The Institution of
StructuralEngineers

Manual for the design of bamboo structures to ISO 22156:2021

Production supported by:

INBAR
INTERNATIONAL BAMBOO AND RATTAN ORGANIZATION

INBAR BAMBOO CONSTRUCTION TASK FORCE

Base

IStructE Manual

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INBAR
INTERNATIONAL BAMBOO AND RATTAN ORGANIZATION

International Bamboo and Rattan Organization

Established in 1997, the International Bamboo and Rattan Organization (INBAR) is an intergovernmental organization that promotes environmentally sustainable development using bamboo and rattan. INBAR's mission is to improve the well-being of producers and users of bamboo and rattan within the context of a sustainable bamboo and rattan resource base, by consolidating, coordinating and supporting strategic and adaptive research and development.

It is currently made up of 52 Member States across the developing areas of Africa, Asia and the Americas. In addition to its Secretariat Headquarters in China, INBAR has five Regional Offices in Cameroon, Ecuador, Ethiopia, Ghana and India. INBAR was recognized as an Observer to the UN General Assembly in 2017, and is also Observer to the UN Economic and Social Council, the UN Forum on Forests, the UN Conference on Trade and Development, and all three Rio Conventions: The UN Convention on Biological Diversity, the UN Framework Convention on Climate Change, and the UN Convention to Combat Desertification, making it possible for INBAR to speak for bamboo and rattan at the UN platforms.

Bamboo, the fast-growing grass plant, and rattan, the spiky climbing palm, are important nature-based solutions to a number of pressing global challenges, including poverty alleviation, green trade, climate change mitigation and adaptation, resilient construction, plastic substitution and environmental protection.

INBAR's work is based around the following strategic goals:

1. Promoting bamboo and rattan in socio-economic and environmental development policies at national, regional and international levels;
2. Coordinating inputs on bamboo and rattan from a growing global network of Members and partners, and representing the needs of Members on the global stage;
3. Sharing knowledge and communicating lessons learned, providing training and raising awareness of the relevance of bamboo and rattan as plants and commodities; and
4. Fostering adaptive research and on-the-ground innovation by promoting pilot case studies, and supporting the upscaling of best practices across INBAR Member States.

INBAR has worked with partners from its Member States and international organisations since its establishment to actively promote the potential and value of bamboo and rattan as nature-based solutions for sustainable development. INBAR has made remarkable achievements in policy-shaping for bamboo and rattan industries, public awareness-raising, action projects for demonstration, and knowledge-sharing at the international, regional and national levels, generating significant momentum for the sustainable development of global bamboo and rattan industries. With its increased influence, INBAR has championed the role of bamboo and rattan as part of the UN Decade on Ecosystem Restoration 2021–2030 and for a number of other prestigious organisations, networks and think tanks, while also co-launching the Bamboo as a Substitute for Plastic (BASP) Initiative with China. INBAR also strives to advance South-South and triangular cooperation, supporting the Belt and Road Initiative and Global Development Initiative, and highlighting the role of bamboo and rattan for meeting the UN 2030 Sustainable Development Goals.

INBAR Bamboo Construction Task Force

INBAR BAMBOO
CONSTRUCTION TASK FORCE

INBAR Bamboo Construction Task Force (INBAR BCTF), facilitated by INBAR since 2013 and officially established in 2014, helps to coordinate activities of international research institutes and commercial companies interested in structural uses of bamboo.

INBAR BCTF supports INBAR's membership of the Global Network for Sustainable Housing: the world's premier knowledge network on sustainable housing, hosted by UN Habitat in Nairobi. Currently, INBAR BCTF consists of a core group of 36 experts from 18 countries, aiming to serve as the world's main science-based information and knowledge repository on structural uses of bamboo and its environmental, economic and social benefits.

The specific objectives of INBAR BCTF are as follows: 1) help drive and refine development of new international standards on structural uses of bamboo, as well as help review and update existing international standards in this area; 2) support global coordination and knowledge dissemination on sustainable bamboo construction; 3) facilitate the development of socio-economically appropriate methodologies for designing and constructing sustainable bamboo housing; 4) contribute towards capacity-building of construction sector stakeholders in sustainable bamboo housing; 5) raise awareness and advocate for bamboo construction being mainstreamed in national housing policies and regulations; and 6) assess the environmental benefits from the production and uses of bamboo-based construction materials.

Since its establishment, INBAR BCTF, thanks to the efforts of its INBAR BCTF experts, has been instrumental to the following activities:

- New ISO standards developed and published in the following areas: strength grading, test methods, structural design of round bamboo structures; test methods and specification of engineered bamboo products.
- New INBAR publications on bamboo construction and related technologies published and openly available online.
- New project proposals jointly developed among INBAR BCTF members on bamboo construction, which has supported new research, training and capacity building.
- An increased number of INBAR Member States recognize bamboo construction in their national housing policy and regulations.
- Membership of the International association of material science laboratories RILEM.
- Development and publication of Life Cycle Inventories of bamboo-based forestry, low industrialized bamboo-based construction materials and engineered bamboo construction materials.

INBAR BCTF's work in these areas has helped promote wider adoption of standards for bamboo at regional, national, and sub-national levels, while increasing applications of structural uses of bamboo internationally. Moreover, better targeted and coordinated research on the structural uses of bamboo has greatly helped drive the development of the global bamboo construction sector.

Base Bahay Foundation, Inc.

Base Bahay Foundation, Inc. (BASE) is a non-profit organisation based in the Philippines. It is initiated by the Hilti Foundation, which provides alternative building technologies to enable a network of partners to build comfortable, affordable, disaster-resilient and sustainable homes with social impact.

BASE developed the Cement-Bamboo Frame Technology (CBFT) that utilises locally grown and renewable materials like bamboo to create housing envelopes and designs suited to the needs of the local communities. This technology also serves as a holistic solution to addressing the global housing gap while mitigating the effects of climate change.

CBFT has a 60% lower carbon footprint compared to conventional materials and is 20–30% more affordable than conventional houses of the same type.

Beyond building durable and sustainable homes globally, BASE has also built non-residential structures like schools, offices, community centers, commercial buildings and industrial spaces that provide economic support to families in need, and showcase the potential of bamboo in building a more multifaceted structure.

In addition, the building solution supports the development of the bamboo value chain — from the local farmers who harvest bamboo poles, to workers in bamboo treatment facilities and builders who construct the houses. Beyond sustainable livelihood, BASE has been promoting a circular economy and enabling the bamboo industry to grow.

As a leading global innovation and research hub for bamboo, BASE through its Innovation Center collaborates closely with local and international institutions to study bamboo and other alternative green building materials and technologies for sustainable construction. The Base Innovation Center (BIC) houses cutting-edge technology and equipment for testing materials, components and wall systems, ensuring the reliability of the building technology.

The research collaborations likewise support organisations in different countries in developing their codes for bamboo, further positioning its use in mainstream construction.

In order to enable more professional builders to engage in sustainable construction, BASE has established the Bamboo Academy Program. This initiative provides multi-level training courses that engage institutions, professional builders, and workers to further propel the adoption of these alternative technologies.

Established in 2014, BASE is committed to fostering sustainable construction practices and community development on a global scale, bringing together institutions and government agencies to make affordable and sustainable homes accessible to families in need.

Permission to reproduce the following has been obtained, courtesy of these individuals/organisations:

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Table A3.8: Derived from equations from Hailwood, A. J. and Horrobin, S. 'Absorption of water by polymers: analysis in terms of a simple model'. *Transactions of the Faraday Society*, 1946, 42(0), pp. B084-B092 (with permission from the Royal Society of Chemistry)

Contents

1 Introduction

1.1 Why bamboo?

Bamboo has many necessary properties for a structural bio-based material. It grows rapidly, it is strong, it has an efficient structural shape and a good strength-to-weight ratio. If treated and designed correctly, it may also be highly durable. To date, the full structural potential of bamboo has not been realised for several reasons, which includes a lack of design guidance. This *Manual* aims to address the knowledge gaps, giving practical advice and guidance on how structural engineers can adopt bamboo within mainstream construction.

There are over 1,600 known species of bamboo distributed natively across all continents, except Antarctica and Europe, although it should be noted that numerous species have been introduced successfully into Europe. Some species of bamboo possess remarkable structural properties comparable to hardwoods. Owing to its fast growth cycle (Section 1.2), bamboo has become a very promising bio-based resource, synonymous with sustainability. Its sustainability credentials as a construction material, however, are dependent on designing and building safe and durable structures, which this *Manual* attempts to facilitate.

1.2 Life cycle and sustainability of bamboo

Bamboo is a *Gramineae*; a giant grass. Therefore, as a plant it differs significantly from trees, particularly in its reproductive and growth cycle. Bamboos reproduce mostly in a vegetative manner (i.e., through expansion of their root network), and to a much lesser extent through seed dispersion. Stems, known as 'culms', emerge periodically from the ground, and these are segmented, tapered and generally hollow (Figures 1.1 and 1.2). One fundamental difference between trees and bamboo is that when culms are harvested, the root network remains alive and undisturbed. Harvesting bamboo is more like mowing a lawn than clear-cutting a forest.

Figure 1.1: Live bamboo plant above and below ground

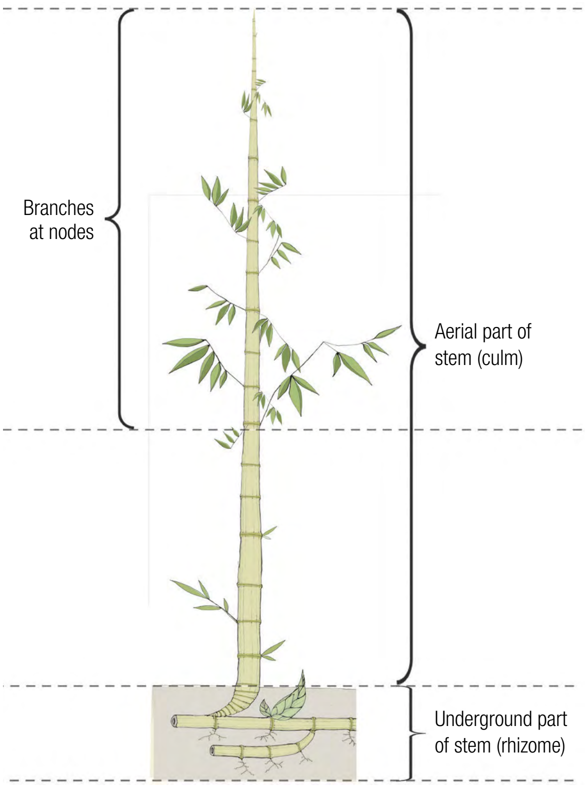
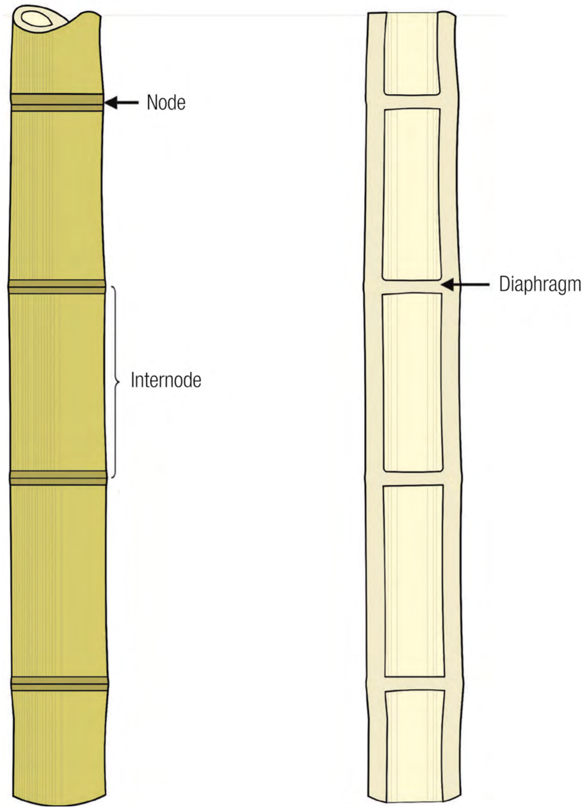


Figure 1.2: Parts of the culm/stem



Another significant difference is that bamboo culms emerge from the ground at their permanent diameter, i.e., there is no secondary growth, unlike trees which become taller and wider with time. In 3–6 months, bamboo culms reach full height and then undergo a process of maturing over 3–6 years. If stems are not harvested, they will eventually die back 7–10 years from first emerging.

The life cycle of bamboo makes it an attractive resource in the context of our climate emergency. In common with trees, bamboo fixes carbon in its leaves, stem, roots and surrounding soil. However, unlike trees, the process of harvesting does not significantly disturb the carbon sequestered in the roots or soil, which means most of the carbon remains fixed. Harvesting stems to be transformed into durable products (such as structures) disrupts the natural carbon cycle of bamboo, preventing the return of carbon to the atmosphere during die-back of the stems. This means that harvesting bamboo increases the carbon-fixing potential of the forest[1.1]. These characteristics make bamboo a very effective carbon sink if its stems are used for structural purposes[1.2, 1.3].

One beneficial characteristic of bamboo is that a plantation reaches productive maturity in less than a decade (much sooner than trees). Compared to trees, bamboo offers a faster path to widespread adoption of structural bio-based materials for construction, especially in parts of the world with no significant commercial forestry.

In addition, bamboo can be used to restore degraded soils so does not compete with agricultural lands or existing primary forests. Instead, bamboo can provide a series of environmental services, including erosion control on slopes and riverbanks, water flow regulation and creating a windbreak in shelterbelts[1.1]. From a societal perspective, bamboo is inexpensive to harvest, and preservation and transformation into poles requires only modest capital investment. Farmers benefit from a crop that, once established, yields annually, not on a decades-long rotation. In fact, bamboo plantations can be harvested continuously without significantly affecting the forest cover. Industries benefit from a continuous supply of feedstock, without dramatically lessening the environmental benefits of the plantation.

In common with trees, monocultures are undesirable and, therefore, plantations should include a diversity of species. One risk of over-reliance on a single species is that some species of bamboo die after flowering and flower in a mostly synchronous manner, which could leave industries starved of the resource for several years.

Overall, bamboo has great potential to contribute to a low-carbon construction sector, as well as offering numerous other societal and environmental benefits. At present, a lack of understanding within structural engineering design is limiting its wider adoption. This *Manual* supports structural engineers embarking on bamboo design. ISO 22156:2021 (Bamboo structures — Bamboo culms — Structural design)[1.4] provides a thorough review of bamboo materials for the construction sector.

1.3 Scope of this *Manual*

From a structural perspective, bamboo's remarkable mechanical properties — comparable to those of hardwoods — make it an appealing resource, with a multitude of applications. The culms can be used as structural members with minimal transformation (other than drying and chemically preserving). Culms can also be flattened (Figure 1.3) or cut

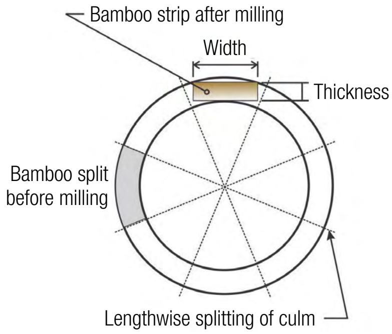
Figure 1.3: Flattened bamboo

into strips/splits or laminae (Figure 1.4). These components may then be reconstituted with adhesives to form engineered bamboo products (EBP).

ISO 22156:2021[1.4] covers only structural use of full-culm bamboo (although flattened bamboo may be used in composite bamboo shear walls (CBSW) (Chapter 8)) but excludes EBP. This *Manual* is limited to the same scope.

Figure 1.4: Bamboo splits and strips

a) Culms cut into bamboo splits



b) Bamboo splits and finished strips

c) Bundles of bamboo strips

This *Manual* has two main aims:

- To explain, justify and, in some instances, critique the contents of ISO 22156:2021.
- To provide a route-map for engineers embarking on the use of bamboo culms as structural members.

It should be noted that bamboo engineering is a very young field and, therefore, has not benefitted from the sort of extensive research undertaken on mainstream materials. In some instances, the bamboo engineer will need to undertake this research. Consequently, this *Manual* contains few design tables, as would be expected from a design manual; instead it provides guidance, procedures and formulae to find the answers.

Bamboo engineers will need to concern themselves with understanding plants, preservation, grading, testing and derivation of characteristic values, with the aim of obtaining reliable design properties and materials. This is one of the challenges (and delights) of working with bamboo.

This *Manual* is structured to support the bamboo engineer along the journey from sourcing bamboo to detailed design. In this *Manual*, the term 'Clause' is exclusively used for citations of codes and standards, while the terms 'Chapter' and 'Section' refer to the *Manual* itself. This *Manual* is divided into the following chapters:

- **Chapter 2: Bamboo supply chain**. The first challenge a bamboo engineer will face is identifying what resource is available. Chapter 2 outlines the considerations needed for a bamboo project when procuring structural quality bamboo.
- **Chapter 3: Grading and mechanical characterisation of bamboo**. In some contexts, design values for bamboo are published in codes and standards. In most other instances, testing and derivation of design values will be required, as well as specifying methods to ensure consistent quality. Chapter 3 explains these processes, with the ultimate goal of deriving reliable design values.
- **Chapter 4: Principles of structural bamboo design**. Bamboo culms should not be viewed as a direct substitute for timber; they are a unique resource with their own qualities, advantages and disadvantages. Chapter 4 provides guidance to ensure the architectural and structural conception is appropriate to bamboo. It also includes guidance on fire and seismic design.
- **Chapter 5: Durability**. This is one of the fundamental challenges of using bamboo for permanent structures, and a key difference of designing bamboo structures compared to designing with more conventional materials. Permanent bamboo structures must be made from preservative-treated bamboo culms and adopt principles of 'durability by design'. Chapter 5 provides extensive guidance on achieving this aim.
- **Chapter 6: Design of full-culm bamboo members**. Designing bamboo columns and beams is a comparatively simple process, although consideration needs to be given to element redundancy (which is desirable) and the means to make elements share loads appropriately. Chapter 6 also explains the background for requirements contained in ISO 22156 with respect to loads.

- **Chapter 7: Design of bamboo connections**. Designing bamboo connections is challenging. There is little consensus on what joints are most appropriate for bamboo. Consequently, the limited research into bamboo connections that does exist is spread thinly across diverse technologies and approaches. This *Manual* aids the calculation process of some simple connections using the component capacities approach, as well as outlining the process of determining connection characteristics through complete-joint testing.
- **Chapter 8: Composite bamboo shear walls**. ISO 22156 includes this simple structural system which is widely considered to be one of the most appropriate ways of building resilient housing with bamboo. Chapter 8 explains the system in detail, including its behaviour in fire and earthquakes and its durability. Structural design rules and guidance are provided, as are minimum structural requirements.
- **Chapter 9: Research and development gaps and needs**. There is much that we still do not know about bamboo. Chapter 9 not only serves as a guideline for researchers interested in supporting the adoption of bamboo, but also informs practising engineers of the limitations to state-of-the-art bamboo engineering.
- **Chapter 10: Worked examples**. The concepts presented throughout the *Manual* converge into three examples, starting from the relatively simple design of a floor joist, expanding to the more involved process of designing a composite bamboo shear wall, and finishing with the design of a connection using the two methods outlined by ISO 22156 — component capacities and complete-joint testing.

1.4 Possible errata in ISO 22156:2021

Structural design codes and standards reflect the state-of-the-art knowledge of the drafting committee **at that time**. Despite the best efforts of those involved in compiling these documents, they may contain typographical errors or omissions. During the writing of this *Manual*, the authors have identified items contained in ISO 22156:2021 that may be classified as such. The authors of this *Manual* are members of the working group that drafted ISO 22156. The most significant issues found in ISO 22156:2021 are:

- Buckling capacity as outlined in ISO 22156, Clause 9.3.3 may be unconservative, as buckling capacity is not reduced by a material factor of safety. A revised procedure is presented in this *Manual* (Section 6.4.2).
- Design by complete-joint testing as specified in ISO 22156, Clause 10.2 requires tests to be undertaken in accordance with ISO 16670[1.5], which specifies cyclic testing. It is contended that there will be numerous applications where full reversal of loading is uncommon, and a monotonic test, as outlined in ISO 6891[1.6], should also be permitted (Section 7.8.1).
- The circumferential bearing capacity procedure contained in ISO 22156, Clause 10.11 contains what are believed to be several typographical errors. Section 7.3.2 presents a corrected procedure.
- ISO 22156, Equation 36 that assesses the likelihood of a cleavage type failure (splitting) under the effect of a dowel acting parallel to the fibres, results in excessively conservative values that do not relate to experimental findings. Section 7.4.1 presents an alternative procedure that ensures the likelihood of cleavage failure is significantly reduced.
- ISO 22156, Clause 10.12.1 states that the strength values for compression strength, f_c, shear strength, f_v, and tension perpendicular to the fibres, $f_{t,90}$, in Equations 34, 35 and 36 should be determined from ISO 22157[1.7] (i.e., directly from testing for mechanical properties). As this would imply that these strength values have no statistical consideration (i.e., determination of characteristic values) or material safety factors, the guidance would potentially be unsafe. These instances should require the adoption of the allowable strength values outlined in ISO 22156, Clause 6.4, making it consistent with the requirements of ISO 22156, Clauses 10.10 and 10.11.

1.5 Further reading

Archila, H.F., Trujillo, D. and Zea Escamilla, E. (2024) 'Bamboo' in *Materials: An environmental primer*. London: RIBA Publishing, 2024, pp34–45.

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1.3 Young, L. *et al*. 'A Comparative Life Cycle Assessment (LCA) of a Composite Bamboo Shear Wall System Developed for El Salvador'. *Sustainability*, 16(17), September 2024, 7602. DOI: https://doi.org/10.3390/su16177602.

1.4 International Standards Organization. *ISO 22156:2021: Bamboo structures — Bamboo culms — Structural design*. Geneva: ISO, 2021.

1.5 International Standards Organization. *ISO 16670:2003: Timber structures — Joints made with mechanical fasteners — Quasi-static reversed-cyclic test method*. Geneva: ISO, 2003.

1.6 International Standards Organization. *ISO 6891:1983: Timber structures — Joints made with mechanical fasteners — General principles for the determination of strength and deformation characteristics*. Geneva: ISO, 1983.

1.7 International Standards Organization. *ISO 22157:2019: Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods*. Geneva: ISO, 2019.

2 Bamboo supply chain

2.1 Introduction

The maturity of bamboo supply chains varies across the globe. As the bamboo supply chain is a relatively young industry with fewer than 30 years of development, it cannot be compared to that of the timber industry.

In some countries, reputable and experienced suppliers have large stocks of dry and preservative-treated bamboo, cut to standard lengths, that have undergone some form of grading (Figure 2.1). However, such grading is rarely fully-compliant with ISO 19624[2.1]. In many countries, the supply chain may need to be established from scratch. This involves identifying available species, evaluating existing stocks, locating suitable bamboo suppliers and setting up a preservation, drying and grading process. Guidelines to help address this need are covered in this chapter.

Figure 2.1: Treated bamboo storage racks

2.2 Species

Identifying suitable species can be challenging, and guidance from experts such as forest engineers, biologists, experienced bamboo designers and builders is highly recommended. Consultation with local farmers who have expertise in bamboo identification and can provide examples in construction can also be a resource. It is important to note that local names for bamboo species may vary across regions or, in some instances, the same local name is given to entirely different species.

It should be noted that some bamboo species have undergone extensive research, such as Guadua (*Guadua angustifolia* Kunth), Giant Bamboo (*Dendrocalamus asper*), Kawayan Tinik (*Bambusa blumeana*), Oldhamii (*Bambusa oldhamii*) and Moso (*Phyllostachys pubescens*) (Figures 2.2–2.5). These species are frequently used in large-scale construction projects, especially in Latin America and Southeast Asia. This list does not cover all bamboo species that have been researched and utilised globally. Table 3.2 in this *Manual* offers guidance to determine what constitutes an 'extensively-studied species' and Table A3.9 shows representative properties of some well-studied species.

Figure 2.2: ***Guadua angustifolia*** **Kunth**

Figure 2.3: ***Dendrocalamus asper***

Figure 2.4: ***Bambusa blumeana***

Figure 2.5: ***Phyllostachys pubescens***

Desirable properties of bamboo species for construction applications include:

- Large diameter (typically ≥ 75mm).
- Relatively thick walls (≥ 10% of the diameter).
- High level of straightness.
- Low taper.
- Low susceptibility to cracking.
- Abundant availability.
- Ease of age determination.

To a lesser extent, it is also desirable that species have a low natural starch content, short internode lengths, and high strength and stiffness.

Selecting the most suitable bamboo species depends also on availability in the specific area or region where the project will take place. It is of little benefit to identify an optimal, yet scarce, resource.

Once a species has been identified, the next step is to characterise its geometry, and its mechanical and physical properties (Chapter 3). A good indicator of adequacy of a species for construction is whether it is already used in construction within the area. However, traditional use does not preclude undertaking characterisation research of a new species as outlined in Chapter 3. Introducing a new species may also be an option, but it is important to consider that it will take at least 7–10 years for a bamboo plantation to mature and start producing culms suitable for construction applications. Importing culms is possible, but it should also be noted that although bamboo has a very small embodied carbon when used locally, transportation of bamboo culms can significantly increase carbon emissions, detracting from its sustainability credentials.

2.3 Harvesting

The supply chain starts here. Generally, bamboo harvesting (Figure 2.6) predominantly occurs within natural forests across most countries, although there are exceptions where bamboo is sourced from commercially-managed plantations. It is important to emphasise the need for implementing good harvesting practices to guarantee sustainable and high-quality bamboo production.

Figure 2.6: Harvesting *Bambusa blumeana*

To ensure a successful harvesting process it is important to consider:

- **Training and education:** Ensure farmers/foresters are appropriately trained to identify bamboo species and determine culm age. Whenever practical, farmers should be encouraged to record when a culm emerged from the ground, creating an objective method for determining age.
- **Sustainable harvesting practices:** Emphasise the importance of sustainable harvesting practices to prevent the depletion of bamboo clumps/forest. Farmers/foresters should be advised to harvest a maximum of 30–40% of mature culms from each clump/forest *per annum*. This allows the remaining culms to regenerate and ensures a healthy and sustainable bamboo population for future harvests. There are also some advantages associated with harvesting in certain seasons of the year, including minimising the risk of damaging young shoots. Chapter 5 details other advantages.
- **Field grading:** Encourage farmers/foresters to implement a grading process in the field. This involves visually inspecting the bamboo forests and selecting the best quality poles to be cut. Other grading requirements such as diameter, straightness and taper can also be incorporated at this step. By implementing these practices, the number of poles rejected at the treatment facility can be significantly reduced, saving time and resources.
- **Monitoring and quality assurance:** Establish a system for monitoring and promoting sustainable harvesting practices. This can include regular inspection of farms and providing feedback and guidance to farmers. By promoting sustainable practices, the long-term viability of bamboo resources can be maintained.
- **Research and development:** Encourage research and development efforts focused on improving bamboo harvesting techniques. Research can also focus on developing efficient tools and equipment for harvesting, reducing waste and improving overall productivity.

By implementing these measures, the harvesting process can be improved, promoting sustainable bamboo cultivation and ensuring long-term availability of this resource.

2.4 Treatment

Treatment is essential to protect bamboo against insect attack. Chapter 5 describes in more detail the different treatment methods and their efficacy. In nearly all cases, chemical treatment is required.

Chemically-treated bamboo is available off-the-shelf in many parts of the world where bamboo grows, albeit using diverse methods, chemicals and quality assurance procedures. When reviewing whether a treatment facility provides adequately treated bamboo, consider:

- What chemical is used? Does it meet the good practice outlined in Chapter 5?
- What treatment method is used? Does it meet the good practice outlined in Chapter 5?
- What are the health and safety arrangements at the treatment facility? (Chapter 5).
- What selection and grading procedures are used?
- What is the quality and consistency of the end-product? Is there low incidence of cracking/splitting and is there rigorous inspection for fissures/cracks?
- What is the track-record of the facility? Have buildings using bamboo sourced from this facility stood the test of time? Note that beetle and termite attacks are not always instantaneous. Therefore, treatment facilities with a longer, successful track-record may be considered a more reliable choice.
- What quality assurance procedures are used by the facility? For example, can the facility provide evidence of minimum retention levels of the active treatment chemical (Chapter 5).

For smaller or one-off projects, setting up a small treatment facility for the project is feasible, but attaining the required quality assurance will take time and requires experience. Treatment facilities are normally the same entities providing grading, and therefore ensuring that their grading processes match the requirements of the project is very important (Chapter 3).

2.5 Delivery and transportation

To ensure a consistent supply of high-quality bamboo, it is important to identify suppliers who can provide seasoned (dry) bamboo. Only dry bamboo culms, which have reached a moisture content in equilibrium with the construction site conditions, should be used for construction. It is strongly advised to avoid using green (i.e., unseasoned) bamboo for construction purposes, to avoid cracks or deformation of joints from shrinkage. It should be noted that ISO 22156 requires the use of seasoned bamboo; using green bamboo in construction is beyond its scope.

The typical equilibrium moisture content (EMC) of bamboo in a fully protected and shaded area of a construction site will be 12–18% in most regions (it can be estimated using Table A3.8). If dry bamboo is not readily available, the project programme will need to be adjusted to make an allowance for the bamboo to dry on site, until the bamboo culms reach the appropriate EMC. When in doubt, or as a general rule, it is recommended to store bamboo on site in a shaded area for at least two weeks before being used.

Bamboo culms are susceptible to damage during transportation, particularly species with large internode lengths, as they can be easily crushed. Installation of spacers in the transportation truck is advisable. Similarly, personnel should be discouraged from dropping culms from the back of trucks as it makes cracking/splitting more likely (Figure 2.7).

Figure 2.7: Bamboo transport and handling

Bamboo must be kept dry at all stages of the supply chain, as even if treated it is still at risk of rot (Chapter 5). This means that bamboo should be kept under cover and protected from rain and sun during storage and drying, and ideally also when being transported.

2.6 Further reading

Rabik, A. and Brown, B. *Towards Resilient Bamboo Forestry*. Bali: Environmental Bamboo Foundation, 2014.

Muyanja, A. *et al. Bamboo Market Value Chain Study*, Beijing: INBAR, 2018.

Anazco, M. and Rojas, S. *Estudio de la cadena desde la producción al consumo de bambú en Ecuador con énfasis en la especie Guadua Angustifolia*, Beijing: INBAR, 2015. [in Spanish]

References

2.1 International Standards Organization. *ISO 19624:2018: Bamboo structures — Grading of bamboo culms — Basic principles and procedures*. Geneva: ISO, 2018.

3 Grading and mechanical characterisation of bamboo

For most conventional structural materials and products, engineers can refer to codes, standards, specifications or manufacturers' publications for material properties and geometric dimensions to be used in design. For established materials, engineers trust that the supply chain will deliver the products specified. Reliable design data for bamboo, however, is relatively scarce, and therefore a structural engineer using bamboo will need to invest time in testing, grading and derivation of characteristic material properties. Structural engineers using bamboo mainly seek published literature about the mechanical properties of the species they intend to use. Available data may be incomplete, unrepresentative, unreliable and often reported in varying, non-standard ways; this approach is far from ideal. Engineers must also be aware that bamboo properties, even within a single species from a single country, can vary considerably. Growing conditions, including year-to-year variation, altitude, and exposure to wind can all affect properties of a bamboo resource.

Most established bamboo suppliers implement some form of grading, although many will be unaware of existing standards, and different suppliers may have different criteria for grade selection. ISO 22156, Clause 14 recommends that bamboo be graded in accordance with ISO 19624[3.1] and mandates this for projects exceeding 10,000 linear metres of bamboo.

This chapter provides guidance on the process of testing, grading and determination of characteristic properties of a bamboo resource, conforming to those required by ISO 22156, Clause 6[3.2].

