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Engineered bamboo: state of the art

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Bamboo is a rapidly renewable material that is available globally and comparable in strength to modern structural materials. The widespread use of bamboo in construction is limited by the inherent variability in its geometric and mechanical properties, and the lack of standardisation. Engineered bamboo aims to reduce the variability of the natural material and is processed and manufactured into laminated composites. Although the composites have mechanical properties similar to other structural materials, the products are currently limited to architectural applications. A field of research on engineering bamboo is emerging with the aim to demonstrate and expand its use to structural applications. To summarise the state of the art, a review of published research is presented with the focus on two types of engineered bamboo: bamboo scrimber and laminated bamboo. The materials are compared with structural timber and laminated veneer lumber to demonstrate the potential applications and practical use.

Notation

r	density of material
Sc	compressive stress parallel to grain
St	tensile stress parallel to grain
t	shear stress parallel to grain

1. Introduction

Interest in bamboo for construction continues to grow as focus shifts towards reducing the environmental impact and embodied energy of the built environment. Bamboo in its natural form is a cylindrical pole, or culm, and is part of the grass family. There are over 1200 species of bamboo worldwide, with structural species varying by location. The different species can be generalised into three types of root systems, sympodial (clumping), monopodial (running) bamboo, as shown in Figure 1, and amphipodial (clumping and running).

Bamboo is a rhizome in which shoots grow from the root base. In sympodial bamboo, the bamboo culms grow in close proximity to each other to form a clump, whereas monopodial bamboo appears to consist of individual culms, although each culm is part of an extensive root system in which individual shoots grow and the roots continue to extend if not controlled. Amphipodial bamboo is a mixture of the two root bases. The composition of the bamboo culm includes longitudinal fibres, aligned in the vertical direction of the bamboo, within a lignin matrix. At locations along the culm, called nodes, there are fibres in the transverse direction. As a functionally graded material, the fibre distribution increases from the inner culm wall, with the greatest density found on the external culm wall (Figure 2). The material growth is rapid, growing to full height of up to 30 m within a year (Liese and Weiner, 1996), after which the culm continues to gain strength, reaching the optimal structural properties within 3–5 years, depending on the species. Proper management of the plant is required to maintain the production of the culms, as the culms that are not harvested will start to decay and will collapse in approximately 10 years.

The rapid growth and renewability of bamboo are ideal characteristics for use in construction; however, the material is used only marginally. The following review explores the development of engineered bamboo and aims to provide background on the use of bamboo in structural applications and emerging research on the development of engineered bamboo products. Although this is a nascent field of research, the following state-of-the-art review identifies areas for further development that will provide a basis to advance this novel material. Through review of published studies, we will identify key areas where further research is needed to determine fully the potential applications for engineered bamboo products.

2. Bamboo in construction

Full culm bamboo construction is not extensively practised around the world, with primary uses of traditional bamboo

