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Mechanical characterisation of bamboo for construction: the state-of-practice and future prospects

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Abstract

Methods for material characterisation of bamboo necessary for the structural design of bamboo and its expanded use in the construction sector are described. Directions for revising the nascent existing ISO 22157:2019 standard and future directions for this standard are discussed. Critical needs identified include i) improved performance of standard shear and flexural tests; ii) the need to establish protocols and methods for quantifying the long-term behaviour of bamboo and its degradation under environmental exposure; and, iii) establishing the efficacy of emerging methods of bamboo treatment. Requirements are placed in the test standards – grading – structural design ecosystem and are intended to guide future revisions of test and design standards.

Keywords: Bamboo; Durability; Flexure; Grading; Time-dependent properties; Shear; Test methods

1 Introduction

Bamboo, both in its full-culm (pole) form and as a constituent material in a variety of engineered bamboo materials (glue-laminated bamboo, cross-laminated bamboo, bamboo scrimber, etc.) is receiving considerable and growing recognition as a sustainable structural material. As a construction material, bamboo holds remarkable potential for its fast growth and short (typically 3-4 years) harvest cycle, high strength-to-weight ratio, and carbon sequestering ability. Bamboo, however, has a unique morphology – it is essentially a unidirectional fibre reinforced material – with very pronounced orthotropy [1].

The term "bamboo" is about as descriptive as "wood". There are on the order of about 100 species (of the 1600 species of bamboo) that are believed suitable – in terms of geometric and material characteristics – for construction use in their full culm (pole) form. Interspecies and intraspecies variation of bamboo is significant. Bamboo resources (plantations, natural forests), typically need to be characterised individually. To achieve the greatest sustainability impact, bamboo must be used as a local or regional resource [2][3]. Depending on circumstance, in some cases imported bamboo components can have a lower impact in respect to traditional construction materials, especially when importation of the latter is also required [4]. Although this paper focussed on the use of bamboo in its full-culm form, the discussion is equally relevant to engineered bamboo [5]. Full-culm bamboo, after all, is the 'feedstock' for all engineered bamboo products.

Substantial literature on the mechanical characterisation of bamboo has been produced in the last few decades. Such experimental studies have expanded knowledge of species from tropical, sub-tropical and temperate climates, including *Guadua Angustifolia* [6], *Dendrocalamus Asper* [7] *Gigantoshloa scortechinii*, *Gigantochloa levis* [8], and significant study of *Phyllostachys edulis* (commonly called Moso bamboo) [9][10], among others.

Nonetheless, there is a recognised need for establishing a consistent and comprehensive worldwide database of bamboo geometric, physical, and mechanical properties [11]. There are relatively few studies assembling interspecies data from multiple sources [12] and these often report significantly varying results. Intraspecies data is also reported with considerable variation in some cases [10].

A shortcoming of the extant literature is the inconsistent use of test methods and standards. For example, the specimen orientation and machine grip boundary conditions under which simple tension tests are conducted can lead to results that vary by a factor of more than two [13]. In other cases, very different data is reported as being the same: some research does not differentiate tension tests conducted with and without the presence of a node (another factor of about two in terms of reported results). Other studies have been identified as reporting shear properties of bamboo culm walls

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*Corresponding authors: Luisa Molari, e-mail: luisa.molari@unibo.it without reference to specimen orientation [14]; results, in this case, vary by an order of magnitude.

To better establish bamboo as an accepted structural material it is necessary to have engineering standards with recognised methods of design and assessment of performance. The path toward the international standardisation of bamboo as a structural material began more than two decades ago and has progressed substantially and rapidly. However, as bamboo becomes of greater interest and achieves greater acceptance, more refined standards addressing more properties of interest need to be established. The mechanical characterisation of the properties of bamboo under static load conditions is relatively well established; ISO 22157:2019 [15] represents the current state-of-practice. Nonetheless, ongoing research has led to, and will continue to lead to recommendations for improvements to such characterisation methods.