3.1 Grading standard ISO 19624

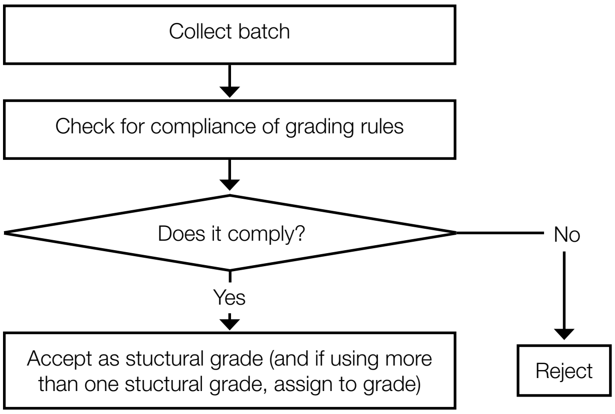
The concept of 'grade' is not explicitly defined in ISO 19624 as it is somewhat axiomatic. In general, a grade is defined as a category of bamboo culms that have one or more common properties/characteristics deemed important to the process of design and construction. As there is not yet strong international consensus on which grades are required for bamboo design, ISO 19624 provides a **framework** for grading bamboo culms (Figure 3.1). ISO 19624 is intentionally not overly prescriptive but instead defines grading as:

> *"The process of sorting every piece of bamboo in a sample into grades according to defined selection criteria."*
>
> *"Criteria are based on non-destructive observations and measurements that have been established to be useful to the grading process."*

If the criteria selected are too onerous, an uneconomical amount of bamboo will be rejected. Conversely, if the criteria are too lax, this will need to be compensated for, potentially resulting in uneconomical designs. ISO 19624 does not call the process 'strength grading', providing the user the opportunity to grade using other criteria beyond strength — dimension or even aesthetic properties, for instance.

ISO 19624 outlines considerations for visual and machine grading of bamboo aligned conceptually to definitions from the timber industry, although these titles are slightly misleading. Visual grading is based on **grading rules** that require visual assessment. Grading rules should be useful to the grading process and can be based on empirical, experimental, traditional or arbitrary criteria. As grading rules form the basis of visual grading, a more appropriate alternative designation for this process is 'rule-based grading'. Fundamentally, it is the process of assignment to grades based on compliance with some observable or measurable rules. For example, a rule could be 'no instances of cracking'. If a culm did not manifest any cracking, it could be deemed of 'structural grade' (Figure 3.1).

Figure 3.1: Visual/rule-based grading



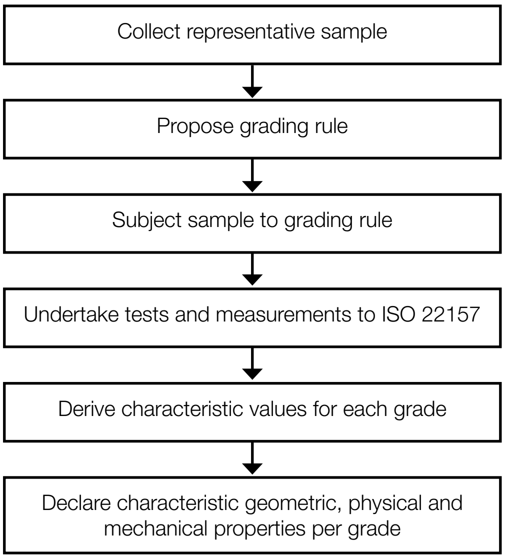
Machine grading is based on non-destructive measurement of properties (so-called 'indicating properties — IP') that can reliably infer properties that can only be measured destructively. Grades are aligned to **grade-determining properties (GDP)**: properties deemed to be critical to structural design. Examples of IP could be density, modulus of elasticity, etc. An example of a GDP could be bending strength. The word 'machine' can also be misleading; a more appropriate terminology is 'inference-based grading', as 'machine grading' can take place using only very simple instruments. It should also be noted that machine grading remains reliant on some initial visual inspection known as 'visual override' intended to identify defects that may not be recorded by 'the machine'. Trujillo et al.[3.3] and Correal et al.[3.4] provide examples of how machine grading could be undertaken. However, machine grading for bamboo culms is a concept still under development, and therefore not central to this chapter.

3.2 Initial evaluation

A fundamental aspect of ISO 19624 is that it requires bamboo culm producers or suppliers (typically the company that seasons and preserves the bamboo) to undertake an initial evaluation or characterisation of the bamboo resource. At present, many distributors do not do this or apply different criteria; it is important that engineers are aware of what initial evaluation entails, as it is one of the key differences between ISO 19624 and other grading practices.

Once a species, supplier and respective source region (i.e., plantation) have been identified, an initial evaluation of the resource needs to be undertaken. Figure 3.2 presents an initial evaluation process for visual grading. Note that reference is made to ISO 22157[3.5], which contains the suite of ISO test procedures used for physical and mechanical characterisation of bamboo culms.

Figure 3.2: Initial evaluation process for visual/rule-based grading



Samples due to undergo initial evaluation should be subject to proposed grading rules, with the aim of avoiding biasing test results. A visual override may also capture and reject obvious physical flaws including significant bamboo splitting, insect infestation or fungal attack (rot). Such considerations are described in ISO 19624, Clause 6.2.2. Depending on the intended final use of the bamboo, excessive geometric variation of the culm may also be a basis for initial rejection. Table 3.1 provides a list of examples of rejection criteria that could be used as grading rules.

Table 3.1: Examples of potential reasons to reject a culm prior to initial evaluation and during grading

Criteria	Basis for rejection/grading rules
Splits, cracks or fissures	• No cracks can be present in the neutral axis of a culm used as a beam. • The sum of all the cracks present in a culm should not exceed 20% of the length of the culm[3.6]. • Fissures are acceptable within the internode, but not if they cross a node[3.7]. • Cracks in adjacent internodes cannot be collinear.
Active insect infestation	Any active insect infestation is grounds for rejecting culm and further investigation of entire batch should be undertaken.
Insect damage	Culms with beetle holes or termite damage should be rejected.
Rot/fungus	Culms exhibiting any fungal attack should be rejected and closer investigation of the entire batch undertaken.
Taper (Eq. 3.2)	Taper greater than 0.10 (ISO 22156, Clause 6.4.1).
Bow (Eq. 3.4)	Bow greater than 0.02 for members intended as axial compression bearing elements (ISO 22156, Clause 9.1), though limiting bow to 0.01 is preferred.
D/t ratio	*D/t* greater than 12 (ISO 22156, Annex A).

3.3 Visual/rule-based grading

As previously mentioned, this *Manual* focuses on criteria required for visual/rule-based grading. Fortunately, visual grading of bamboo can be much simpler than for timber. Some aspects are straightforward, such as that insect and fungal damage should be limited, while others require a greater understanding of the species' characteristics and the intended use of the bamboo. Examples may include acceptable limits for bow and taper. Figure 3.3 shows the process of initial evaluation for a visual grading process. Sections 3.3.1–3.3.8 expand on each step of the process.

3.3.1 Geometric characterisation of bamboo resource (Figure 3.3, Step 1)

The most important and least expensive task to undertake is characterising the geometry of the culm. This consists of recording the diameter (D), wall thickness (t), internode length and degrees of taper, ovality and bow for the culms from the resource. (Wall thickness in ISO 22156 is assigned the notation, δ. This notation seems atypical, so t has been adopted in this *Manual*.) Reliable knowledge of typical culm dimensions will ultimately make the process of design and construction more efficient and are a logical and typical starting point.

Culm diameter (D) is defined as the average of two perpendicular measurements made across opposite points on the culm circumference (ISO 22156, Clause 3.15). In order that ovality can also be assessed (Equation 3.1), typically measurements are made to capture the maximum (D_{max}) and minimum (D_{min}) diameters of a section. When ovality is not required (or is known to be acceptable), diameter may simply be determined from the culm circumference divided by $\pi = 3.14$. Calibrated 'pi-tape measures' are commercially available for directly determining diameter from circumference. The diameter is conventionally measured near the centre of an internode which will typically be a local minimum diameter.

Culm wall thickness (t) is defined as the average of four wall thickness measurements taken around the circumference of the culm at intervals of 90° (ISO 22156, Clause 3.20). Culm wall thickness can only be measured at the ends of culms or at cut sections.

Figure 3.4 shows the locations at which diameter (D) and wall thickness (t) are measured, with the subscript *b* signifying 'bottom' or 'base' and the subscript *t* signifying 'top' or 'tip' of the culm length, respectively.

Figure 3.3: Flowchart for initial evaluation

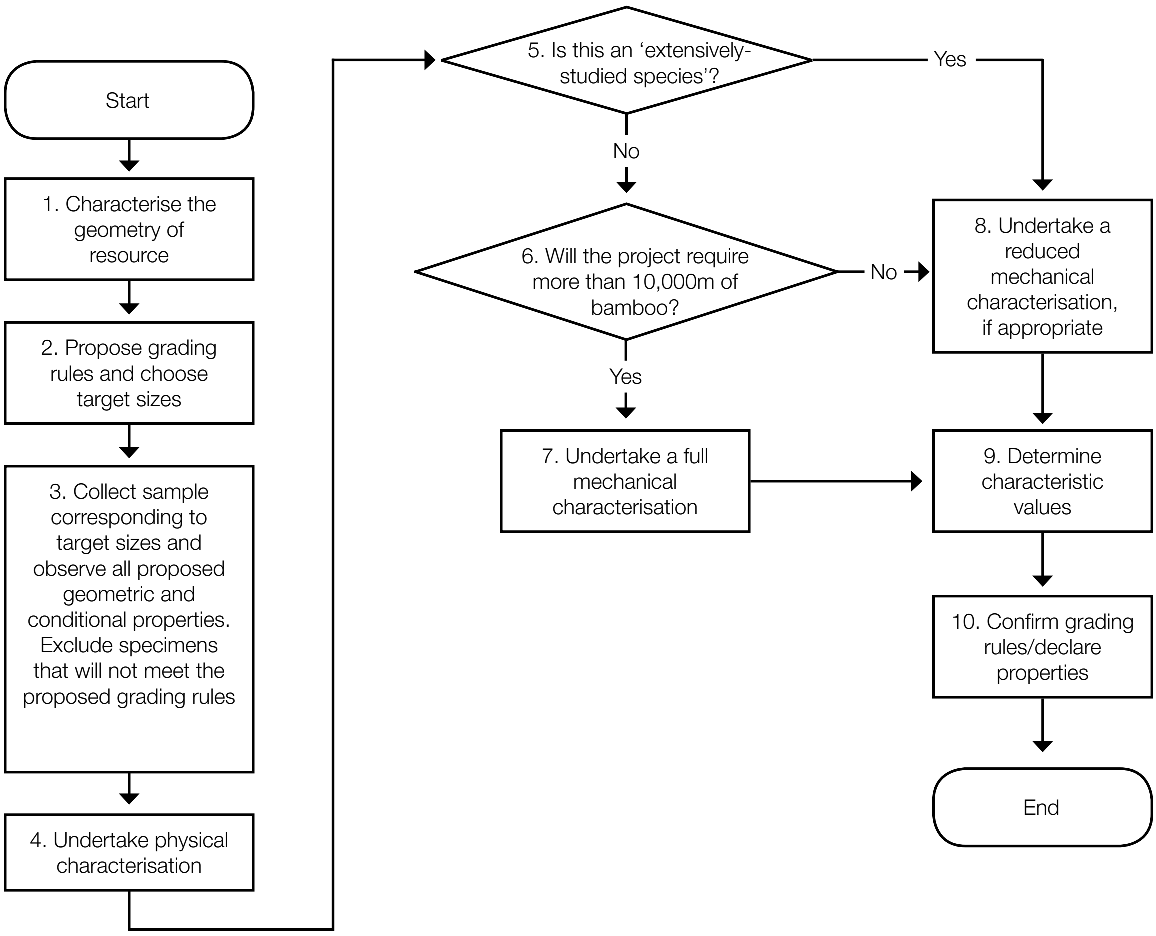
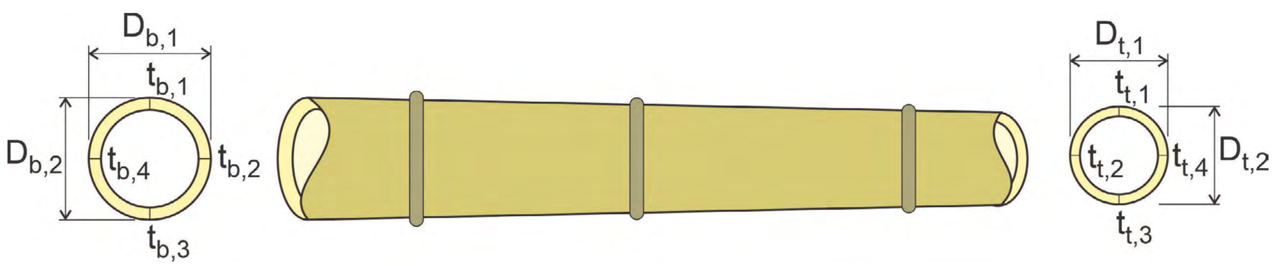


Figure 3.4: Locations at which diameter and wall thickness are measured



The ratio D/t (sometimes reported as t/D or $2t/D$) is an immediately obtainable characterisation parameter. An upper limit of D/t can be defined that excludes culms having walls that are too thin from progressing further in the characterisation.

The degree to which a culm section varies from round is described by its ovality (d_o) (Equation 3.1); an upper limit on ovality may be a means of excluding culms from use in certain applications (e.g., flexure).

$$d_o = \frac{2(D_{max} - D_{min})}{(D_{max} + D_{min})} \quad \text{Equation 3.1}$$

ISO 19624 defines two types of taper — external taper (α_e) and internal taper (α_i), defined by Equations 3.2 and 3.3, respectively. Since culm wall thickness can only be measured at cut ends, these definitions necessarily assume that taper is linear, which is adequate for most purposes. Taper is known to affect the behaviour of beams and columns. It is particularly important to ensure that the degree of taper is representative during initial evaluation. High variation of taper may affect interpretations of strength (Figure 3.5).

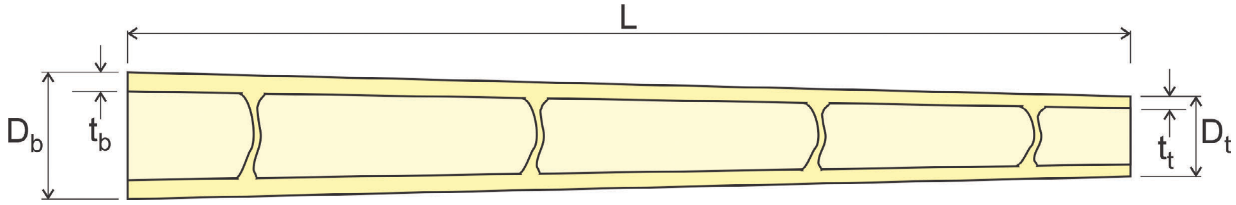
$$\alpha_e = \frac{D_b - D_t}{L} \quad \text{Equation 3.2}$$

$$\alpha_i = \frac{D_b - 2t_b - D_t - 2t_t}{L} \quad \text{Equation 3.3}$$

Where:

L = culm length and subscripts b and t indicate dimensions measured at bottom and top of culm, respectively.

Figure 3.5: Determination of taper

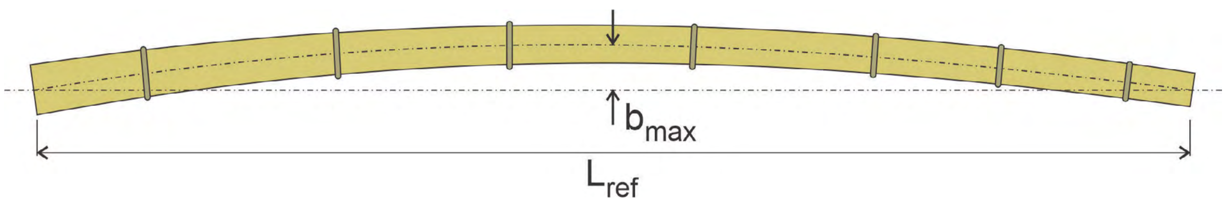


Bow (b_o) describes the curvature or 'sweep' of a culm. Bow (Equation 3.4) is determined from the maximum perpendicular distance (b_{max}) from the centre of the culm cross-section to the chord drawn from the centres at either end of the reference length (L_{ref}):

$$b_o = \frac{b_{max}}{L_{ref}} \quad \text{Equation 3.4}$$

Bow may be determined over any reference length, although, most typically, the reference length will be taken as the member length (L) (Figure 3.6).

Figure 3.6: Determination of bow



Bow is most critical in axial compression bearing members (columns) and is limited by ISO 22156, Clause 9.1 to $b_o \leq 0.02$. This limit is important as it is compatible with the axial buckling checks in ISO 22156. It is important to accurately capture common levels of bow for a resource and that the bow limit selected for grading reflects typical levels of bow, notwithstanding the limits placed by ISO 22156 to column design. It is also important to report to designers the bow limit adopted during grading.

Culm cross-section geometric properties are determined from Equations 3.5–3.7 (ISO 22156, Clause 6.4.1), assuming a round section having a uniform wall thickness (i.e., a 'pipe'):

Cross-sectional area: $A = \frac{\pi}{4}[D^2 - (D-2t)^2]$ Equation 3.5

Moment of inertia/second moment of area: $I = \frac{\pi}{64}[D^4 - (D-2t)^4]$ Equation 3.6

Elastic section modulus: $S = \frac{\pi}{32D}[D^4 - (D-2t)^4]$ Equation 3.7

The values of D and t are taken as the average of the values measured at each end of the culm, provided the diameter and thickness do not vary by more than 10% from one end of the culm to the other; i.e., taper ≤0.1. For culms having a taper greater than 0.1, minimum values of D and t determined over the length of the culm are used in Equations 3.5–3.7. Typically this will be D_t and t_t (Figure 3.4). This permits the use of culms having significant taper but penalises the design capacity for doing so. In practice, it is impractical for a designer to know the D and t of every single culm that is to be used in a structure, hence the need for a grading regime, as this will provide a notion of the sizes to be used. Worked calculations presented in Chapter 10 illustrate this point more clearly. An example of geometric data and its expected variation is given in Appendix 3.1.

3.3.1.1 Culm geometry limits in ISO 22156

Although ISO 22156 does not limit culm dimensions that may be employed, the intent (ISO 22156, Annex A) is that a culm diameter of 50mm is a practical lower limit for a structural load-bearing element. Exceptions may be made in bundled compressive load-carrying members such as columns, arches and truss chords, however buckling of the individual small culms in such assemblies must be addressed. A further exception are the culms used in the panel portions of composite bamboo shear walls described in ISO 22156, Clause 12 (Chapter 8).

Full culm bamboo used in load-bearing structural applications will typically have a diameter-to-wall thickness ratio (D/t) less than 12. Above this threshold, local buckling of the culm walls, particularly in the compression regions of members in bending, becomes a concern.

3.3.2 Select target sizes and propose grading rules (Figure 3.3, Step 2)

With knowledge obtained from the geometric characterisation, one or more target sizes (typically dictated by culm diameter) can be set as part of the grading rules. These target sizes could be the basis for selecting grades if intending to use **diameter-based grading** (i.e., grading based on external diameter). ISO 19624, Annex A provides an example of diameter-based grading. The proposed grading rules should be decided at this point, so no lower quality material is included in the sample.

3.3.3 Sampling (Figure 3.3, Step 3)

Collect at least 30 specimens per target size (or grade) that pass the proposed grading rules. Criteria to consider include presence of cracks/fissures, insect and/or fungal attack as well as excessive bow, taper, ovality or D/t ratio. In this approach, 100% of the 30-specimen grade samples are free from potential sources of initial rejection. Sampling should be undertaken randomly from the graded batches.

3.3.4 Physical characterisation (Figure 3.3, Step 4)

Physical characterisation of samples should include the determination of bamboo moisture content (ISO 22157, Clause 7) and lineal mass (i.e., mass per unit length; ISO 22157, Clause 9) or density (ISO 22157, Clause 8). Lineal mass has been shown to be a sound surrogate for density and is considerably easier to obtain, requiring only the measurement of culm length and mass[3.3].

Whereas ISO 22157, Clause 7.1 provides a means of determining moisture content (MC) using a conventional 'oven-dry' method (appropriate in a laboratory environment), Clause 7.2 permits MC to be determined by means of an appropriately-calibrated electronic moisture meter, simplifying this step in the grading process. Such an alternative approach is also permitted for timber by ISO 4470[3.8]. Cacanando et al.[3.9] provides an example of the process of calibrating a moisture meter. Without reliable determination of moisture content, calculation of lineal mass or density is pointless. Lineal mass or density are reported for their as-tested moisture condition (q_{MC} or ρ_{MC}, respectively). By convention, and as permitted by ISO 22157, these values are often normalised to 12% moisture content as in Equation 3.8:

$$q_{12} = q_{MC}[1.12/(1 + \mathrm{MC})] \text{ or } \rho_{12} = \rho_{MC}[1.12/(1 + \mathrm{MC})] \qquad \text{Equation 3.8}$$

Where:

MC = moisture content (expressed as a ratio) determined at time of testing.

3.3.5 Reduced mechanical characterisation

ISO 19624, Clause 8.2.1 requires that all tests contained in ISO 22157 are undertaken as part of the initial evaluation process. However, testing for mechanical properties can be costly, time-consuming and complex, especially if the necessary expertise or equipment is not locally available. Therefore, ISO standards for bamboo culms provide two paths to reduce the number of mechanical tests required:

- Permitting the adoption of secondary properties for extensively-studied properties (ISO 19624, Clause 8.4).
- Permitting a reduced (or 'streamlined') grading protocol for smaller projects (ISO 22156, Clause 14).

3.3.5.1 Use of secondary properties for extensively-studied species (Figure 3.3, Step 5)

In general, structural design of culm elements is governed by deflections and shear strength (for beam members) and buckling (for columns), although structures are often also ultimately governed by their connection capacities. In most cases, modulus of elasticity (E) or flexural stiffness ($E \times I$) and shear strength are critical properties to design, while other properties may be less likely to govern. ISO 19624 calls these less-critical properties 'secondary properties' which do not need to be measured or inferred during grading. Examples of potential secondary properties are compression parallel-to-fibre, bending and tension strengths (both parallel and perpendicular to fibres). ISO 19624, Clause 8.4 makes an allowance to avoid testing for secondary properties if the species has been 'extensively-studied'. This is because for better-understood and better-reported species, an appreciation of the scale of intra-species and inter-region variation may be known. Care should be taken, however, to ensure that 'extensively-studied species' indeed include geographic variation. For example, whereas Chinese *P. edulis* (Moso) is 'extensively-studied', *P. edulis* grown in Brazil has been shown to have very different mechanical properties[3.10]. Table 3.2 provides proposed criteria to determine what constitutes an 'extensively-studied species' to which a reduced mechanical characterisation approach may be applied. For these species, the values reported in literature may be adopted, provided that characteristic strength can be determined (Section 3.3.8).

Table 3.2: Criteria to determine an 'extensively-studied species'

	Commentary
Species Does the bamboo resource correspond to the studied species?	This may not be a trivial matter, even for experienced specialists, as identification of bamboo species can be complex, especially once culms have been harvested and seasoned. Resources obtained from established plantations are likely to be well-known.
Data source Is this primary data? Was data published in a peer-reviewed publication or other reliable source?	Regional sources of data such as Departments of Agriculture (or similar) are often available.
Tests methods Were tests undertaken using ISO 22157-1:2004[3.11], ISO 22157:2019[3.5] or other bamboo-specific test methodology?	Test methods used for other materials — including wood — are not appropriate for bamboo without modification and can result in erroneous data. There are several national standards for bamboo that would be deemed appropriate.
Metadata Is data accompanied by appropriate metadata; examples include bamboo density (or lineal mass), moisture content, the presence of nodes in test coupons, etc.	Many factors affect reported properties. Mechanical properties reported without moisture content are not useful. The presence or absence of nodes in tension tests is known to affect reported properties, often by a factor greater than two.
Variation Is data reported from different source regions?	It is desirable to assess the regional variation for a species. Intra-species variation should typically be less than 30%.
Statistical quality Do reported data include required measures of variability (standard deviation or coefficient of variation) and sample size (n)? Is sample size appropriately representative?	Without an appreciation of variability, it is not possible to determine characteristic values required for design. ISO 19624 and ISO 12122-1[3.12] require minimum sample sizes of 30, although obtaining appropriate data may require larger sample sizes.
Plausible data Are reported mechanical properties credible?	The mechanical properties of bamboo are not widely dissimilar to those of other bio-based materials, particularly hardwood timber. Reported values outside this range should be treated with caution.
Corroboration Is there more than one source of quality data available?	Quality publications are those for which all previous answers are 'yes'. To qualify as 'extensively-studied', at least two distinct sets of data for each mechanical property should be identified. Also test whether the data is statistically similar; intra-species variation should typically not exceed 30%.

3.3.5.2 Magnitude of project (Figure 3.3, Steps 6 and 8)

ISO 22156, Clause 14 requires grading in accordance with ISO 19624 for projects exceeding 10,000 linear metres of bamboo. Clause 14 permits a 'streamlined procedure' for smaller projects.

For the streamlined approach, Clause 14 states that *"[only] mechanical, physical and geometric properties relevant to design*" need be determined. Not all mechanical properties listed in ISO 22157 are required for all designs; for instance tension perpendicular to fibres is of limited practical use to design of elements. Indeed, it is the opinion of the authors that ISO 22157 should not be interpreted as being a mandatory list of mechanical tests to be conducted, but rather as a 'tool-box' of methods available to the engineer and specifier. It may be worth undertaking a sensitivity analysis to determine which properties are most critical to design. A discussion of what properties are critical to design of elements is contained in Section 3.4.

Because of their importance in bamboo design, regular checking of flexural stiffness ($E \times I$) and shear strength is required by ISO 22156 at intervals not exceeding 2,000 linear metres of bamboo used.

3.3.6 Mechanical characterisation (Figure 3.3, Step 7)

According to ISO 19624 and ISO 22156, if a species or resource has not been extensively tested, a full set of tests will be required for larger projects. A full mechanical characterisation requires a sample size of at least 30 specimens per test, for each grade that is being proposed.

Strengths determined using ISO 22157-defined material tests are compression (f_c), tension (f_t), bending (f_m) and shear (f_v) strength parallel to fibres, and tension (f_{t90}) and bending (f_{m90}) strength perpendicular to fibres (edge bearing). All are expressed as stresses (e.g., N/mm^2). The bamboo modulus of elasticity (E) is determined from tension or compression tests. Apparent modulus of elasticity in bending can be determined from bending stiffness ($E \times I$).

3.3.6.1 Variation of material properties with moisture content

As with timber, mechanical properties obtained from bamboo having a moisture content (MC) greater than the fibre saturation point (FSP) exhibit little variation with changing MC — these are properties of so-called 'green' bamboo. Strength and stiffness increase as moisture content falls below the FSP. Strength and stiffness of bamboo having a low MC of about 5% are typically twice those of green bamboo. By convention, properties are normalised at 12% MC. Material properties must be reported with their MC at the time of testing; the same culm tested at 10% and 20% MC will yield different results.

In a structure, bamboo will achieve its equilibrium moisture content (EMC) which is a function of the ambient environment. ISO 22156 addresses the variation of material properties with EMC, partially through the definition of Service Classes (Appendix A3.7) and reduction factors associated with these. Appendix A3.2 provides guidance for adjusting strength parameters to account for different values of EMC.

3.3.7 Determination of characteristic values (Figure 3.3, Step 9)

Characteristic values of both member and connection capacity and strength used in ISO 22156 are defined as the 5th percentile value expressed at the 75% confidence interval. Modulus of elasticity (E), stiffness ($E \times I$) or joint stiffness (K_e) used in ISO 22156 are defined as the mean characteristic value expressed with 75% confidence. These definitions of characteristic value are the same as those typically used in timber design. A description of methods for calculating characteristic values is given in Appendix A3.3.

3.3.8 Proposing grading rules (Figure 3.3, Step 10)

Once the initial evaluation has been completed, the grading operation may commence. The basis for this operation is strict adherence to proposed grading rules (Table 3.1). The simplest form of grading is to sort material into **structural grade bamboo** and **non-structural grade bamboo**. However, it may be beneficial to divide structural grade bamboo further, for example by diameter, into multiple grades. The criteria used to assign a grade would constitute part of the grading rules. The geometric, physical and mechanical properties determined during the initial evaluation are only valid for batches of bamboo that meet the same selection criteria and originate from the same plantation(s).

Examples of the development and application of grading rules based on diameter (ISO 19624, Annex A), flexural properties[3.3, 3.13] and compression[3.14, 3.15] are available. An example of an initial evaluation of a bamboo resource is presented in Vilanueva et al.[3.7]. An example of diameter-based grade creation is given in Appendix A3.4.

3.4 Critical properties in the design process

Geometric properties of bamboo are the most important and simplest properties to evaluate. Bamboo member design is most often governed by flexural stiffness or compressive buckling — both are functions of $E \times I$. Moment of inertia, I, is a function of D^4 and t^4 (Equation 3.6); so the dominant contribution of culm diameter to bamboo design should be evident.

Figures 3.7 and 3.8 illustrate the sensitivity of compression and flexural capacity to culm geometry and material properties. In each case, the normalised capacity of a single culm is shown where only a single parameter is varied by ± 20%, keeping the others constant. The baseline parameters are shown in each case and the dominant effect of varying D is plainly evident.

