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Sustainable structures: bamboo standards and building codes

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The investigation of natural products for use in construction continues to grow to fulfil the need for sustainable and locally available materials. Bamboo, being globally available and rapidly renewable, is an example of such a material. Structural and engineered bamboo products are comparatively low-energy-intensive materials with structural properties sufficient for the demands of modern construction. However, the lack of appropriate building codes and standards is a barrier to engineers and architects in using the material. This paper describes the existing national and international codes and looks towards the future development of comprehensive standards directly analogous to those in use for timber.

1. Introduction

Bamboo has been used for centuries as a material for construction, furniture, crafts and food, among others. In recent years, the use of bamboo has been transformed, both in terms of design and products created. Simple structures constructed from full culm bamboo have demonstrated a way forward for complex structures constructed with bamboo laminates and composites (Figure 1).

Increased interest in, and the development of, bamboo in modern construction have been driven by increasing needs for sustainable materials to meet rising demand due to rapid urbanisation. Although timber offers a low-cost material for construction, increasing urbanisation and deforestation have depleted tropical resources. Timber forests require 30–50 years to establish growth, with European oak taking up to 80 years (Mulligan and Ramage, 2013). In comparison, bamboo is rapidly renewable: structural material can be harvested every 3 to 5 years.

Within academia, the study of engineered bamboo is rapidly growing into a research field of its own, with emphasis on characterising the material and its mechanical properties (Correal *et al.*, 2010; Mahdavi *et al.*, 2012; Sinha *et al.*, 2014; Xiao *et al.*, 2013). Industry is following this new trend with the development of new types of bamboo products to expand the current use from surfaces to structures (see Figure 1(c)).

To adopt and implement structural and engineered bamboo as a construction material, a major barrier of the lack of standards and building codes needs to be addressed. Although design and testing standards exist for full culm bamboo (ISO, 2004a, 2004b, 2004c), they do not provide the foundation from which builders, engineers and architects can design and construct (Harries *et al.*, 2012). The result is that bamboo properties, joints and connections are studied on a case-by-case basis rather than universally designed, which is prohibitive for new methods of construction (Finch, 2005). To overcome the geometric and material variability of bamboo, the development of products that can be easily incorporated into practice is becoming increasingly necessary.

2. New materials in construction

The history of the development of engineering materials typically begins with a new material introduced and designed with a large factor of safety, which is then adjusted over the

Figure 1. Examples of full culm and engineered bamboo construction: (a) rural construction, Estancia, Philippines (photo: Ana Gatóo); (b) Tiga Gunung, Bali, Indonesia, by Jörg Stamm (photo: Ana Gatóo); (c) KPMG-CCTF community centre, Cifeng village, Sichuan province, China (by Lin Hao, reproduced with permission of Zhou Li and Lin Hao)

years based on research and practice (Ellingwood, 1994). Acceptance of non-conventional structural materials, as in the case of carbon fibre, typically takes more than 30 years (Maine and Garnsey, 2006; van der Lugt, 2008). This slow acceptance of new construction materials and techniques is necessary to satisfy not only performance but also insurance and regulatory requirements (Blayse and Manley, 2004). Around the world, building codes and regulations ensure the safety of occupants and the surrounding vicinity of buildings. When enforced, compliance with codes is a requirement for a building to be completed and occupied. In comparison, standards or norms, which provide additional guidance on the standardisation and testing of materials to ensure quality, are used voluntarily.

The introduction of standards and codes further stimulates innovation. For example, emerging green construction standards, which may be voluntary or can be mandated by regulatory agencies in the UK and USA, are leading to increased development of building materials and processes that assist in meeting the requirements of the standards. Gann *et al.* (1998) note that the benefits of a regulatory framework are to create accessible knowledge, leverage investments and demand for technology.

Innovation in the built environment extends beyond creating a new product or material. The additional layers of marketing and associated institutions need to be tailored to the new product (OECD, 2009). Geels (2005) describes this system innovation as a multi-phase process in which the initial phase is emergence in a niche market with design under development. The next phase is application to specialised markets that encourage the development of additional technical aspects of the product. The product is then deployed in the mainstream market, which in turn leads to the final phase of replacement of the inferior products or processes. Structural bamboo and engineered bamboo have both reached the initial and specialised market phases and are on the cusp of being deployed as mainstream products. While the movement forward is positive, the adaptation of bamboo as a building material requires not only technological substitution but also a holistic transformation.

