Keynote Speaker

DEVELOPMENTS IN STRUCTURAL DESIGN STANDARDS WITH BAMBOO

David Trujillo, MSc DIC CEng MIstructE
Senior Lecturer (School of Energy, Construction and Environment, Coventry University, UK)
david.trujillo@coventry.ac.uk (corresponding author)

Abstract
Structural design standards and codes emerged over 100 years ago. Their development has been supported by multi-billion dollar industries. Efforts to develop codes and standards for bamboo started in the late 20th century, but only until the early 21st century did the first design codes emerge. Most of these have quite limited application. Two codes stand out in this field: chapters E.7 and G.12 to the Colombian design code. More recent efforts within ISO and supported by INBAR have taken place, these include a revised ISO 22157 and the new ISO 19624. Development of standards and codes is a slow and costly process, efforts need to be coordinated and pooled in order to make the best use of limited resources.
Keywords: standards, codes, bamboo, INBAR, ISO

The origin of standards

Structural design standards, or codes (either term will be used interchangeably in this paper), emerged at the beginning of the 20th century (Addis, 2007) when countries developed the need to standardise the design procedures for steel-frames and reinforced concrete structures. According to Addis (2007), national standards collected three types of information:

- *"Properties of materials, including the quality of their manufacture*
- *The various loads that building structures should be designed to carry*
- *Codes of design practice that provided suitable methods for designing the various structural elements of buildings – columns, beams, floors and shear walls – and the connections between them."*

In the case of the UK, the birth of the *Institution of Structural Engineers* is directly linked to the process of trying to standardise the procedures for the design of reinforced concrete (Addis, 2007). The development of standards permitted breaking the monopoly over reinforced concrete that the first inventors had, allowing any engineer to design with it, and allowed the authorities to check the designs to ensure their safety (Bussell, 1996).

It is important to note that these standards emerge as a need to address the technological developments of framed structures that were much taller than anything that preceded them. Prior to the emergence of standards, designs were done on the basis of published material (e.g. textbooks). Committees of code writers have typically consisted of representatives of the product manufacturers, representatives of the structural designers and researchers (Addis, 2007). Development of codes and standards is a slow and lengthy process, it requires a compromise between the parties and needs to be underpinned by extensive experimental research, which is expensive.

It is worthwhile remembering that the industries behind steel, concrete, and even timber, are gigantic. In 2016, the global market for steel was USD 807 billion (grandviewresearch.com), whereas for cement it was USD 395 billion (statista.com), and for forest products it was USD 227 billion (FAO). Bearing in mind the size of these industries, it is evident that they have had, and continue to have, the financial capacity and political influence to ensure that the research required to develop the standards was funded. Structural and material researchers all over the world still remain committed to further improving these materials and the design methods that ensure their economical use.
In contrast, according to INBAR (2012), the export of industrialized bamboo products in 2012 was USD 539 million (roughly 1500, 700 and 400 times smaller than the steel, concrete and timber industries respectively). Research into the structural properties of bamboo is also much younger and more sparsely undertaken. Bearing this in mind, it is quite remarkable that any progress has been made in the process of development of standards and codes for the structural use of bamboo.

Code and standard development of bamboo: a brief history

The first standard aimed at understanding the mechanical properties of bamboo was 'IS:6874 – Methods of tests for round bamboos' which was introduced by the Bureau of Indian Standards in 1973 (BIS, 1973). In the late 1990s, Dr Jules Janssen from Eindhoven University of Technology led the development of a series of test standards for round bamboo in the name of the International Network for Bamboo and Rattan (INBAR). These INBAR 'standards', as they would become known, were based on IS:6874 and formed the basis of 'ISO 22157-1 Bamboo – Determination of physical and mechanical properties – Part 1: Requirements', and 'ISO 22157-2 Bamboo – Determination of physical and mechanical properties – Part 2: Laboratory manual', which were published in 2004 by the International Organization for Standardization (ISO). Another strand in bamboo testing emerged from China under the name of JG/T 199-2007 'Testing methods for physical and mechanical properties of bamboo used in buildings'.