Figure 3.7: Effects of variations of single-culm parameters on compression capacity (N_{cr}) of 3,000mm long culm

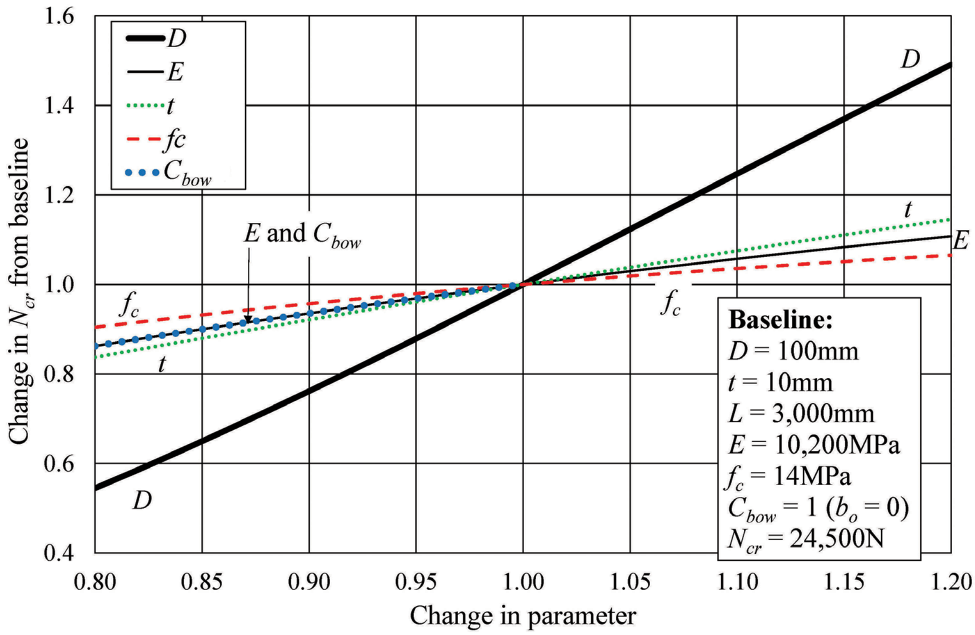
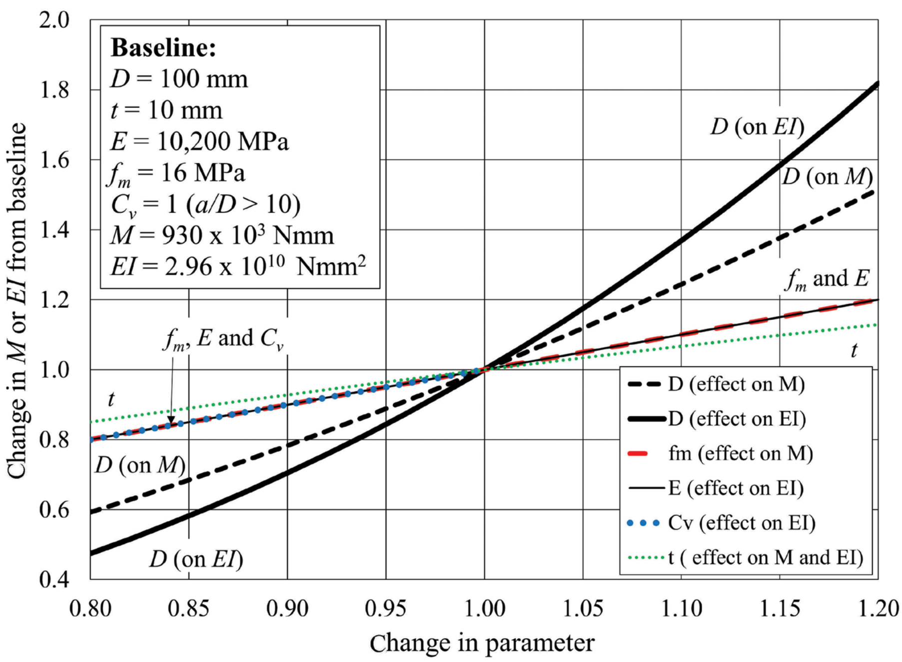
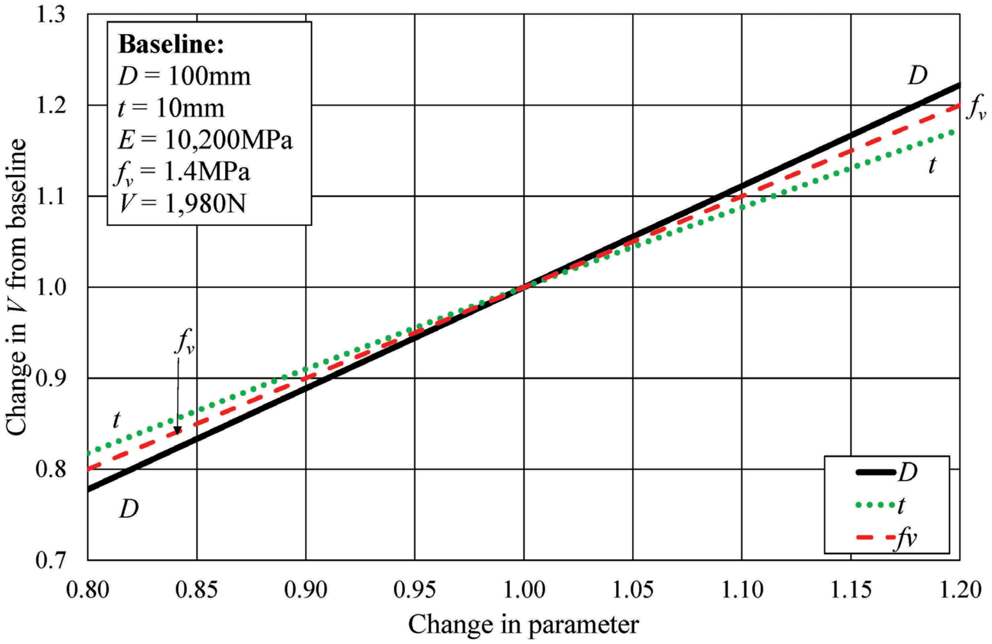


Figure 3.8: Effects of variations of single-culm parameters on flexural capacity (M) and stiffness ($E \times I$) of culm in flexure



Culm geometry (*D* and *t*) and shear strength (f_v) each have essentially the same linear contributions to bamboo shear capacity (Figure 3.9). Because flexural design in ISO 22156 is often governed by shear capacity, it is important to determine the shear strength of the source material. Shear strength can be determined in accordance with ISO 22157[3.5], often using quite simple equipment[3.16].

Figure 3.9: Effects of variations of single-culm parameters on shear capacity *V*



3.5 Allowable material properties

ISO 22156 has been written without considering a specific national jurisdiction. Therefore, it uses **allowable capacity** (also known as 'permissible capacity') or **allowable stress** (permissible stress) methods of design; these are described in Chapter 6.1 of this *Manual*. ISO 22156, Clause 5.11.1 permits a **limit state design** approach to be adopted based on adherence to an applicable national building standard. Appendix A3.5 describes the differences between allowable stress/capacity and limit state design approaches and describes the reasoning behind ISO 22156 being drafted with respect to the former.

Allowable design values are obtained from characteristic material capacities or strengths. Factors are applied to the characteristic values to determine an allowable design capacity or strength — a value that cannot be exceeded in design. These factors are enumerated in ISO 22156, Clauses 6.3 and 6.4. The allowable member capacity is given in Equation 3.9:

$$X = x_k \frac{C_R \times C_{DF} \times C_T}{FS}$$ Equation 3.9

Where:

x_k = characteristic member strength or capacity described in Section 3.3.8 and Appendix A3.3, and is defined by ISO 22156 (Clauses 6.3 and 6.4) for capacity and strength design, respectively.

C_R = modification factor intended to encourage use of redundant structural details described in Section 6.3 of this *Manual* and defined by ISO 22156, Clause 5.4.

C_{DF} = modification factor accounting for Service Class described in Appendix A3.6 and A3.7 and defined by ISO 22156, Table 3.

C_T = modification factor for service temperature greater than 38°C defined by ISO 22156, Table 4, (Appendices A3.6 and A3.7).

FS = component factor of safety. *FS* = 2 for load or force actions dominated by the longitudinal behaviour of the bamboo: compression, tension and bending of the culm. For actions susceptible to splitting phenomena such as shear, *FS* = 4 (this incorporates a crack factor similar to that adopted for timber in Eurocode 5[3.17] and Appendix A3.6).

The modulus of elasticity used for design is given in Equation 3.10:

$$E_d = E_k \times C_{DE} \times C_T \qquad \text{Equation 3.10}$$

Where:

E_k = characteristic modulus.
C_T = same modification described for strength.
C_{DE} = modification factor accounting for Service Class and the expected duration of load defined by ISO 22156, Table 7.

Additional discussion of allowable design values and the provenance of the modification factors is provided in Appendix A3.6. A summary of typically-reported nominal and characteristic material properties is given in Appendix A3.8.

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Appendices

A3.1 Example of measures of geometric variation

There are few studies from which measures of culm variation are fully reported. As an example of what may be expected in the field, the data reported in Table A3.1 was obtained from sampling 72 3.5m-long *B. blumeana* culms intended for a construction project in The Philippines (bow is only reported for 40 culms from the sample). The effect of statistical variation (reported as coefficient of variation: *COV = standard deviation/mean*) of directly measured data (D and t) is compounded in the derived section properties, area and moment of inertia (A and I), and measures of culm variation, bow and taper (d_o, α_e, α_i). Despite the higher *COV* of the derived values, the sample is well-suited to structural load-bearing applications; it exhibits little ovality and taper, and the extent of bow would be suitable for using this resource for compression members.

Table A3.1: Variation observed in *B. blumeana* culm geometry

		Sample size, n	Average	COV
Diameter	D	72	91.7mm	0.085
Wall thickness	t	72	7.78mm	0.134
Area	A	72	2055mm^2	0.175
Moment of inertia	I	72	1.88 x 10^{6}mm^4	0.333
Ovality	d_o	72	0.022mm/mm	0.783
External taper	α_e	72	0.0034mm/mm	0.513
Internal taper	α_i	72	0.0022mm/mm	1.008
Bow	b_o	40	0.0055mm/mm	0.588

A3.2 Variation of material properties with moisture content

ISO 22156 does not address adjustment of characteristic strengths based on differences between equilibrium moisture content (EMC) and the moisture content (MC) at which strengths are determined. Best practice dictates that material properties should be determined at the values of EMC expected in use, although this is not always feasible. It is therefore informative to consider other approaches for adjusting material properties for MC.

Chinese Standard JG/T 199-2007[A3.1] requires normalisation of material properties at MC = 12%. Recognising that tests will be conducted over a range of moisture contents, JG/T 199 specifies factors applied to the experimentally-determined material properties to correct these to equivalent strength or modulus at a moisture content of 12%. The Colombian NSR-10 Standard[A3.2] also prescribes corrections for moisture content, although these are intended to correct characteristic strength and modulus obtained from test data normalised at 12% moisture content for *in situ* moisture content in a structure. The factors (K_{fi}) recommended by both JG/T 199 and NSR-10 to determine the material properties at EMC (f_{EMC} or E_{EMC}) (Equation A3.1) from those reported at 12% MC (f_{12} or E_{12}) are summarised in Table A3.2 and illustrated in Figure A3.1.

$$f_{EMC} = K_{fi} \times f_{12} \qquad \text{Equation A3.1}$$

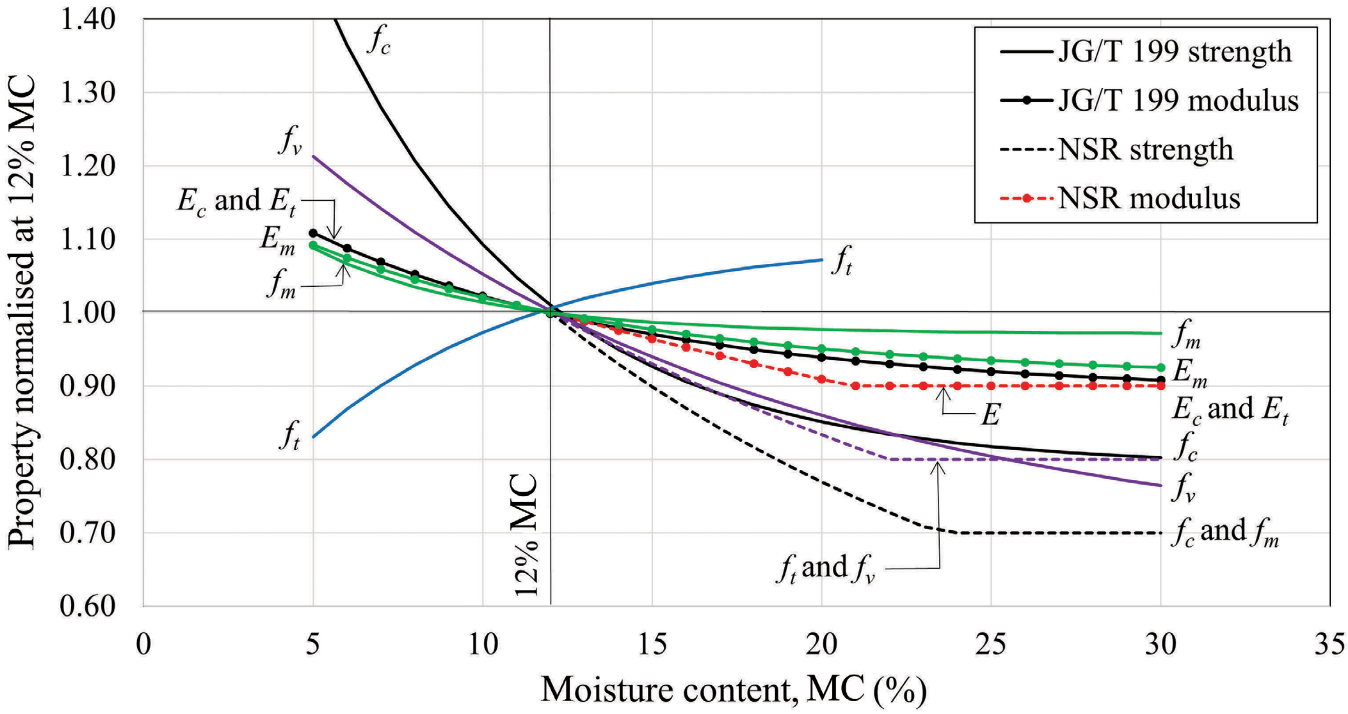
Table A3.2: Correction factors, K_{fi}, for moisture content

Parameter	JG/T 199–2007 correction	MC range	NSR-10 correction	MC range
f_c	$K_{fc} = 0.79 + 1.5e^{-0.16MC}$	5–30%	$K_{fc} = [1 + 0.0375(MC - 12)]^{-1} \geq 0.7$	$MC > 12\%$
E_c	$K_{Ec} = 0.89 + 0.36e^{-0.10MC}$	5–30%	$K_E = [1 + 0.0125(MC - 12)]^{-1} \geq 0.9$	$MC > 12\%$
f_t	$K_{ft} = 1.10 - 0.57e^{-0.15MC}$	5–20%	$K_{ft} = [1 + 0.0250(MC - 12)]^{-1} \geq 0.8$	$MC > 12\%$
E_t	$K_{Et} = 0.89 + 0.36e^{-0.10MC}$	5–30%	$K_E = [1 + 0.0125(MC - 12)]^{-1} \geq 0.9$	$MC > 12\%$
f_v [a]	$K_{fv} = 0.67 + 0.77e^{-0.07MC}$	5–30%	$K_{fv} = [1 + 0.0250(MC - 12)]^{-1} \geq 0.8$	$MC > 12\%$
f_m	$K_{fm} = 0.97 + 0.32e^{-0.20MC}$	5–20%	$K_{fm} = [1 + 0.0375(MC - 12)]^{-1} \geq 0.7$	$MC > 12\%$
E_m	$K_{Em} = 0.91 + 0.30e^{-0.10MC}$	5–25%	$K_E = [1 + 0.0125(MC - 12)]^{-1} \geq 0.9$	$MC > 12\%$

Note: In all equations, MC is given as a percentage; i.e., 15% = 15; not 0.15.

[a] The equation presented in JG/T 199 for K_{fv} appears to have a typographic error. In JG/T 199 the exponent is given as –0.77MC. However, based on the source material[A3.3], the exponent should be –0.07MC.

Figure A3.1: Strength and modulus normalised to values at 12% MC



The apparently contradictory trend for f_t prescribed by JG/T 199 is confirmed from the original source[A3.4]. A more recent study[A3.5] was initiated to address this apparent contradiction. Wang et al. confirmed the trend recommended by JG/T 199 and proposed simplified linear correction factors (Table A3.3) based on a large study (n = 270 for **each** of six mechanical properties) of *P. edulis* bamboo. Although the equations postulated in Table A3.3 were derived for a single species, they represent a rigorous study and are believed to provide an adequate basis for other species, unless demonstrated otherwise.

Table A3.3: Experimentally-determined normalisation and best fit parameters

Measured property at MC = (12 ± 0.5)%	Linear best fit
$f_{t,12}^{in}$ = 160.7MPa (COV = 0.23)	K_{ft}^{in} = 0.88 + 0.010 MC
$f_{t,12}^{n}$ = 100.7MPa (COV = 0.25)	K_{ft}^{n} = 0.69 + 0.026 MC
$E_{t,12}$ = 12,990MPa (COV = 0.10)	K_{Et} = 0.98 + 0.002 MC
$f_{c,12}$ = 58.7MPa (COV = 0.14)	K_{fc} = 1.12 – 0.010 MC
$f_{vJG,12}$ = 17.8MPa (COV = 0.27)	K_{fvJG} = 1.10 – 0.008 MC
$f_{vISO,12}$ = 16.2MPa (COV = 0.10)	K_{fvISO} = 1.17 – 0.014 MC

Note: In all equations, MC is given as a percentage; i.e., 15% = 15; not 0.15.

A3.3 Determination of characteristic values for design

As mentioned in Section 3.5, ISO 22156 uses allowable (or permissible) stress (or capacity) design methods. However, the allowable stress/capacity needs to be calculated separately for each load combination. The starting point for calculating the allowable values are characteristic properties. Characteristic values of strength or capacity used in ISO 22156 are defined as the 5th percentile value expressed with 75% confidence. Characteristic values of modulus or stiffness used to calculate deflection are based on mean values expressed with 75% confidence. Additional discussion of appropriate characteristic values for design is provided in Chapters 6 and 7 of this *Manual*. Annex A of ISO 12122-1[A3.6] provides three approaches to determine characteristic values:

- The non-parametric approach of ASTM D2915[A3.7].
- Using ranked test data as described by AS/NZS 4063.2[A3.8].
- Fitted distributions for which values for lognormal and normal distributions are provided (that is, for which the Kolmogorov-Smirnov goodness of fit test[A3.9] is significant at 0.05).

For large sample sizes ($n > 100$), the first two approaches should be essentially identical. For smaller sample sizes there are some differences due to the coarseness of ranked-value data. Only the last approach is recommended for use with sample sizes less than $n = 30$, although the ASTM D2915 method does tabulate confidence level factors for $n < 30$. The first two approaches are non-parametric, whereas the third approach is parametric, requiring a goodness of fit test.

The fundamental definition of a characteristic value, f_k, is some number (K) of standard deviations less than the experimentally-determined mean value of strength or capacity, f_{mean} (Equation A3.2):

$$f_k = f_{mean}\,(1 - K \times COV) \qquad \text{Equation A3.2}$$

Where:

COV = standard deviation/mean, expressed as a ratio, the experimentally-determined coefficient of variation.
K = confidence level factor obtained from a noncentral t-inverse approach.

ASTM D2915 tabulates values of K as a function of the sample size n, for a number of tolerance and confidence intervals. A closed-form solution for determining the value of K is given by Link[A3.10]. For 5th percentile characteristic strength given at 75% confidence, the value of K may also be approximated to two significant figures using Equation A3.3 for parametric distributions[A3.11]. This approximation is increasingly conservative for $n > 35$ and marginally unconservative for $n < 35$.

$$K = \frac{6.5n + 6}{3.7n - 3} \qquad \text{Equation A3.3}$$

Alternatively, the AS/NZS 4063.2 approach is written as:

$$f_k = f_{0.05}\left(1 - \frac{k_{0.05,0.75} \times COV}{\sqrt{n}}\right) \quad \text{Equation A3.4}$$

Where:

$f_{0.05}$ = 5th percentile value determined from ranked data.

AS/NZS 4063.2 tabulates values of $k_{0.05,0.75}$ as a function of sample size n. $k_{0.05,0.75}$ can also be approximated using Equation A3.5:

$$k_{0.05,0.75} = \frac{0.49n + 17}{0.28n + 7.1} \quad \text{Equation A3.5}$$

For large sample sizes ($n > 100$), $f_{0.05}$ may be estimated as: $f_{0.05} = f_{mean} - 1.645 \cdot COV$. This approach should not be adopted for small sample sizes ($n < 30$).

Modulus of elasticity (E), stiffness ($E \times I$) or joint slip (K_e) used in ISO 22156 are defined as the mean characteristic value expressed with 75% confidence. For design scenarios where these properties affect stability, the same procedure as for strength should be used (Equation A3.6) (Section 6.4.2):

$$E_k = E_{mean}\left(1 - \frac{1.15 \times COV}{\sqrt{n}}\right) \quad \text{Equation A3.6}$$

A3.3.1 Determination of characteristic values

Data reported in Table A3.4 was obtained from sampling a large batch of *Guadua angustifolia* Kunth bamboo intended to establish characteristic design values for a construction project. The characteristic values determined using the ASTM D2915 and AS/NZS 4063.2 methods are shown to be essentially identical. This is expected for the large sample sizes for which $f_{0.05}$ will be more closely estimated. The third approach permitted by ISO 12122-1[A3.6] requires a measure of goodness of fit which requires the complete data set. An example is provided in ISO 12122-1, Annex C.

Table A3.4: Characteristic strengths obtained from *G. angustifolia* test data

	Bending strength, f_m	Compressive strength, f_c	Shear strength, f_v
Summary of test data			
Sample size, n	228	922	138
Mean, f_{mean} (MPa)	81.2	55.1	9.39
Standard deviation (MPa)	21.0	10.3	2.82
COV	0.26	0.19	0.30
Characteristic value using ASTM D2915			
ASTM D2915 K	1.723 (n = 200)	1.681 (n = 900)	1.739 (n = 140)
K estimated from Eq. A3.3	1.77 (conservative)	1.76 (conservative)	1.78 (conservative)
Characteristic value, f_k (MPa) Eq. A3.2 and ASTM K	81.2 (1 – 1.723(0.26)) = 45.0	37.8	4.5
Characteristic value using AS/NZS 4063.2			
$f_{0.05} \approx f_{mean} - 1.645 \cdot COV$ (MPa)	46.7	38.2	4.8
AS/NZS 4063.2 $k_{0.05,0.75}$	1.76 (n > 100)	1.76 (n > 100)	1.76 (n > 100)
Characteristic value, f_k (MPa) Eq. A3.4	46.7(1 – 1.76(0.26)/√228) = 45.2	37.8	4.5

A3.4 Example of diameter-based grade creation

There is currently no established guidance for the creation of grades. An example of a practical approach to the creation of diameter-based grades for a sample of *Dendrocalamus asper* is presented.

Figure A3.2 presents the measured diameter along the culm for 11 specimens of *D. asper* (thin lines with markers). The variation of diameters between culms and along each culm is notable. A summary of this geometric characterisation is given in Table A3.5. From the data, and according to the argument presented in Section 3.4, using the average culm diameter in capacity calculations is inappropriate. Instead, three arbitrarily-selected diameter-based grades are proposed for this sample (Grade 90, Grade 100 and Grade 110). Grade would be defined by the smallest diameter of each piece, measured at the top of the culm (D_{min}).

Figure A3.2: Diameter vs. position along the culm for a sample of *D. asper,* with three diameter-based grades

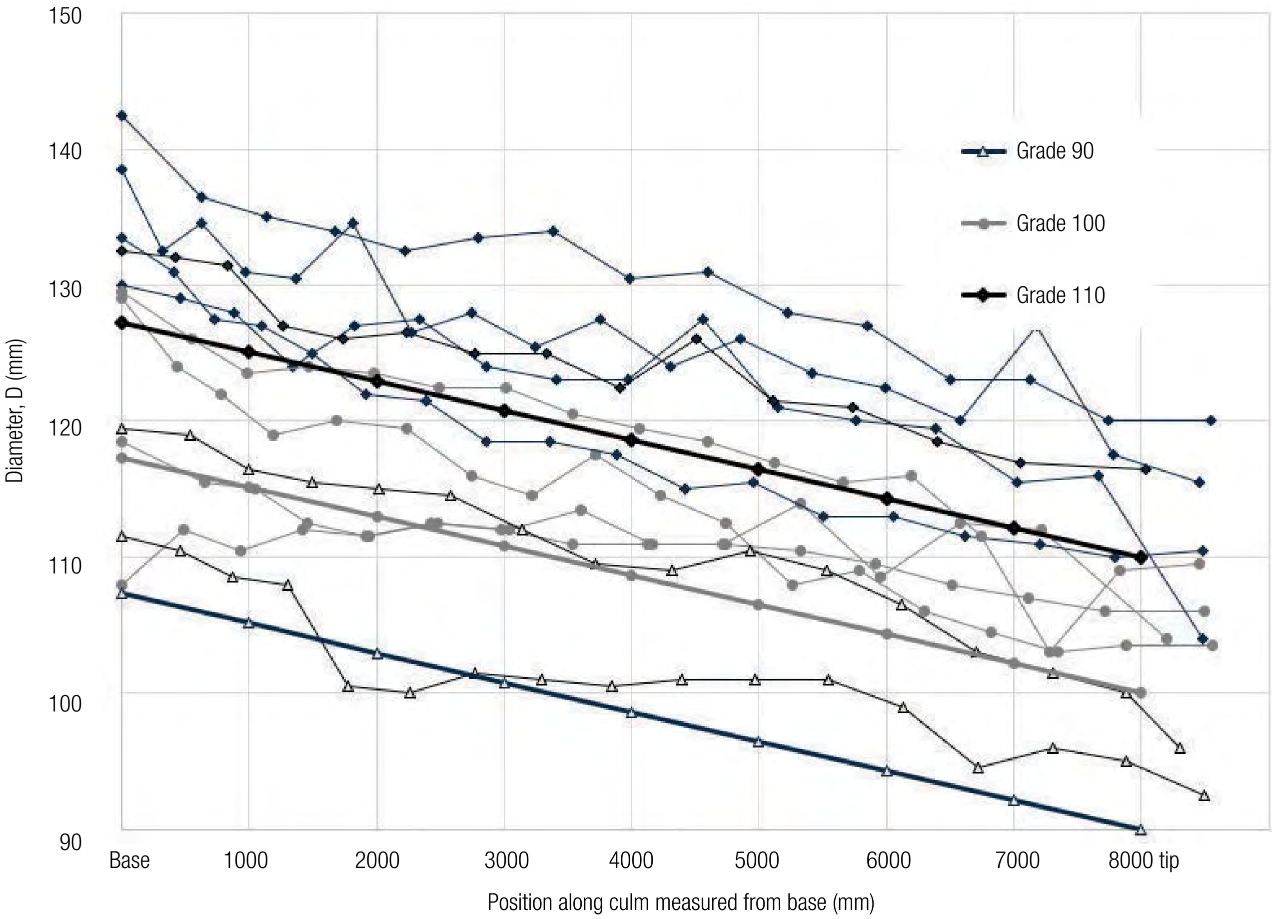


Table A3.5: Summary of geometric characteristics of a sample of *D. asper* culm

			Minimum	Mean	Maximum	COV
Diameter	D	mm	93	116	137	0.087
Wall thickness	t	mm	7.5	9.5	11.5	0.256
External taper	α_e	mm/mm		0.0022		
Internal taper	α_i	mm/mm		–0.00007		
Bow	b_o	mm/mm		0.014		
D/*t* ratio			6.5	10.5	15.8	0.185

The names of the grades represent the **nominal** diameter (in mm) associated with each grade. The different thick line types shown in Figure A3.2 represent the three different grades to which the specimens are assigned according to this criterion. For example, a piece with a minimum diameter, D_{min}, ≥ 90mm, but < 100mm, would be assigned to Grade 90. The markers (e.g., triangles) of each line show to which grade each culm would be assigned. The negative gradient of the lines represents the average external taper, α_e, for the sample (Table A3.5).

Although calculations may conservatively be based on the nominal D_{min} for each grade, a less conservative approach would be to account for taper in the calculations according to Equation A3.7:

$$D_{mean} = D_{min} + \frac{\alpha_e L}{2} \qquad \text{Equation A3.7}$$

Where:

L = length of culm considered.
D_{mean} = mean diameter for a given length of culm assigned to a particular grade having nominal diameter D_{min}.

For the sample described, taper is less than 0.1. In such a case, ISO 22156 permits use of D_{mean} for the calculation of section properties (Section 3.3.1). For culms having taper exceeding 0.1, or for instances where a conservative calculation is desired, D_{min} is used to calculate section properties.

Given the very high variation of *D/t* present in the sample (Table A3.5) and the ISO 22156 recommendation that *D/t* be limited to 12, this can also be incorporated in the grading. The minimum permitted wall thickness, t_{min} can be conservatively taken as $D_{min}/12$ (Equation A3.8):

$$t_{mean} = t_{min} + \frac{\alpha_i \frac{L}{2} + D_{min} - D_{mean}}{2} = \frac{D_{min}}{12} + \frac{\alpha_i \frac{L}{2} + D_{min} - D_{mean}}{2} \qquad \text{Equation A3.8}$$

Where:

t_{mean} = mean wall thickness for a given value of L.

On this basis, the geometric properties of each grade could be presented in tabular form (Table A3.6). For some calculations, such as shear capacity, it is probably more appropriate to use t_{min} than t_{mean}.

Table A3.6: Geometric properties for the three proposed grades of *D. asper*

Grade	Property	Units	D_{min} at tip of element	Element length measured from tip, *L* (m)							
				1	2	3	4	5	6	7	8
110	D_{mean}	$10^3 \times mm^4$	110	111	112	113	114	116	117	118	119
	t_{mean}	$10^3 \times mm^3$	9.2	9.7	10.3	10.9	11.4	12.0	12.6	13.1	13.7
	I	mm	3,721	4,018	4,324	4,639	4,963	5,296	5,639	5,992	6,354
	S	mm	67.7	72.3	77.1	81.9	86.8	91.7	96.7	102	107
100	D_{mean}	$10^3 \times mm^4$	100	101	102	103	104	106	107	108	109
	t_{mean}	$10^3 \times mm^3$	8.3	8.9	9.5	10.0	10.6	11.2	11.7	12.3	12.9
	I	mm	2,541	2,765	2,996	3,234	3,480	3,734	3,995	4,265	4,543
	S	mm	50.8	54.7	58.6	62.6	66.7	70.8	75.0	79.2	83.5
90	D_{mean}	$10^3 \times mm^4$	90	91	92	93	94	96	97	98	99
	t_{mean}	$10^3 \times mm^3$	7.5	8.1	8.6	9.2	9.8	10.3	10.9	11.5	12.0
	I	$10^3 \times mm^4$	1,667	1,831	2,000	2,175	2,357	2,544	2,739	2,940	3,147
	S	$10^3 \times mm^3$	37.0	40.2	43.4	46.6	49.9	53.3	56.7	60.2	63.7

A3.5 Allowable stress vs. limit state design approach

The ultimate objective of any design standard is to ensure structural safety — that the capacity of the structure exceeds the demands placed on it. Additionally, it is required that capacity exceeds demand by some margin — the 'factor of safety' — with some confidence. The reliability of the structure or its probability of failure, is affected by both demand and capacity 'sides' of the equation; both loading and material resistance, respectively.

In simplistic terms, an allowable stress design (ASD) approach applies a factor of safety to the characteristic material strength value that combines both the material partial factor (reduction factor) and the load factors, reducing the factor of safety to a single variable. In contrast, a limit state approach — also referred to as either 'partial safety factor design' (PSFD) or 'load and resistant factor design' (LRFD) — separates the material factor from load factors, allowing each to be defined separately. This permits a more nuanced approach to design but results in two variable factors. Typically, the load factors are 'fixed' by the applicable building standard and material partial factors are calibrated to achieve a desired reliability against failure.

Allowable stress approaches were generally used historically, especially when data (and computational power) was scarce. However, with increasing quantities of material data available, most conventional material-specific design standards have moved towards a limit state design approach.

ISO 22156 intentionally adopts an allowable stress approach for the following reasons:

- ISO 22156 is intended to be a globally-applicable design standard for bamboo, written without a specific building standard loading definition in mind. Prescribing a limit state design approach necessitates knowing the load factors to be used for the design. The simpler allowable stress approach, where both the load and material factors are combined, was considered to be more universally applicable.
- Strictly speaking, partial material factors for limit state design approaches for new data sets need to be calibrated through a complex process (which also presupposes load factors). The available data for bamboo are not yet sufficient to derive material factors with confidence. An allowable stress approach does not require such a process; the combined factor of safety can often be judgement based.

Notwithstanding, compared to an allowable stress approach, a limit state design approach offers significant benefits:

1. A clearer approach to dealing with non-linear materials.
2. The ability to define different limit states for design.
3. The ability to capture pattern or patch loading better.
4. Greater transparency for the components of the factor of safety, which permits designers to be both more efficient with their design and to increase (or reduce) conservatism when appropriate.

Although (1) and (2) do not apply to bamboo, (3) and (4) remain relevant, with the ability to capture pattern loading particularly important.

ISO 22156, Clause 5.11.1 provides an alternative method permitting a limit state design approach similar to that promulgated by the US NDS for timber design. The proposed partial material factors described in ISO 22156, Annex C.3 are consistent with European[A3.12] and North American (IBC and IRC) load factors. The final design of a typical structure should not vary substantially if an ASD or PSFD/LRFD approach is used, and the latter has advantages if it can be adopted. It should be noted, however, that within a given design the approaches must not be mixed.

A3.6 Determination of allowable design properties

In Equation 3.9 C_{DF} is a modification factor accounting for Service Class (Section A3.7 provides a definition of Service Class) and expected duration of load. This factor is similar to that used in timber design. Like timber, bamboo is susceptible to creep under sustained or permanent loading conditions and exhibits apparently greater strength when subject to instantaneously applied loads, such as wind and seismic loads. The behaviour is known to be affected by the moisture content of the bamboo, and therefore C_{DF} is also a function of Service Class.