International standardisation and codification would promote structural and engineered bamboo as a renewable structural product worldwide. Blayse and Manley (2004) note that standards create a demand for improved technologies that otherwise would be commercially unsuccessful. Standards provide a way to ensure quality of products and cover specific details, such as test methods, which may be referenced by building codes. Ellingwood (1994) states that structural codes bridge the technology transfer gap between research and practice and are a legal underpinning to assure public safety. Therefore, the need for the development of a structural code for bamboo construction, supported by a previous body of standards, is necessary to promote the material in construction. To be accepted by both designers and policymakers as an engineering material, standardisation is needed to develop the widespread use of bamboo (Janssen, 2000). Without further standardisation of the material, the growing interest and motivation for creating more sustainable infrastructure from bamboo will not be achieved.

3. Standardisation

Standardisation is dependent on the coordinated involvement of stakeholders involved in construction, who promote and accelerate the standardisation process as a collective. The development of an international standard for structural and engineered bamboo products would encourage manufacturers to create a high-quality, safe and efficient product and to reduce environmental impacts and social inequalities associated with processing.

Increased standardisation of the manufacturing process has the potential to drive the development of industry and improve efficiency overall. For example, the use of fibre reinforced polymers was adapted from aeronautical engineering to other markets such as structural engineering. This shift of application required changes in manufacturing, not only for increased diversity of products but also due to the need to reduce costs to remain competitive.

3.1 Existing standards and codes

In 2004, the International Organization for Standardization (ISO) published three standards on bamboo construction, which was the first step to standardise bamboo for this purpose (ISO, 2004a, 2004b, 2004c). These standards build on existing traditional knowledge and reference existing ISO timber standards with testing methods adapted to bamboo (Sharma, 2010). The standards also serve as a basis for further standardisation of bamboo as a structural material. However, full development of codes and standards is still necessary to utilise bamboo as a structural material in the USA and Europe.

A decade later, the field has advanced with increased global interest and research, but the call for further standardisation and codification of bamboo construction continues (Harries *et al.*, 2012; Jayanetti and Follet 2008; van der Lugt *et al.*, 2006). Countries with local bamboo resources (e.g. China, Colombia, Ecuador, India and Peru) have taken the lead in creating a framework for bamboo construction codes. Sections in national building codes and standards on bamboo testing, construction and structural design have emerged, mainly focusing on whole culm bamboo. The available codes and standards for structural design and construction with bamboo are summarised in Table 1 and reviewed in the following sections.

3.1.1 International Organization for Standardization (ISO)

ISO 22156: Bamboo – structural design (ISO, 2004a) provides basic design guidance for full culm construction. The standard is supported by ISO 22157-1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b), which specifies test methods, and ISO 22157-2 (ISO, 2004c), a laboratory manual for determining material properties. An emerging field is the study of laminated bamboo products for construction. ISO 22156 (ISO, 2004a) addresses the structural application not just of full culm bamboo, but also plybamboo, which is composed of woven bamboo mats glued together or layers of split bamboo strips laid across each other and glued together. The standard indicates that characterisation of the material should be conducted based on national standards for plywood.

3.1.2 China

Research on bamboo construction continues to increase in China. Standards on full culm bamboo, such as JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007), provide guidance for material and mechanical testing. The standard includes the physical and mechanical tests found in ISO 22156 (ISO, 2004a), but differs in the test methods and parameters. For example, JG/T 199 uses sections of the culm wall for all of the mechanical tests whereas the ISO standard uses the full culm for compression, shear and flexure tests. The Chinese standard also uses separate tests to obtain the modulus of elasticity in compression, tension and flexure. JG/T 199 provides a correction factor, which utilises an empirical equation to account for moisture content in the specimen, to obtain strength and stiffness values.

3.1.3 Colombia

The Colombian code for seismic-resistant structures includes a chapter on structures built with the most common bamboo species in Colombia, Guadua (*Guadua angustifolia* Kunth) (ICONTEC, 2010). This chapter establishes the minimum requirements for structural and seismic-resistant design for Guadua. The chapter utilises allowable stress design in which a modified allowable stress is determined from mechanical properties, obtained from experimental tests and modified by multiple factors to account for uncertainty in test conditions and test methods. Similar equations are found in the ISO design standard (Trujillo, 2013). As shown in Table 1, additional Colombian standards are NTC 5407, on structural joints with *Guadua angustifolia* Kunth (ICONTEC, 2006), and NTC 5525, which concerns methods and tests to determine the physical and mechanical properties of *Guadua angustifolia* Kunth (ICONTEC, 2007).

