. levis* in the present study had higher flexural strength.

The flexural strength comparison was done to illustrate how the ALBL in the present study fared with commercially produced E-bamboo, as well as those made from previous researches. It is clear that samples' form and geometry plus type of glue and spread as well as species influence the flexural strength value of E-bamboo.

Mechanical Properties – Bond Delamination Test (BDT)

G. levis gave better bond performance than *B. blumeana* (Figure 2). As per PNS 196:2000 delamination test, after three cycles of soaking in water and drying in the oven, 85% of all samples should pass the test. However, only *G. levis* – regardless of combination of glue type and glue spread – passed the test or less than 15% (below red horizontal line) of delaminated specimens (Figure 2).

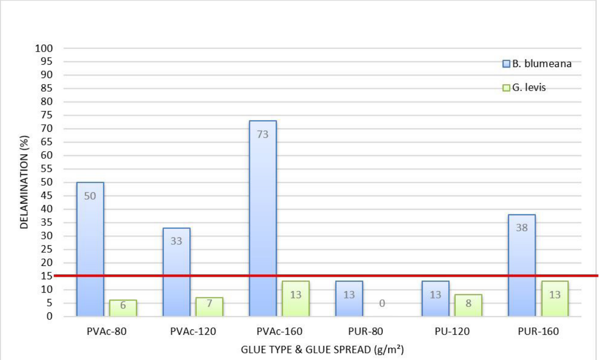


Figure 2. Delamination percentage of ALBL.

In contrast, *B. blumeana* bonded with PVAc failed the test regardless of glue spread used. However, for PUR, two glue spreads passed the delamination test – 80 and 120 g/m². The poor bond performance of *B. blumeana* may be due to its cutin layer, which affected the quality of the laminates surface preparation. The waxy cutin layer of *B. blumeana* seemed still smooth after sanding compared with *G. levis*. Scanning electron microscope 3-D reconstruction of the surface images (Figure 3) of the unsanded and sanded *G. levis* and *B. blumeana* showed that the former has rougher texture than the latter even after sanding. This suggests better mechanical anchorage of the glue on the surface of *G. levis* than the *B. blumeana*. This probably explained for the lower glue adhesion and poorer bond performance of *B. blumeana*.

Table 7 shows the surface roughness values of the two bamboos used in the study. The average roughness (Ra) of unsanded *B. blumeana* was 0.885 µm, while its sanded surface had 1.66 µm. Compared with *G. levis*, even before sanding its Ra was higher with 2.13 µm, but when sanded its Ra decreased to 1.81 µm. The mean peak-to-valley height (Rz) also shows higher values for *G. levis* both in the unsanded and sanded surface. This finding shows that surface roughness indeed affects the bond performance of the laminates. Higher Ra and Rz values for this study result to better adhesion of the glue. Similar result was obtained by Ocku *et al.* (2015) when they evaluated the effect of surface roughness on adhesion resistance of wood. They concluded that adhesion resistance values decrease when surface roughness increases and *vice versa*. Further research on the relation of bond performance with anatomical structure of the arc bamboo laminates is recommended. Also, shear strength test of the glue line may be a better way of comparing the strength of the bond formed.