C_{DE} is a modification factor applied to modulus accounting for Service Class and expected duration of load. For calculations requiring modulus, creep is the dominant effect. For Service Class 1, C_{DE} = 1 for instantaneous and transient loads and C_{DE} = 0.5 for sustained loads causing creep[A3.13]. A small additional reduction is prescribed for Service Class 2 based on Gutierrez[A3.14].

C_T is a modification factor for service temperature greater than 38°C. When heated, the strength and stiffness of bamboo decrease[A3.15]. The effects of elevated temperature are immediate and their magnitude varies depending on the moisture content of the bamboo. Up to 65°C, the immediate effect is reversible upon cooling. Prolonged exposure to temperature greater than 65°C can cause permanent loss of strength and stiffness in bamboo culms. Temperatures above approx. 150°C result in initiation of pyrolysis of the hemicellulose component of bamboo, resulting in permanent chemical modification[A3.16]. At 200°C, compression strength and modulus retention (following return to ambient temperature) of only 20% and 70% respectively is reported[A3.16]. In tension, strength and modulus retention was reported to be 42% and 79%, respectively. It is on the basis of this poor strength retention that ISO 22156 limits prolonged service temperatures of bamboo to 50°C and short-term exposure (no more than three hours) to 65°C (ISO 22156, Clause 5.8). As bamboo is cooled below normal ambient temperatures, its strength increases and C_T may be taken as unity.

FS is the component factor of safety. *FS* = 2 for load or force actions dominated by the longitudinal behaviour of the bamboo: compression, tension and bending of the culm. For actions susceptible to the splitting phenomena, *FS* = 4. The larger value of *FS* = 4 for bending-induced shear is intended to enforce 'flexure critical' behaviour in members subject to bending. In addition, the greater factor of safety for shear provides an allowance for splitting, similar to the crack factor of 0.67 prescribed in Eurocode 5[A3.17]. It is also an example of how robustness against splitting is embedded in the philosophy of ISO 22156.

Under indoor, air conditioned conditions (Service Class 1) (Section A3.7), the combination of factors $C_{DF} \times C_T/FS$ is calibrated to be equal to 0.30 for permanent loads, 0.38 for transient loads and 0.50 for instantaneous loads (50% of these values for shear). This is reduced for both conditions of higher anticipated equilibrium moisture content and higher ambient temperature — both of which have the effect of reducing bamboo strength. There is insufficient data to calibrate modification factors for Service Class 3 in which bamboo equilibrium moisture content exceeds 20% in service. Experimental validation of modification factors for such conditions is required to understand the risks of using bamboo at such a high moisture content (Chapter 5).

For a bamboo capacity or strength having a relatively typical coefficient of variation, *COV* = 15%, based on a large sample size (suitable for establishing strength as a grade-determining property), the ratio of allowable (Service Class 1) design strength to the average observed experimental strength will be approximately 0.22 for permanent loads, 0.28 for transient loads and 0.38 for instantaneous loads (50% of these values for shear). These ratios are a measure of the utilisation efficiency of the material and are impacted by the test programme used to generate characteristic values. The resulting ratios are inversely proportional to *COV* and proportional to the square root of the sample size. For example, if a minimum sample size, n = 30 is used and a *COV* = 20% is found, the utilisation efficiency falls to approximately 0.19 for permanent loads, 0.24 for transient loads and 0.31 for instantaneous loads.

ISO 22156, Annex C.3 provides some guidance for adopting a limit states design approach over the allowable capacity or strength approach taken in the body of the Standard. A description of the differences in these approaches is provided in Appendix A3.5.

A3.7 Service Classes and equilibrium moisture content (EMC)

ISO 22156 adopts three Service Classes aligned with those contained in Eurocode 5, as a simple framework to equate service environment and EMC of the bamboo. Service Classes affect only mechanical properties (Appendix A3.2) and should not be confused with Use Classes (Section 5.5), although there is an element of commonality between them (Table A3.7). A more refined approach for estimating EMC is described in Section A3.7.1.

Service Class 2 will be the most appropriate for the majority of design conditions.

Service Class 3 conditions are likely to lead to poor durability (Chapter 5).

Table A3.7: Service Classes contained in ISO 22156

Service Class	Characteristic EMC	Environment	Typical corresponding Use Class
1	EMC ≤ 12%	Corresponds to environments with temperatures of approx. 20°C throughout the year and relative humidities rarely exceeding 65%. Service Class 1 is normally achieved by most indoor air conditioned and/or heated environments.	1
2	12% < EMC ≤ 20%	Corresponds to environments that differ from Service Class 1, yet where relative humidities rarely exceed 85%. Service Class 2 normally corresponds to unheated and non-air conditioned indoor spaces and outdoor environments protected from driving rain.	2 and 3.1
3	EMC > 20%	Corresponds to environments that result in EMC greater than those in Service Class 2. Examples of Service Class 3 include: • Bamboo in Use Class 2 with high condensation potential. • Bamboo in Use Class 2 or 3.1 in very high humidity environments. • Bamboo in Use Classes 3.2, 4 and 5. (Appendix A3.7.1 and Chapter 5).	3.2, 4 and 5

A3.7.1 Estimating EMC

Hygrothermal effects, the synergistic effects of temperature (T) and relative humidity (RH), affect the EMC in bamboo. In this sense, bamboo is similar to softwood timber and the Hailwood-Horrobin (H-H) sorption model[A3.18], equating ambient T and RH to EMC, has been shown to model bamboo sorption relatively well. Zhang et al.[A3.19] considered 14 species of bamboo and determined that the sorption isotherm at 25°C was lower than that typically adopted for softwood timber. Other studies report similar findings for *P edulis* bamboo[A3.20, A3.21]. No known study has determined isotherms for bamboo over a range of temperatures. Additionally, sorption behaviour of bamboo is species dependent[A3.19].

It is proposed that adopting the H-H model for softwood timber[A3.18] (Table A3.8) is appropriate for bamboo, and yields marginally conservative (i.e., high) estimates of EMC for bamboo[A3.22].

Table A3.8: Equilibrium moisture content (EMC) model showing assignment to Service Classes described in Table A3.7

Ambient dry bulb temperature, T (°C)	Relative humidity, RH (%)										
	≤50	55	60	65	70	75	80	85	90	95	100
0.0	≤9.5	10.4	11.3	*12.4*	*13.6*	*14.9*	*16.5*	*18.5*	**21.0**	**24.4**	**29.0**
5 .0	≤9.5	10.4	11.3	*12.3*	*13.5*	*14.9*	*16.5*	*18.5*	**21.0**	**24.4**	**29.1**
10.0	≤9.5	10.3	11.2	*12.3*	*13.4*	*14.8*	*16.4*	*18.4*	**20.9**	**24.3**	**29.1**
15.0	≤9.4	10.2	11.1	*12.2*	*13.3*	*14.6*	*16.2*	*18.2*	**20.7**	**24.1**	**29.0**
20.0	≤9.3	10.1	11.0	12.0	*13.1*	*14.5*	*16.0*	*18.0*	**20.5**	**24.0**	**28.9**
25.0	≤9.1	10.0	10.8	11.8	*12.9*	*14.2*	*15.8*	*17.8*	**20.3**	**23.7**	**28.6**
30.0	≤9.0	9.8	10.6	11.6	*12.7*	*14.0*	*15.6*	*17.5*	*20.0*	**23.4**	**28.4**
35.0	≤8.8	9.6	10.4	11.4	*12.5*	*13.7*	*15.3*	*17.2*	*19.7*	**23.1**	**28.1**
40.0	≤8.6	9.4	10.2	11.1	*12.2*	*13.4*	*15.0*	*16.9*	*19.3*	**22.7**	**27.7**
	Service Class 1				*Service Class 2*					**Service Class 3**	

A3.8 Typical geometric and material properties

Table A3.9 summarises typical experimentally-determined material properties and geometries reported for a variety of bamboo species. Data reported is for dry (MC ranging from 8–15%), mature bamboo that is free of visual defects and is obtained from tests that were generally in compliance with ISO 22157:2004 or ISO 22157:2019. All data shown is based on samples having $n > 30$. Characteristic material properties necessary for design may be estimated (Appendix A3.3) from this table as being approximately:

$$f_k = f_{mean}(1 - 1.86 \times COV) \quad \text{Equation A3.9}$$

$$E_k = E_{mean}(1 - 0.13 \times COV) \quad \text{Equation A3.10}$$

The data aggregated in Table A3.9 comes from a range of published sources[A3.5, A3.23–A3.28] and also includes unpublished data generated by the authors. Table A3.9 is not intended to provide definitive values but rather a broad indication of material properties and their variation across a number of species.

A3.8.1 Inclusion of nodes in test specimens

For compression (f_c) and shear (f_v), data is shown without regard for whether the test specimens include a node or were obtained from the internode region. Gauss et al.[A3.24] shows that the presence or absence of a node in these tests does not affect the significance of the results. In compiling this table, the authors confirmed this conclusion; the presence of a node in a standard ISO 22157 compression or shear test has no significant effect (at a confidence level of 95%) on the resulting strength reported, and data may be pooled from both test conditions. However, it is well known that tension strength (f_t) is reduced in the presence of a node. For this reason, ISO 22157-compliant tension tests should be conducted with a node in the specimen gauge length, and data from tests with and without nodes cannot be pooled. Flexural tests (f_m) consider a longer length of culm and therefore naturally include the effects of nodes.

Table A3.9: Reported bamboo mean culm geometry and material properties

Species	ρ_{dry}	D	t	f_c	E_c	f_t node	f_t internode	E_t node	E_t internode	E_m	f_m	f_v
	kg/m³	mm	mm	MPa	GPa	MPa	MPa	GPa	GPa	GPa	MPa	MPa
P. edulis	760–800 (0.15)	60–110	6–9	54–75 (0.14)	8–20 (0.12)	100–140 (0.22)	147–275 (0.16)	11–17 (0.17)	16–18 (0.11)	–	≈90 (0.22)	16–18 (0.10)
***G. angustifolia* k.**	680 (0.19)	105 (0.14)	11 (0.3)	73.6 (0.21)	21.8 (0.29)	121 (0.18)	–	13.9 (0.17)	–	18.1 (0.21)	83 (0.25)	11 (0.25)
D. asper	690–700 (0.11)	60–160	6–22	60–78 (0.11)	22.2 (0.20)	–	270 (0.18)	–	–	21 (0.20)	93 (0.25)	9.1 (0.31)
B. pervariabilis	709 (0.12)	40.7 (0.14)	5.2 (0.27)	69 (0.17)	9.3 (0.31)	–	–	–	–	–	82 (0.21)	–
B. blumeana	788 (0.15)	93.3 (0.08)	7.7 (0.13)	–	–	–	–	–	–	20 (0.17)	88.7 (0.21)	11.3 (0.28)
B. philippines	744 (0.07)	63.1 (0.09)	6.9 (0.25)	–	–	–	–	–	–	–	–	9.5 (0.15)
B. vulgaris	–	94.7 (0.11)	12.0 (0.22)	–	–	–	–	–	–	–	–	9.2 (0.18)

Note: *COV* reported in parentheses when available.

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4 Principles of structural bamboo design

4.1 General principles

The structural design of bamboo should follow similar 'good practice' timber design principles, although with some important differences which are discussed in this chapter. Design of bamboo members and structures must be based on calculations applying the principles of fundamental applied structural mechanics. It is important to remember throughout the design process that bamboo culms exhibit numerous brittle failure modes and are highly prone to splitting/cracking (more so than timber). Because of this, bamboo structures are less forgiving than, say, most steel or reinforced concrete structures, which tend to have inherent ductility. Therefore, mistakes in modelling of bamboo structures are likely to have more significant consequences in practice.

The implications of these characteristics require the design of bamboo structures to:

- Incorporate ductility into the joints (Chapter 7).
- Aim for simple statically-determinate structures that have clear load paths.
- Avoid statically-indeterminate structures, and when not possible, explore alternate load paths that may arise due to variability in the stiffnesses of elements and connections (both due to varying geometric and material properties (Section 4.2). Note that dimensional variations may be more significant in this exercise than material variations, which is why adoption of grading practices is fundamental (Chapter 3).
- Incorporate redundancy of elements and adopt connections that exhibit 'robustness against splitting' (ISO 22156, Clauses 5.4 and 10.7[4.1]).
- Have a clear and well-defined lateral load-resisting system.

These steps should be followed for any bamboo structural design:

- Define the design criteria. This should include loads, design life, relevant national standards, robustness and fire requirements, and load combinations.
- Develop a calculation plan appropriate to the particular stage of the project, relevant national standards, types of load the structure will be exposed to (e.g., wind or seismic), size of the building and building type. This should cover the specific analyses to be carried out, tools required and the formal checking and review processes.
- Develop appropriate structural concepts. These need to consider the type of bamboo available (including the geometric and material characteristics), the skills of local contractors, the types of load the structure will be exposed to and the exposure condition of the bamboo (Chapter 5). The structural concept at this stage must include a clear and unambiguous lateral load-resisting system (e.g., bracing, portal frame, composite bamboo shear walls, masonry or reinforced concrete shear walls, etc.) and avoid relying on more than one type of system.
- Conduct a full load-path analysis of the structure. The load-path analysis should start from the point of application of the loads (e.g., external surfaces for wind, centre of mass for seismic forces) and follow the flow of these forces from one element to another. Understanding the load path is essential to a robust design — the 'litmus test' is if the designer can articulate the load path with confidence without using computer software. It is usually advisable to sketch or draw to scale the connections, even at preliminary stages, as the geometry of the different members and their connectors, with their three-dimensional properties and eccentricities, will influence the forces and moments each element will be subjected to.
- Develop a simplified hand calculation model for loads on the structure. Even apparently complex indeterminate structures can usually be simplified with a high level of accuracy. Compare these with simple hand calculations or 'rules of thumb' for the capacities of important elements. This will provide a check of the feasibility of structural concepts (e.g., Tables 4.1–4.3).
- Select a detailed modelling technique (compliant with relevant national standards) that is appropriate to the complexity of the structure and types of load the structure will be exposed to. Designers should consider if only a specific part of the building or the overall structure requires modelling. The type of 'model' could range from simple hand calculations to a detailed 3D finite element model. For simple bamboo structures, even at detailed design, it is often easier, quicker and more reliable to model the structure using hand calculations (noting also that

complex computer models can be prone to errors, and brittle materials such as bamboo are not as forgiving to errors as steel or reinforced concrete structures, which have more inherent ductility).
- Whenever computer models are adopted, it is essential to incorporate joint slippage (or translational stiffness) at connections, as they are likely to be as significant in the analysis as the stiffness of the elements.
- Check the model using sensitivity analyses (Section 4.2) and compare these to simple 'back of an envelope' hand calculations. IStructE's *Computational engineering*[4.2] is an excellent guide in this respect.
- Check capacities of elements and connections against the demands determined from the models and iterate as appropriate. Check that the deflections of the elements and system are within limits.
- Verify and iterate design as needed once elements and connections are confirmed and results of any laboratory tests are analysed, as these can all effect the load path.
- Ensure all other key design criteria are addressed throughout the design process, including robustness and fire.
- Ensure technical design reviews are conducted at appropriate times and by suitably experienced engineers.

4.2 Sensitivity analysis

A sensitivity analysis is a powerful tool to determine how the load path might be reasonably expected to vary in an indeterminate structure. Any indeterminate structure, by definition, has multiple load paths proportional to the geometry and member and connection stiffnesses. As all models are idealised simplifications of a structure, there is no single 'true' load path and no model is entirely correct. The aim of a sensitivity analysis is to capture the variation of possible load paths within an indeterminate structure, so the load path is captured and the analysis is safe.

In practice, a sensitivity analysis involves:

- Determining which variables could feasibly vary in reality. For most structures these are member stiffnesses, connection stiffnesses, element geometry (element dimensions) and structural geometry.
- Determining the expected bounds of these variations. Member stiffnesses and element geometry may vary within bounds established by grading protocols; connection stiffness generally requires experimental evidence.
- Analysing the structure for the expected bounds of the variations. Not all permutations of variations need to be analysed; engineering judgement can be used to determine the governing cases and reduce the number of permutations.
- Reviewing the results and design for the envelope of the load paths. Where the envelope is excessive, review the first and second points to determine if the bounds were overly conservative.

4.3 General modelling principles

Typically, models of bamboo structures will require that:

- Bamboo should be modelled as a linear elastic material.
- Bamboo culms should be modelled to satisfy Euler-Bernoulli beam theory[4.3] (i.e., plane sections remain plane).
- When determining load paths, if taper is small (ISO 22156, Clause 6.4.1), it is generally appropriate to model culms using average cross-section dimensions. For greater degrees of taper, it may be more appropriate to use minimum cross-section dimensions.
- For determining capacities, it is generally conservative to use the smallest dimensions of the culm. ISO 22156, Clause 6.4.1, however, permits average geometry to be used in most cases, provided the culm taper is limited. Particular care should be taken about appropriate dimensions when checking shear capacity, as average geometry may not be appropriate.
- The relevant national building standard should be used for the derivation of appropriate dead, live, wind and seismic loads, notional horizontal loads and any other loads (e.g., minimum eccentricities).
- Real eccentricities between elements and especially at connections are always accounted for in analysis.
- Second-order effects (such as P-Δ) resulting from imperfect (not straight) members should be considered. This is particularly important with bamboo since all culms are inherently curved (bowed) to some degree. Since elastic properties are assumed, moment and/or axial load amplification factors (such as B defined in ISO 22156, Clause 9.5) based on prescribed imperfections may be adopted *in lieu* of second-order analyses. For elements solely loaded in compression, C_{bow} accounts for this and additional analysis is not normally required, provided the limits prescribed by ISO 22156 are met (Chapter 6).
- Joints in bamboo structures are assumed to be true pins with finite translational stiffness, unless otherwise permitted by ISO 22156 and substantiated by experimental data justifying the use of a finite rotational stiffness (spring) or fixed joints. Joints and connection stiffnesses are defined in ISO 22156, Clause 10.5. Where joint stiffness is explicitly included, the deformation or slip of the joint needs to be accounted for in the analysis.

- Flexibility of supports are considered in the analysis in a similar way to joints.
- When determining loads in statically-indeterminate bamboo frames, variation in the load path resulting from variations in stiffness of the connections and members is considered. This is best accomplished by performing a sensitivity analysis of the structural load path (Section 4.2).

Good practice tips on modelling include:

- Start with a simple model and refine it step-by-step. At each stage review the results, comparing these to simple hand calculations where possible, to assess whether they are acceptable.
- Keep the model as simple as practical at all stages. More precise and complicated modelling should focus on key structural components and connections, while simplifications can be made on parts of the structure of secondary importance.

4.4 Seismic design

Bamboo as a material is brittle in most failure modes, meaning it cannot reliably provide energy dissipation (through strain energy or material hysteretic behaviour) in an earthquake. Bamboo connections, especially with metal fasteners, have the potential to provide some energy dissipation (similar to timber), however there is limited experimental data on this. In ASCE 41[4.4] terminology, bamboo structures, elements and connections would be described as 'force controlled'. Similarly, in Eurocode 8 terminology, bamboo structures would be described as 'brittle'[4.5].

ISO 22156 permits force reduction or behaviour factors to be derived by testing (ISO 22156, Clause 5.11.3), provided the prescriptions of the relevant national standard are also followed. Owing to the lack of test data on force reduction or behaviour factors on bamboo structures, an upper-bound on force reduction[4.6] (R) or behaviour factors[4.5] (q) of 2.5 is imposed by ISO 22156.

Without full-scale testing, bamboo frame structures should be assumed to exhibit limited hysteretic energy dissipation and be considered only nominally ductile. As such, they should typically be designed to remain elastic, with displacement ductility not exceeding approximately 1.0–1.3. The maximum response modification factor, R = 1.5 or behaviour factor, q = 1.5, compatible with the ASCE 7[4.6] and Eurocode 8[4.5] frameworks respectively, are recommended. The exception is that R = 2.0 and q = 2.0 are appropriate for modern composite bamboo shear wall structures designed and detailed in accordance with the *Norma Andina*[4.7] (Chapter 8). The increased value is justified because there is a significant amount of testing supporting this system of construction. Available standards, including ISO 22156, give clear minimum detailing and design rules. Similar structures not designed using these standards or guides should be assigned R = 1.5 or q = 1.5.

ISO 22156 also requires that joints in bamboo in seismic zones have a minimum level of ductility (ISO 22156, Clause 10.6). However, this ductility cannot be used to reduce the seismic demand, unless full-scale cyclic testing of the entire structural system indicates a reduction is appropriate (ISO 22156, Clause 5.11.3).

Additional general recommendations for structural and seismic design of the most common whole-culm bamboo structural systems currently in construction around the world are:

- Contrary to popular belief, bamboo structures are not automatically seismically-resilient — the seismic performance of bamboo structures depends on how they are designed, detailed, built and maintained.
- For all bamboo structural systems in seismically-active regions, it is desirable to minimise the building's mass. Floors and roofs should ideally be made from bamboo or timber systems. Designers should be cautious of inadvertently increasing seismic vulnerability by introducing heavy materials, especially in roof structures.
- Providing structural continuity (tying the structure together) and redundancy is fundamental to good bamboo seismic performance. Such continuity is also good practice for wind design.
- When applying 'equivalent to code' standards of ISO 22156, Clause 5.11.2 *Experience from Previous Generations*, it is essential that all aspects of the traditional bamboo construction system, including construction practices, be maintained to the standard from which the equivalence is derived.
- Attaining good seismic performance in the long term requires careful consideration of durability in the initial design (Chapter 5). Other elements of the building such as timber and steel should have similar durability considerations.
- When determining the natural period of bamboo structures, variations in stiffness of the connections and members must be considered, as these can vary significantly, affecting the calculated period of the structure. Most low-rise bamboo structures (≤ three storeys) are likely to fall within the plateau of most seismic response design spectra.

More information on seismic performance of bamboo structures is presented in Reference 4.8.

4.5 Design for wind

Bamboo has a high strength-to-weight ratio, which generally results in relatively lightweight structures. Traditional bamboo connections have limited tensile strength, and traditional buildings generally do not have a high degree of vertical load path continuity (tying) from roof to foundations, nor do they typically have heavy foundations. For these reasons, vernacular bamboo buildings often display poor performance in strong wind events (e.g., tropical cyclonic storms).

Heavy roof and heavy wall systems are simple (passive) measures to improve structural performance in wind (although must be considered with great caution as seismic loads are also a design consideration). Two other design considerations to resist wind forces are:

- Providing connections with a high tensile capacity (Chapter 7) to allow a continuous vertical load path to be created from roof to foundations.
- Adopting a robust lateral load-resisting system to transfer horizontal forces from roof to foundations.

The composite bamboo shear wall system (Chapter 8), for instance, combines reasonable mass with high lateral load resistance. Such systems have been designed and demonstrated to work effectively in tropical cyclone-prone areas[4.9].

4.6 Fire resistance of bamboo

As a material, bamboo is chemically very similar to softwood timber. At temperatures above approximately 230°C, combustion is possible with the aid of a pilot flame, while above approximately 280°C, pyrolytic gases become volatile, smoke particles appear and char begins to form, as the physical structure of the bamboo degrades. Compared to timber, bamboo's thin-walled geometry makes it more susceptible to damage and ultimately consumption in a fire event. The hollow culm allows both inner and outer surfaces of the thin culm wall to burn and may serve to assist fire spread, especially in vertically-oriented culms. As such, ISO 22156, Clause 13 is clear:

> *"Bamboo shall be assumed to have very little fire resistance by itself."*

Additionally, exposed bamboo should be considered a combustible material for the purpose of building or fire code classification. A brief review of the meaning and intent of fire resistance and fire performance rating is provided in Appendix A4.1.

The lack of substantial knowledge of fire performance of bamboo structures was a primary consideration in limiting the scope of ISO 22156 to "one- and two-storey residential, small commercial or institutional and light-industrial buildings not exceeding 7m in height". Many structures falling into this scope may be exempt from required fire performance ratings, and designers can leverage these exemptions. For example, low-rise single-family residential construction with adequate means of egress typically requires no fire performance rating, provided the separation between adjacent structures exceeds a minimum value to avoid fire spread from one structure to another (e.g., the International Building Code requires 3m).

If a national building standard or other regulation requires bamboo to perform in fire, some form of fire protection will be required. Similar to softwood or light-gauge steel, encapsulation of the bamboo is the only practical option. Fire retardant treatments or coatings for bamboo are not recommended. While these may reduce surface spread of flame, they have no significant effect on fire resistance. Additionally, most known fire-retardant treatments are expensive, require pressure treatment and are toxic during application. Claims that boron-based treatments improve fire resistance are unfounded at the boron-retention levels typically used in bamboo treatment to resist biological attack.

When fire resistance ratings for bamboo structural assemblies (e.g., wall panels) are required, these should be determined in accordance with ISO 834[4.10] or applicable national standards for fire testing. It is important to recognise that fire ratings are based on testing of an assembly which includes the structural load-bearing element, encapsulation and any other required components, attachments and appurtenances. To achieve the qualified rating, the assembly must be used in the same arrangement as tested. Bamboo itself will not have a fire rating.

Where there is an immediate fire risk, for example near a cooking stove, furnace, log burner or fireplace, ideally other non-combustible materials should be used. If bamboo is to be used in these scenarios, it should be encapsulated to avoid the potential for fuelled combustion and to keep the bamboo temperature low.

4.6.1 Composite bamboo shear walls

An exception to the ISO 22156 height limits is made for composite bamboo shear walls (CBSW), also referred to as 'light cement bamboo frames' (LCBF) (Chapter 8). These may be built to three storeys or 9m in height. It has been shown in limited studies using BS 476-22[4.11] and ISO 834[4.10] that non-load-bearing CBSW panels with cement mortar render having a thickness of 25mm can achieve 30-minute fire resistance rating (FRR)[4.12–4.14]. A discussion of these tests and guidance for the design of fire-resistant CBSW panels is found in References 4.9 and 4.15.

4.7 Efficient structural forms in bamboo

The shape and mechanical properties of bamboo imply that there are some forms for which it is well-suited and some which should be avoided. As will become evident in Section 4.8, bamboo culms are excellent columns but serve less well as beams, frequently limited by shear and crushing at the supports. Beam spans should ideally be limited to 2–3m, while columns made from the largest culms can achieve lengths of up to 4–6m. Bundling culms together to make bigger beams does not significantly resolve this limitation, because current connection techniques between culms only achieve low levels of composite action, and crushing at the supports remains a common issue.

As a result of these characteristics, efficient shapes to adopt in bamboo are:

- **Fan-shaped portal frames.** Colombian architect Simón Vélez has frequently adopted this shape in his designs. The beams in flexure are short while the compression struts are long. The fan shape helps to provide a large overhang which protects from wetting (Figure 4.1).

Figure 4.1: Fan-shaped roof truss

- **Stud-frames.** Housing consisting of regularly-spaced studs, joists and rafters, similar to platform-timber frame or stud frames used in timber, are an effective way to build bamboo housing, and keep floor beam spans short. Walls are typically built using the composite bamboo shear wall system (Chapter 8).
- **Trusses.** Bamboo is very strong in tension as well as in compression, therefore, in theory, trusses should work very well. In practice, however, performance of trusses is hampered by connections, particularly those that transfer shear or tension. Current bamboo connection technology results in connections that are not very stiff and are quite weak when loaded perpendicular to the axis of the culm.
- **Geodesic domes and space frames.** In theory, both forms should work well with bamboo yet are still uncommon. This could be because connections are relatively expensive and inefficient, therefore systems that maintain continuity of the culm are preferred.
- **Arches and domes.** Increasingly common structural forms in bamboo that exploit its high compressive strength and efficient cross-section, arches and domes can also make use of bamboo's natural curvature (Figure 4.2). Further curvature may be achieved by forcing an additional level of curvature on individual culms making use of their high bending strength. Heat-bending of culms is another increasingly common practice, although the effect this has on mechanical properties needs further investigation, as it may be detrimental. Arches and domes retain culm continuity, minimising joints and use predominantly end bearing joints which are stiff, efficient and inexpensive.

Figure 4.2: An arch structure using bamboo: INBAR Pavilion at 2019 Beijing International Horticultural Expo

There are some shapes that have been associated with poor results in bamboo:

- **Long-span beams or heavily-loaded beams.** These types of beams may either present excessive deflections or can fail in shear or crushing at the supports.
- **Congested joints.** The geometry of a joint needs to be carefully considered as culms are relatively bulky (Figure 4.3).
- **Trusses with horizontal chords**. Bamboo trusses can manifest very large deflections because commonly-used joints have low stiffness. Deflections are more perceptible if a chord is set to be horizontal. Scissor, fish-belly and lenticular trusses help to avoid this problem.

Figure 4.3: Joints that rely on the confluence of many elements can be problematic

4.8 Tables for scheme design

In common with other materials, it is important for the design team to have an approximate idea of the achievable spans and loads for bamboo culms during conceptual design. Tables 4.1–4.3 provide an indication of maximum spans that roof and floor beams can achieve, as well as the maximum loads that columns of different lengths can support. These tables cannot be used *in lieu* of a full set of calculations, but provide the designer with a starting point for member design at scheme design stage. The tables have been derived using the mechanical and geometric characteristics of a range of species and are based on allowable stress/capacity design. It has been assumed that the maximum allowable D/t for any species is 12, which is consistent with the recommendations of ISO 22156. Additional examples of the development of load and span tables are provided in Reference A6.3.

4.8.1 Single-culm bending members

For single-culm bending members (e.g., joists), the unfactored uniformly-distributed load (UDL) on the member is limited to:

- For floors: unfactored UDL in kN/m ≤ $D/133$ (D in mm).
- For roofs: unfactored UDL in kN/m ≤ $D/100$ (D in mm).

This does not account for crushing at supports, which can be addressed by reinforcing the end of the culm with a wooden plug or cement mortar.

An initial size estimate for a bamboo beam that is likely to be governed by bending or deflection, and not shear is:

Span ≤ 27*D*

Example:

Q: A residential floor with total unfactored areal load = 1.8kN/m^2. What is the maximum span and required joist spacing for culms with 100mm diameter?
A: Span ≤ 27 × 100mm = 2,700mm.

UDL on each joist ≤ 100mm/133 = 0.75kN/m.
From areal loading, required joist spacing is found: 0.75kN/m/1.8kN/m^2 ≈ 400mm spacing.

Tables 4.1 and 4.2 provide approximate spans for single-culm bamboo roof and floor members (e.g., rafters and joists) depending on mean diameter and load. These tables have been derived from checks for bending strength (rarely governs), shear strength and deflection in accordance with ISO 22156. They do not include checks for crushing at supports. The tables have been derived for simply-supported members subjected to a UDL. For floors, the total allowable UDL, w_{total}, is the sum of the unfactored dead and live gravity load. In the case of roofs, the total allowable UDL, w_{total}, is the sum of the vertically-acting loads (dead load and wind, typically).

Tables 4.1 and 4.2 have been derived for bamboo culms located in a Service Class 2 environment and calculated considering a long-term deflection limit of L/150. This deflection limit is consistent with that typically used for soffits without plaster or plasterboard ceilings. Shaded entries (coloured orange) are those likely to be governed by shear capacity and are, therefore, less efficient load-span combinations. Entries in **bold** are governed by the L/150 deflection limit. Plain entries indicate a transition between the two, depending on the species being considered.