Mechanical characterization of bamboo is necessary for structural design using bamboo. Design using ISO 22156:2021 [16], the structural design standard for full-culm bamboo, requires the full suite of mechanical and geometric characterisation provided by ISO 22157:2019 [15]. Nonetheless, ISO 22157:2019 does not consider the change of material and mechanical properties over time associated with the viscoelastic nature of the material or resulting from environmental degradation. ISO 22156:2021, addresses viscoelastic behaviour in a cursory manner, reducing characteristic modulus as a function of load duration. Environmental exposure is addressed through Exposure and Use Classes, and property reductions associated with these. Due to a lack of long-term and durability data for bamboo, these reductions are taken to be very conservative, and the use of bamboo is not permitted in some exposure conditions. Essentially, the current state of bamboo design reduces many unknowns to empirically derived and overly conservative material property modification and safety factors. A primary example of this is the factor of safety for longitudinal shear and perpendicular tension – those actions associated with splitting – being (admittedly arbitrarily) taken as twice those of other actions.) Thus, while there is a need to improve upon established test methods, new and refined tests able to provide rational bases for establishing modification and safety factors are required.

To establish more reliable and robust measures of long-term performance, it is necessary to formalise tests and/or sampling protocols to establish the change of mechanical parameters over time due to both viscoelastic behaviour and environmental degradation. Improved behaviour and degradation models will lend greater credibility and confidence to design with bamboo, overcoming some of the negative perceptions of bamboo and allowing more refined design to be carried out.

An additional relatively poorly studied area is the need for preservation treatment and its impact on the mechanical characterisation of bamboo. It is universally understood that bamboo requires treatment when used for construction and, conventionally, there is an assumption that characterisation is conducted of materials in their treated condition. However, as the industry grows, this assumption may prove impractical, especially as alternative, more ecologically friendly treatment methods are developed.

In this paper, static characterisation test methods presented in ISO 22157:2019 are reviewed and areas for improvement indicated. Next, alternative test methods, particularly those for determining the variation of mechanical parameters over time are reviewed. Both the viscoelastic behaviour and environmental degradation are considered. Finally, the identification of properties that could be used in efficient grading systems is discussed.

2 ISO 22157:2019: possible variations and future revision

The efforts to develop a suite of ISO standards for bamboo were initiated in the late 1990s and culminated in the 2004 publication of ISO 22157-1:2004 [17] and ISO 22156:2004 [18]; a test methods standard and design standard, respectively. The 2004 standards were based on traditional knowledge and the early seminal work of Janssen [19] and Arce-Villalobos [20]. Colloquially, the 2004 standards are “version zero” (v0) standards [21]. These v0 standards are fundamentally inadequate for performing holistic design for most potential end-users [22], yet function well as an impetus for collaborative research by developing a *lingua franca* and exposing gaps in domain knowledge [21][22]. A v0 document is intended to be revised as new knowledge is generated through research and practice; indeed, Janssen himself reports that many of the original [2004] chapters “only give a general outline” [23].

It would be more than 15 years before a reconstituted ISO bamboo subcommittee (ISO TC 165 WG 12) published revised standards for mechanical characterisation, ISO 22157:2019 [15], and structural design, ISO 22156:2021 [16]. A bamboo grading standard, ISO 19624:2018 [24] was also produced. ISO 22156:2021, enabled by ISO 19624:2018, permits allowable capacity design as well as allowable stress design [25] while preserving the ability to design structures based on local experience from previous generations. Adopting allowable capacity or stress approaches, rather than a load and resistance factor (LRFD) or partial safety factor (PSF) approach, reflects the still limited engineering knowledge of bamboo and is better aligned with allowing traditional knowledge to inform design. In this way, the criticisms of [22] are addressed. This paper focusses on ISO 22157:2019 [15].