To the author's knowledge the first document enabling the use of bamboo as a structural material is the International Conference of Building Officials' "AC 162 - Acceptance for Structural Bamboo" published in California in 2000. The document contains the skeleton of a standard, providing even factors of safety to be used to derive Allowable Stresses. In terms of derivation of mechanical properties, it refers the user to the INBAR 'standards' and numerous ASTM standards. In reality, a standard that requires the user to undertake numerous tests is of very little value to most applications.
Arguably the first fully fledged standard that provided guidance and design values for the use of bamboo as a structural member was Colombia's chapter E.7 of the national seismic design code NSR-98, which was published as an addendum in 2002. The name of this chapter roughly translates "cement-rendered *bahareque* one and two storey houses". "*Bahareque*" is the name given to a broad range of wall construction techniques that combine a bamboo (and/or timber) stud wall with a cladding product. Traditionally the cladding consisted of flattened bamboo rendered with a mixture containing soil and horse-dung. Variations to the technique included infilling the wall with more soil. The technique is not too dissimilar to wattle-and-daub. The adoption of *bahareque* in the Coffee-growing region of Colombia obeyed to the high seismicity of the region (Robledo, 1996). Eventually,

with the arrival of cement in the early 20th century, cement mortar was used as the cladding product of choice for its superior performance and durability.

The 1999 Coffee-growing region earthquake of Colombia, acted as a reminder of the superior performance of both traditional and modern *bahareque*, in terms of earthquake resistance, particularly when compared to unreinforced masonry (Macdonald, 1999). During the reconstruction of the Coffee-region several national and international NGOs selected modern *bahareque* as the structural system of choice. Similarly, the Fund for the Reconstruction of the Coffee-growing Region (FOREC) commissioned the development of a code and a handbook to promote and enable its further adoption. The essence of the work is contained in (López and Silva, 2000; and Farbiarz, 2001).
This standard has acted as the template for Peru's E.100, Ecuador's NEC – SE – GUADÚA and the Andean standard (INBAR, 2015). It has also influenced similar developments taking place in Mexico and the Philippines. However, the 2002 version of chapter E.7 limits the role of bamboo to that of a component within a system. It contains no guidance on beam design, and very limited and prescriptive values for column and connection design. Chapter E.7 is a standard that enables the use of bamboo in structures, provided it is part of a modern *bahareque* system.

In 2004 ISO also published 'ISO 22156 Bamboo – Structural', which has the merit of being the first international standard and as such drew from the experience of numerous experts from across the world. In a similar manner to AC 162, it provides factors of safety, procedures to determine characteristic values and discusses design philosophy and precautions. However, it does contains barely any design equations and no mechanical properties. In a similar manner to AC 162, a user is required to undertake significant testing in order to obtain design values. Also in 2004, the Bureau of Indian Standards published Part 6, Section 3B – Bamboo within the National Building Code of India, which contains some important developments such as proposing a grading system, containing some mechanical properties for 20 species of bamboo, and Safe Working Stresses for 16 species – although only compressive strength, modulus of rupture and modulus of elasticity are listed. However, it does not contain any connection design values or specific procedures to design columns, shear walls, or beams, and bizarrely for a code, it contains very few equations. A user would struggle to design anything more complex than a simply supported beam.

In 2010 arguably the most comprehensive and developed standard for structural design with bamboo was published as chapter G.12 within the Colombian NSR-10. This code contains some visual grading guidance, factors of safety, a process to derive characteristic values, mechanical properties (albeit only for Colombian *Guadua angustifolia Kunth*), design procedures for beams and columns, some design values for connections, and, by linking it to chapter E.7, shear wall strength values. Chapter G.12 is not without fault or omission, for example, the procedure for the determination of connection design values is opaque and the listed moduli of elasticity values are peculiar, nevertheless, it is arguably the first standard in the world that would allow a user to undertake the complete structural design of a bamboo building.