Table 4.1: Floor beams — achievable spans (mm)

D_{mean} (mm)	Total uniformly-distributed load (dead + live) in kN/m										
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
50	**1,700**	1,000	650	500	400	300	250	250	200	200	150
75	**3,000**	2,300	1,500	1,150	900	750	650	550	500	450	400
100	**4,400**	**3,450**	2,750	2,050	1,600	1,350	1,150	1,000	900	800	700
125	**5,950**	**4,700**	**4,100**	3,250	2,600	2,150	1,850	1,600	1,400	1,250	1,150
150	**7,600**	**6,000**	**5,200**	4,600	3,750	3,100	2,650	2,350	2,050	1,850	1,650

Table 4.2: Roof beams — achievable spans (mm)

D_{mean} (mm)	Total uniformly-distributed vertical load (dead + wind) in kN/m										
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
50	**1,800**	1,300	850	650	500	400	350	300	250	250	200
75	**3,100**	**2,450**	2,000	1,500	1,200	1,000	850	750	650	600	550
100	**4,550**	**3,600**	**3,150**	2,700	2,200	1,800	1,500	1,300	1,150	1,050	950
125	**6,150**	**4,900**	**4,250**	**3,850**	3,400	2,850	2,450	2,100	1850	1,650	1,500
150	**7,850**	**6,250**	**5,400**	**4,900**	**4,550**	4,050	3,500	3,050	2,700	2,450	2,250

Example:

Q: A roof is composed of 100mm diameter bamboo rafters @ 400mm culm column and is subjected to 0.35kN/m^2 deadload combined with either a 2.25kN/m^2 wind uplift pressure OR 1.13kN/m^2 wind downward pressure. Using Table 4.2 what is the maximum achievable span?

A: First, determine the worst combination. w_{total} = (0.35kN/m^2 + 1.13kN/m^2) x 0.4m = 0.59kN/m (downward) OR w_{total} = (0.35kN/m^2 – 2.25kN/m^2) x 0.4m = 0.76kN/m (uplift — expressed as an absolute value). As the worst combination is for uplift pressure, use this for estimating the rafter dimension. Therefore, from the table, the maximum span would be 3,150mm. In this case, the roof supports would be required to have sufficient resistance to uplift — typically requiring tension ties having continuity to an adequate foundation.

4.8.2 Columns

Table 4.3 provides approximate maximum axial loads that may be resisted by single bamboo culms depending on their diameter (at the bottom of the culm, D_b) and length. Larger loads are resisted by assembling individual culms into multiple-culm columns. Table 4.3 has been derived from the requirements of ISO 22156 (Clause 9) and a Service Class 2 environment. The loads reported are the total unfactored vertical loads in the element — typically the sum of dead and live loads. Load duration is assumed to be governed by transient (live) loads. The assumed bow, b_0, is L/100 or 1%.

Table 4.3: Columns — maximum (unfactored) loads (kN) (interpolation is NOT permitted)

D_b (mm)	Effective length (KL) of column (mm)									
	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	5,500	6,000
50	**1.7**	**0.9**	**0.5**	**0.3**	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.0**
63	4.2	2.3	1.4	0.9	0.6	0.4	0.3	0.2	0.2	0.1
75	**8.5**	**4.9**	**3.0**	**2.0**	**1.4**	**1.0**	**0.8**	**0.6**	**0.5**	**0.4**
88	15.0	9.0	5.7	3.9	2.7	2.0	1.5	1.2	0.9	0.7
100	**23.5**	**15.1**	**9.9**	**6.8**	**4.8**	**3.6**	**2.7**	**2.1**	**1.7**	**1.3**
113	33.4	23.4	15.8	11.0	7.9	5.9	4.5	3.5	2.8	2.3
125	**44.6**	**33.9**	**23.7**	**16.7**	**12.2**	**9.2**	**7.1**	**5.6**	**4.5**	**3.6**
138	56.9	45.9	33.7	24.4	18.0	13.6	10.6	8.4	6.7	5.5
150	**70.2**	**59.4**	**46.1**	**34.1**	**25.5**	**19.5**	**15.2**	**12.1**	**9.8**	**8.0**

Example:

Q: A 3,500mm-long pin-ended culm (K = 1) needs to support a total unfactored load of 12kN. What diameter of culm is required?

A: A single culm is nonredundant (ISO 22156 Clause 5.4) requiring an additional factor, C_R = 0.9 to be applied. Thus, the design load is 12kN/0.9 = 13.3kN. The required diameter is D = 138 mm.

A three-culm multiple-culm column having 100mm culms (capacity = 3 culms x 4.8kN x C_R = 13.0kN) or nine-culm having 75mm culms (capacity = 9 culms x 1.4 = 12.6kN) will also be adequate. C_R = 1 for the nine-culm column.

4.9 Characteristic strengths and stiffnesses for scheme design of bamboo

At the scheme or initial design stage of a project, properties of bamboo species are not always immediately available or may derive from unreliable sources. Table 4.4 provides suggested lower-bound characteristic strengths and stiffnesses for scheme design of any species of dry, mature bamboo, free of visual defects (splits, decay, etc.), normalised for instantaneous loads (C_{DF} = 1.0), for use with ISO 22156. Comparisons with C24 softwood and D50 hardwood from BS EN 338:2016[4.16] are also provided. The values given are intended to be lower-bound, meaning a rigorous testing/grading regime (as described in Chapter 3) should result in higher strengths in most cases. Care should be taken however, as some species may yield lower strengths. The values presented in Table 4.4 are not intended for detailed design use. A summary of typically-reported nominal and characteristic material properties are given in Appendix A3.6.

Table 4.4: Characteristic strengths and stiffnesses recommended for scheme design of bamboo

		Bamboo	C24 softwood[4.16]	D50 hardwood[4.16]
Mean density	kg/m^3	700	420	740
Compression, f_{ck}	MPa	35	21	30
Tension, f_{tk}	MPa	40	14.5	30
MOR, f_{mk}	MPa	40	24	50
Shear, f_{vk}	MPa	3	4	4.5
Modulus of elasticity[a], E_k	GPa	10 or 15[b]	11	14

[a] E_k is the mean value with 75% confidence (Appendix A3.3).
[b] For tropical bamboos with typical D/t ratios ≥ 10, use E_k = 15GPa. For all other species adopt 10GPa.

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Appendix

A4.1 Fire resistance and performance rating

Building components constructed to resist fire are designed by understanding their material properties, and performance is proven through fire testing (e.g., ISO 834[A4.1], ASTM E119[A4.2], UL 263[A4.3]). Fire resistance is measured through fire testing, in which a building element or 'assembly' is exposed to a standard heating protocol and the time to failure is determined. The assembly typically has structural loads applied during testing and is assessed for its performance in three different criteria:

- Structural resistance: the ability of the assembly to continue to carry the applied loads.
- Integrity: the resistance of the assembly to intrusion of hot gases or flame passing through the assembly.
- Insulation: the ability of the element to limit temperature rise on the non-fire side.

If an assembly such as a wall can continue to carry applied loads, prevent hot gases from passing through it and adequately limit the temperature on the cold side of the assembly when exposed to the standard heating protocol for a period of 60 minutes, the assembly will be 'certified' as having achieved a 60-minute fire rating. This is referred to as a fire resistance rating (FRR). Certified assemblies become 'qualified designs' for the purposes of determining fire resistance. Such assemblies are constructed with specific materials, dimensions, insulation materials and other features. Qualification does not extend beyond the limitations of the tested assemblies.

Building materials can also be designed to limit flame spread in the early stages of a fire, which is intended to provide adequate time for occupants to evacuate. To measure how quickly flames spread along a wall or ceiling, tests are undertaken to understand the influence of the material properties and their resistance to heat.

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5 Durability

5.1 Introduction

Designing for durability is an essential part of the design process — as important as designing structural elements and connections. Unlike some species of timber, bamboo does not have naturally-occurring toxins and contains high levels of starch, making it particularly susceptible to rot, termite, beetle and marine borer attack. Following BS EN 350[5.1] classification, all species of bamboo should be considered 'not durable' to attack by decay fungi, wood-boring beetles, termites and marine organisms. 'Not durable' is defined as durability class (DC) '5' for fungi, and is defined as durability class (DC) 'S' for wood-boring beetles, termites and marine organisms. This places bamboo in line with the most vulnerable species of timber. Combining this vulnerability with its typically thin walls, a small amount of decay in bamboo can cause a significant proportional change in structural capacity.

Bio-deterioration mechanisms of bamboo and methods for improving durability, are largely the same as those for wood. In general, similar principles and approaches developed for ensuring durability in modern timber design also apply to bamboo. Although minor variations in natural durability occur between species, in particular for beetle attack, the differences are not considered significant, especially for termite attack and rot. Modern chemical treatments can effectively bring all bamboo species up to similar levels of durability. This removes the need to select a specific bamboo species which may anecdotally exhibit slightly greater natural resistance to, say, beetles.

Despite vulnerability to fungi, beetles and termites, bamboo structures can relatively easily be designed to achieve a design life of 50 years or more with little maintenance (Figure 5.1). This can be achieved through a combination of appropriate chemical treatment and simple design decisions (i.e., keep the bamboo dry and away from all sources of water, including driving rain).

'Modern' or 'formal' bamboo construction, being a relatively new field, is affected by some common misconceptions, particularly around bamboo durability, especially regarding fungal attack. For this reason, many modern 'permanent' bamboo buildings unfortunately have short lifespans, sometimes just 10–20 years[5.2]. Inadequate durability is also one of the main reasons why bamboo structures fail in earthquakes, since degradation of elements leads to reduced capacities[5.3–5.6].

Figure 5.1: Examples of durable bamboo houses

a) A traditional bamboo house in Colombia, over 100 years old. The perimetral veranda fully protects the walls from driving rain

b) A modern bamboo house in El Salvador. The upstand elevating the structure, the render protecting the bamboo wall and the large roof overhang minimise the impact of driving rain

Metal elements in bamboo construction should also be designed to achieve a 50-year design life.

The principles within Chapter 5 and its appendices are also covered in Reference 5.7.

5.2 Attack mechanisms

There are three main causes of biotic decay in bamboo:

- Fungal attack (rot).
- Insects (primarily beetle and termite attack).
- Marine borers.

Appendix A5.1 describes these mechanisms, their geographic extent and how they can be identified.

Cyclic hygrothermal effects are also known to degrade exposed bamboo. Such mechanisms are complex and involve effects of drying and wetting (sun and rain exposure) which lead to swelling and shrinkage of bamboo. Although not strictly an attack mechanism, such cyclic exposure has been observed to lead to splitting (or fissuring) of exposed bamboo. Splitting not only breaks any external waterproofing coating (such as paint or varnish) but weakens the culm and, in particular, structural connections.

Additionally, prolonged exposure to ultra-violet radiation (UVR) can weaken the tough outer and waxy layer of bamboo (cortex) reducing its water-repellent characteristics. These effects further increase the vulnerability of bamboo to insect attack and rot.

5.3 Design life

Design life is the minimum expected lifespan of the primary structure of a building. In conventional construction, during its design life the building is expected to perform its intended purposes, be serviceable with minimal maintenance and without major repair being necessary. Minimum maintenance is usually considered to include facade repair, repair of leaks and associated damage due to water ingress, painting and replastering. Maintenance is not generally intended to include repair or replacement of primary structural elements. Similar to other common primary structural materials such as reinforced concrete, timber, masonry and steel, a 50-year design life is typically required for permanent bamboo structures, including those constructed in lower- and middle-income countries.

Design life should not be literally interpreted that a building will not last more than 50 years. Many well-designed, well-built and maintained bamboo buildings will be able to continue to operate beyond 50 years.

Bamboo can be designed to achieve the conventional design-life paradigm. Detailed means of accomplishing this are described in appendices A5.2–A5.7. More information specifically on design life is provided in Appendix A5.2.

5.3.1 Design for replacement

ISO 22156:2021[5.8] also enables a second paradigm for achieving long-lived structures: '*design for replacement*'. While not addressing durability directly, Clause 5.9 encourages consideration during initial design of the "*future need to replace individual culms in a member or structure*" that may split or be otherwise damaged in service. The potential ability to replace members or components is reinforced by Clause 5.4, which encourages redundant structures and, therefore, the ability to temporarily remove and replace a member under controlled circumstances.

Note that designing for replacement does not mean that individual elements should typically be permitted to have an expected design life of less than 50 years, nor does it mean that a structure can be designed with bamboo elements exposed to rain, in the knowledge that they will rot. Design for replacement instead is meant to address unexpected splitting or damage.

5.4 Methods of providing durable bamboo structures

Presented here are the six key steps required for achieving adequate durability of bamboo in most scenarios for a design life of 50 years, which satisfy the criteria described in Section 5.5. The steps are presented in order of application in the construction process, not necessarily efficacy:

- Select mature bamboo. This is when it is strongest and most durable (Appendix A5.5).
- Harvest at an appropriate time of year. This should follow local practice when the starch and/or water content are lowest, and to avoid damaging the plant (Appendix A5.5). This criteria is not always possible to adopt for practical reasons.
- Season (dry) the bamboo adequately down to the equilibrium moisture content (EMC) of the ambient environment (typically 12–18%) (Appendix A3.7 and Section 5.4.1).
- Modern chemical treatments. Boron is generally the most appropriate chemical available worldwide (Section 5.4.2).
- Provide 'durability by design'. In particular, only use bamboo in Use Class 1, 2 and 3.1 (Sections 5.4.3 and 5.5).
- Provide adequate corrosion protection to metal structural and connection elements (Section 5.4.4).

If any of these steps are not implemented correctly, the lifespan of the structure is likely to be shortened significantly.

There are no known effective and appropriate ways to improve durability against marine borers. Bamboo placed in salt water marine environments will not endure and should be avoided.

5.4.1 Seasoning (drying)

Seasoning of bamboo involves reducing its water content to be in equilibrium with the surrounding air (Appendix A3.7). Seasoning of bamboo reduces the risk of insect and fungal attack, increases its strength and significantly reduces the risk of splitting in service. Seasoning should be considered crucial for all bamboo, regardless of the chemical treatments used.

5.4.2 Modern chemical treatments

5.4.2.1 Boron

Boron is the most common method of treating bamboo. Boron-based preservatives are relatively cost-effective, low-tech, widely available, have low toxicity and a high efficacy against both termites and beetles. They also have some efficacy against fungal attack. However, because they are readily soluble in water, they are easily leached out of bamboo in water or when exposed to driving rain, and therefore can only be used effectively where bamboo is protected from wetting.

More information on additional considerations for treatment is provided in Appendix A5.6 and more information on boron treatment is provided in Appendix A5.7.

5.4.2.2 Chemically-fixed

Modern chemically-fixed treatments are those that are fixed into the bamboo so they do not wash out as easily as boron when exposed to water. The most common safe treatments of this type are copper organic-based preservatives (e.g., copper azole), which can be very effective against insects and rot[5.9]. Owing to their higher cost, however, they are not currently widely used with bamboo.

Where preservative treatments do not penetrate the full thickness of the culm wall, special attention should be given to treatment of saw cuts, drill holes or other intrusions into or through the bamboo section. These may require additional post-assembly treatment or end caps to prevent local degradation.

5.4.3 Durability by design

The single most effective method of reducing risk of attack is by reducing or removing the hazard altogether — known as 'durability by design' (Figures 5.2 and 5.3). All bamboo designs should specify some form of durability by design. Durability by design involves:

- Keeping the bamboo dry and protected from radiation (UVR).
- Allowing the bamboo to 'breathe' (i.e., well-ventilated).
- Disrupting subterranean insect paths.

Figure 5.2: Key recommendations for 'durability by design'

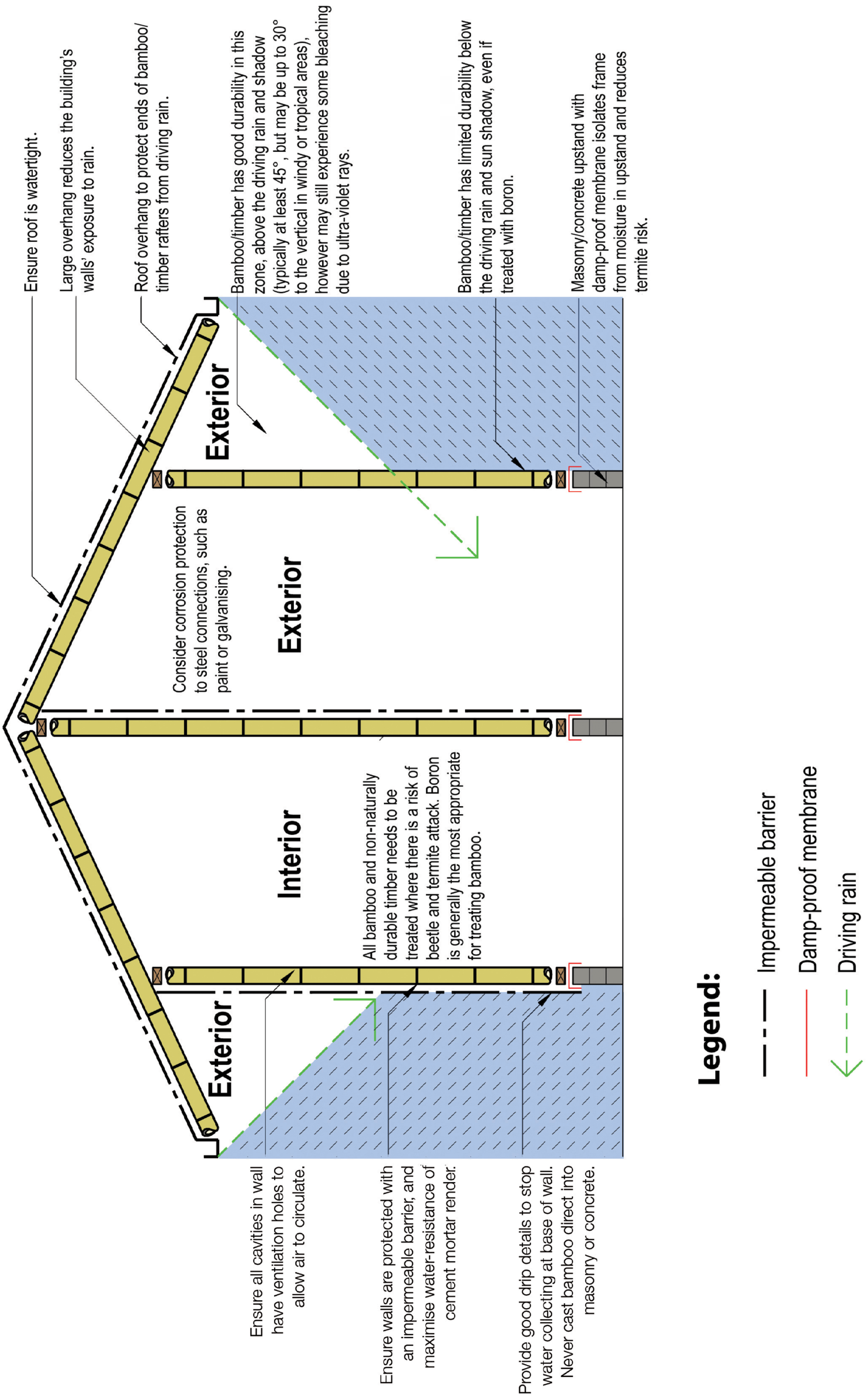


Figure 5.3: Modern bamboo house highlighting key recommendations for 'durability by design'

5.4.3.1 Keeping the bamboo dry

All fungal growth and many bamboo-destroying insects require bamboo moisture content greater than 20%. By ensuring moisture content remains below this value, risk of attack is significantly reduced.

Sources of water include rain, flooding, condensation and moisture in the ground. Rain does not only fall vertically; driving rain exposes all bamboo outside the rain 'shadow' of the roof eaves (Figure 5.2). Typically, this rain shadow is at least 45° from the eave, however the exact angle will vary depending on wind speed and exposure — in particularly windy areas or tropical countries with high rainfall, a smaller 30° angle to the vertical may be more appropriate. The 30–45° shadow line also applies to exposure to UVR.

Above the rain shadow, the risk of rot reduces but is not eliminated — i.e., it should not be seen as a sudden cut-off, where everything above that point no longer requires consideration. It is therefore also recommended to avoid horizontal bamboo elements and water traps for the region above the rain shadow; up to around 30° to the vertical at least.

In some instances, driving rain or rain running off a roof eave can splash off a hard surface surrounding a structure and dampen the lower parts of walls.

Keeping bamboo dry is best achieved by keeping all bamboo within the weather line (the area inside the waterproof envelope or protected from driving rain by the rain shadow) and isolating ground floor columns and walls from foundations with damp-proof membranes. The same approaches serve to protect the bamboo from wet-dry cycles and UVR exposure. Externally-exposed bamboo must be avoided and the hazard can be reduced by:

- Providing protection in the form of a roof overhang or veranda.
- Elevating columns above the foundation and ground level.

- Detailing elements, connections and interfaces to shed water and avoid water traps or exposed culm ends, particularly on horizontal beams, at connections and at the bases of columns.
- Ensuring the bamboo is completely protected on the outside, although ideally the bamboo will still be able to 'breathe' on the inside face.
- Providing sacrificial facades.

5.4.3.2 Providing good ventilation

Accidental wetting can occur during extreme events, when weather barriers fail or from other sources of leaks. Some building details may also encourage condensation which should be avoided. Bamboo should ideally always be allowed to 'breathe' inside the waterproof envelope, even if there is no obvious risk of water exposure. Flat roofs are particularly vulnerable to undetected leaks in waterproofing membranes and should contain a ventilation cavity to allow any water penetration to evaporate. Peaked roofs should be adequately vented at their peaks to avoid condensation accumulation. Ideally, bamboo elements should be designed to be easily inspectable to allow leak detection and repair.

Bamboo should never be cast into concrete. Concrete is hygroscopic, meaning it will absorb nearby water and create suitable conditions for rot.

In addition, there is always a risk that some bamboo culms are not fully dried before use or have not reached their equilibrium moisture content in the environment in which they are placed. This is another reason to ensure proper ventilation of all bamboo components *in situ*.

5.4.3.3 Disrupting subterranean insect paths

Keeping bamboo within the weather envelope and raised off the ground will deter many subterranean insects and make identifying their pathways easier. In some countries additional barrier membranes are used in foundations to prevent termite attack (termites can pass through cracks in concrete as small as 0.8mm)[5.10]. Additional measures include bait boxes.

5.4.4 Corrosion protection of metal structural elements

Metal fasteners and other structural connections should, where necessary, be inherently corrosion-resistant or be protected against corrosion.

Examples of minimum corrosion protection and material specifications to achieve a 50-year design life for different service classes are given in Table 5.1. These are based closely on the recommendations provided in BS EN 1995-1-1[5.11] and relate to ISO 2081[5.12]. These assume an environment *without* significant airborne pollutants, de-icing salts or airborne salts from marine environments (the risk of airborne salts from marine environments is highest within the area of land one kilometre from the mean high water sea level). Where the environment is exposed to these higher risks, the risk of corrosion increases and specialist advice must be sought — stainless steels will typically be required.

Table 5.1: Minimum corrosion protection and material specifications for 50-year design life

Fastener	Service Class (Appendix A3.7)		
	1	2	3
Nails and screws with d ≤ 4mm	None	Fe/Zn 12c	Fe/Zn 25c
Bolts, dowels, nails, screws with d > 4mm	None	None	Fe/Zn 25c
Staples	Fe/Zn 12c	Fe/Zn 12c	Stainless steel
Steel plates ≤3mm in thickness	Fe/Zn 12c[a]	Fe/Zn 12c[a]	Stainless steel
Steel plates 3–5mm in thickness	None	Fe/Zn 12c[a]	Fe/Zn 25c
Steel plates >5mm thickness	None	None	Fe/Zn 25c

[a] Properly-applied anti-corrosion paint may also be adequate, but may require periodic maintenance.

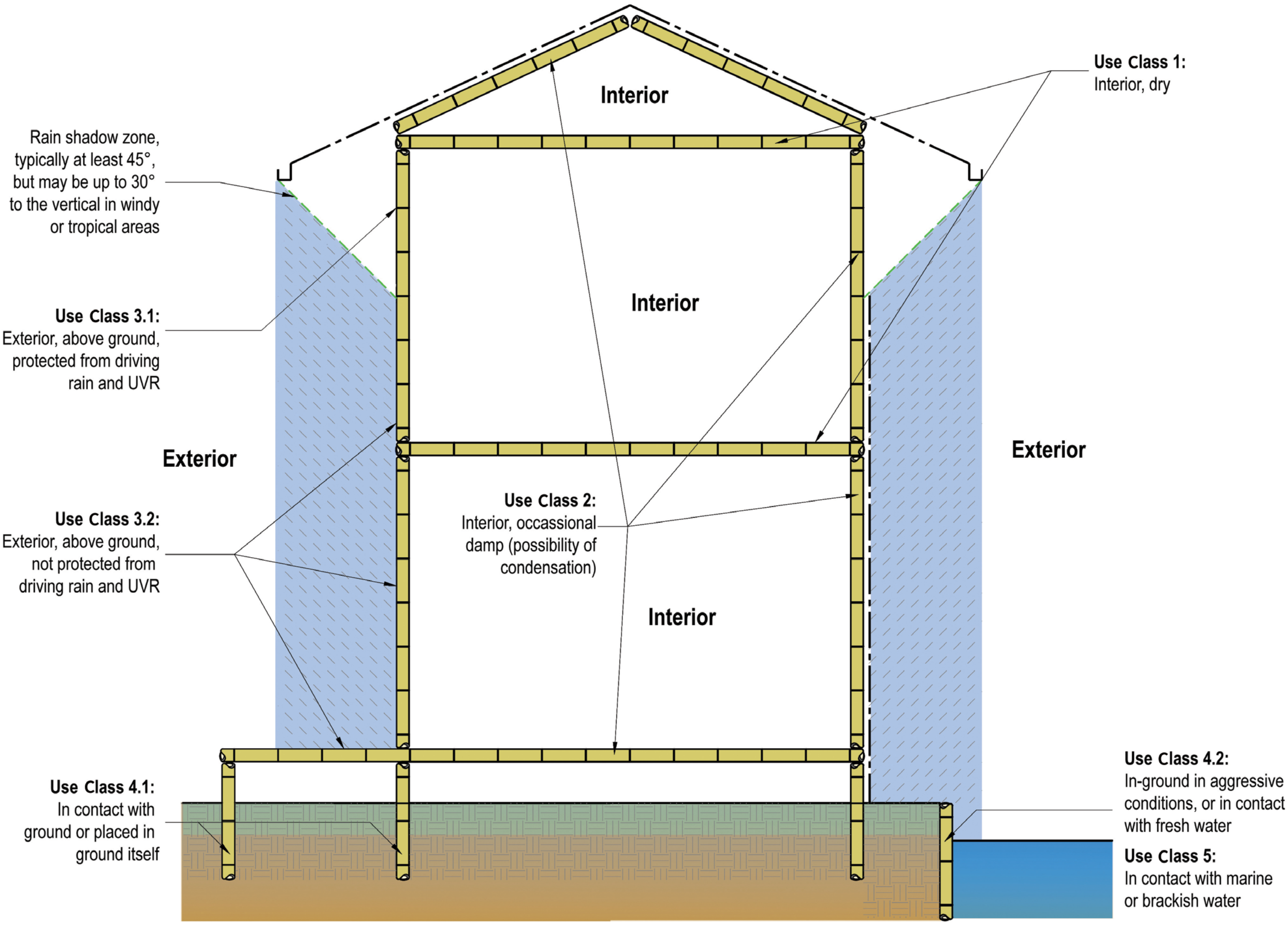
5.5 Classifying exposure and resulting design requirements

ISO 22156 draws on the principles of ‘Use Classes’, adopted in international timber codes[5.13, 5.14] to provide a simple matrix of service conditions to guide the designer. Each Use Class corresponds to a different environment in terms of exposure to water and weather. Table 5.2 presents Use Classes, corresponding representative conditions and treatment requirements for bamboo in a high beetle, termite and/or marine borer risk zone. Figure 5.4 provides examples of Use Classes visually.

Table 5.2: ‘Use classes’ and durability considerations (ISO 22156)

Use Class	Service conditions	Typical uses	Protection against biological agents			
			Fungal	Beetles	Termites	Marine borers
1	Interior, dry	Framing, pitched roof members	Not required since EMC <20%	Required where risk of beetle attack exists (common in most warm countries)	Required where risk of termite attack exists (found in all continents)	Not required; no risk
2	Interior, occasional damp (possibility of condensation)	Framing, roof members, ground floor joists, framing built into exterior walls	Required to protect against rot from occasional dampness			
3.1	Exterior, above ground protected from driving rain and UVR	Exterior elements (both horizontal and vertical) that sit **above** the 30–45° to the vertical rain and UVR shadow and do not have water traps	Required to protect against rot from occasional dampness			
3.2	Exterior, above ground not protected from driving rain and UVR	Exterior elements (both horizontal and vertical) that sit **below** the 30–45° to the vertical rain and UVR shadow	Required (but not possible to achieve 50-years)	Required where risk of beetle attack exists (common in most warm countries)	Required where risk of termite attack exists (found in all continents)	Not required; no risk
4.1	In contact with ground or placed in ground itself	Sole plates or columns at ground without damp-proof membrane, columns built into ground, piles	Required (but not possible to achieve 50-years)	Required where risk of beetle attack exists (common in most warm countries)	Required where risk of termite attack exists (found in all continents)	Not required; no risk
4.2	In ground in aggressive conditions, or in contact with fresh water	Piles, columns placed in fresh water				
5	In contact with marine or brackish water	Marine piles including splash zone, columns placed in marine water		Not generally required; water prevents attack	Not generally required; water prevents attack	Required (but not possible to achieve 50-years)

Figure 5.4: Examples of 'Use Classes'



The distinction between UC 1 and 2 may be hard to determine. The key metric is whether the bamboo remains dry throughout its life. If, for example, a designer has confidence that due to the design of the building, the purlins, valley gutter members and even elements built into solid walls will remain dry throughout their life and there is no risk of wetting, these could be classified as UC 1. For these examples, such a design would normally require confidence in the waterproof envelope design, the position of the vapour barrier (such that condensation risks are negligible) and for all parts of the member to be entirely in a well-ventilated space. Note that the waterproof membrane may inadvertently trap water that leaks in or condenses.

The distinction between UC 2 and 3.1 is primarily that UC 2 is restricted to occasional limited wetting only. Where there is a risk of moisture due to direct wind-driven rain, UC 3.1 is generally more appropriate. Where there is a risk of moisture from the ground through hygroscopic action in a concrete foundation without a damp-proof membrane, UC 3.2 or even 4 may be more appropriate.

The distinction between UC 3.1 and 3.2 may sometimes be hard to determine and depends not only on the exposure condition and detailing, but also the frequency of rainfall, the ambient temperature, the UV exposure and the ambient humidity. The key metric is how much water the bamboo is likely to absorb, how exposed it is to UV light, the risk of fissuring and whether it will be able to dry out between wetting intervals. Elements above the minimum 45° to the vertical rain and UVR shadow line are likely within UC 3.1, however in some cases this angle should be 30° to the vertical. Elements below the 45° shadow line are nearly always within UC 3.2.

Following the summary within Table 5.1, the requirements in ISO 22156 state:

- Only Use Classes 1, 2 and 3.1 are permitted for permanent bamboo structures. This is because otherwise bamboo cannot achieve a design life of 50 years.
- Use Class 3.2 is only permitted for temporary structures with a design life of less than five years.
- Use Classes 4.1, 4.2 and 5 are not permitted in the context of ISO 22156.

Although chemically-fixed preservatives such as copper improve the design life in exposed conditions, it is still difficult to achieve 50 years. Additionally, there is little precedence or test data available to support the use of fixed preservatives in aggressive environments. Regardless of what preservatives are used in Use Classes 3.2 and 4.1, because the bamboo is exposed to the sun, it is more likely to split (or fissure) under cyclic sun and rain exposure and experience UVR-caused surface deterioration.

The requirements reported here are largely identical to the design requirements for timber with little natural durability treated with boron (Table 5 of BS 8417)[5.15]. The permitted Use Classes are an effective way of ensuring that good 'durability by design' principles can be adopted by the designer.