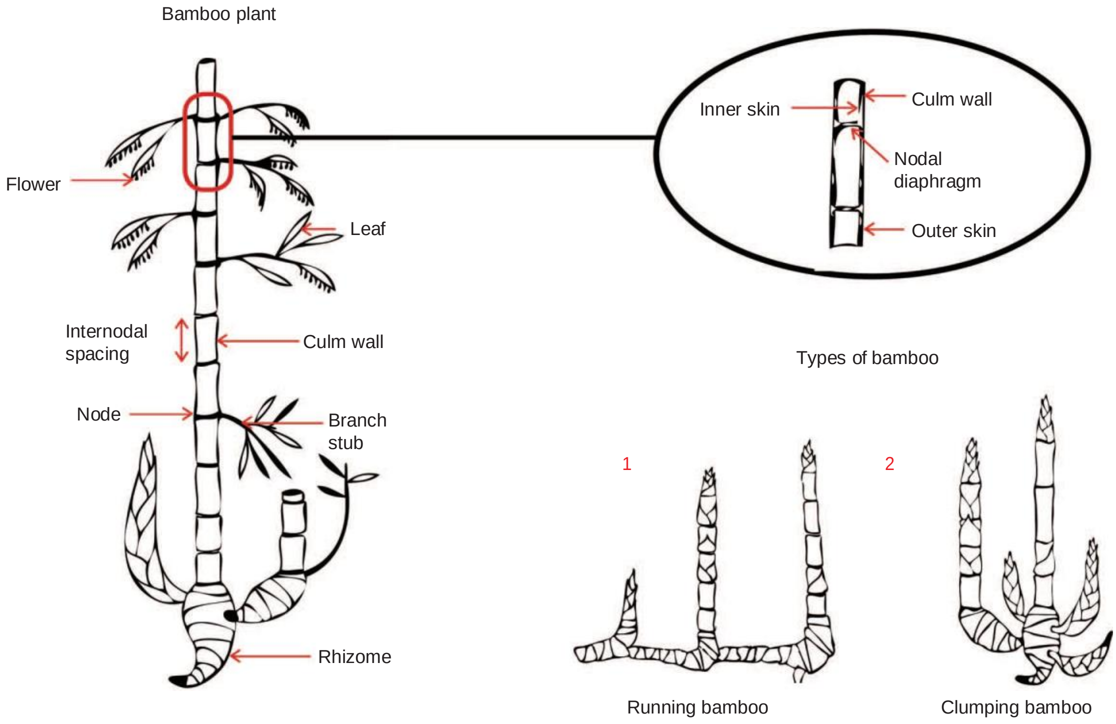

Figure 1. Bamboo plant, types and parts

construction found in Asia, Latin America and East Africa. In Colombia, Trujillo *et al.* (2013) noted five types of bamboo structures: traditional construction, social housing, luxury housing, long-span buildings and footbridges. Additionally, vehicle bridges have been constructed in Colombia (Stamm, 2002) and in China (Xiao *et al.*, 2010). In Ethiopia, the structural use of bamboo is part of traditional construction methods and is used in the form of full culm and split bamboo with other materials (Kibwage *et al.*, 2011). Other traditional structural uses of full culm bamboo include scaffolding in India, China and Hong Kong (Chung and Yu, 2002; Muthukaruppan, 2008; Yu *et al.*, 2003; 2005). Although examples of bamboo construction continue to increase, the extensive use of bamboo in the design and engineering of conventional structures is limited by several factors. First, the natural material itself varies in geometry and material properties, between species and within a species, and within a single culm. Additionally, the material is round or elliptical in form, which makes joints and connections difficult. Finally, design and testing standards exist for full culm bamboo (ISO, 2004a, 2004b, 2004c), but the standards themselves do not fully provide the foundation from which builders, engineers and architects can design with bamboo (Harries *et al.*, 2013). To overcome these limitations, development of engineered bamboo products is increasingly explored for construction purposes.

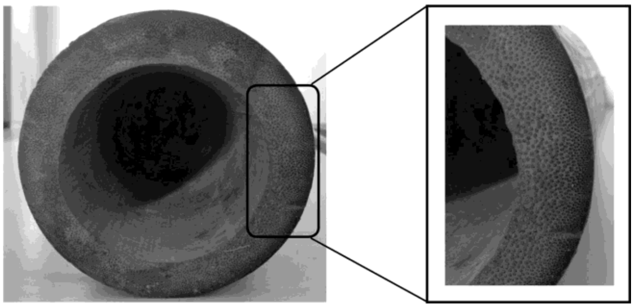

Figure 2. Bamboo culm and wall thickness

The advantage of engineered bamboo products is the ability to create standard sections for members and connections, and to reduce the variability within a single member. Bamboo in its natural form is a light material that is comparable in strength to steel in tension and concrete in compression, yet acceptance is limited by the variance in cross-section and mechanical properties. Although past studies have explored the design of bamboo composites in relationship to efficiency (e.g. Beukers and Bergsma, 2004), the research focused on the use of extracted short fibres rather than laminated sections of bamboo. Growing interest in the design of engineered bamboo products is driven by the fact that the manufacturing process eliminates the round cross-section by creating bundles or strips, which maintain the longitudinal fibres in a section that can be laminated together to form a standard shape and size used in construction (Paudel, 2008). The process allows production of standard sections with more uniform properties.

3. Bamboo manufacturing

The production of bamboo products in China utilises the whole culm, with different sections used for various manufacturing processes. The use of the entire culm is highly efficient, but within the individual manufacturing processes, the material use efficiency decreases, although waste material is often used for energy (van der Lugt, 2008). Of particular interest is the use of bamboo culms for boards, which can be easily compressed or laminated to form larger sections. The process of manufacturing bamboo boards in China began in the 1970s and has increased in production through industrialisation of the manufacturing process (Ganapathy *et al.*, 1999). China leads in production and export of bamboo-based products; export is mainly to Western countries and Japan (Lobovikov *et al.*, 2007). The Chinese processes for manufacturing two bamboo-based products, bamboo scrimber and laminated bamboo, are shown in Figure 3.