Current developments within ISO and INBAR Task Force

In September 2013 INBAR attended the annual meeting of ISO Technical Committee 165 in Stuttgart, with the purpose of reactivating the ISO standards work that had delivered ISO 22156 and ISO 22157 nearly a decade earlier. At this meeting 'Working Group 12 – Structural Use of Bamboo (WG12)' was created. WG12 contains experts from Colombia, the United Kingdom, the United States of America, China, the Netherlands and Ecuador, amongst others. WG12 started with two proposals, revising ISO 22157-1, so that it contained a test to determine the tensile strength perpendicular to the fibres for bamboo, and writing a brand new standard for the grading of bamboo.

In parallel to this development, INBAR launched in 2015 the Bamboo Construction Task Force. The INBAR website states that the Task Force "*coordinates the activities of international research institutes and commercial companies interested in the structural uses of bamboo"* (INBAR, 2018), and it does so by linking individuals who are experts in the field. The intention is to pool and coordinate the isolated and disparate efforts occurring throughout the world. The objectives of the Task Force are:

- *"Help drive and refine the development of new international standards on the structural uses of bamboo and review and update existing international standards*
- *Support global coordination and knowledge dissemination on sustainable bamboo construction*
- *Facilitate the development of pro-poor methodologies for designing and constructing sustainable bamboo housing*
- *Strengthen the capacity of construction sector stakeholders in sustainable bamboo housing*
- *Raise awareness and advocate for bamboo construction being mainstreamed in national housing policies and regulations."*

(INBAR, 2018)

As noted in the first objective, the Task Force engages itself with the development of standards, and as such it has acted as the incubator for the new generation of ISO bamboo standards.

ISO 19624 Bamboo structures — Grading of bamboo culms — Basic principles and procedures

What is grading? ISO 19624 defines grading as:

"(…) the process of sorting every piece of bamboo in a sample into grades according to defined selection criteria. The criteria identify dimensional, visual, geometric, mechanical and/or physical properties that reflect the bamboo's mechanical strength or structural capacity and may affect the utility of the product."

In timber, grading is frequently referred to as strength, or stress, grading, which alludes to the fact that grading is done on the basis of the material's strength. Because bamboo does not come in regularised sizes, it may be necessary to adopt alternative grading procedures. ISO 19624 is not prescriptive about what these procedures should be it simply acts as a framework under which grading procedures could be developed. Grading can be aligned to the source material (i.e. the bamboo species and plantation) or the end application i.e. what do we want to use it for. Grading in timber is typically undertaken either visually or mechanically (machine grading). ISO 19624 proposes a framework for either of these methods. INBAR's Working Paper 79 (Trujillo and Jangra, 2016) and Trujillo et al. (2017) expand on the work behind this standard.

ISO 22157 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods

During the aforementioned process of revising ISO 22157, it was decided that it was probably best to rewrite the whole document. In the process it was greatly simplified, two mechanical tests were added, one physical test was removed (shrinkage) and greater consideration was given to the procedures to ensure adequate accuracy and precision. Consideration was also given to the process of homogenisation, which is that all ISO standards are similar. The outcome is a standard that is more closely aligned to modern timber testing standards, yet making allowance for technological limitations that some bamboo researchers may have, and is written in such a way that it complements well ISO 19624.

ISO 22156 Bamboo – Structural Design

In many developing countries steel, concrete and timber codes are a straight adoption or adaptation of codes written in developed economies. Code drafting is an expensive and slow process. Awaiting for every country to develop their own standards will slow the adoption of bamboo. As outlined earlier, since the first version of ISO 22156 was published in 2004, significant developments have taken place in terms of code development and research throughout the world. It was therefore deemed necessary to update ISO 22156, and change it from a code about design philosophy to a template standard that could be adopted by different countries according to their species and practices.

The new version of ISO 22156 will aligned to the new ISO bamboo standards ISO 19624 and ISO 221577, but will continue to borrow from timber standards in terms of derivation of characteristic values, connection testing and shear wall testing. These standards are well suited for the testing of any natural ligno-cellulosic material and are not prescriptive in terms of element shapes or sizes.