When recommendations are followed (in particular 'durability by design' coupled with modern chemical treatment), traditional methods of improving durability, such as using more naturally durable species, harvesting at specific times of the month and water soaking, are generally not required simultaneously. However, where these form part of the local traditions or value chain, there is normally no harm in allowing them to continue. They may also be more useful in humanitarian or international development contexts, where chemical treatments are more difficult to implement. The exception is smoke or fire treatment, which is not environmentally friendly, can weaken the bamboo and be harmful to workers, and therefore is always discouraged.

Although harvesting at appropriate times of the year should not affect the long-term durability of properly-treated bamboo, it has other benefits and should also be encouraged; it improves the harvest, minimises damage to the plant and reduces the risk of beetle attack in the window between harvest and treatment.

A summary of common misconceptions on durability and treatment of bamboo is provided in Appendix A5.8.

5.6 Selecting alternative methods of providing durable bamboo structures

When selecting an appropriate method of providing durability, many aspects need to be considered (Appendix A5.3). Two of the most important are the efficacy and health and safety considerations of treatment methods intended to achieve durability. Although there are a wide variety of traditional and modern methods used and promoted globally to enhance durability of bamboo, many do not sufficiently address these considerations. Alternative methods of treatment are described in greater detail in Appendix A5.5.

Efficacy is an unbiased scientific assessment of how effective a method of improving durability of bamboo in structures really is. Anecdotal evidence is generally inadequate to provide efficacy, since actual efficacy of a method depends on a range of different factors, many of which may not be immediately obvious. When reviewing any new preservation method of bamboo for efficacy, remember:

- To conduct impartial inspections of treated bamboo after multiple years of use (5, 10, 15, 20, etc.), observing the condition of the bamboo and aggressiveness of exposure to sun, water and insects. Inspections should be conducted by an appropriately-experienced person[5.16, 5.17].
- There should be a large sample size of treated bamboo in different exposure conditions and different communities.
- There already exists significant traditional knowledge on how to marginally improve the durability of bamboo. Modern formal construction, however, requires preservation methods which provide reliable efficacy for 50+ years.

Safety to human and animal health of the preservative used should be carefully considered for all stages of the building's life, especially in regions where regulations are lacking or not rigorously adhered to. Safety is covered in more detail in Appendix A5.4.

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Appendices

A5.1 Biological attack mechanisms

A5.1.1 Fungal attack (rot)

Rot is caused by fungal attack. For fungi to survive, the bamboo needs to be relatively wet with at least 20% moisture content, which means that the bamboo must be exposed to rain or ground moisture for a period of time, without being allowed to dry[A5.1] (Figure A5.1).

Figure A5.1: Examples of fungal rot of bamboo

a) Rotten bamboo columns exposed to driving rain

b) Rotten bamboo chord of a bridge, where a bolt hole allowed driving rain to enter; use of mortar infill and surround helped to maintain a moisture-laden environment

c) Rotten timber and bamboo inside a wall (water trap)

d) Rotten bamboo where a beam was exposed and collected water

e) Dampness to external wall of modern bamboo house lacking a roof overhang

f) Rot to internal bamboo frame of modern bamboo house lacking an upstand and damp-proof membrane; extent of damp region is evident from discolouration

Bamboo is particularly vulnerable when exposed to water in the ground, driving rain, leaks in roofs or water traps in buildings. Warm tropical climates with high rainfall provide the harshest conditions, however, rot can still easily occur in cold temperate areas, e.g., due to condensation.

Rot is not always immediately evident as it is more likely to occur in hidden areas (which are poorly ventilated and therefore stay wet). Additionally, the fruiting bodies of fungi are not always visible. Evidence of severe rot includes a change in sound if the bamboo is tapped, a softening of the culm or a change in colour and texture of the fibres when drilled[A5.2, A5.3]. Rot is often an underestimated risk to bamboo buildings because it is not always obvious and may take years to manifest.

Since rot requires oxygen in addition to water, when bamboo is fully submerged or in an otherwise oxygen-free (anaerobic) environment, it will not rot. In practice, this scenario is rare, as water and/or soil normally contain sufficient oxygen to allow fungal attack. For these reasons, bamboo piles, for instance, will have a limited useable life.

More information on different types of fungi is provided in BS EN 335[A5.4].

A5.1.2 Insect attack

The prevalence of individual insect species varies according to country, climate, soil, temperature and altitude, among other factors[A5.5]. Unless it is categorically known from specialists that insects which attack bamboo do not live in a specific region or cannot survive there, it must be assumed that there is an insect risk (i.e., it is not adequate simply to assume that just because locally no insects have been seen, they do not survive there). If national standards do not specify the risk of insect attack, local or national experts should be consulted for advice on risk and nature of insect attack. The impacts of climate change should also be considered. Warmer, wetter summers and progressively shallower ground frost depths, for example, are resulting in termites surviving in more northerly climates where they were previously unknown. Past experience may not be an accurate indication of future risk.

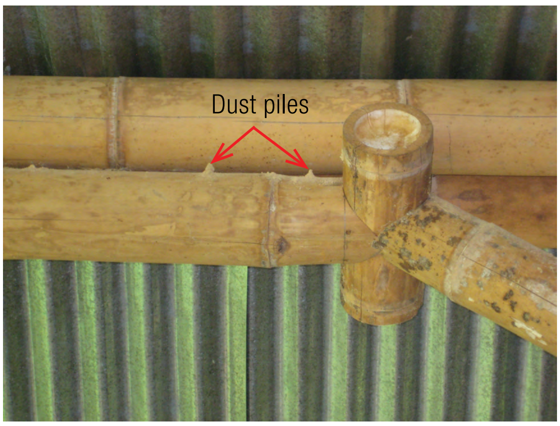
The main types of insects that attack bamboo are beetles and termites. In addition, there are other types of insects that can damage bamboo, such as carpenter ants; however, their damage is normally not as significant and the same principles of prevention apply.

A5.1.2.1 Beetle attack

Certain beetles are attracted to the starch in bamboo and lay their eggs inside the culm wall. Upon hatching, the larvae eat the soft and less dense cell-tissue inside the culm wall and eventually through the culm walls to escape, leaving small round or oval exit holes (approximately 1–6mm diameter)[A5.2] (Figure A5.2a). These may be accompanied by small piles of dust of a similar colour to the bamboo (Figure A5.2b). Bamboo which is young (immature), green or exposed to high humidity appears to experience greatest beetle attack. However, even mature and dry bamboo in air conditioned environments can be attacked by some species. Bamboo species with higher levels of starch such as *Bambusa vulgaris* have reportedly greater occurrences of beetle attack. There are many different types of beetles worldwide that can attack bamboo[A5.2]; most are found in warm climates. However, since the method of protecting against beetles remains the same, there is generally no need to distinguish between them.

Figure A5.2: Beetle attack on bamboo

a) Beetle exit holes visible on side of bamboo



b) Beetle damage to bamboo beam, with dust from exit holes visible

A5.1.2.2 Termite attack

Termites are small ant-like insects which live in colonies and feed on plant material (Figure A5.3). Termites are also attracted to the starch in bamboo but, unlike beetles, they have enzymes which enable them to break down cellulose[A5.6]. Living in large colonies, they can cause significant and rapid damage. Termite attack is characterised by longitudinal tunnels (known as 'galleries') inside the bamboo.

There are three generic types of termites: subterranean, drywood and dampwood. Subterranean termites live in large colonies in the (preferably damp) ground and connect their nests to food sources (i.e., bamboo) via mud tunnels, which provide protection against sunlight and predators. Drywood termites live in dry bamboo, and do not require a pathway to the soil. Drywood termites can fly and live in generally smaller colonies. Dampwood termites live in damp wood/bamboo, so they are rarely found in bamboo buildings which, under normal service conditions, should typically not be damp. Subterranean termites normally cause the most damage to timber and bamboo structures because of their large colony size[A5.7].

Termites are found on all continents (except Antarctica) and prefer warmer, wetter climates. In tropical countries attacks appear to be worse when humidity and temperatures are high (i.e., during the wet season). Evidence of termite attack is a hollow sound when the bamboo is tapped, as termites eat the inside of the culm wall, leaving the thin protective, harder and highly fibrous cortex/outer wall. Evidence of subterranean termites includes external termite shelter tubes, while evidence of drywood termites is frass (termite droppings) which are normally dark in colour.

Figure A5.3: Significant termite damage to bamboo columns

A5.1.3 Marine borers

Marine borers are invertebrates which thrive in a certain salinity of water. Borers 'hollow out' extensive tunnels and cavities in timber and bamboo. Unless confirmed otherwise, it should be assumed that marine environments have a risk of marine borers.

A5.2 Design life

Although not specifically stated, ISO 22156 infers a specified minimum design life of 50 years for permanent bamboo structures. This follows BS EN 1990[A5.8] and most major international standards for mainstream building materials: steel, reinforced concrete, masonry and timber. It is worth stressing that the requirements described in this document and required by ISO 22156 for achieving a minimum design life would be largely identical if the intended design life were reduced to say 15 years — essentially, treatment that is effective for 15 years is likely to be effective for 50. This is best illustrated in Table 5 of BS 8417[A5.9], which provides identical recommendations for design and treatment of timber using boron for service lives of 15, 30 and 60 years. Performance in bamboo is not expected to differ substantially.

Bamboo is often proposed in humanitarian and developing world contexts by donors, designers and implementing agencies, sometimes for temporary solutions that — intended or not — become permanent. In these contexts, there is often a common belief by designers that the end-user or beneficiary will replace key structural elements if/when they fail. However, in many cases this will not be the case because:

- The end-user may not have been informed clearly.
- The end-user may forget or not be aware of the importance of this, or they may move out and someone else occupies the building.
- The end-user may not have the technical expertise to identify when a structural element needs replacing.
- The end-user may not have the resources or the technical expertise to carry out the replacement.
- The replacement of key structural elements may be challenging, owing to the design not adequately accounting for this scenario.
- The end-user may have accepted the use of bamboo, or in some cases even personally contributed financially to the building, on the understanding that the building would have a design life equal to 'next door's masonry house', which is usually 50 years.

For these reasons, in humanitarian and developing world contexts, the recommended minimum design life for 'permanent' bamboo structures is 50 years, which is easily achievable with proper design and construction. The exceptions to this are humanitarian emergencies, transitional buildings constructed as part of properly-managed reconstruction programmes or construction programmes utilising regional vernacular systems, with which the end-user is already familiar.

A5.3 Selecting appropriate methods to provide durability

When selecting appropriate ways to improve durability of bamboo, it is important to consider:

- Availability of treatment chemicals and facilities.
- Quantity of bamboo to be treated.
- Species of bamboo; some species are more readily treatable than others.
- Intended exposure to the elements (Use Class) of the bamboo.
- Country-specific legislation, particularly associated with environmental health and safety.
- Transport time from harvest location to treatment facility; some treatment methods require freshly-cut bamboo.
- Efficacy of the treatment type or chemical and application method (Section 5.4).
- Ease of applying the treatment.
- Whether the chemical affects the structure of the bamboo or metal fastenings.
- Toxicity of the chemical to humans and animals in both the form in which it is applied and in its final fixed state (Appendix A5.4).
- Toxicity of the chemical as it pertains to residual quantities, leaching, combustion hazards and end-of-life of the structure (Appendix A5.4).
- Whether the full-culm wall thickness of the bamboo is effectively treated.
- Impact on harvesting and productivity of bamboo clump.
- Project budget.

A5.4 Health and safety considerations of preservation methods

The safety of the preservative in terms of human and animal health should be carefully considered for all stages of the building, especially in countries where health and safety regulations are lacking or are not rigorously adhered to (Sections A5.4.1–A5.4.4). Regardless of treatment, respiratory personal protective equipment (PPE) is required when cutting bamboo using power tools. Bamboo sawdust is finer than wood sawdust and presents an inhalation hazard.

A5.4.1 During treatment

- Is the treatment facility following good practices for the health and safety of its workers? Workers should use appropriate PPE.
- How will the by-products of the treatment process be disposed of safely?

A5.4.2 During construction of building

- Workers should use appropriate PPE (e.g., to prevent breathing in dust from cutting the treated bamboo).
- How will offcuts be safely disposed of? In humanitarian and developing world projects there may be a risk that the treated bamboo will be used as domestic fuel at its end-of-life.

A5.4.3 During life of building

- Is the treatment suitable for the intended use? Some treatments can leach out of the bamboo and are not suitable for use where contact with humans, animals or food is possible.
- Does the treatment comply with the local volatile organic compounds (VOC) emissions regulations?

A5.4.4 At building end-of-life

- How will treated bamboo be safely disposed of? Many treatments prevent the bamboo from being recycled or composted at end-of-life.
- Burning of treated bamboo can release harmful gases and should only be carried out at an approved incinerator. In humanitarian projects and/or projects in low- and middle-income countries, there may be a risk that the bamboo will be used as domestic fuel at its end-of-life.

A5.5 Methods of providing durable bamboo structures

Various methods of providing durability of bamboo in structures can be:

- Using more naturally durable species.
- Selecting mature bamboo.
- Harvesting at appropriate times.
- Traditional methods of reducing sugar content.
- Smoke or fire treatment.
- Other traditional methods of preservation.
- Surface coatings.
- Seasoning (drying) (Section 5.4.1).
- Modern chemical treatments: boron-based (Section 5.4.2.1).
- Modern chemical treatments: chemically-fixed (Section 5.4.2.2).
- Modern chemical treatments: others including bio-based alternatives.
- Durability by design (Section 5.4.3).

A5.5.1 Using more naturally durable species

All species of bamboo should be considered highly susceptible to rot, termite and beetle attack.

Minor variations in natural durability do appear between species[A5.10] in particular for beetle attack, but less so for termite attack and rot. However, modern chemical treatments can effectively bring all bamboo species up to the same level of durability, and therefore negate the need to select a specific bamboo species which may anecdotally exhibit slightly greater natural resistance to, say, beetles. In addition, proper identification of bamboo in the wild can be difficult even for specialist botanists. At times, communities may be mixing species or grouping similar species under a single local name.

The exceptions to this are:

- When chemical treatments are unavailable (for example, in a humanitarian or international development context).
- Where there is a higher risk of beetle attack in the window between harvesting and chemical treatment. This is when beetle attack is greatest, as the bamboo is still green, and therefore there are some benefits in avoiding species such as *Bambusa vulgaris,* which has higher starch levels and, therefore, experiences particularly acute beetle attack.

A5.5.2 Selecting mature bamboo

Although maturity does affect durability, even mature bamboo should still be considered highly susceptible to insect attack, rot and marine borers.

A5.5.3 Harvesting at appropriate times

Although harvest times affect durability, even optimally-harvested bamboo can still be susceptible to beetle attack and remains highly susceptible to termite attack, rot and marine borers. In some countries, bamboo is harvested at very specific times of the month (and even day), typically associated with harvesting when the water content is at its lowest.

Although some studies have shown the starch content to vary even over these short durations, the variation is unlikely to have a significant effect on the durability of the bamboo.

A5.5.4 Traditional methods of reducing sugar content

There are several traditional methods of reducing sugar content in bamboo, such as soaking in water and clump curing. These reduce (but do not eliminate) the risk of beetle attack, and have no significant effect on termite or fungal attack[A5.10, A5.11]. They have limited efficacy, so are not recommended except in humanitarian emergencies when chemical treatment is not available, or where the time between harvesting and chemical treatment is significant enough that there is a high risk of beetle attack prior to treatment.

A5.5.5 Smoke or fire treatment

Smoke or fire treatment involves exposing bamboo to fire or smoke for a period ranging from 30 minutes to several hours. This method may provide some protection, however its efficacy is questionable. The elevated temperature may damage and weaken the bamboo fibres[A5.10, A5.11]. In addition, it is not environmentally friendly and can be harmful to workers. Smoke and fire treatment are not recommended for these reasons in any scenario.

A5.5.6 Other traditional methods

Other traditional methods exist that may anecdotally provide some protection to bamboo. However, these have limited or unproven efficacy, and some 'natural chemicals' can be dangerous to humans[A5.11].

A5.5.7 Surface coatings

Surface coating such as paint, varnish, coal tar, bitumen and used engine oil can reduce the amount of water absorbed or provide a thin toxic outer protective barrier. However, they only provide partial protection against water to the culm exterior and are largely ineffective against insect and fungal attack on the culm interior. None are therefore considered effective methods of protection by themselves. Many also have other disadvantages such as toxicity or requiring frequent reapplication[A5.11]. In general, paints and varnishes should not be considered to protect against water ingress or biological organisms, although they may offer some protection against bleaching caused by UVR.

A5.5.8 Modern chemical treatments: others including bio-based alternatives

There are many other modern preservatives such as copper sulphate, copper-chrome arsenic (CCA), copper-chrome boron (CCB), creosote, Dursban® and sodium pentachlorophenate. While some of these can be effective, most are either expensive, difficult to apply or carry significant health risks during application and at end-of-life[A5.11]. Many of these treatments are banned or only permitted for heavy industry in many jurisdictions.

More recently, some modern 'bio-based' or 'sustainable' methods that provide some protection to bamboo have been proposed[A5.12]. However, these have had limited or unproven efficacy and some can be dangerous to humans.

A5.5.9 Summary

When combining all the different methods of providing durable bamboo structures, even bamboo from the most supposedly naturally durable species, which is harvested mature and at the optimal time of the year, has had its sugar content reduced by leaching, and is properly seasoned, may still be vulnerable to beetle attack (albeit reduced), and is still vulnerable to termite and rot attack. While the combination of all these traditional methods certainly helps, it does not eliminate the risk. Therefore, durability by design and modern methods of preservation are always required. The exception is in humanitarian and development contexts where chemical treatments such as boron are not available, and therefore the only alternative is the combination of these traditional methods to reduce (but not eliminate) the risk.

For modern methods of preservation, boron is generally the most appropriate chemical with which to treat bamboo and works very well in conjunction with durability by design. Unfortunately, at the time of publication, there are no known safe chemicals that can protect bamboo in conditions exposed to rain or water, and therefore durability by design is always required.

A summary is provided in Table A5.1.

Table A5.1: Minimum recommendations for durable bamboo structures

Context	Minimum recommendations	Result
Humanitarian or international development context: temporary or transitional buildings, with accepted limited design life, and boron (or similar safe and effective chemical) is either unavailable or too expensive.	• Use more naturally durable species. • Select mature bamboo. • Harvest at optimal times. • Reduce starch by water soaking. • Season (dry) the bamboo. • Implement rigorous 'durability by design'.	• Beetle attack risk reduced but still present. • Termite attack risk high. • Rot risk low. Design life could be 2–15 years, depending on prevalence of termites and beetles.
All other contexts.	• Select mature bamboo. • Harvest at optimal times. • Treat with boron or similar safe and effective chemical. • Season (dry) the bamboo. • Implement rigorous 'durability by design'.	• Beetle attack risk controlled. • Termite attack risk controlled. • Rot risk controlled. Design life 50+ years.

A5.6 Additional treatment considerations

General additional items to consider when treating bamboo are:

- Pre-dimensioning: in most established supply chains, bamboo is preservative-treated to standard lengths. This results in disposing of treated off-cuts, which is wasteful. An alternative is to treat elements that match the sizes to be used on-site. Where possible, this alternative should be explored.
- Longitudinal perforation: wherever bamboo is preservative-treated through immersion in a solution, it is necessary to perforate the internodes. There are two common ways: to perforate the culm walls (typically with a power-drill) or to perforate the diaphragm (typically with a sharpened piece of rebar). The latter is preferable as it is less likely to induce cracks during drying, however it may slightly reduce the diaphragm strength.
- Starch removal: an uncommon practice, but one that may be worth considering, is to place freshly-cut bamboo in running water prior to preservation to remove as much starch as possible. This prevents early insect infestation and reduces the need to replace the preservative solution as frequently.

A5.7 Boron treatment

A5.7.1 Introduction

Bamboo can be treated with boron in a number of different ways[A5.10, A5.13]. All commonly-used methods allow boron to diffuse through the walls of the culm, with the aim of treating the entire thickness of the culm walls. All boron compounds are soluble in water and will therefore leach out when exposed to rain. It is not currently possible to fully chemically-fix boron into the bamboo.

There are several boron-containing compounds which can all be used for treating bamboo. These compounds are slightly different in their ease of use, but they are all broadly equally effective and can be used interchangeably with the different methods of treatment. The compounds are normally available as fertilisers:

- Disodium octoborate tetrahydrate ($Na_2B_8O_{13}\cdot 4H_2O$) (also known as DOT) comes as a single ready-to-use compound. It is the most readily water-soluble of the boron-containing compounds. Trade names include 'Borosol®' and 'Solubor®'.
- Borax ($Na_2[B_4O_5(OH)_4]\cdot 8H_2O$) and boric acid ($H_3BO_3$) are two boron-containing compounds used together, since they are only soluble in water when mixed. A general rule for quantities is 3kg borax + 2kg boric acid, per 45 litres of water[A5.14].

In order to be effective, it is recommended to add boron to water so the concentration reaches 10–12% (typically achieved through the ratio previously described), although lower concentrations will still probably have some effect[A5.10].

It is recommended to treat bamboo with boron via the methods given in Section A5.7.2 while it is still fresh — usually 7–14 days after cutting. If bamboo which is less fresh is treated, the treatment methods are still likely to be relatively effective, but it is harder for the boron to diffuse through the full thickness of the culm wall.

The water used for boron treatment should be clean fresh water. Salt water may interfere with the solubility of the boron. If there is a demand to use salt water for boron treatment, it is recommended that a laboratory boron solubility test be conducted, to determine the extent to which the salt interferes with the boron solubility, and whether this is acceptable (i.e., whether enough boron dissolves for the treatment method to be effective).

The prepared boron solution can be reused in all the methods, however, over time, the liquid will become contaminated with dirt and sap, which may affect the hydrometer reading (a hydrometer measures the relative density of liquids and can be used to determine the concentration of boron in the solution), and may interfere with the efficacy of the treatment. The liquid should therefore be periodically cleaned by:

- Filtering through a fine filter to remove dirt.
- Coagulating the sap and then removing and disposing of it safely[A5.15].

A5.7.2 Common methods of treating bamboo with boron

- Cold water bath: This method involves placing the bamboo in an unheated water bath for 10–14 days, during which time the boron diffuses through the bamboo walls. After treatment, some diffusion continues. It is a 'low tech' method and therefore the least likely to go wrong and the easiest to replicate. However, it is slow. This is the most common method used around the world.
- Vertical soak diffusion (VSD): This method involves treating the culms by placing them upright, filling the inside with the boron-containing liquid and leaving them for 10–14 days, during which time the boron diffuses through the bamboo walls[A5.14]. After treatment, some diffusion continues. This method is similar in effectiveness to the cold water bath, however has the potential for a slightly higher output rate since it is not limited by bath size or number although the method is a little more complex. The VSD method can only be conducted on large-diameter culms, and if the bamboo arrives cracked through the full thickness, the liquid will leak and therefore this method will not work. This method is popular in Indonesia.
- Hot water bath: This method is identical to the cold water bath, however by heating the liquid to approximately 50°C, the boron diffuses much faster and therefore the treatment duration can be reduced considerably, to around eight hours. This is more 'high tech' than the cold water or VSD method, and therefore more costly to construct, operate and maintain and is more likely to go wrong. However it is fast and likely to be more effective when conducted properly. This method is often used in Colombia.
- Modified *boucherie*: This method involves displacing the sap inside the culm with a pump from one end and filling the culm with boron solution under pressure. It is more complex and requires the culm to be treated within 24 hours of harvesting (otherwise the cell walls close), however it can be conducted relatively quickly (about 30 minutes). This method is popular in Costa Rica. It has the added advantage that the diaphragm is not ruptured.

Different organisations and countries have experience of each of these methods. More information is available[A5.10, A5.11, A5.14].

A5.7.3 Disposal of boron-based treatment liquid

In high concentrations, boron can cause health problems in humans and can damage plants. However, in low concentrations boron is an essential plant mineral and used routinely as a fertiliser. Waste boron liquid must, therefore, be disposed of properly — it cannot simply be poured into soil, river or sea. This is particularly important in contexts where potable water is obtained from surface water or nearby wells. Possible safe disposal methods include selling boron waste liquid to farmers for fertilisers, and disposal in managed reed beds.

A5.7.4 Testing for efficacy of boron treatments

For boron treatment to be effective, it must have penetrated the full thickness of the culm and be present in sufficient quantities through the entire culm wall thickness.

Several methods having varying complexity are available to determine this efficacy; these are presented in Table A5.2, and Sections A5.7.4.1–A5.7.4.3 describe these methods in more detail. Efficacy tests should be conducted first to establish and confirm an appropriate and functioning treatment protocol, and secondly to ensure quality assurance of that protocol once it has been established. Efficacy tests should be undertaken at an appropriate frequency and of an appropriate number to detect any likely variability. A typical protocol for setting up and monitoring a new treatment facility might be:

- Stage 1: Experimentation phase. Multiple laboratory tests (Method C) conducted at various times to explore variances in the treatment protocol and identify the best method.
- Stage 2: Confirmation of protocol. 10x laboratory tests (Method C) + 10x turmeric reagent (Method A) conducted of final protocol to confirm efficacy and calibrate the turmeric reagent test to the lab test.
- Stage 3: Production:
  - First two months: 2x turmeric reagent test (Method A) per batch + 2x laboratory test (Method C) every month.
  - Next four months: 5x turmeric reagent test (Method A) per month + 2x laboratory test (Method C) every two months.
  - Post six months: 5x turmeric reagent test (Method A) + 2x laboratory test (Method C) every two–three months.

Table A5.2: Summary of different methods to determine efficacy of boron treatment in bamboo

Method	Results provided	Advantages	Requirements
A: 'Turmeric reagent' method.	• Approximate qualitative visual representation of boron present. • Useful for periodically checking indicative quality assurance of a treatment facility. • Does not provide actual retention of boron.	• Quick. • Relatively easy to perform.	• Equipment and chemicals of the complexity that can be found in most high/secondary schools.
B: 'Weight before and after treatment' method.	• Retention of boron in a specific sample.	• Quick. • Relatively easy to perform.	• Concentration of treatment liquid to be accurately known. • Change in weight of the sample to be accurately known. • Any precision weighing scale is adequate.
C: Laboratory methods.	• Retention of boron in a specific sample.	• Can be carried out on a dry sample. • Most accurate.	• Specialist lab (although many universities and private labs should have these facilities).

A5.7.4.1 Method A: 'Turmeric reagent' method

The following method is proposed in the *Bamboo Preservation Compendium*[A5.10]. This method can be conducted in many high school laboratories. It only gives an approximate qualitative visual representation of the amount of boron present, and does not provide an indication of the retention of the active chemical — other methods are required for this.

a) Reagents

Solution 1: Mix 10g turmeric powder with 90ml ethyl alcohol. Decant or filter to obtain clear solution

Solution 2: Dilute 20ml of concentrated hydrochloric acid in 100ml with ethyl alcohol and then saturate with salicylic acid (approximately 13g per 100ml)

b) Sample

Cut the bamboo through the entire section using a clean fine-toothed saw blade. A smooth surface shows the results of the spot test better than a rough surface. The surface must be dry and clean.

c) Method

Solution 1 is applied preferably by spraying or with a dropper to the cut face of the section. The surface is then allowed to dry for about 10 minutes. Solution 2 is then applied in a similar manner to the area that has been coloured yellow by the application of Solution 1. The colour-changes should be observed carefully and will appear a few minutes following application of the second solution. In the presence of boron, the yellow colour of Solution 1 is turned red (Figure A5.4). After reagent application, placing the bamboo in a warm oven accelerates and intensifies the colour reaction to differentiate between treated and untreated regions better.

Depending on the quantity of boron present in the culm wall, a grade of 0–4 can be assigned to each sample: e.g., 0 = no penetration; 1 = 0–25% penetration; 2 = 25–50% penetration; 3 = 50–75% penetration; 4 = greater than 75% penetration[A5.15]. Examples of penetration grades for boron are shown in Figure A5.4. The left sample is an untested boron-treated culm. Degrees of boron penetration are shown (there were no Grade 1 samples in this study). Colours are indicative and may vary slightly between species and exact boron compound[A5.16].

Figure A5.4: Boron-treated bamboo tested with the simple method

A5.7.4.2 Method B: 'Weight before and after treatment' method

The simplest method to calculate boron retention is to weigh some bamboo samples before and after treatment[A5.17]. This measures the amount of treatment liquid absorbed by the bamboo, and if the concentration of the bamboo salt is known, will enable the theoretical concentration of the boron salt in the bamboo to be calculated using Equation A5.1:

$$Retention,(kg/m^3) = \frac{wet\ treated\ weight - initial\ weight * c}{v} * 10 \qquad \text{Equation A5.1}$$

Where:

C = grams of boron salt compound in 100g of treating solution.
V = volume of sample in cm^3.

The wet treated weight must be the weight immediately after treatment and before drying, although allowing the loose water to drip off. The treated sample used is typically a small sample of a culm, however in theory an entire culm could be checked in the same way (although determining its net volume accurately may be challenging).

The retention generally needs to be converted into boric acid equivalent (BAE) (Section A5.7.5).

When the concentration of the treating solution or the change in weight of the bamboo as a result of the treatment is not known, other analytical methods should be used to determine retention.

A5.7.4.3 Method C: Laboratory methods

Laboratory methods are the most complex but can accurately determine the concentration of boron in dry bamboo, and no prior measurements of the solution or weight are required.

The results are generally converted from ppm boron in the bamboo sample to boric acid equivalent (BAE) retention in kg/m^3. Sometimes they are presented as a wt% boron in bamboo, which can be converted to BAE in kg/m^3 by multiplying by the bamboo density. However, they could be given as the retention of a different boron-containing salt that was used in the treatment. Care needs to be taken in ensuring the units are understood.

a) Boron extraction

The first step is to extract the boron salt from the bamboo. If a method is given in a national standard this should be used. However, this may not always be the case, and a generic method can be used. DD 257-1[A5.18] gives an extraction method for use with titrimetric and colorimetric quantitative analysis methods. The boron compounds in this method are extracted from the treated timber or bamboo by boiling with hydrochloric acid under reflux.

A sawdust sample is normally required. How to create such a sample that is representative of the variation in concentration through the thickness of a piece of treated timber is described in BS EN 212[A5.19]. A uniform-width saw cut is made through the section and the sawdust collected.

In one study, researchers[A5.20] used hot water extraction for three hours on small (2g) samples of wood milled to pass through a 50 mesh (300μm sieve openings with 0.2mm diameter wires) to provide aqueous samples for chromatographic analysis. It is likely that there are numerous variations in sample preparation and boron extraction between standards.

b) Boron concentration measurement

Boron concentration can be measured by spectroscopic or wet titration methods according to American Wood Protection Association standards. While the titration method is more accurate[A5.21], it is not practical for large batches and cannot be used at low concentrations or to determine preservative distribution over a small area[A5.22]. Wet chemistry methods[A5.21, A5.23] are much slower than the spectroscopic method[A5.24]. All provide an accurate indication of the retention of boron, and any can be used.

Other national standards exist for methods based on the same principles, including in Australia, Japan and New Zealand.

c) Comparison of different methods

These wood analysis methods are essentially the same as those used in boron analysis of plant tissues in the agricultural sector, quantification of levels in water, fertiliser, etc. As a result, many university and private laboratories working in these sectors could run these analyses.

Methods using titration with sodium hydroxide have been described as 'tedious and lengthy'[A5.22].

A5.7.5 Boric acid equivalent (BAE)

There are many salts of boron used to treat bamboo. As each salt has a different proportion of boron, the retention level of boron needs to be converted into boric acid equivalent (BAE), which is the amount of boric acid that contains the same amount of boron retained by the bamboo. This allows a fair comparison to be made between treatment chemicals and methods.

To convert to BAE retention in kg/m^3:

- Calculate the mass of boron in the treatment used (= retention *[mass of boron/molecular mass of the treatment compound]).
- Calculate the mass of boric acid that would contain this much boron (= mass of boron in the bamboo/proportion of boron in boric acid).