Bamboo scrimber, also known as strand-woven or parallel-strand bamboo, is manufactured from crushed sections of the bamboo culm, which are coated in a resin, compressed and then heated to cure the resin (Figure 3(a)). The term scrimber originates from a timber-based product that was developed in Australia to utilise small-diameter material that maintained the longitudinal direction of the fibres (Bowden, 2007). In contrast, laminated bamboo is manufactured with strips of bamboo that are processed to form rectangular sections, which are then laminated to form a board (Figure 3(b)). Comparison of the material input and output in the production of a product can be described as the production efficiency. In timber, van der Lugt (2008) estimates the efficiency of sawn timber as approximately 30–40% of the original volume of logs, with the remaining material accounted for in losses due to processing. For bamboo, the production efficiency varies by manufacturer and is approximately 80% for bamboo scrimber and 30% for laminated bamboo (van der Lugt, 2008). In comparison the material efficiency of glulam production in the USA is approximately 82% (Puettmann and Wilson, 2006). Figure 3 details the manufacturing process and illustrates the difference between the two products, with bamboo scrimber, primarily used in external applications, utilising the entire culm, whereas the laminated bamboo, used in indoor flooring and surface applications, is based on multiple levels of selection to create the final product.

3.1 Bamboo products

Laminated bamboo and bamboo scrimber are typically formed into boards for flooring and surface applications. Table 1 compares the mechanical properties of natural and commercially produced bamboo, as well as structural and laminated timber products. The table is a compilation of experimental studies and aims to show the potential of engineered bamboo as a structural material; the table summarises commercially produced bamboo board products and their basic material properties. The mechanical properties in tension and compression for both board products are comparable to other structural materials, yet the products themselves are limited to architectural applications. The properties in bending of the single-ply laminated boards have a modulus of rupture (MOR) and flexural modulus of elasticity (MOE) that are comparable to the flexural properties of other structural materials.

3.2 Comparison to timber

Wood is an orthotropic material with varying mechanical properties along the longitudinal, radial and tangential axes, with strength and stiffness different in each direction. Also an orthotropic material, bamboo has varying strength and stiffness in the longitudinal, radial and tangential directions. Bamboo’s strength is found in the longitudinal direction through fibres within a lignin matrix, which makes it strong in tension and compression but weaker transverse to the fibre direction. Table 1 also includes mechanical properties for two types of wood products, timber and laminated veneer lumber (LVL), tested by different standards. Lavers (2002) reports mechanical properties for small clear specimens of Sitka spruce tested to ASTM D143: Standard test methods for small clear specimens of timber (ASTM, 2009) and BS 373 Methods of testing small clear specimens of timber (BSI, 1957). Kretschmann *et al.* (1993) tested LVL made with Douglas fir using ASTM D4761: Standard test methods for mechanical properties of lumber and wood-base structural material (ASTM, 2013), to obtain the bending and tension strength. As shown in Table 1, the mechanical properties of Sitka spruce are less than the bamboo in compression and shear, but comparable in tension and bending. Bamboo is comparable in bending, but stronger in compression and tension parallel to grain. Research indicates that bamboo scrimber and laminated bamboo are comparable to structural timber and LVL in bending and stiffness, but significantly stronger in tension and compression. While the comparison to timber appears to be straightforward, the use of bamboo board products for structural applications requires additional investigation to understand the basic mechanical properties of the material and the best way in which to utilise those properties.

4. Recent studies on engineered bamboo products

The following review explores published studies on bamboo scrimber and laminated bamboo. The authors acknowledge the