3.1.4 Ecuador

Chapter 17 of *Norma Ecuatoriana de la Construcción* on the utilisation of *Guadua angustifolia* Kunth in construction (INEN,

Country	Code	Standard
China		JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007)
Colombia	*Reglamento Colombiano de Construcción Sismoresistente* – chapter G12 Estructuras de Guadua (Guadua structures) (ICONTEC, 2010)	NTC 5407: Uniones de Estructuras con *Guadua angustifolia* Kunth (Structural unions with *Guadua angustifolia* Kunth) (ICONTEC, 2006) NTC 5525: Métodos de Ensayo para Determinar las Propiedades Físicas y Mecánicas de la *Guadua angustifolia* Kunth (Methods and tests to determine the physical and mechanical properties of *Guadua angustifolia* Kunth) (ICONTEC, 2007)
Ecuador	*Norma Ecuatoriana de la Construcción* – chapter 17 Utilización de la Guadua Angustifolia Kunth en la Construcción (Use of *Guadua angustifolia* Kunth in construction) (INEN, 2011)	INEN 42: Bamboo Caña Guadua (bamboo cane Guadua) (INEN, 1976)
India	*National Building Code of India*, section 3 Timber and bamboo: 3B (BIS, 2010)	IS 6874: Method of tests for round bamboos (BIS, 2008) IS 15912: Structural design using bamboo – code of practice (BIS, 2012)
Peru	Reglamento Nacional de Edificaciones, Section III. Code E100 – Diseño y Construcción con Bamboo (ICG 2012)	
USA		ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013)
International		ISO 22156: Bamboo – structural design (ISO, 2004a) ISO 22157-1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b) ISO 22157-2: Bamboo – determination of physical and mechanical properties – part 2: laboratory manual (ISO, 2004c)

Table 1. Existing structural bamboo standards and codes

2011) addresses processing, selection, construction and maintenance. Similar to the Colombian norms on joints and preservation (ICONTEC, 2006, 2007), the chapter describes the process but does not include design calculations. Similarly, INEN 42 (INEN, 1976) promotes useful aspects of bamboo as a construction material in Ecuador, but also does not include any design guidance.

3.1.5 India

Section 3B of the *National Building Code of India* (NBCI) (BIS, 2010) provides strength limits for three classes of bamboo, representing species commonly found in India. While some examples of bamboo joints and connections are provided, detailing with dimensions and capacities is not addressed (Sharma, 2010). In addition to the NBCI, several Indian standards are centred on structural design. For example, IS 15912: Structural design using bamboo – code of practice (BIS, 2012) provides the minimum requirements for structural design of bamboo buildings. Similarly, IS 6874: Method of tests for bamboo (BIS, 2008) can be utilised to determine the physical and mechanical properties of full culm bamboo.

3.1.6 Peru

The Peruvian code for bamboo was approved in 2012 (ICG, 2012). The code covers design and construction with bamboo for seismic-resistant structures. Various other codes and standards are also referenced, including the Colombian code and the ISO standards on bamboo construction. Modified versions of the structural design calculations from the Colombian code (although not as detailed as their original source) and construction design from the Ecuador code are included.

3.1.7 USA

ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013) is the first to recognise laminated veneer bamboo as a structural product and provides guidance on manufacturing standards and test methods. The material is treated as an equivalent to structural composite lumber products such as laminated strand lumber, laminated veneer lumber, oriented strand lumber and parallel strand lumber, as shown in Figure 2.

4. Future standardisation

The brief review of international standards and codes for bamboo construction presents two pathways forward for further standardisation of bamboo construction. First, the review demonstrates that many of the existing standards and codes reference the ISO standards, which have been shown to be insufficient for widespread use. The ISO standards provide a foundation from which to design with bamboo, but they need to be updated and expanded to reflect the growing research on test methods and material characterisation, as well as the development of new structural bamboo products. The second pathway is to create standards and codes that are analogous to timber-based standards. The trend to utilise timber-based test methods for characterisation and design is increasing in research and provides a simple pathway to engage architects and engineers in the use of bamboo for construction.