Table A5.3 shows the proportion of boron in some common treatment compounds, and the conversion factor by which to multiply the retention to convert to BAE. These values are calculated using the atomic mass of the elements in each compound.

Table A5.3: Conversion factors to BAE for common boron treatments

	Molecular formula	B	O	Na	H	K	N	Molecular mass	Proportion of boron	Conversion to BAE
	Atomic weight	**10.81**	**15.99**	**22.99**	**1.01**	**39.10**	**14.00**			
Boric oxide	B_2O_3	2	3					69.6	0.311	1.776
Sodium tetraborate decahydrate (Borax)	$Na_2B_4O_7.10H_2O$	4	17	2	20			361.2	0.120	0.685
Sodium tetraborate pentahydrate (trade name: Neobor®)	$Na_2B_4O_7.5H_2O$	4	12	2	10			291.3	0.148	0.849
Boric acid	H_3BO_3	1	3		3			61.8	0.175	1.000
Sodium metaborate octahydrate	$Na_2B_2O_4.8H_2O$	2	12	2	16			275.7	0.078	0.449
Sodium metaborate tetrahydrate	$Na_2B_2O_4.4H_2O$	2	8	2	8			203.7	0.106	0.607
Sodium perborate tetrahydrate	$NaBO_3.4H_2O$	1	7	1	8			153.9	0.070	0.402
Potassium tetraborate tetrahydrate	$B_4K_2O_7.4H_2O$	4	11		8	2		305.5	0.142	0.810
Potassium pentaborate octahydrate	$B_{10}K_2O_{16} \cdot 8H_2O$	10	24		16	2		586.4	0.184	1.054
Ammonium biborate tetrahydrate	$(NH_4)_2B_4O_7 \cdot 4H_2O$	4	11		16		2	263.4	0.164	0.939
Ammonium pentaborate	$(NH_4)B_5O_8 \cdot 4H_2O$	5	12		12		1	272.2	0.199	1.136
Disodium octaborate tetrahydrate	$Na_2B_8O_{13}{\cdot}4H_2O$	8	17	2	8			412.5	0.210	1.199

A5.7.5.1 Minimum retention levels of BAE and durability

There is little published information providing minimum BAE retention levels in bamboo to ensure durability. It is likely that different species will require different BAE retention levels to remain effective. The following guidance for timber provides a reasonable starting point for bamboo:

- 1.8kg/m^3 BAE is required in the UK to protect against beetles (non-termite risk)[A5.25].
- 2.7kg/m^3 BAE is commonly used in the US to give protection against beetles and some native termites[A5.25].
- At least 4.5kg/m^3 BAE is commonly recommended commercially worldwide to protect against most beetles and native termites[A5.25, A5.26]. This is also supported by the Indian Standard IS 9096[A5.27], which specifies a minimum absorption of preservatives of 5kg/m^3 for green structural bamboo treated with boric acid + borax, which when converted to BAE gives 4.1kg/m^3.
- Some termites such as the Formosan termite have been reported[A5.26] to require over 6kg/m^3.

As a point of reference, the Brazilian *P. edulis* bamboo represented in Figure A5.4 was immersed in an 8% DOT solution for seven days. The average boron penetration was determined to be Grade 3 (50–75%) and the retention, determined to be 2.2kg/m^3 of DOT[A5.16], which equates to 2.6kg/m^3 BAE.

A5.7.5.2 Long-term durability

Note that boron will be washed out if exposed to water, including driving rain, and so effective treatment with boron requires the bamboo to be kept dry at all times. Overhanging eaves are typically not enough — the base of the bamboo wall or column needs to be protected with a waterproof treatment such as a plastic sheeting or render. Paint is only partially and temporarily effective as it breaks down when exposed to UVR and cracks, leading to water ingress.

A5.8 Common misconceptions about bamboo durability

This is a summary of the most common misconceptions regarding durability of bamboo:

- *Painting bamboo with coal tar/bitumen/used engine oil is effective against insects and rot.* This method is ineffective against preventing insects and rot — the toxic chemicals provide only a thin layer on the outside of the bamboo; the interior remains largely unprotected.
- *Casting bamboo into concrete is effective against insects and rot*. This method is ineffective against preventing insects and rot — concrete is porous and termites can still enter[A5.28]. The concrete also prevents the bamboo from ‘breathing’, often leading to rot. The interface where the bamboo exits the concrete can be particularly susceptible to standing water.
- *Once bamboo is treated with boron, it can be exposed to rain.* Boron-treated bamboo cannot be exposed to rain because the boron is washed out over time.
- *Only a small roof overhang is required to protect bamboo from rain.* Rain in the tropics does not fall vertically — with wind it can quickly soak a wall protected by only a small overhang. Splashback from water falling from the roof and hitting the ground can also dampen the base of the wall. All material below at least the 45° to the vertical rain shadow of the eaves should be considered exposed to rain and UVR.
- *The species of bamboo greatly affects its durability.* It is a common misconception that natural durability of bamboo varies significantly between species. It is likely that this originates due to the real and visible difference in observed beetle attack of different bamboos, due to their differing starch content, especially shortly after harvest when the bamboo is most vulnerable. In practice however, even the most supposedly ‘naturally durable’ species of bamboo are susceptible to beetle attack, and the termite and rot resistance is not considered to vary significantly between species. This focus on early beetle attack is likely to have led to this misconception.
- *Natural durability combined with traditional methods is adequate*. Some traditional and modern treatment methods are claimed to be very effective, however those making the claims tend to be the vendors of these materials. The most reliable reviewer of the efficacy of a treatment method is the end-user. A comprehensive study of bamboo housing in India[A5.29] confirmed that community knowledge of durability and the efficacy of different traditional methods was extensive. The study also found that treatment facility workers and vendors had an unrealistically positive view of the efficacy of their methods.

The root causes of these durability issues have been observed to be:

- Misconceptions of the various attack mechanisms of bamboo and of the efficacy of preservation treatments.
- The desire for externally-exposed bamboo for aesthetics.
- Lack of standards and guidance for designing durable bamboo buildings.

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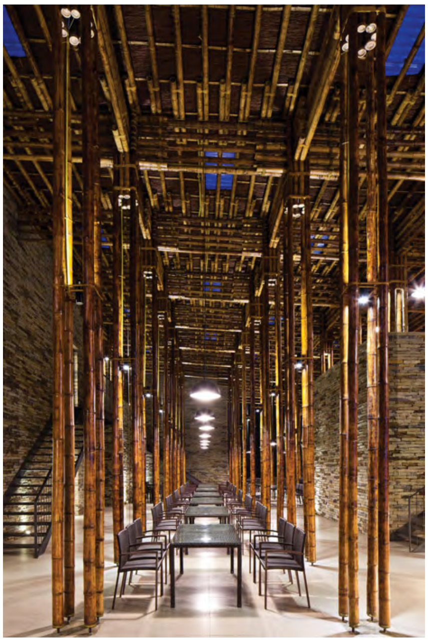
6 Design of full-culm bamboo members

Bamboo culms and assemblies of culms are highly effective compression members, so work well as columns, props and arches (Figure 6.1). Culms and assemblies of culms are also regularly used for carrying bending loads — most often when supporting floor systems (Figure 6.2). Bamboo culms are also used as both compression and tension members in trusses and braced-frame structures, although these latter applications can be more challenging. This chapter discusses the design of bamboo members for axial and flexural-induced loading, corresponding to ISO 22156, Clauses 9 and 8, respectively[6.1].

Figure 6.1: Multiple-culm bamboo compression elements

a) Four-culm corner column supporting perpendicular roof truss and rafter

b) Compression members (main arch, arch ribs and roof supports)



c) 'Columns' comprised of four single-culm compression members

Figure 6.2: Two-storey home with multiple-culm beams and columns

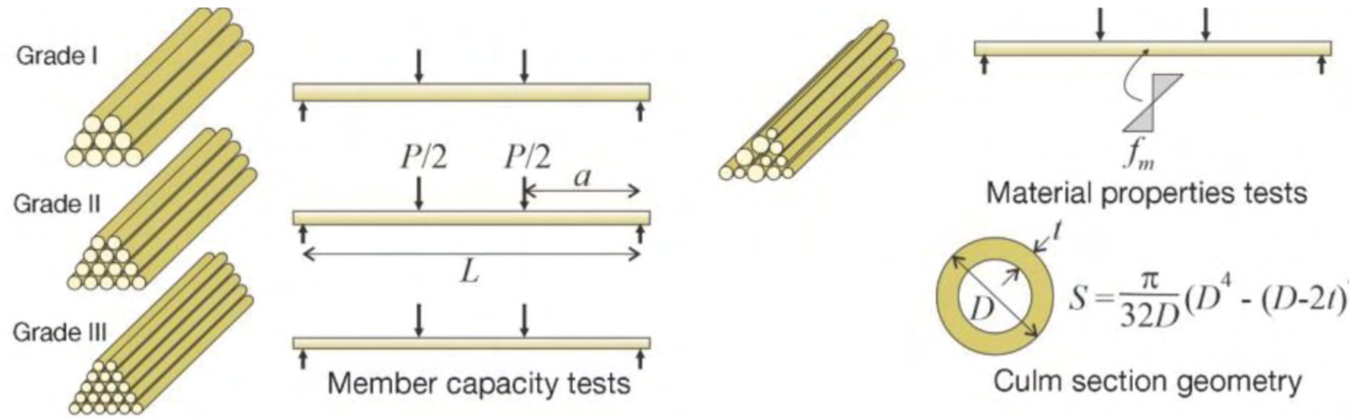
6.1 Capacity and strength design approaches

The nature of full-culm bamboo construction and the inherent natural variation of both geometric and material properties make full-culm bamboo uniquely suited to an allowable load-bearing 'capacity-based' design approach (ACD) rather than (or in addition to) an allowable stress-based 'strength' design approach (ASD). Allowable capacity is determined at the member level and may be related to component grades — effectively combining material and geometric properties (Figure 6.3). Allowable stress requires separate knowledge of material and geometric properties. ISO 22156 specifically permits either approach.

Strength is a property of bamboo material (i.e., an intensive property) whereas capacity results from the combination of material properties and member geometry (i.e., an extensive property). Taking the example of a flexural member (Figure 6.3), the modulus of rupture or bending strength (f_m) is the stress at the extreme fibre at failure, expressed in units of force per unit area (N/m^2). The flexural moment capacity (units of N·m) of the cross-section of the member is $M = S \times f_m$, where S is the elastic section modulus, a geometric property of the culm given by Equation 3.7. Similarly, the bamboo material has a modulus of elasticity (E) and the member has a flexural stiffness $E \times I$, where I is the section moment of inertia (Equation 3.6).

Member capacity (ISO 22156, Clause 6.3) is expressed directly in units of load-bearing capacity; that is: Newtons (N) for axial load (N_t) and shear (V) and Newton-metres (N·m) for moment (M). Member flexural stiffness (EI defined in ISO 22156, Clause 6.5) is defined in units of N·m^2. Member capacity is determined directly from component tests — tests that are representative of the cross-section of the bamboo being used — or may be inferred from 'machine grading' procedures and may be a grade-determining property (Chapter 3).

Figure 6.3: ACD and ASD determination of flexural capacity



Moment capacity determined for each grade:

$M = Pa/2$

a) Allowable capacity design (ACD)

Moment capacity determined as:

$M = S \times f_m$

b) Allowable strength design (ASD)

Strength (ISO 22156, Clause 6.4) is determined from standard material tests and is defined independently of bamboo section geometry. Strengths determined using ISO 22157-defined[6.2] material tests are compression (f_c), tension (f_t), bending (f_m) and shear (f_v) strength parallel to fibres, and tension (f_{t90}) and bending (f_{m90}) strength perpendicular to fibres. All are expressed as stresses (e.g., N/m^2). Similarly, the bamboo modulus of elasticity (E) is determined from tension or compression tests. Additional discussion of allowable capacity and strength design is provided in Appendix A6.1.

6.2 Assumption of no composite behaviour

ISO 22156 addresses the design of single- and multiple-culm members. A critical aspect of multiple-culm member design is that ISO 22156 **does not permit an assumption of composite behaviour.** That is, the capacity of multiple-culm members is determined as the sum of the capacities of the individual culms comprising the member; i.e., the parallel axis theorem does not apply. This may be a conservative assumption, however full-scale testing has demonstrated very limited composite action between culms in practice. Therefore, no general approach for addressing composite or partially-composite behaviour of multiple-culm bamboo has been proposed.

Although composite behaviour cannot be achieved, culms in multiple-culm members must be ‘stitched’ together at intervals along their length for adequate load sharing to take place. ISO 22156 requires such ‘stitch’ connections to be spaced no greater than 10 times the smallest culm diameter comprising the member, and provide a force transfer capacity in tension and compression orthogonal to the axis of the culm of at least 1,500N/m between adjacent culms. These stitch connections force all culms in the multi-culm member to deflect in the same direction and help to limit buckling of culms placed in compression, although stitches are not considered adequate to make the member act in a composite manner in flexure.

6.3 Redundancy in bamboo structures and multiple-culm members

ISO 22156, Clause 5.4 defines and promotes the use of redundant structures and structural members by permitting the use of a redundancy factor, $C_R = 1.1$, increasing allowable design capacity or strength. Redundancy is defined as the instance of four or more structural members of the same (or similar) stiffness connected to a continuous load distribution path capable of redistributing load. That is, a load path in which the loss of a single member will not result in global failure. The specific case of floor joists, having a spacing ≤ 600mm and with a decking that is continuous over at least two spans, are identified as being a redundant system.

While redundant structural systems are preferable in most structure types, in bamboo construction redundancy is also applied at the member level. This is done to facilitate replacement of individual culms in the event of splitting (ISO 22156, Clause 5.3) or other damage. This replacement is addressed in ISO 22156, Clause 5.9 requiring "*consideration of the future need to replace individual culms in a member or structure*". A multiple-culm member comprised of four or more culms of the same stiffness is considered to be redundant and the redundancy factor C_R = 1.1 may be applied to allowable capacity. At the member level, the concept is that replacing a single culm in a four- (or more) culm member should be possible without additional considerations of shoring. This approach is consistent with ISO 22156, Clause 5.3, that recommends splitting of an individual culm in a multiple-culm member should not result in loss of capacity of more than 25% of the capacity of the member.

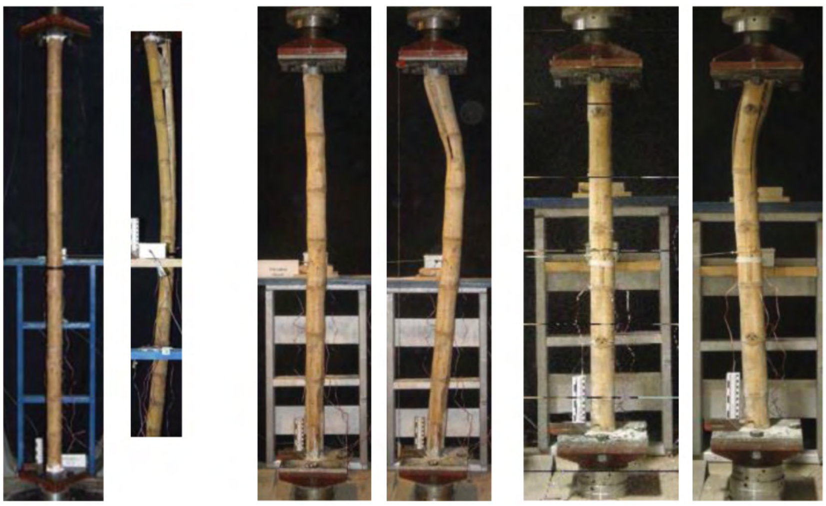
Non-redundant structures and members are assigned a redundancy factor, C_R = 0.9. Therefore, the design capacity of single-, double- and three-culm members is reduced based on the lack of redundancy.

6.4 Design for compression

Considering the way bamboo grows, internode geometry and spacing is such that buckling of the thin bamboo culm wall is unlikely[6.3]. As described in ISO 22156, Annex A, structural load-bearing bamboo will typically have a diameter-to-wall thickness ratio (*D/t*) less than 12 helping to ensure that local wall buckling is not normally a design limit state.

For most applications, compression behaviour will be governed by lateral instability of the bamboo culm over its length. Although this is referred to as member or global 'buckling', for bamboo the behaviour is more complex. For relatively long culms, conventional elastic buckling behaviour (i.e., Euler column buckling) is observed, typically followed by longitudinal splitting (Figure 6.4a). For shorter compression members, as may be used in a truss, elastic lateral behaviour is observed at moderate load levels (Figure 6.4b and c). However, as the axial load is increased, a behaviour characterised by longitudinal splitting of the culm into smaller independent circumferential slats is commonly observed (Figure 6.4). The splitting may be driven by lateral bending of the culm or stresses induced at column-end connections resulting in a 'kink' (Figure 6.4b and c) or 'blooming' (Figure 6.5) of the member. Once splitting occurs, the reduced buckling capacity of the resulting partial-culm circumferential slats dominates compression behaviour, effectively forming a hinge, resulting in culm instability[6.4, 6.5].

Figure 6.4: Single *B. stenostachya* culms subject to axial load[6.4]



a) Culm S4
A = 3,600mm^2
L = 2,600mm
L/r = 103
P_{cr} = 63kN
$f_{cr} = P_{cr}/A$ = 17.5MPa

b) Culm SH1
A = 3,600mm^2
L = 1,830mm
L/r = 71
P_{cr} = 65kN
$f_{cr} = P_{cr}/A$ = 18.1MPa

c) Culm SH2
A = 4,600mm^2
L = 1,218mm
L/r = 54
P_{cr} = 131kN
$f_{cr} = P_{cr}/A$ = 28.5MPa

Figure 6.5: Axial failure of *G. Angustofolia* culm[6.5]

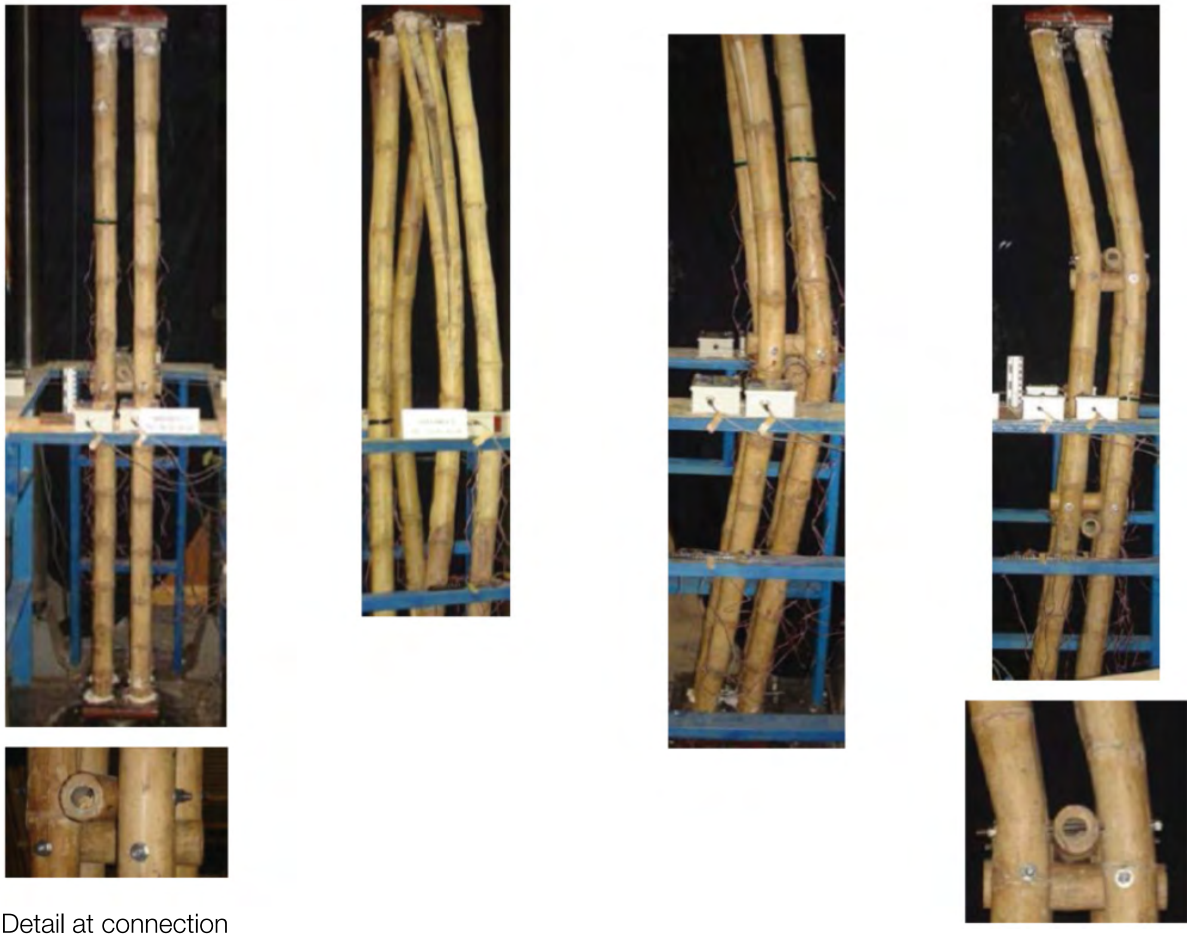
Culm S48
A = 2,465mm^2
L = 1,731mm
L/r = 66
P_{cr} = 66kN
$f_{cr} = P_{cr}/A$ = 26.8MPa

6.4.1 Multiple-culm compressive member behaviour

Multiple-culm columns are commonly required and are recommended. These permit larger loads to be carried, and facilitate concentric connections with horizontal structural elements using simple connections. They will also typically comply with the redundancy requirements of ISO 22156, Clause 5.4.

Although full composite behaviour cannot be achieved, providing ‘stitch’ (Section 6.2) connections mitigates uncontrolled compression failure of individual culms comprising the column (Figure 6.6b). The stitch connection forces all culms in the multi-culm member to deflect in the same direction (Figure 6.6c and d) which effectively imparts a small degree of composite behaviour[6.6], and although this is not explicitly considered in the design capacity, the stitches represent ‘good detailing practice’.

Figure 6.6: Four-culm columns *(B. stenostachya)* subject to axial load[6.4]



Detail at connection

Kinking at connection

a) Test arrangement
(M2 shown)

b) Column M1
no stitch connections
ΣA = 11,200mm^2
L = 2,590mm
One culm L/r = 119
P_{cr} = 140kN
f_{cr} = 12.5MPa

c) Column M2
one stitch at mid-height
(spacing = 16D)
ΣA = 11,700mm^2
L = 2,590mm
One culm L/r = 109
P_{cr} = 159kN
f_{cr} = 13.6MPa

d) Column M3
stitches at third points
(spacing = 10D)
ΣA = 13,600mm^2
L = 2,590mm
One culm L/r = 106
P_{cr} = 138kN
f_{cr} = 10.1MPa

For example, Sharma et al.[6.7] demonstrated that the effective flexural stiffness of a four-culm column base — calculated to be approximately $9EI_{culm}$ — was greater than the sum of the stiffnesses of the individual culms (i.e., $4EI_{culm}$) but barely 20% of the theoretical stiffness of the composite column (calculated to be approximately $45EI_{culm}$ for the case considered).

The interaction between culms at the stitch connection potentially results in high compression forces being applied perpendicular to the culm wall. As shown in Figure 6.6d, this can result in local crushing or 'crippling' of the culm wall and a kink to form at the connection location. However, for this behaviour to manifest, instability of the column must first be initiated.

ISO 22156 prescribes additional requirements for multiple-culm compression members. Most important is the determination of redundancy (Clause 5.4.1). If the removal of any single-culm from an ideal multiple-culm member results in residual capacity less than 75% of the intact member, the member is non-redundant and the redundancy factor is $C_R = 0.90$. A four-culm member, having all culms nominally the same, is considered a redundant member ($C_R = 1.1$) by this definition.

Multiple-culm members should be symmetric about two axes or radially symmetric; equilateral triangular arrangements are also permitted. The individual culms in a multiple-culm member must not be separated by a clear distance of more than the average member culm diameter. The intent of this requirement is to ensure that the stitch connections remain sufficiently stiff to maintain the culms in the element acting as a group (Figure 6.6d). One implication of this requirement is that when interlaced connections such as those shown in Figure 6.1a are used, the culms comprising the column may have no smaller diameter than those of the member(s) connected through it (Section 6.7.1.2 and Figure 6.7). In cases in which the connection or spacing requirements are not met – an example is shown in Figure 6.1c — the element is not a multiple-culm member but rather a collection of single-culm members. This may have little effect on total design capacity but will require the application of $C_R = 0.90$.

6.4.2 Compression capacity

ISO 22156, Clause 9.3.1 adopts the member compression capacity promulgated by Ylinen[6.8]. This approach has been used in North American timber design practice since 1991[6.9]. The Ylinen equation[6.8], given here as Equation 6.1, presents characteristic column capacity ($N_{cr,k}$) as a continuous function of slenderness, which inherently accounts for the interaction between crushing and global buckling failure modes. This "*is caused by any departure from the assumptions of elementary elastic-plastic theory, that is, by nonlinear stress-strain behaviour, inhomogeneity, crookedness, and accidental eccentricity*"[6.10] — all factors common to bamboo construction.

$$N_{cr,k} = \frac{P_{c,k} + P_{e,k}}{2c} - \sqrt{\left(\frac{P_{c,k} + P_{e,k}}{2c}\right)^2 - \frac{P_{c,k}P_{e,k}}{c}} \qquad \text{Equation 6.1}$$

Where:

$c = 0.8$ (Appendix A6.2)
$P_{c,k}$ = characteristic crushing capacity of compression member (a slight modification to Clause 9.3.2, which uses the allowable crushing capacity):

$$P_{c,k} = f_{c,k} \times \sum A \qquad \text{Equation 6.2}$$

and $P_{e,k}$ = characteristic buckling capacity (a slight modification to Clause 9.3.3, which uses the allowable buckling capacity):

$$P_{e,k} = \frac{n\pi^2 E_{k,mean} I C_{bow}}{(KL)^2} \qquad \text{Equation 6.3}$$

Where:

$f_{c,k}$ = characteristic compression strength parallel to fibres of bamboo.
ΣA = sum of areas of n culms comprising member.

Moment of inertia (I) or flexural stiffness (EI) are taken as the minimum such value for all n culms comprising the member. In a multiple-culm member, the 'weakest' culm will buckle first and the residual capacity of the member will be reduced to that of the remaining culms. For single-culms, determine the moment of inertia using D and t values according to the criteria contained in Clause 6.4.1.

The reduction factor, C_{bow}, accounts for the initial bow (b_o, defined by Equation 3.4) of the culm:

$$C_{bow} = 1 - b_o/0.02 \qquad \text{Equation 6.4}$$

The effect of C_{bow} in Equation 6.3 is perhaps more pronounced than elastic buckling theory would predict. However, it is intended to enforce the use of culms having the smallest value of b_o possible. For this reason, b_o may be an appropriate grading property for compression members. Additional discussion of single- and multiple-culm member compression capacity is provided in Appendices A6.2 and A6.3.

The allowable column capacity, N_{cr}, would be determined as:

$$N_{cr} = \frac{N_{cr,k} \times C_R \times C_T \times C_{DF}}{FS_m} \qquad \text{Equation 6.5}$$

The difference between the procedure postulated in this *Manual* and that contained in ISO 22156, Clause 9.3, is that the latter applies modification and safety factors inconsistently: applying these to P_c but not P_e. The approach presented here corrects this inconsistency and applies modification and safety factors to the resulting $N_{cr,k}$ as given by Equation 6.5. It is therefore recommended to use the procedure contained in this *Manual* instead of that contained in ISO 22156.

6.4.2.1 Unrestrained length, *L*

The length of a member between points of restraint is the length over which it is assumed to buckle. Buckling behaviour constitutes a loss of member stability. For this reason, little force is required to restrain buckling. ISO 22156, Clause 9.2.1 requires a restraint capacity of 1% of the axial load resisted by the member, augmented by the effects of initial bow (P_u/C_{bow}), in order to restrain lateral movement about both principal axes of a member cross-section.

For columns, floor diaphragms will typically be adequate to restrain column ends. In truss applications, out-of-plane restraint is required and, for net downward loads, will often be provided by perpendicular purlins. Stitch connections in multiple-culm members do not provide restraint against member buckling (since all the individual members can still buckle in the same direction), and therefore do not reduce the unrestrained length of the multiple-culm member.

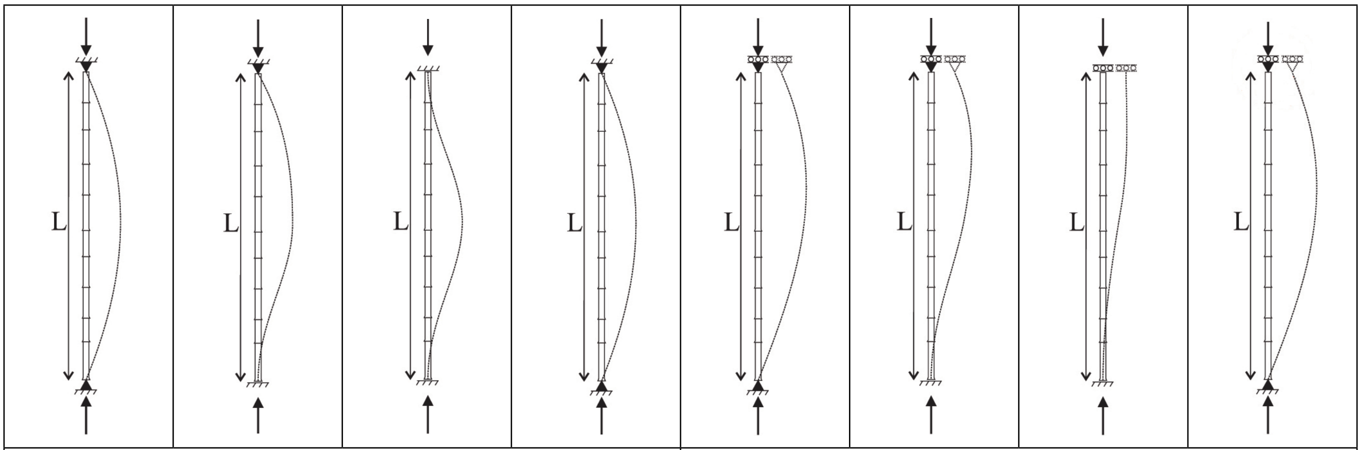
The effective length of a bamboo compression member is the product of the member length between points of restraint, L, and the effective length factor, K, given by ISO 22156, Table 8 (Table 6.1 in this *Manual*). The effective length, KL, defined by ISO 22156 is greater than the theoretical values derived from fundamental elastic buckling theory. The increase is intended to reflect realistic *in situ* restraint conditions.

6.4.3 Component buckling capacity

Owing to the reliance of buckling behaviour on a range of factors, especially the *in situ* length and restraint conditions, ISO 22156 does not explicitly permit member capacity-based design for compression members.

However, using the design by testing provisions of ISO 22156, Clause 5.11.3 or a grading protocol that includes the effects of column length and end condition[6.11], a capacity approach could be adopted for very specific design scenarios. An example may be the mass production of bamboo frame or truss elements using a well-established material source. Here, members having specified length and end conditions may be ubiquitous, making a capacity-based grading scheme justifiably appropriate.

Table 6.1: Effective length of bamboo compression elements



Lateral restraint provided				No lateral restraint			
Pin-pin	Pin-fixed	Fixed-fixed	Truss element/ stud in wall	Pin-pin	Pin-fixed	Fixed-fixed	Truss element
1.1L	0.8L	0.65L	1.0L	2.4L	2.1L	1.2L	Not permitted

6.5 Tension capacity

When used in tension, it is unlikely that member behaviour will govern design. In most practical applications, it is not possible to design a connection adequate to develop the tension capacity of a bamboo culm. Nonetheless, the member tension capacity — without consideration of the connection — is calculated (ISO 22156, Clause 9.4) as:

$$N_{tr} = n \times f_t \times A_{min}$$ Equation 6.5

Where:

f_t = allowable tension strength parallel to fibres of bamboo.
A_{min} = area of smallest culm of n culms comprising member.