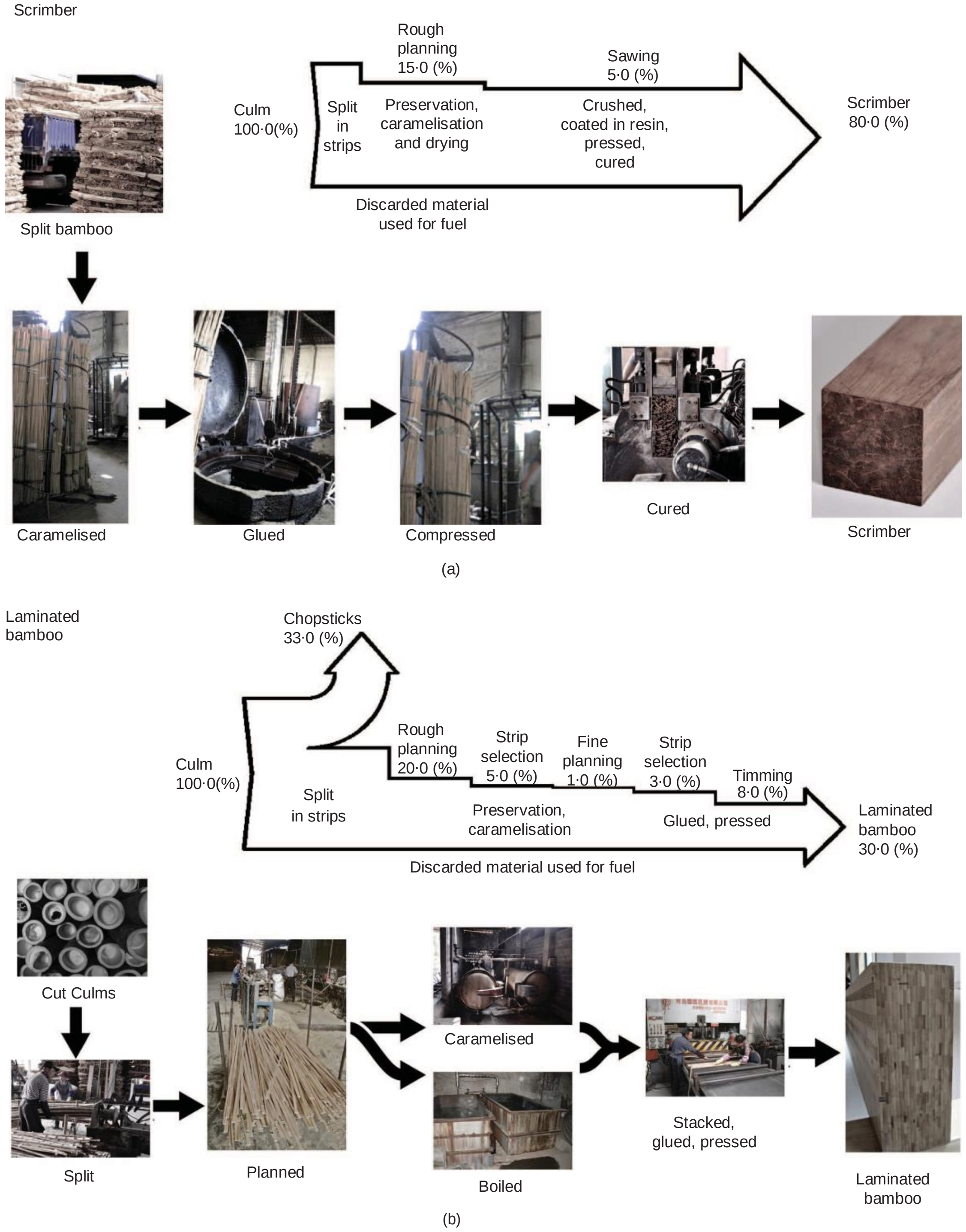

Figure 3. General processing efficiency and manufacturing process for (a) bamboo scrimber and (b) laminated bamboo in China. Material efficiency estimates based on van der Lugt (2008)

		Compression stress: MPa		Tension stress: MPa		Shear stress: MPa	Flexural	
	Density: kg/m^3	Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain	Parallel to grain	MOR: MPa	MOE: GPa
Bamboo scrimber[a]	801	–	–	41	7	–	102	2
Laminated bamboo[b,c]	577–750	63–64	20	102–191	3–4	4	78–88	1–12
Phyllostachys pubescens[d]	666	53	–	153	–	16	135	–
Sitka spruce[e]	383	36	–	–	–	9	67	8
Douglas fir LVL[f]	520	–	–	49	–	–	68	13

[a] Plyboo (2013a).
[b] Lamboo (2013).
[c] Plyboo (2013b).
[d] Ghavami and Marinho (2001).
[e] Lavers (2002).
[f] Kretschmann *et al.* (1993).

Table 1. Material properties for natural bamboo, commercially produced bamboo and timber products

review is not all encompassing and have selected publications that focus on investigation of the material and mechanical properties rather than applications. A summary of the studies and selected data is presented in Table 2.

4.1 Test standards

The studies utilised test standards from around the world to obtain mechanical properties, although all used an equivalent timber standard. The bamboo scrimber studies focused on the material properties for boards, with standards from Japan, China and the USA used to characterise the material (Table 2). Pereira and Faria (2009) investigated glue laminated bamboo made from *Dendrocalamus giganteus*, a species commonly found in Brazil, using Brazilian standards for wood. An increasing number of recent publications utilise ASTM (2009) D143: Standard test methods for small clear specimens of timber (Correal *et al.*, 2010; Mahdavi *et al.*, 2012; Sinha *et al.*, 2014; Xiao *et al.*, 2013). Testing and development of engineered bamboo through timber standards will aid in the development and application of this novel material. Through creation of analogous testing and design methods, engineered bamboo has the potential to be a competitive alternative to timber.