ISO 22157:2019 includes six tests for determining mechanical properties (Figure 1): (a) compressive strength and stiffness parallel to the fibres; (b) tension strength and stiffness parallel to the fibres; (c) bending strength and stiffness parallel to the fibres; (d) shear strength parallel to the fibres; (e) tension strength perpendicular to the fibres; and (f) bending strength and stiffness perpendicular to the fibres. The standard also provides methods for determining moisture content, density, and mass per unit length of bamboo. ISO 22157:2019 evolved substantially from 2004: methods (e) and (f) and that for reporting mass per unit length and revised moisture content methods were added in 2019. The boundary condition requirements for the compression test (a) were revised to permit alternative methods and the tension test method (b) was revised substantially based on [13].

With the exception of the tension test method, ISO 22157:2019 focusses on test methods that utilise full-culm specimens. This was done to better address the needs of ISO 22156:2021 design [21] and allow for relatively simple, compression driven test methods to be used. Typically, compression tests are easier to implement in an environment that may not be as technically well-equipped as a modern materials lab [22]. Like most structural materials, ease of appropriate field testing must be a consideration when selecting or designing test methods. Complex methods will be relegated to well-equipped laboratories with their attendant costs and potential for project delays. Relatively simple and repeatable tests are those that will be used in the field and must ultimately stand as a surrogate for properties that can only be derived from complex texts. Taking concrete as an example: typically, simple compression strength tests are conducted and necessary design parameters (such as modulus of elasticity, modulus of rupture, etc.) derived from these. More complex laboratory testing is conducted an a much lower frequency to validate the derivations.

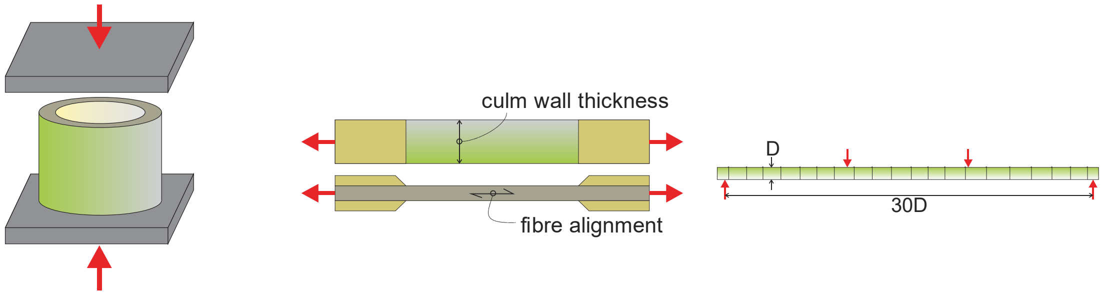
2.1 Tension parallel to fibres

Since bamboo is highly anisotropic, gripping tension tests can be a challenge. ISO 22157:2019 prescribes a straight specimen having a width equal to the culm wall thickness with softwood tabs recommended for gripping (Figure 1b). This test geometry was established by [13]. The specimen geometry was confirmed by [26] to be appropriate for full-culm applications and to result in a lower coefficient of variation of results. Reduced area specimens (so-called dog-bone specimens) were prescribed in the older ISO 22157:2004; however, such a geometry is poorly suited to capturing the full section behaviour of a functionally graded material such as bamboo [13]. Different methods of gripping tension test specimens are proposed [9][27] and other methods suitable for unidirectional fibre-reinforced composite materials are likely also suited to bamboo – these alternatives need to be considered for future revisions of ISO 22157:2019. Often overlooked, tension results are affected (by a factor of about two) by the presence of a node in the specimen. It is rare that bamboo internode tension strength will be relevant in structural design; tension should always be reported using specimens containing a node in the gage length. It has been shown that the presence of a node has little effect on other ISO 22157:2019 test methods [10].