4.1 Benefits of timber-based standards for engineered bamboo

As discussed previously, the adoption of timber standards is an initial way to create widely marketable bamboo products. Engineered bamboo products have the potential to be manufactured in standard sizes and shapes, analogous to timber and glulam. Timber, structural bamboo and engineered bamboo all have different properties, but presented together within the timber standards could serve as a foundation for the creation of engineered bamboo product standards. Figure 3 demonstrates an example of how bamboo standards could be developed, based on existing and European norms and ISO standards. The figure illustrates the physical and mechanical properties for engineered bamboo, determined using timber-based standards.

Recent research studies are shifting towards timber standards for testing and characterising engineered bamboo products

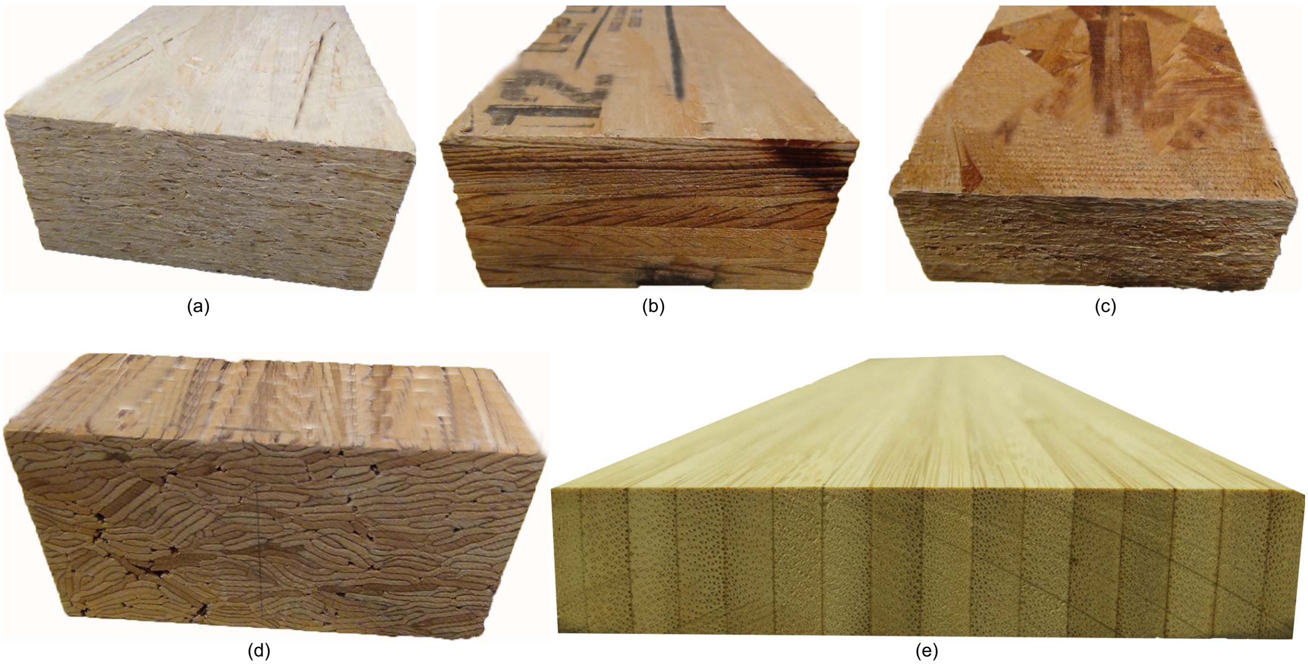

Figure 2. ASTM D5456 structural composite lumber products: (a) laminated strand lumber; (b) laminated veneer lumber; (c) oriented strand lumber; (d) parallel strand lumber; (e) laminated veneer bamboo (reproduced with permission of Greg Smith, Katherine Semple and Ana Gatóo)