4.2 Manufacturing method

Mahdavi *et al.* (2011) reviewed different methods used to manufacture different types of bamboo products: scrimber, laminated and rolled bamboo. The studies presented in Table 2 varied in the method used to obtain the base bamboo material for the laminates from culms split in half and flattened by a plate (Lee *et al.*, 1998), roller flattening (Nugroho and Ando, 2000; 2001), hammer (Mahdavi *et al.*, 2012) to splitting of bamboo into strips which are then planed to size (see Figure 4). Comparison of the low-technology approach (manual methods with minimal mechanical processing) and the high-technology approach (substantial processing and use of heat for lamination) are of particular interest. Studies have shown increased mechanical processing requires additional energy inputs (Xiao *et al.*, 2013) and losses in material as illustrated in the comparison of bamboo scrimber and laminated bamboo in Figure 3.

Mahdavi *et al.* (2012) studied a low-cost method for laminated bamboo using *Phyllostachys pubescens* Mazel ex J. Houz. The laminates were manufactured with culms that were split in half and then hammered to replicate production of strips, which were still integral to the culm. The method is similar to bamboo scrimber manufacturing in which the culm is split and crushed maintaining the fibre direction (Huang *et al.*, 2013; Zhou and Bian, 2014). High-technology processes include splitting and planing the bamboo into thin strips of bamboo that are glued then heated and pressed to form the laminate. An example of such processing is the trademarked material called GluBam, which is used in the construction of bridges and housing in China (Xiao and Yang, 2012). Xiao *et al.* (2013) outlined the process for creating GluBam, in which the beams are created from bamboo sheets, which are composed of thin strips of *Phyllostachys pubescens* that are pressed together. The process creates a high-strength composite that reduces the influence of the fibre gradation, which can affect the mechanical performance.

Study	Species	Test standard	Adhesive	Laminate method	Glue rate: g/m^2	Initial MC: %	r: kg/m^3	Parallel to grain: MPa			MOR: MPa	MOE: GPa
								Sc	St	t		
Bamboo scrimber												
Nugroho and Ando (2000)	*P. pubescens* Mazel	–	Iso	Hydraulic hot press	–	8–12	600–900	–	–	–	54–79	6–7
Nugroho and Ando (2001)	*P. pubescens* Mazel	JIS A-5908, JIS Z-2113	R	Cold pressed	300	–	870–1010	–	–	–	67–81	10–12
Guan *et al.* (2012)	M. baccifera	GB/T 17657-1999	PF	Hot pressed	–	9–12	1240	–	–	–	266	15
	P. pubescens						1090				203	11
Huang *et al.* (2013)	–	–	–	–	–	–	–	62	138	–	–	–
Zhou and Bian (2014)	–	ASTM D198-02	–	Hot pressed	–	12	–	–	–	–	89	13
Laminated bamboo												
Lee *et al.* (1998)	*P. pubescens*	ASTM D5456-94, D198-94	R	Hydraulic press	220–420	10–15	620–660	–	–	–	71–86	8
Bansal and Prasad (2004)	*B. bambos*	BIS 1708-1986	UF, MUF, PF	Hydraulic hot press	Brush	8–10	728–796	–	–	–	123–145	12–17
Correal and Lopez (2008)	*G. angustifolia* Kunth	ICONTEC 775, 784, 785, 663	PVA	Hydraulic cold press	–	6–8	–	36	–	9	82	–
Correal *et al.* (2010)	*G.angustifolia* Kunth	ASTM D143-94	PRF, MUF, PRF-MUF	Hot press	260–450	–	730	60	95	9	111	–
Sulastiningsih and Nurwati (2009)	*G. apus* *G. robusta*	ASTM D1037-93, JS-2003	TRF	Cold pressed and clamped	170	12	710–750	49–56	–	–	39–95	7–10
Pereira and Faria (2009)	*D. giganteus*	NBR 7190-97	PVA	–	–	–	–	66	144	–	99	14
Mahdavi *et al.* (2012)	*P. pubescens* Mazel ex J. Houz	ASTM D143	PRF	Mechanical press	–	16	510	–	–	–	77	9
Sinha *et al.* (2014)	–	ASTM D198, D905, D143	PRF	Clamped	–	–	–	9–10	–	16	42–70	22–23
Xiao *et al.* (2013)	*P. pubescens*	ASTM D143-94	PF	Hydraulic hot press	–	15	800–980	51	82	7	99	9

Adhesives: R, resorcinol; Iso, isocyanate; PF, phenol formaldehyde; UF, urea formaldehyde; MUF, melamine urea formaldehyde; PRF, phenol resorcinol formaldehyde; TRF, tannin resorcinol formaldehyde; PVA, polyvinyl acetate.