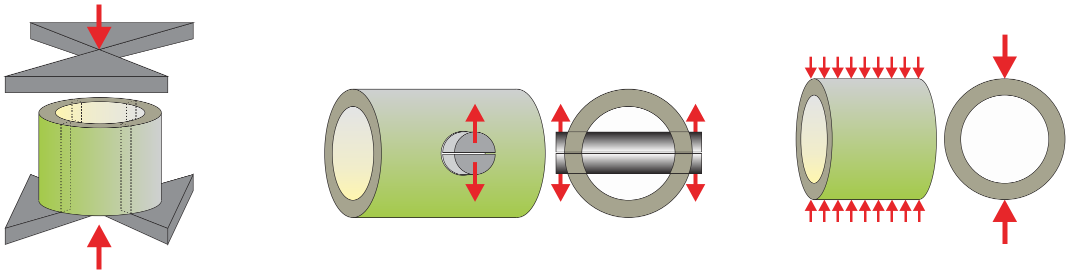
2.2 Shear parallel to fibres

The ISO 22157:2019 shear test (the so-called “bow-tie” test shown in Figure 1d) is a legacy from the 2004 version. The test activates four failure planes although it is rare that all four planes fail; the number of failure planes must be reported in test results. Nonetheless, the shear strength derived from this test assumes four failure planes and therefore must be interpreted as a lower bound shear strength for the culm. A revised shear test setup having only two failure planes (Figure 2a) and reported lower variation of results has been proposed [28].

Other shear test arrangements are proposed in the literature. A torsion-based test, similar to that promulgated for timber in ASTM D198 [29] has been proposed [30] and shown to be reliable [31] (Figure 2b) although difficult to implement. Other small sample shear tests have been proposed based on a typical S-shaped specimen (Figure 2c) [32], and on a two-plane specimen (Figure 2d) [33]. Small single shear specimens are often used for engineered bamboo applications [34][35] as shown in Figures 2e and 2f. Consideration of these alternate arrangements for future revision of ISO 22157:2019 should be made.

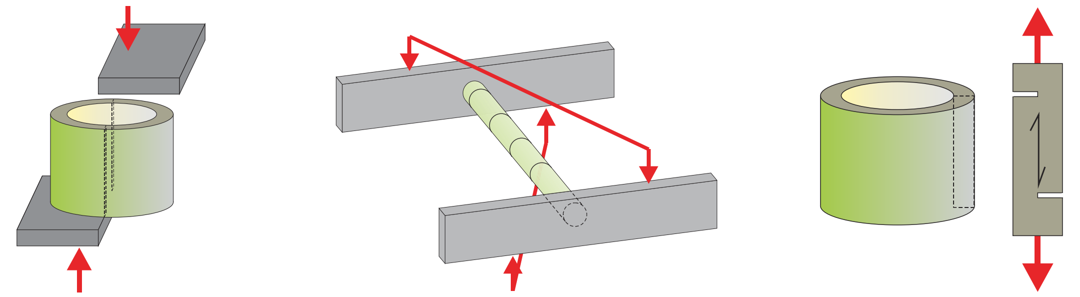


a) compression parallel to fibres b) tension parallel to fibres c) full-culm bending



d) shear parallel to fibres e) tension perpendicular to fibres f) bending perpendicular to fibres

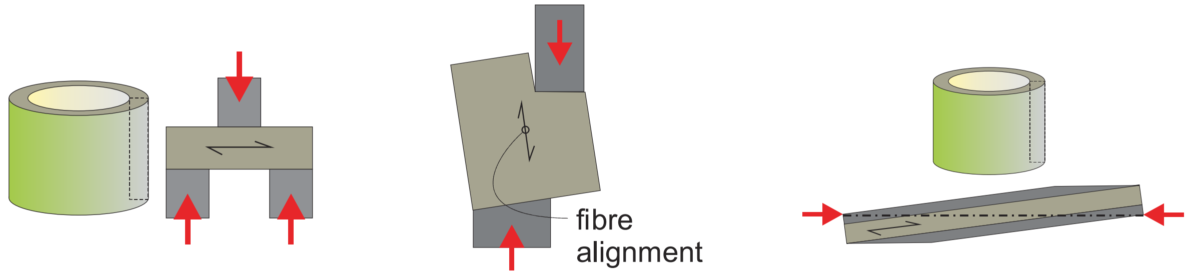
Figure 1. ISO 22157:2019 schematic representations of bamboo materials test methods.



a) two-plane full culms tests [28]

b) torsion test [31]

c) S-shaped specimen [32]



d) two-plane specimen [33]

e) single plane shear test [34]

f) sloped single plane shear test [35]

Figure 2. Schematic representations of alternate shear test arrangements.