In many other respects, ISO 22156 will pick up where G.12 left off.

ISO/NP 23478 – Bamboo structures — Glued laminated bamboo — Test methods for determination of physical and mechanical properties

It is important to note that due to its circular hollow section and range of available sizes, the scope of possible structural applications for bamboo culms is limited. Instead, the scope for Engineered Bamboo Products (EBPs) is much larger. EBPs are a regularised and standardised product that can be engineered to be more durable and fire resistant than bamboo culms. EBPs also hold the promise of job creation in rural communities.

Members of the INBAR Task Force deliberated about the best way to promote the development of structural EBPs, and concluded that standardisation was needed at an international level, and that the starting point was the development of a testing standard for laminated bamboo elements for structural applications. The alternative of simply adopting timber testing standards was studied deemed inappropriate. As from September 2018 a new standard was been initiated within TC 165 with this purpose.

Final thoughts

Standards need to be supported by reliable and verifiable data. Structural testing is expensive because it requires undertaking numerous tests of full-scale elements. Structural testing of a natural material has the added requirement of undertaking large number of repetitions to account for variability. Testing facilities in developed countries are far away from the resource, which increases transport costs and may result in limiting sample size. It also limits experimental work with bamboo to dry specimens and may affect controlling for origin i.e. it is difficult to know how the material was sourced and where. Testing facilities in middle-income countries are mostly adequate and close to the resource, but all too often there is little know-how about timber engineering research, so technology transfer is hindered. This tends to hinder the implementation of processes such as conditioning, control of moisture content, loading rates, etc. Testing facilities in low-income countries, are frequently inadequate for the rigours of modern data generation, it may well be too that researchers are not familiar with timber engineering or recent developments. These set of circumstances result in insufficient good quality data to underpin the development of standards.

The normal path towards acceptance of data is academic publishing, which is time consuming and requires a great deal of effort and expertise. Without peer-reviewed publication of the experimental work, it is unlikely that bamboo research will be taken seriously.

Development of standards is expensive, particularly ISO standards, as they require a lot of travel, and we have no large multinational to bank-roll our efforts. National standards may result in isolated efforts that do not necessarily reflect the technological advances made elsewhere in the planet, or the latest thinking. To an extent it is analogous to returning to the early 20th century.

Structural engineering is a profession with a very large social responsibility: an error could be fatal. Most structural engineers are understandably risk averse. Young generations of engineers are educated to expect standards and codes to meet a certain set of requirements. If bamboo standards do not meet their expectations or require an engineer to make a lot of judgements, it is likely that they will not be implemented.

The solution to these problems is cooperation. Future structural research needs to be rigorous, planned and coordinated, and centred around the needs of standardisation.

References

Addis, W., (2007) Building: 3000 years of design engineering and construction. London/New York: Phaidon.

Asociación Colombiana de Ingeniería Sísmica (AIS) (2010) NSR-10: Reglamento Colombiano de construcción sismo resistente. Titulo G: Estructuras de madera y estructuras de guadua. AIS, Bogotá, Colombia.

Asociación Colombiana de Ingeniería Sísmica (AIS) (2002) NSR-98: Capítulo E.7: Reglamento colombiano de construcción sismo resistente - Casas de uno y dos pisos en bahareque encementado. AIS, Bogotá, Colombia

Bureau of Indian Standards (BIS) (1973) IS 6874-1973: Method of tests for round bamboos.