Table 2. Summary of published studies on bamboo scrimber and laminated bamboo

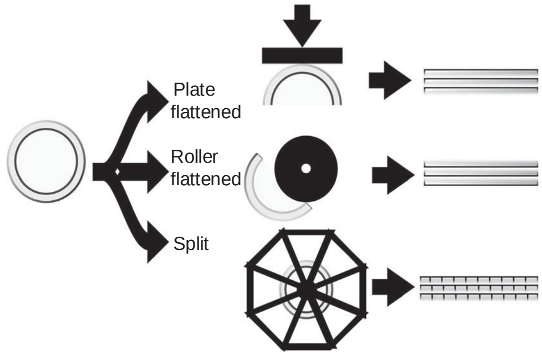

Figure 4. Methods for obtaining base material for laminated bamboo

Scrimber is manufactured by compression of the fibre bundles into a beam section. Although the fibre direction is maintained, the gradation is not maintained with the bundles crushed to form the section. In contrast, initial processing for laminated bamboo (Figure 3) removes the lowest density interior and highest density exterior, however, a slight fibre gradation is visually apparent in the strip. To explore the influence of the density of the fibres within a composite, Nugroho and Ando (2001) created laminated bamboo from crushed mats of *P. pubescens* Mazel. The mats were created using split culms that were flattened to maintain the fibre direction. The crushed mats were planed to remove the inner and outer surfaces as in the processing of laminated bamboo strips (see Figure 3). The authors then varied the orientation of the inner and outer surfaces of the crushed bamboo within the laminate. The study indicated there was no significant difference in the orientation of the inner and outer fibres.

Bidirectional composites orient fibres in the selected direction to optimise the strength properties of the materials. Bansal and Zoolagud (2002) reviewed the process of manufacturing bamboo mat board (BMB) in India utilising woven mats, dipped in phenolic formaldehyde resin, which are then pressed together in various plies to form boards. The mats are formed with split bamboo with the epidermal layer (assumed to be the inner layer) removed and then woven at a 45° angle. Xiao *et al.* (2013) also utilised a bidirectional composite by organising bamboo into longitudinal and transverse plies in GluBam. Xiao *et al.* noted a 4:1 ratio of longitudinal to transverse plies, with a comparable MOE and MOR to other laminated bamboo studies. In comparison to a unidirectional bamboo laminate, the added stiffness of the bidirectional composite is advantageous for some applications. Nugroho and Ando (2001) also noted that the orientation of the glue line influenced the mechanical properties, with the vertical glue line achieving higher values in both the MOE and MOR.

4.3 Adhesives

Adhesives have an essential role in composites and must provide proper penetration and interface bond between the fibres and laminas. In the USA, structural wood adhesives are categorised for exterior, limited exterior and interior applications (Frihart and Hunt, 2010). Commercial manufacturing of bamboo scrimber primarily uses phenol formaldehyde owing to its durability for exterior applications, and its low cost. Commercial laminated bamboo is produced for interior uses and utilises isocyanate for lamination. Bio-based resins, such as soy-based resins (Plyboo, 2013c), are also of interest owing to the formaldehyde-free formulation, although the additional costs have limited their use commercially.

Table 2 lists the types of adhesives used in the studies, which are also used in wood composites. In the reviewed studies, a variety of wood structural exterior adhesives were utilised, including: resorcinol formaldehyde, isocyanate, phenol resorcinol formaldehyde, tannin resorcinol formaldehyde and phenol formaldehyde (Frihart and Hunt, 2010). The only classified wood limited exterior adhesive explored in the bamboo studies was melamine urea formaldehyde, although polyurethane is also of interest because most formulations are formaldehyde-free. Urea formaldehyde, a wood structural interior adhesive, was studied as well as polyvinyl acetate, which is considered to be a non-structural wood interior adhesive (Frihart and Hunt, 2010).