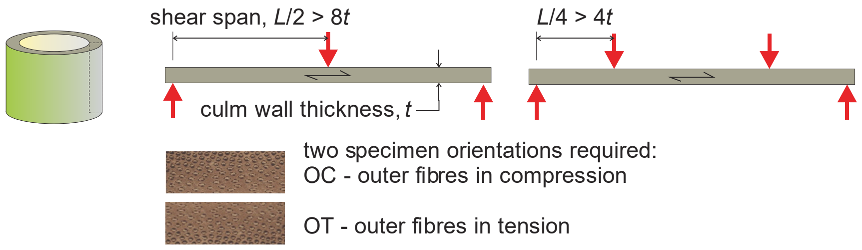
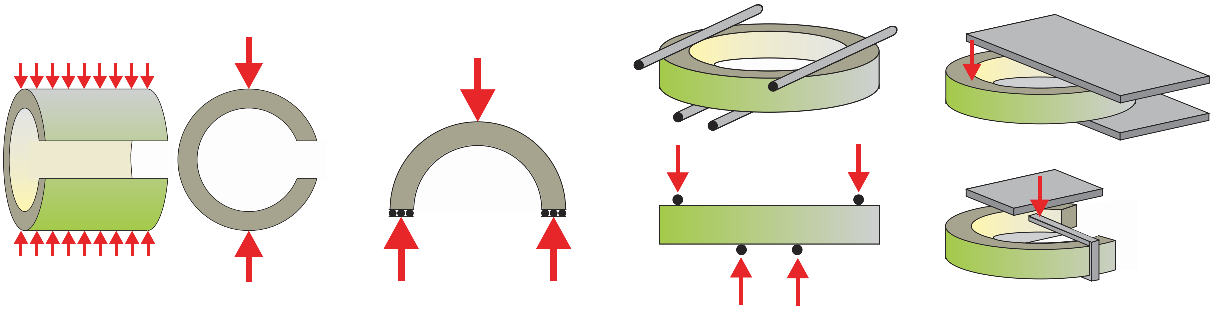


Figure 3. Schematic representations of bending tests inspired by ASTM D7264 (ASTM D7264 permits two different test arrangements and specifies that overall length (*L*) should exceed at least 16 times the specimen depth).



a) C-shaped specimen [42]

b) arch specimen [42]

c) flat ring flexure [43]

d) variations of clamped flat ring flexure [44]

Figure 4. Schematic representations of alternate test arrangements for determining properties perpendicular to fibres.

2.3 Bending parallel to fibres

The third-point bending test promulgated in ISO 22157:2019 is performed on a full bamboo culm having equal shear spans that must exceed 10 culm diameters making the total specimen length at least 30 culm diameters. (Figure 1c). While the test reports the "flexural capacity" of the culm, behaviour is rarely flexural in nature, but is rather governed by longitudinal shear behaviour of the highly anisotropic material [19][36]. Additionally, the prescribed test is cumbersome and requires a relatively large test arrangement deformation capacity. Many researchers (e.g., [10][37][38]) have adopted a small rectangular bending sample and a test method based on, or similar to, that of ASTM D7264 [39] as shown in Figure 3. Using such a test, the bimodular behaviour [40] of bamboo can be assessed based on the orientation of the test specimen (having the outer culm wall in compression (OC) or tension (OT)).