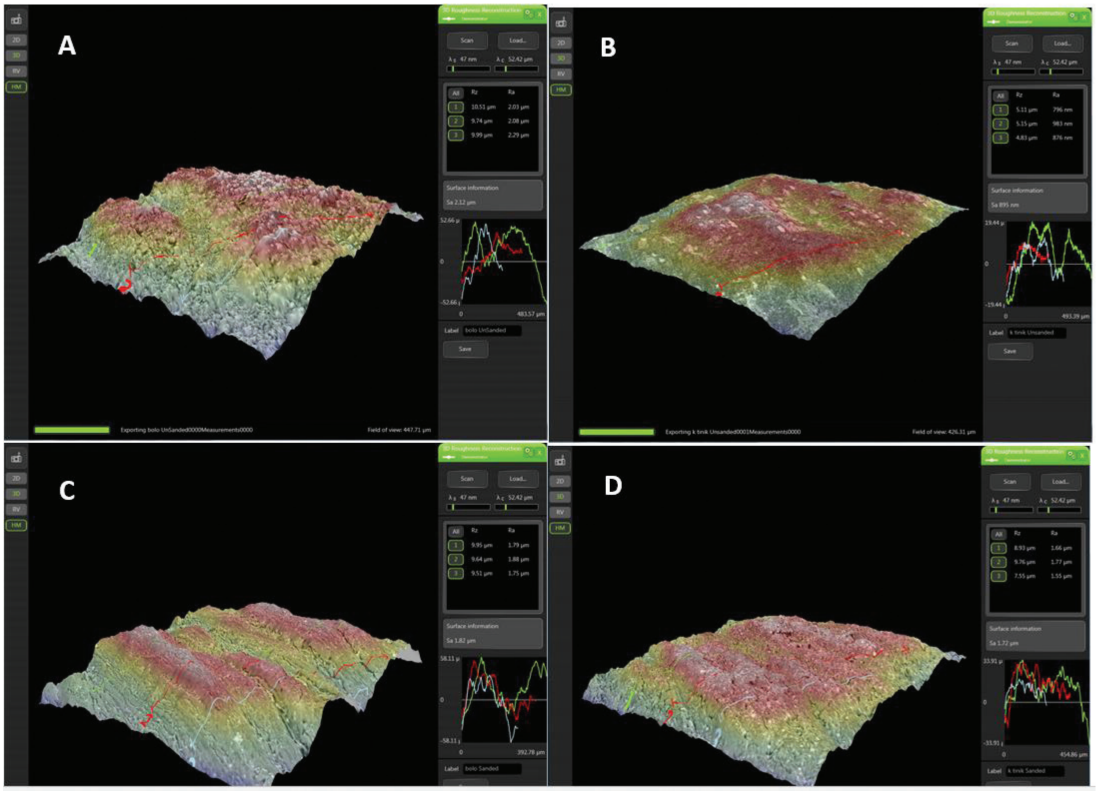
Prototype Products

G. levis was used as raw material in the production of prototype products due to ease in processing and longer internodes compared to *B. blumeana*. The lowest glue spread, 80g/m^2, was used in the lamination of split culm.

Figure 4 shows a sample of ALBL from *G. levis* culms. It resembles the prominent annual growth ring of temperate wood species when viewed at cross-section.

Table 7. Surface roughness values of the two bamboos used in the study.

Line	***Bambusa blumeana***				***Gigantochloa levis***			
	Unsanded Rind		**Sanded Rind**		**Unsanded Rind**		**Sanded Rind**	
	Ra (µm)	Rz (µm)	Ra (µm)	Rz (µm)	Ra (µm)	Rz (µm)	Ra (µm)	Rz (µm)
1	0.796	5.11	1.66	8.93	2.03	10.51	1.79	9.95
2	0.983	5.15	1.77	9.76	2.08	9.74	1.88	9.64
3	0.876	4.83	1.55	7.55	2.29	9.99	1.75	9.51
Ave.	**0.885**	**5.03**	**1.66**	**8.75**	**2.13**	**10.08**	**1.81**	**9.70**
Std. Dev.	0.090	0.17	0.11	1.12	0.14	0.39	0.07	0.23
Std. Error	0.050	0.10	0.06	0.64	0.08	0.23	0.04	0.13



A

λs 47 nm λc 52.42 µm

All	Rz	Ra
1	10.51 µm	2.03 µm
2	9.74 µm	2.08 µm
3	9.99 µm	2.29 µm

Surface information
Sa 2.12 µm

Label bolo UnSanded

Exporting bolo UnSanded0000Measurements0000
Field of view: 447.71 µm

B

λs 47 nm λc 52.42 µm

All	Rz	Ra
1	5.11 µm	796 nm
2	5.15 µm	983 nm
3	4.83 µm	876 nm

Surface information
Sa 895 nm

Label k tinik Unsanded

Exporting k tinik Unsanded0001Measurements0000
Field of view: 426.31 µm

C

λs 47 nm λc 52.42 µm

All	Rz	Ra
1	9.95 µm	1.79 µm
2	9.64 µm	1.88 µm
3	9.51 µm	1.75 µm

Surface information
Sa 1.82 µm

Label bolo Sanded

D

λs 47 nm λc 52.42 µm

All	Rz	Ra
1	8.93 µm	1.66 µm
2	9.76 µm	1.77 µm
3	7.55 µm	1.55 µm

Surface information
Sa 1.72 µm

Label k tinik Sanded

Figure 3. SEM reconstruction (600x) of the surface of the bamboo rind used in the study: (A) unsanded *G. levis*, (B) unsanded *B. blumeana*, (C) sanded *G. levis*, and (D) sanded *B. blumeana*.