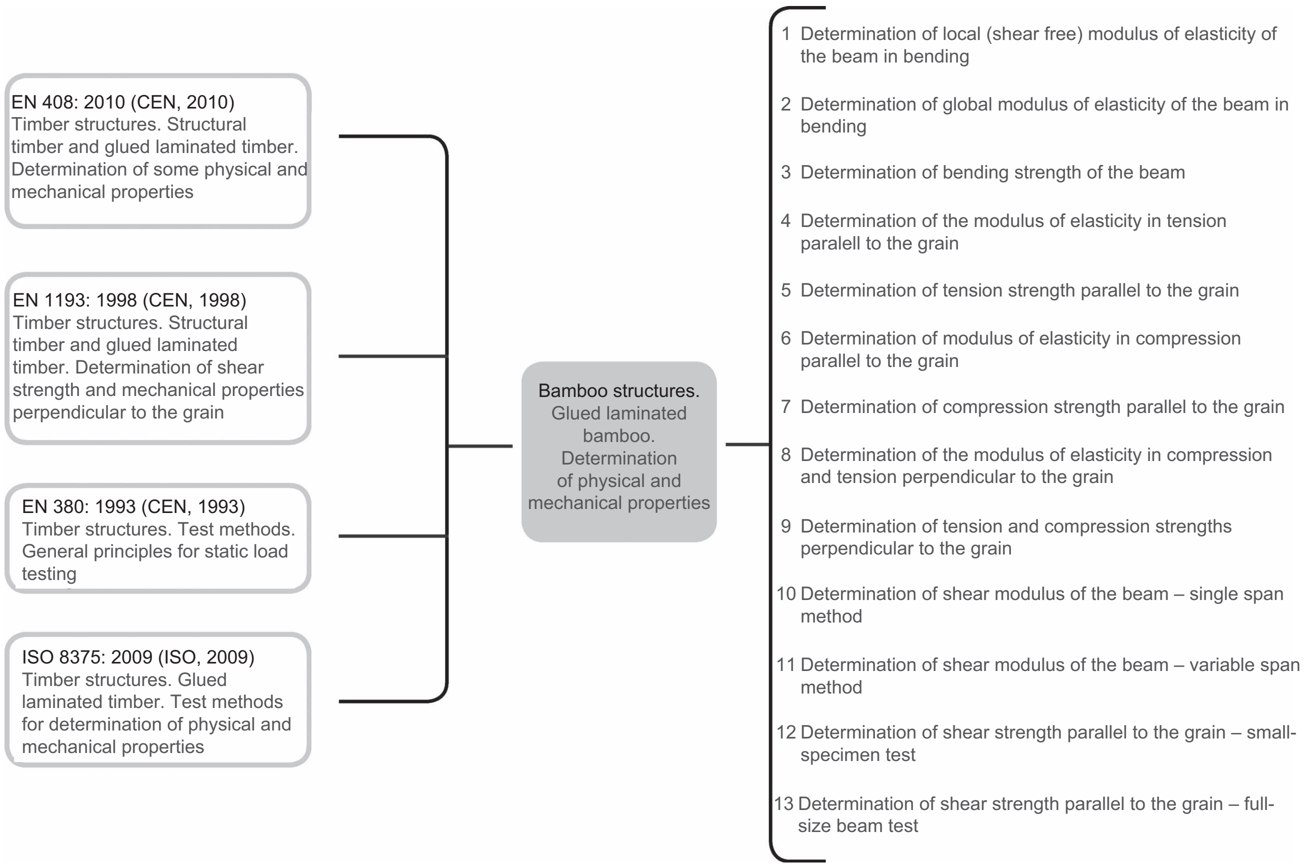

Figure 3. Relevant European norms and ISO timber standards and their application to bamboo

that no longer resemble whole culm bamboo. For example, ASTM D143: Standard test methods for small clear specimens of timber (ASTM, 2009) has been used to evaluate the mechanical properties of laminated bamboo (Correal *et al.*, 2010; Mahdavi *et al.*, 2012; Sinha *et al.*, 2014; Xiao *et al.*, 2013). The development of timber-based standards will provide a comparison to other timber products as well as broaden the potential markets for structural and engineered bamboo products.

5. Conclusion

The standardisation of structural bamboo products reflects the growing interest from society and policymakers and provides a new opening for sustainable industrial development. The emergence of comprehensive codification of structural bamboo products may be inevitable in the near future, but without coordinated participation from interested stakeholders the process will be slow and ineffective. Academia, industry and policymakers must improve their collaboration and communication to make the process efficient. Although the development of standards and codes thrives globally, there is a need to address the growing demand for bamboo-based products. Academic research should aim to inform the process, through experimentation and analysis, from which industry and policymakers can work towards creating the foundation for standardisation. The joint contribution of each of the stakeholders will help guide the growing economic and environmental interest and will be a crucial step towards the standardisation of structural and engineered bamboo products.

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