2.4 Properties perpendicular to fibres

As a highly anisotropic material, properties perpendicular to the fibres often control design capacity. The split-pin tension test (Figure 1e) in ISO 22157:2019 was developed based on the work of [14]. This test is viewed as cumbersome to conduct outside of well-equipped laboratories. The bending test perpendicular to fibres (Figure 1f) was adopted based on the work of [41]. The values reported in this test are based on a round specimen; the failure plane location and test results vary with specimen geometry, especially those that are more oval (depending upon the orientation in which they are tested. Different test arrangements are proposed to better establish transverse properties. Two variations of the ring flexural test are proposed by [42]: a C-shaped specimen (Figure 4a) and a half ring (or arch) subjected to load (Figure 4b). With these geometries the failure plane is controlled and bimodular behaviour is easily determined. A "flat ring" flexure specimen is proposed by [43] that also reliably captures properties perpendicular to the bamboo fibres (Figure 4c). A similar "clamped flat ring" arrangement and a torsional variation thereof (Figure 4d) intended to determine the radial-circumferential Young's modulus and the circumferential-axial shear modulus of bamboo is proposed by [44]. These test methods should all be considered for adoption into ISO 22157:2019 as variations or alternatives to the existing tests.

3 Bamboo characterisation: variation of parameters with time

At present, there are no known standards and relatively little known research addressing the impacts of the viscoelastic nature of bamboo or the impacts of environmental exposure on the physical and mechanical properties of bamboo. As such, the remainder of this paper is mostly addressing perceived future needs for bamboo test method development and standardisation.

3.1 Viscoelastic behaviour of bamboo

The quantities that describe viscoelasticity, relaxation and creep in the directions parallel and orthogonal to the fibres are important parameters for design in the presence of permanent loads. To account for a relative lack of data, ISO 22156:2021 prescribes what are believed to be conservative safety factors with respect to permanent loads. The ISO 22156 creep provisions are based on typical small flexure specimen creep specimens, similar to those used for wood and tested out for as long as 120 days [38]. Although creep performance was reported to be marginally better than wood, the orientation of the specimen was found to have a significant effect on both creep behaviour and residual strength of creep-conditioned specimens.

Relaxation tests of rings, semirings and C-shaped specimens of *Guadua angustifolia* were used to characterise mechanical behaviour under sustained transverse displacement [45]. Tests shorter than one hour showed a behaviour typical of viscoelastic material that could be modelled by a generalised linear Maxwell's model. For longer tests, up to 24h, displacements, and the force–time relaxation curves showed recoveries and oscillations, due to relative humidity change, which viscoelastic theory could not explain. The effective circumferential modulus showed substantial reductions over time equal to 49%, 74%, and 41% for the rings, semirings, and C-shaped specimens, respectively, indicating an effect of stress field (specimen) geometry.

Based on the limited extant evidence, it is likely that a suite of tests will be required to adequately capture the viscoelastic behaviour of bamboo.

3.2 Durability

Quantifying durability is a challenge for most construction materials. There are few consensus standards or test protocols and those that do exist are often adopted from other sectors (metallic and FRP durability quantification is often adapted from aerospace, for instance).

Bamboo, while chemically similar to wood, is known to be less resistant to typical vectors of decay (insect, fungal and hygrothermal) [46]. There are few studies that address bamboo durability in a standard manner [47][48]; most available data is anecdotal. The adoption of tests of durability suitable for wood [49][50] must account for the unique thin-walled geometry of bamboo.

3.3 Bamboo treatments

Bamboo must be treated for use in load-bearing applications expected to have a life longer than a few months. There are many traditional and chemical treatment options commonly used throughout the world – usually exhibiting a regional preference; an excellent summary is provided in [51]. There is considerable recent interest in more ecologically sound methods of treatment and these are being developed – often in an *ad hoc* manner. While some studies have addressed the effects of treatment on physical and mechanical properties [52][53], few have attempted to quantify the efficacy of the treatment itself.

4 Identification of mechanical characteristics for grading bamboo culms

ISO 19624:2018 provides a framework for the grading of bamboo culms, defining grading as "the process of sorting every piece of bamboo in a sample into grades according to defined selection criteria" [24]. If the criteria selected are too onerous, more bamboo will be rejected; if the criteria are too lax, this will need to be compensated through more conservative and potentially inefficient designs.