Figure 4. ALBL from split culms along the middle portion of *G. levis* poles.

ALBL samples were subjected to further lamination then cross-cut for the production of decorative table top (Figure 5) showing a wavy geometrical pattern that can serve as design highlight of a coffee table. Another table top sample (Fig.6) was produced by lamination on the tangential sides of ALBL to create wide sample similar to a panel highlighting straight line figure on the wide surface

Figure 5. Decorative coffee table top made from cross-cut arc laminated Bolo *(G. levis)* bamboo lumber.

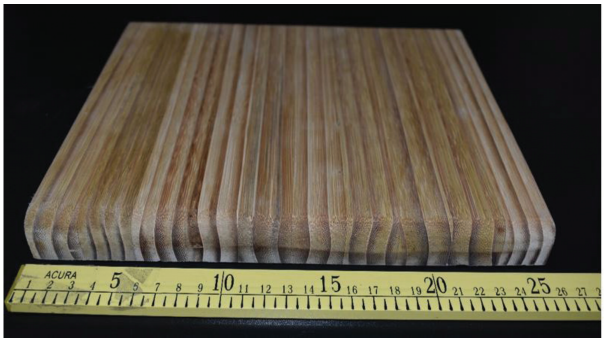


Figure 6. Decorative side table top from arc lamination of *G. levis*.

and arc segment on the edge. The sample products made highlighted the decorative applications of ALBL, which can be used as furniture and handicraft components.

CONCLUSIONS

The present study showed that the strength of PVAc- and PUR-bonded ALBL was lower than most of the commercially produced local E-bamboo. This is attributed to the cutin layer of the arc laminates that was not completely removed by sanding. Thus, other methods such as using a mechanical cutin scraper should be employed to obtain better strength. In general, the arc-laminated *B. blumeana* has better physical properties than *G. levis* – as shown by the former's lower radial and tangential swelling for both PVAc and PUR adhesives regardless of glue spread. This implies that *B. blumeana* is more dimensionally stable than *G. levis* in ALBL.

The mechanical properties and delamination tests show that the best glue spread is 80 g/m² for both species of bamboo. Specifically, the MOR for *B. blumeana* shows that PVAc-80 is higher than PVAc-120 and PVAc-160 by 19 and 28%, respectively; whereas PUR-80 is higher than PUR-120 and PUR-160 by 6 and 10%, respectively. For *G. levis*, PVAc-80 is higher than PVAc-120 and PVAc-160 by 18 and 21%, respectively; whereas PUR-80 is higher than PUR-120 and PUR-160 by 17 and 23%, respectively. This implies that glue spread can be lowered up to 80 g/m² for ALBL to reduce glue consumption of this type of E-bamboo. For MOE, the 80 g/m² glue spread is generally higher but this can be affected by the density and quantity of the arc laminates in the flexural sample.

In general, the 80 g/m² glue spread can be recommended for ALBL – having attained the best physical and mechanical properties that conformed to the minimum strength requirement for E-bamboo required for general purpose, as per PNS 2009 (DTI-BPS, 2015). Other methods of removing cutin layer should be explored (*e.g.*, using a spokeshave or a mechanical remover) and compared with sanding to determine which method of surface preparation of laminates would give better adhesion strength. Further, to increase the utility of ALBL for furniture and construction, finger-jointing is recommended. However, finger joint should be tested to determine its strength on ALBL applications. Also, it would be worth trying to use structural thermosetting adhesives *i.e.*, urea formaldehyde and phenol formaldehyde adhesives, for arc lamination of the middle and top portions of bamboo culms to increase rate of production of ALBL and maximize bamboo pole utilization. Finally, lower glue spread (*i.e.*, 60 g/m²) may also be tried to find out if that spread rate would cause glue starvation on the surface of the adherends.

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