BIS, New Delhi, India.
Bureau of Indian Standards (BIS) (2004) National Building Code of India – Part 6, Section 3B. CED 13(7702). New Delhi, India.
Bussell, M.N (1996) The Era of the proprietary reinforcing systems. ICE Proceedings, Structures and Buildings, Special issue: Historic Concrete, 116(3/4), pp295-316
Farbiarz, J. (2001) 'Estudio sobre el Comportamiento de Conexiones con Guadua' (Study about guadua connection behaviour), Boletín técnico, Asociación Colombiana de Ingeniería Sísmica, 56.
Food and Agriculture Organisation of the United Nations (FAO) (2016) Global Forest Products – Facts and Figures. Available from: http://www.fao.org/forestry/statistics
Grand View Research (2017) Steel Market Analysis By Product (Hot, Cold, Direct Rolled, Tubes), By Application (Pre-engineered Metal Buildings, Bridges, Industrial Structures), By PMB, By Region, And Segment Forecasts, 2018 – 2025 [online] available from www.grandviewresearch.com
International Conference of Building Officials (2000) AC162: Acceptance Criteria for Structural Bamboo, ICBO Evaluation Service, Inc , Whittier, California, USA.
Instituto de la Construcción y Gerencia (ICG) (2012) Reglamento Nacional de Edificaciones, Section III. 2 Code E100 – Diseño y construcción con bambú. ICG, Lima, Peru.
International Network for Bamboo and Rattan (2014) International Trade of Bamboo and Rattan 2012, INBAR, Beijing, China.
International Network for Bamboo and Rattan (INBAR) (2018) Bamboo Construction Task Force [online] available from http://www.inbar.int/focusareas/design-construction/construction-taskforce/
INBAR (2015) Norma Andina para diseño y construcción de casas de uno y dos pisos en bahareque encementado, Red Internacional para el Desarrollo del Bambú y el Ratán, Oficina para América Latina y el Caribe, Quito, Ecuador.
International Organization for Standardization (ISO) (2004) ISO 22156: 2004 Bamboo – structural design. ISO, Geneva, Switzerland.
International Organization for Standardization (ISO) (2004) ISO 22157-1: 2004 (E): Bamboo – determination of physical and mechanical properties – part 1: requirements. ISO, Geneva, Switzerland.
International Organization for Standardization (ISO) (2004) ISO 22157-2: 2004 (E): bamboo – determination of physical and mechanical properties – part 2: laboratory manual. ISO, Geneva, Switzerland
International Organization for Standardization (ISO) (2018) ISO 19624: Bamboo structures -- Grading of bamboo culms -- Basic principles and procedures. ISO, Geneva, Switzerland.
International Organization for Standardization (ISO) (2004) ISO 22157: 2018: Bamboo structures -- Determination of physical and mechanical properties of bamboo culms -- Test methods. ISO, Geneva, Switzerland.
Janssen, J.A. (1998-2000) INBAR standard for determination of physical and mechanical properties of bamboo, Eindhoven, The Netherlands.
Lopez, L. F. and Silva, M. F. (2000): 'Comportamiento Sismo-resistente de estructuras en bahareque' (Seismic resistant behaviour of bahareque structures), Undergraduate Dissertation, Manizales, Colombia, Facultad de Ingeniería y Arquitectura, Universidad Nacional de Colombia.
Macdonald, J. (1999) 'The Quindío, Colombia Earthquake of 25 January 1999', SECED Newsl., 13/2, p 1-3

Ministerio de Desarrollo Urbano y vivienda (2016) CÓDIGO NEC – SE – GUADÚA ESTRUCTURAS DE GUADÚA NEC Norma Ecuatoriana de la Construcción, Quito, Ecuador.
Ministry of Housing and Urban-rural Development (MOHURD) of China. 1996. Testing methods for physical and mechanical properties of bamboo used in building. Chinese Standard JG/T 199–2007, Beijing, China.
Robledo, J. E. (1996) La ciudad en la colonización antioqueña: Manizales (The city within the Antioquian colonisation: Manizales), Manizales, Colombia, Editorial Universidad Nacional.
Statista (2018) Major countries in worldwide cement production from 2012 to 2017 (in million metric tons) [online] available from www.statista.com
Trujillo D and Jangra S (2016) Grading of Bamboo – INBAR Working Paper 79. International Network for Bamboo and Rattan, Beijing, China. ISBN: 978-92-990082-2-5
Trujillo D, Jangra S and Gibson J (2017). Flexural properties as a basis for bamboo strength grading, Structures and Building - Proceedings of the Institution of Civil Engineers The institution of Civil Engineers, London 170(4), pp.284-294