ISO 19624:2018 outlines "rule-based" or "inference-based" grading processes based on the non-destructive measurement of "indicating properties" (IP) that can reliably infer "grade-determining properties" (GDP) properties needed for the design that can only be measured destructively. ISO 19624:2018, however, does not identify IP and GDP, nor does it prescribe the required inference relationships between these. Although the grading framework reflects that used for wood [54], because full-culm bamboo remains in its natural form (whereas timber is cut to standard dimensions), the grading process is more complicated and requires greater flexibility. It is not clear that grading bamboo in manner similar to wood will ultimately be appropriate. ISO 22156:2021 permits allowable capacity design which suggested capacity, rather than property-based grading approaches. In general, this is the direction most attempts at grading bamboo have gone, as described next.

Several candidate IP, including density [55] and linear mass [56] have been proposed. These have been used in studies of specific bamboo resources to propose GDP for compression [55][57] and flexure [37][56][58][59] capacity. Due to interspecies variation, all grading schemes must consider species. Intraspecies variation must also be considered when considering diverse resources. The lack of reliable and consistent data for bamboo makes univeralising IP selection and IP-to-GDP inference challenging. Machine learning [60] and material informatics [61] approaches have been proposed to accelerate this development.

5 Conclusions and the path forward

Although important advances have been made to standardise the use of bamboo, many technical challenges remain before bamboo can be fully accepted as a structural material. With the publication of test standards [15], researchers have identified areas for improvement as described in Section 2 of this paper.

It is also necessary to provide builders, engineers, and architects with tools to allow them to select bamboo in construction design. Developing the tools and data to permit bamboo to be treated as any other material in the realm of digital design is an important objective. An early of example of this approach is described by [62] in which the potential for extending the service life of bamboo through algorithmic design approaches is explored. Improved knowledge for working with bamboo will also support innovation in the engineered bamboo industry: one cannot produce an engineered material, without understanding the constituent materials [5].

Uniformly accepted and robust methods of characterising bamboo materials are necessary. While there are extant materials test methods [15], these provide no guidance as to what properties are required for design [16] and, critically, how these properties may interact. The inference of grade-determining properties (GDP) from indicating properties (IP) provides a guiding premise.

A widely acknowledged shortcoming of existing bamboo standards is that there is no single property (or small handful of properties) that can reliably characterise bamboo materials (as compression testing does for concrete). Test standards [15] must be viewed as a toolbox from which one selects the needed test(s) not as a required suite of characterisations.

A second acknowledged barrier to bamboo construction is the largely *ad hoc* and variable nature of available material property data. Harmonisation and synthesis of both test methods and data curation are required.

Finally, the selection of bamboo is often predicated upon its sustainability credentials. In order to complete the picture of which species are more appropriate for construction in the context of the global climate emergency, information on carbon capture and embodied carbon (resulting from processing) and the link between these and the mechanical characterization data is needed to help support the decision process when considering or selecting bamboo.

5.1 RILEM Technical Committee

A new RILEM Technical Committee (TC) has been approved with a focus on bamboo. The TC will first analyse the state-of-the-art and the state-of-practice associated with bamboo materials characterisation (this paper is a starting point). Starting with ISO 22157:2019, the TC aim to harmonise international standards – effectively establishing a much-needed *lingua franca* within the bamboo community. A key objective will be to establish a reporting protocol and worldwide database of bamboo geometrical, physical and mechanical properties [11]. This data will be available broadly to allow researchers to experiment with emerging approaches to materials informatics [61]. A hypothesised outcome of establishing a data-rich environment is the development of a simple and easy-to-use classification methodology (or procedure) that will be largely independent of bamboo species, similar to timber classifications of softwood and hardwood.

Guided by gaps in the knowledge base and the international bamboo community, the TC will broaden the scope of bamboo characterisation, prioritising the needs of the bamboo design community. Long-term behaviour, durability and treatment efficacy are immediate needs. The committee will have its inaugural meeting in April 2024.

Authorship statement (CRediT)

Both co-authors contributed equally to all aspects of this review paper. Opinions expressed are those of the co-authors.

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