Bansal and Prasad (2004) tested laminated bamboo made from *Bambusa bambos*. The research explored three types of resins: urea formaldehyde, melamine urea formaldehyde and phenol formaldehyde. Phenol formaldehyde and phenol resorcinol formaldehyde provide higher strengths in comparison to the other adhesives (Bansal and Prasad, 2004; Correal *et al.*, 2010). Current industrial practice utilises phenol formaldehyde for manufacturing of bamboo scrimber and laminates, although soy-based and formaldehyde-free adhesives are also used (Plyboo, 2013c). Formaldehyde-free adhesives are of interest owing to the associated human health impacts. Frihart and Hunt (2010) note that phenol, resorcinol and phenol resorcinol formaldehydes do not release detectable amounts of formaldehyde after production; however, the levels of free formaldehyde in products is controlled by acceptable limits globally. The use of formaldehyde-based resins in some bamboo products continues to be the current industry practice and cost-effective choice (Xiao *et al.*, 2013). Further study is needed to determine an adhesive that performs well both structurally and environmentally.

To achieve a good bond, the moisture content of the material is essential. For interior applications of wood products in the USA, the average moisture content varies regionally between 6 and 11% (Frihart and Hunt, 2010). Owing to the hydrophilic nature of the fibre, bamboo laminates are difficult to maintain at low moisture content and oven drying the specimens is the preferred method before lamination. As noted in Table 2, the studies varied in initial and test moisture content from 8 to 16%. Lee *et al*. (1998) explored the impact of the initial moisture content on the strength of bamboo and found little to no effect on the mechanical properties; however, the moisture content affected the dimensional stability. Lee *et al*. (1998) also found the glue spread rate impacted both mechanical and physical properties.

The glue spread rate is often specified by the manufacturer and several studies have explored varying the rate and the effect on strength. Correal *et al*. (2010) explored the glue spread rate on glue laminated Guadua (GLG). The results indicated that there was little difference between the types of adhesives and the mid-level spread rate was ideal, approximately 300 g/m^2 for the wide face and 150 g/m^2 for the narrow faces. The studies presented in Table 2 varied in the method of lamination (clamps or press), temperature (cold or heated), pressure and time. The different species of bamboo and methods of manufacturing led to a range of product densities, with the bamboo scrimber ranging from 600 to 1240 kg/m^3 and the laminated bamboo ranging from 510 to 980 kg/m^3 (Table 2).

4.4 Mechanical properties

As noted above, there is significant variation in the method of production for bamboo scrimber and laminated bamboo; however, the mechanical properties between the studies are not orders of magnitude different from each other. Although the material properties are similar, standardised test methods would allow for better comparison between studies. Figure 5 illustrates the general experimental set-up for the mechanical tests parallel to grain based on small clear specimens from BS 373 and ASTM D143.

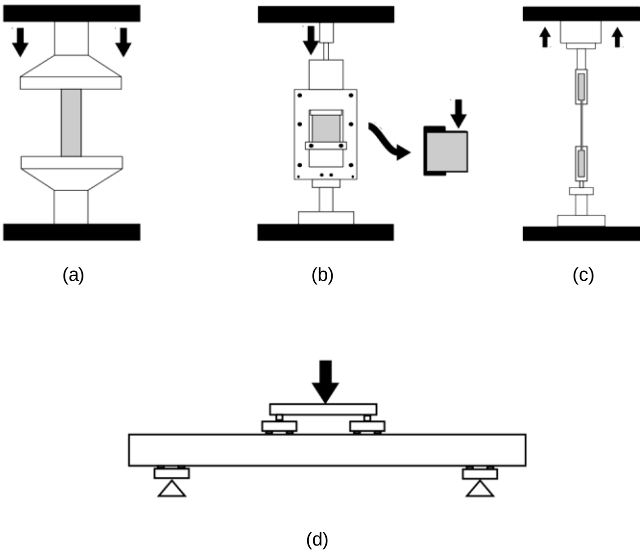

Figure 5. Test methods to obtain mechanical properties in small clear specimens parallel to grain: (a) compression; (b) shear; (c) tension; and (d) bending

Huang *et al*. (2013) was the only study on bamboo scrimber that reported the compressive (s_c 5 62 MPa) and tensile stress (s_t 5 138 MPa) parallel to grain. The tensile strength is similar to full culm bamboo (see Table 1), which is attributed to the maintenance of the longitudinal direction of the fibre. For laminated bamboo, the tension and compression properties are noted to be similar to the bamboo scrimber (s_c 5 36–66 MPa, s_t 5 82–144 MPa). The properties for both products are similar to the properties of Sitka spruce and LVL in compression, but exceed the properties of LVL in tension (see Table 1). In shear parallel to grain, the laminated bamboo compares well to the bamboo board and timber products with a reported range of shear stress between 9 and 16 MPa from the studies. The shear strength of bamboo scrimber was not reported in the reviewed studies.

The bending MOR and MOE varied significantly in the studies for both the bamboo scrimber and laminated bamboo. In comparison to the Sitka spruce and LVL (Table 1), both the bamboo scrimber (MOR 5 54–266 MPa) and the laminated bamboo (MOR 5 39–145 MPa) provided a greater flexural strength, which is attributed to the natural flexibility and high tensile strength of the bamboo. The modulus of elasticity for both the bamboo scrimber (MOE 5 6–15 GPa) and laminated bamboo (MOE 5 7–14 GPa), was within range of the Sitka spruce and LVL (MOE 5 8–13 GPa, Table 1).

The reviewed studies demonstrate that bamboo products are comparable to and in some cases outperform timber and glue laminated timber in terms of mechanical properties. While the studies show the potential of engineered bamboo, further research is needed to fully characterise and standardise products to develop viable alternatives to timber products.

5. Engineering selection: strength, efficiency, cost and environmental performance

The traditional method of selecting engineering materials is no longer solely based on strength, efficiency and cost, but is now supplemented by another criterion: environmental performance. With interest in reducing their environmental impact, structural materials are scrutinised in terms of source, manufacturing, construction, operation, maintenance and disposal. Additional consideration must be given to the performance of the material, not only in terms of structural capacity, but also in terms of the environment. Bamboo in its natural form is a highly efficient material. With these additional parameters under consideration, bamboo quickly becomes a potential material for structural use.

The life-cycle analysis of structural bamboo is increasingly explored with studies focusing on the environmental impacts associated with full culm construction (Yu *et al.*, 2011). Zea Escamilla and Habert (2014) explored the environmental impact of different bamboo-based products. The study showed that engineered bamboo (glue laminated bamboo) has a higher environmental impact than lower industrialised products, which is attributed to the higher level of processing and contributions from other inputs into the products. The authors also noted the differences in contribution of the electricity mix to the environmental impacts, with China twice the environmental impact from electricity in comparison with Brazil and Colombia (Zea Escamilla and Habert, 2014). An additional area of interest is the type of resin utilised in the manufacturing process. Life-cycle inventories on wood resins are available (Puettmann and Wilson, 2006; Wilson, 2010); however, these studies focus on production in specific locations (USA) and, as with the electricity mix, the variability of production is increased when the analysis is shifted to other parts of the world and uncertainty in the analysis is increased.

While research on various bamboo-based products continues to grow and expand to investigate the life-cycle analysis and the associated environmental costs (van der Lugt *et al.*, 2006; 2009; Vogtlander *et al.*, 2010), the cradle-to-cradle analysis of engineered bamboo is limited. For example, Xiao *et al.* (2013) investigated GluBam and analysed the environmental performance of the manufacturing process in comparison to other traditional construction materials, such as timber, plywood, cement, aluminium and steel. The analysis of the manufacturing method provides a glimpse of the embodied energy and associated impacts, although an expanded scope to include the additional inputs is necessary to fully understand the environmental impacts and costs associated with engineered bamboo products.

6. Practical relevance and potential applications

Engineered bamboo has the potential to be a competitive product in the marketplace. Bamboo has several advantages over other materials and offers not only strength but aesthetic value too. The use of bamboo in construction is still an emerging field, as is the use of engineered bamboo products. These products have mechanical properties that are comparable to or exceed those of structural timber and laminated veneer lumber, yet they are used inefficiently in solely architectural and surface applications. Several factors need to be addressed for engineered bamboo products to be used in construction. Engineering quantification of mechanical properties will determine the potential structural applications. While the presented review of recent studies on engineered bamboo demonstrates the increasing interest, there is also a need for further testing based on standardised methods, such as existing timber testing methods. With a consensus on the test methods utilised to characterise bamboo materials, a knowledge base will be formed to develop structural products, as well as the codification necessary to utilise these materials in the mainstream market. In addition to the technical aspects of engineered bamboo, the environmental impacts associated with the production of the products need to be explored. Research on the various inputs and processes used to develop these novel products will provide a foundation on which to increase efficiency and reduce the associated impacts. With increased research and development engineered bamboo can serve as a competitive and sustainable alternative to conventional structural materials.

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