Equation 6.5 implies that strain compatibility is maintained (all culms carry load in proportion to their area) and failure is represented by the first culm to fail. If the value for f_t is not known, the value for f_c or f_m may be used, as these will be conservative estimates of tension capacity. These are conservative assumptions but unlikely to govern overall design, since connections are likely to be critical.

6.6 Truss structures

ISO 22156, Clause 11 addresses truss structures. Truss members are designed by the provisions of Clause 9 with the exception that compression members may be designed using an effective length factor K = 1.0. To the extent possible, truss chords should be continuous across the span of the truss. This eliminates the need for connections to be designed to transmit large tension forces. A critical aspect of truss design is to include the effects of joint deformation in analysis (Chapter 4). Providing continuous members in the chords limits joint deformation to the web elements.

6.7 Design for flexure

Because bamboo typically exhibits a relatively high ratio of flexural strength to modulus of elasticity (i.e., f_m/E), it is flexible, and design will be governed by allowable deflections[6.12], although shear failure may also be critical.

Allowable deflections are not prescribed by ISO 22156; these fall into the jurisdiction of local or national building standards. It is important to note that these may require consideration of the effects of creep. ISO 22156, Clause 8.4.3 describes the procedure for considering the effects of creep (Appendix A6.3).

6.7.1 Flexural capacity

As ISO 22156 does not permit an assumption of composite behaviour, flexural capacity (M_r) of a single- or multiple-culm bending member is determined as the sum of the constituent culm capacities (ΣM_i) or from the sum of the constituent culm elastic section moduli (ΣS_i), that is:

$$M_r = \sum M_i \quad \text{[capacity design]} \qquad \text{Equation 6.6a}$$

$$M_r = f_m \times \sum S_i \quad \text{[strength design]} \qquad \text{Equation 6.6b}$$

Where:

f_m = allowable bending strength parallel to fibres of bamboo.

Capacity design here is short for capacity-based design. It should not be confused with the concept of capacity design used in earthquake engineering.

Deflections are similarly determined based upon the sum of the culm stiffnesses ($\Sigma(EI)_i$) or moments of inertia (ΣI_i):

$$EI = \sum (EI)_i \times C_V \quad \text{[capacity design]} \qquad \text{Equation 6.7a}$$

$$EI = E_d \times \sum I_i \times C_V \quad \text{[strength design]} \qquad \text{Equation 6.7b}$$

While ISO 22156 goes to great lengths to ensure that load-induced longitudinal splitting does not affect culm bending behaviour, the strain compatibility assumption inherent in Bernoulli beam theory is that the culm may degrade before splitting occurs[6.13]. This effectively 'softens' the flexural behaviour. The modification factor for shear deformations given by Equation 6.8 reduces the bending stiffness for members having a shear span-to-culm diameter ratio (*a/D*) less than 10:

$$C_v = 0.50 + 0.05\left(\frac{a}{D}\right) \leq 1.0 \qquad \text{Equation 6.8}$$

The shear span, *a*, is the shortest distance between a location of maximum moment and the nearest point of inflection or contraflexure (zero moment). For a simple span beam subject to uniformly-distributed load, the shear span is equal to one half the span. The introduction of the modification factor is intended to incentivise flexure-dominant members having spans longer than 20*D*.

6.7.1.1 Component capacity-based design and inherent composite behaviour

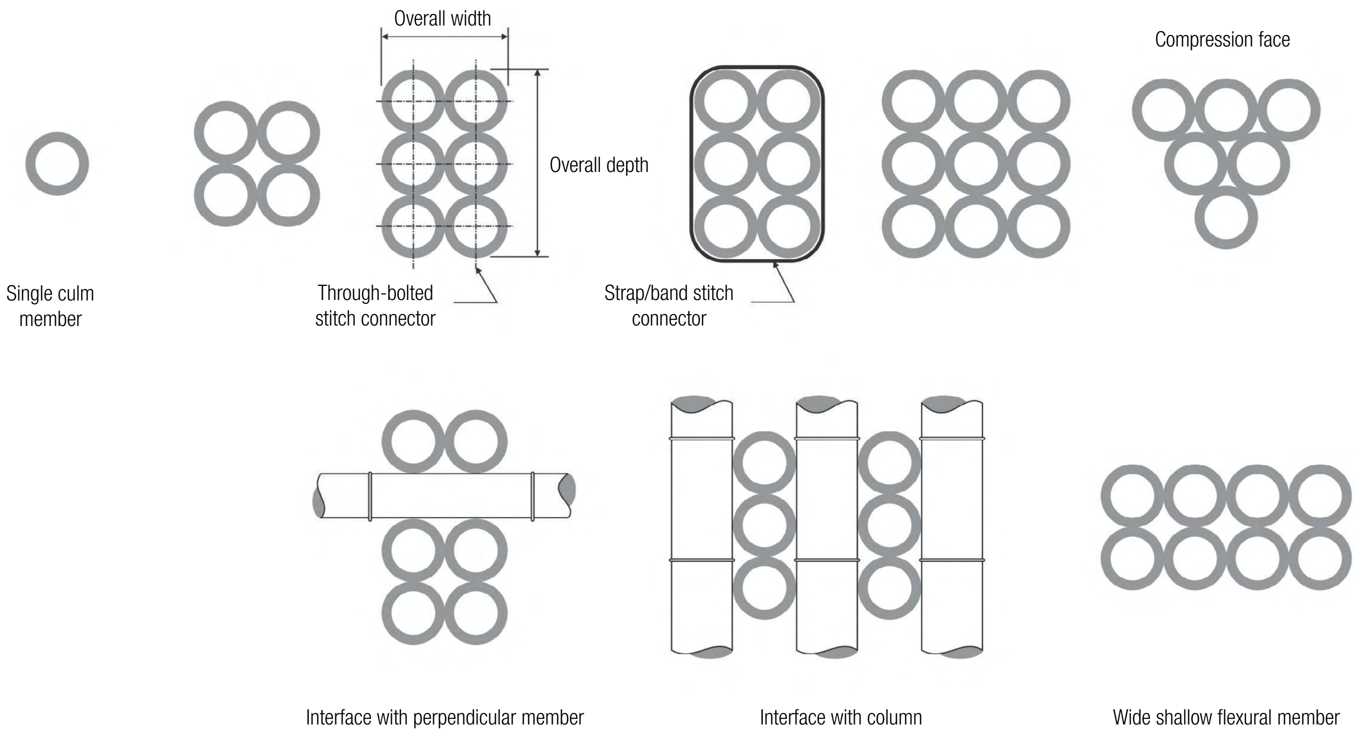
Using capacity-based design ISO 22156, Clause 8.3.1 permits the allowable flexural design capacity and component flexural stiffness of a multiple-culm member to be used explicitly. This requires a robust grading protocol to define this value or a 'design-by-testing' protocol conducted in accordance with ISO 22156, Clause 5.11.3. An advantage of design-by-testing is that the extent of partial composite behaviour in multiple-culm members is implicitly captured in the resulting characteristic or design capacity for such members.

6.7.1.2 Geometric limitations on flexural members

Although ISO 22156 does not implicitly consider composite action, some composite action may occur. Similarly multiple-culm members that have been designed based on design-by-testing protocols may exhibit composite action. In such cases, multiple-culm flexural members may be susceptible to so-called 'lateral torsional buckling' or 'flexural torsional buckling' about their weak axes. Similarly, the circular cross-section of the culms can make transmission of loads in multiple-culm beams through the depth of the section inherently unstable, so requiring 'stitching'. For these reasons, the permitted overall-depth-to-overall-width ratio of multiple-culm members is limited to three (ISO 22156, Clause 8.2). Additionally, members must be symmetric about the centreline of their cross-section. Triangular-shaped members are permitted provided they are oriented with one side of the triangle located along the compression edge of the member and no moment reversals are expected. For this reason, triangular members should only be used in regions of single curvature (i.e., simply-supported beams). Figure 6.7 shows a variety of acceptable multiple-culm flexural member geometries.

Typically, the individual culms in a multiple-culm flexural member will be in contact with each other, constrained by the required stitch connections. In order to accommodate intersection with perpendicular members, ISO 22156, Clause 8.2 permits culms in a flexural member to be separated by a distance no greater than the average diameter of the culms comprising the member and still be considered a single multiple-culm member (Figure 6.7).

Figure 6.7: Permitted multiple-culm flexural member geometries



Because composite behaviour is not accounted for, wide shallow flexural members (Figure 6.7) are equally as efficient as deeper sections having the same number of culms. Additionally, shallow members are less susceptible to shear deformations, do not require lateral bracing and have less risk of crushing at supports.

6.7.1.3 Lateral bracing requirements

Flexural members having an overall-depth-to-overall-width ratio greater than 1.5 require lateral bracing at their compression face (Clause 8.2.1). The use of a depth-to-width ratio of 1.5 was selected to accommodate the variation of bamboo diameters and dimensions without requiring bracing of single-culm members.

When required, bracing must be located at intervals not exceeding 10 times the overall width of the member. The sum of the capacity of all restraints provided to a member must exceed:

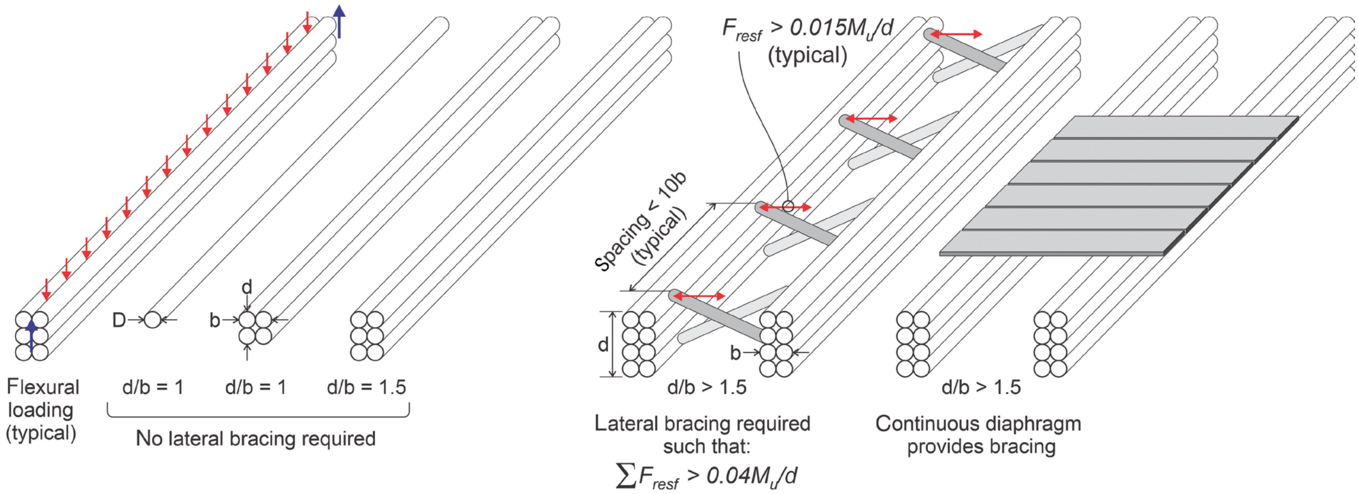
$$\Sigma F_{resf} \geq 0.04 \times M_u/\mathrm{d} \qquad \text{Equation 6.9}$$

Where:

M_u = maximum moment resisted by member.
d = overall depth of member.

Bracing forces are distributed based on restraint spacing, and individual restraints must have a capacity of at least 38% of the total required (i.e., 0.015M_u/d). Assuming discrete restraints are equally spaced, a member requires at least four restraints: one at each support and two at the third points of the member (Figure 6.8). A member supporting a positively connected floor or roof diaphragm is considered to be 'laterally-braced'. Restraints must be connected through a load path to elements able to resist the lateral forces. Effective lateral restraint is not achieved by simply connecting adjacent flexural members to each other.

Figure 6.8: Lateral bracing requirements



6.8 Combined axial and flexural loads

At the time of publication, there were no known studies of combined axial and flexural behaviour on bamboo culms, therefore a conservative linear interaction relationship defining the failure criteria of such members was adopted in ISO 22156, Clause 9.5 (Figure 6.9):

$$\frac{N_d}{N_r} + \frac{BM_d}{M_r} \leq 1.0 \qquad \text{Equation 6.10}$$

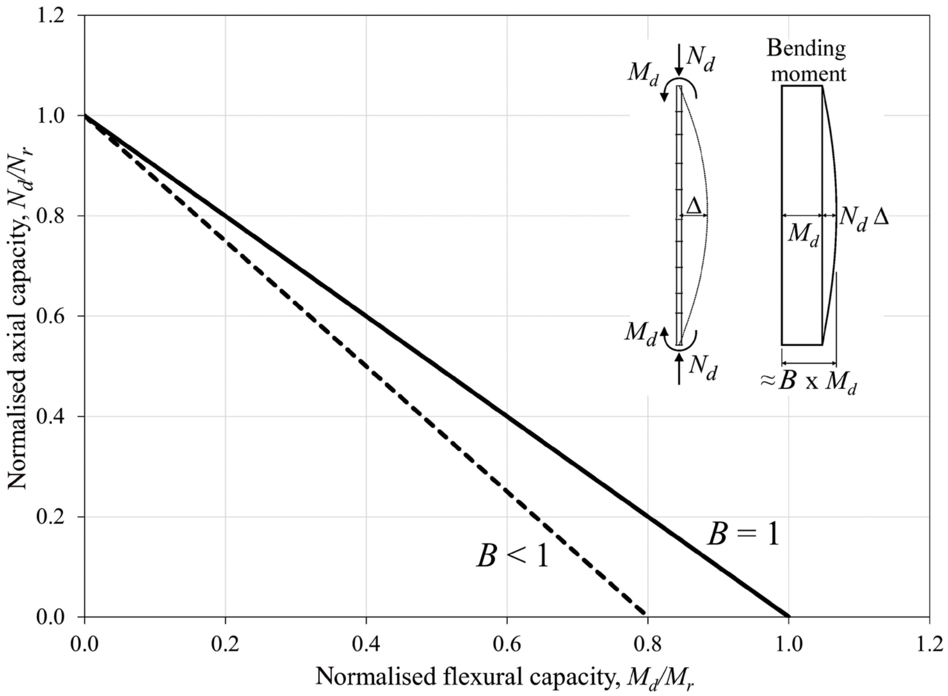
Where:

N_d = design axial force.
M_d = design moment including effects of eccentricity (Section 6.8.1).
N_r = member compression or tension resistance defined in ISO 22156, Clause 9.3 or 9.4, respectively.
M_r = member flexural capacity defined by Clause 8.3. The moment amplification factor, B, conservatively accounts for second-order effects (the so-called P-Δ effect) (inset in Figure 6.9) and is given by Equation 6.11 (Appendix A6.4).

$$B = \frac{1}{1 - N_d/N_{cr,k}} \quad \text{for compression members } (N_d \text{ and } P_{cr,k} \text{ are both positive}) \qquad \text{Equation 6.11a}$$

$$B = 1 \quad \text{for tension members} \qquad \text{Equation 6.11b}$$

Figure 6.9: Axial load-flexure interaction failure surface and representation of *B*



6.8.1 Eccentricity of axial load

Regardless of the presence of external applied moment ($M_{d,ext}$), if eccentricity (e) of applied axial load (N_d) exceeds one quarter of the smallest dimension of an axial load-bearing member, the interaction of axial load and resulting eccentricity-induced flexure must be considered (ISO 22156, Clause 9.1). The design moment therefore becomes:

$$M_d = M_{d,ext} + N_d e \qquad \text{Equation 6.12}$$

6.9 Shear capacity

Provisions of ISO 22156 attempt to enforce a 'flexure critical' behaviour for bamboo members through greater factors of safety (ISO 22156, Clauses 6.3 and 6.4) for shear. Using strength-based design, the shear capacity of a member in flexure is determined as the sum of the shear capacities of the culms comprising the member (ISO 22156, Clause 8.3.2.1):

$$V_r = f_v \times \Sigma A_v = f_v \times \Sigma \frac{3\pi t}{8} \frac{D^4 - (D-2t)^4}{D^3 - (D-2t)^3} \qquad \text{Equation 6.13}$$

Where:

f_v = allowable shear strength parallel to fibres of bamboo.

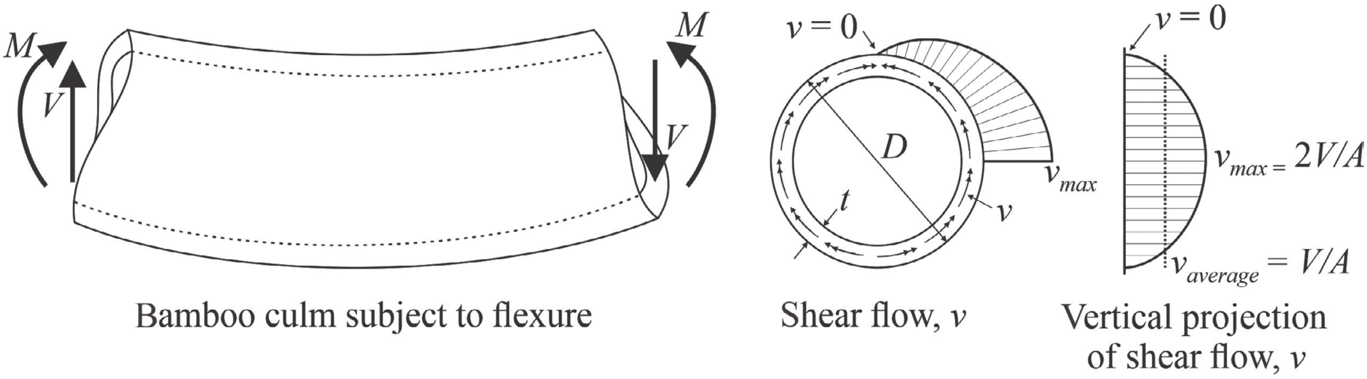
The term in the summation is the shear area (A_v) of the cross-section. Equation 6.13 defines the shear capacity of a bamboo culm based on fundamental mechanics, which places the maximum shear at the neutral axis of the cross-section (Figure 6.10). The capacity is derived from the equations for shear flow at this longitudinal section. Equation 6.13 trends to 0.75 for a solid cylinder (i.e., D/t = 2) and to 0.50 as the culm wall gets thinner (i.e., large D/t). For common values of D/t, Table 6.2 provides the value of A_v calculated using Equation 6.13, illustrating that adopting $A_v = A/2$ is more convenient and marginally conservative. Therefore, Equation 6.13 can be approximated conservatively to Equation 6.14 without significant error.

$$V_r = f_v \times 0.5\Sigma A = f_v \times \Sigma \frac{\pi}{8}\left[D^2 - (D-2t)^2\right] \qquad \text{Equation 6.14}$$

Table 6.2: Calculated and estimated shear area of bamboo culm

D/t	4	6	8	10	12
Calculated (Equation 6.13)	$0.536A_v$	$0.513A_v$	$0.507A_v$	$0.504A_v$	$0.503A_v$
Estimated as *A/2*			$0.5A_v$		

Figure 6.10: Shear distribution in a bamboo culm



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Appendices

A6.1 Capacity and strength design approaches

An advantage of using capacity-based over strength-based design is that the former is able to capture explicitly the anisotropic nature of bamboo and the often complex interactions between actions that may result.

Consider, for example, the interaction between shear and flexure in a member subject to bending. A strength design approach correlates strength with capacity through assumptions of fundamental mechanics. Due to the complex morphology and highly anisotropic nature of bamboo, some of these assumptions may not hold true in all cases. Examples include the assumption of strain compatibility in flexure. While ISO 22156 goes to great lengths to ensure that load-induced longitudinal splitting does not affect culm bending behaviour, the strain compatibility assumption inherent in Bernoulli beam theory is that the culm may degrade before splitting occurs[A6.1]. In the same culm, subject to bending, research indicates improved prediction of bamboo mechanical behaviour when it is considered as a bimodular material — that is tension and compression moduli are different[A6.2]. ISO 22156 does not address bimodular behaviour in strength-based design, although the effect is implicitly considered in the capacity-based approach.

Member capacity will typically be prescribed by grading or some other means within a jurisdictional building standard. Design aids in the form of load tables or span tables can be developed for bamboo. Such tables are well-known to engineers and commonly used in timber and steel design. They facilitate the rapid design of well-known and commonly used structural elements subject to common loading conditions. Design tables, however, are predicated upon a number of fundamental assumptions, not least of which is known material properties and geometries. With the acceptance of allowable capacity design (ACD) for bamboo, coupled with methods of grading, sufficient basis for the development of design load tables is possible. Examples of the development of design aids for both compression and flexural members is reported in Reference A6.3. It must be emphasised that the development of design aids requires an established grading process to be implemented.

Member capacity should not, however, be confused with 'design-by-testing' permitted by ISO 22156, Clause 5.11.3. The latter is intended for structural systems where design or analysis differs from those described in ISO 22156. Design-by-testing is intended for unique design situations and requires additional rigour and conformance of tests to the structure being designed. Due to more rigorous testing regimes, the 10th percentile capacity determined from tests is permitted to be used in limited, conforming cases.

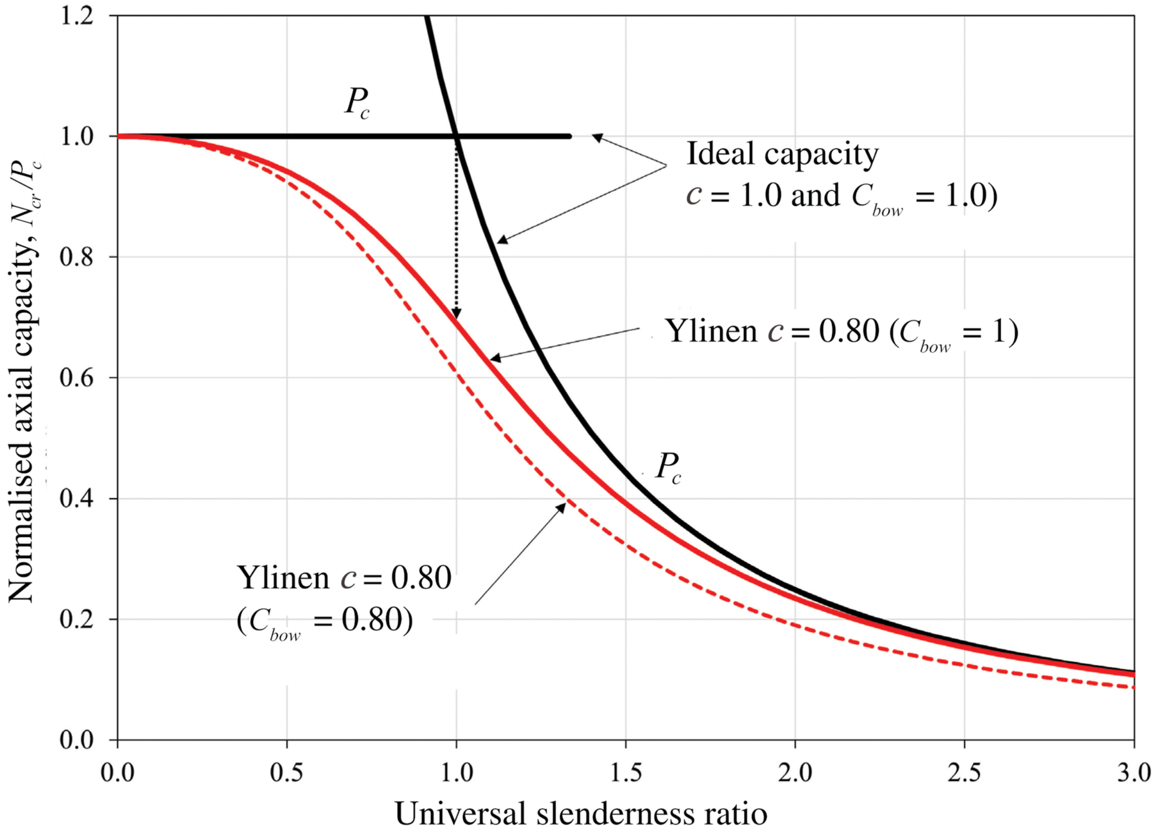
Another disadvantage of strength-based design of bamboo culms is that it adopts a timber-based approach for determination of characteristic strength values (5th percentile with 75% confidence) and compounds it with a lower-bound criteria for section size, creating two levels of conservativeness. In timber, the latter does not occur, as section sizes have a much tighter tolerance. Capacity-based design using 'machine-grading' or 'inference-based grading' could use characteristic capacity values, which may set the level of conservativeness on parity with that of timber[A6.4].

A6.2 Ylinen empirical parameter *c*

The Ylinen coefficient c in Equation 6.1 models the degree of interaction between crushing and buckling; that is, between P_c and P_e (Figure A6.1). The theoretical case in which $c = 1$, represents the ideal upper-bound member capacity representing the case of no interaction. In this case, N_{cr} is simply the lesser of P_e and P_c; this is the theoretical Euler buckling behaviour (P_e) limited by cross-section yield (P_c).

For solid timber in compression, $c = 0.80$[A6.5, A6.6]. In the absence of sufficient data with which to calibrate c for bamboo, this value was adopted in ISO 22156. It is important to note that the parameter c, when used in timber design, is intended, among other effects, to include the effect captured by C_{bow}. Recognising that bamboo may have a greater tolerance in terms of expected bow, C_{bow} is explicitly included in Equation 6.3. In addition to using $c = 0.80$, this adds a degree of conservatism to the ISO 22156 calculation (dashed line in Figure A6.1).

Figure A6.1: Effect of the Ylinen coefficient *c*



The coefficient *c* can be determined by experimentation. The value of *c* is best determined at a slenderness ratio at which P_c and P_e are equal; this is referred to as the universal slenderness ratio = 1. It is under these conditions that the deleterious effect of interaction is maximised (Figure A6.1). A well-developed experimental programme will consider a range of slenderness values bracketing this value. Additionally, for full-culm bamboo where bow may vary considerably, it is thought to be best to maintain the independence of the value *c* from the effects of bow.

A6.3 Long-term deflections (creep)

Sustained load on bamboo results in creep. Little research has been conducted on the creep behaviour of bamboo. Janssen[A6.7] concluded that creep of full-culm bamboo is negligible, but the authors of this *Manual* believe this is incorrect. Tests on small, clear specimens exhibit significant creep-induced plastic deformations and strains[A6.8]. The limited available data and anecdotal evidence indicates that creep of bamboo is marginally less pronounced than creep in softwood timber. For this reason, and lacking further data, the same factors used for softwood were adopted in ISO 22156 to account for long-term creep deformations.

Long-term deflections are calculated using adjusted values of *EI* or *E* applied to the permanent or sustained portions of the applied load. 'Instantaneous' values of *EI* or *E* are used to calculate deflections associated with transient loads. The effects of load duration are combined with those of Service Class (Chapter 5) in modification factor C_{DE} given in ISO 22156, Clause 6.5. For instantaneous loads, C_{DE} = 1.0. For permanent and sustained loads, C_{DE} = 0.50 and C_{DE} = 0.45 Service Classes 1 and 2, respectively. Essentially, this represents a creep factor of two for sustained loads.

A6.4 Combined axial and flexural loads

The calculation of *B* using Equation 6.11 assumes a culm to be bending in uniform single curvature over its unbraced length. This is the most likely case for a bamboo structure. The application of Equation 6.11 is conservative for members having a significant moment gradient and those in double curvature. The behaviour of such members has not been experimentally validated, in which case a conservative calculation of *B* was deemed appropriate.

Equation 6.10 implies that behaviour of a member subject to combined loading is governed by the greatest resulting tension or compression stress in the cross-section — that at the extreme tension or compression fibres. This disregards the potential for stress redistribution within the cross-section. Again, there is insufficient experimental data available to confirm the presence or extent of redistribution and the conservative, linear combination of Equation 6.10 is adopted.

References

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7 Design of bamboo connections

7.1 Context and introduction

Unlike many conventional materials, there is little consensus on what constitutes a 'conventional' connection or joint in bamboo construction. Similarly, there is very little design data about the load-bearing capacity, stiffness and ductility of different joints used for bamboo. For this reason, ISO 22156[7.1] provides two paths to bamboo joint design which will be explained in this chapter; these approaches are 'complete-joint testing' and 'component capacities'.

7.2 Terminology and classification of bamboo joints

ISO 22156, Clause 10 uses the term 'joint' to describe "*a means of transferring design forces between two or more individual culms or structural members*". 'Splices' (ISO 22156, Clause 10.8) are a subset of joints in which two culms are connected along their longitudinal axes.

In general, the approach taken in ISO 22156 is to classify joints by their force transfer mechanism. This approach was originally proposed by Janssen[7.2]. The refined classification[7.3, 7.4] was adopted for ISO 22156. This is described in Appendix A7.1. Appendix D of ISO 22156 provides a non-exhaustive listing of qualitative descriptions of fundamental force transfer mechanisms in joints — some are covered in this chapter. Appendix D also provides direction on which ISO 22156 clauses are associated with each joint type.

It is important to distinguish that the 'joint' includes both the bamboo and hardware or other elements (e.g., bolts, gusset plates, etc.) required to make the connection. Apart from some general requirements provided in Clause 10.9, however, ISO 22156 does not address the capacities or design of non-bamboo components of a joint. For example, the selection of a bolt grade (strength) and diameter used for a bolted bamboo joint is beyond the scope of the standard, although the selection may be limited by factors affecting the bamboo components of the joint, such as maximum permitted diameter (ISO 22156, Clause 10.12). Joints may also include connections of bamboo to another structural element; ISO 22156 does not address the design of this other, non-bamboo element.

There is comparatively little research on bamboo joint behaviour and capacity. Although a few well-established joint types are provided with specific design requirements (ISO 22156, Clauses 10.10–10.12), most joints will require qualification either through complete-joint testing (ISO 22156, Clause 10.2 and Section 7.8 of this *Manual*), or through component capacities (ISO 22156, Clause 10.3 and Section 7.3 of this *Manual*) when these can be reliably correlated with joint behaviour. An example of the latter is the end bearing capacity of bamboo culms given in ISO 22156, Clause 10.10, which is easily related to allowable bamboo compression strength, f_c. Caution is required when adopting the component capacities approach for species not listed in Annex A of ISO 22156, as lesser-studied species may exhibit failure modes not yet observed.

7.3 Joint design by component capacities

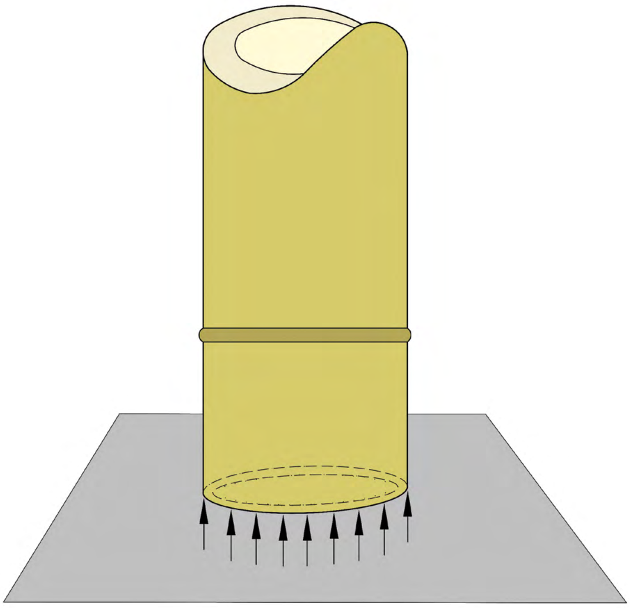
ISO 22156, Clause 10.3 permits the design of joints by component capacity provided the failure mode of the joint type is "*well-understood and reliably predictable*". Joint capacity is determined as the least capacity of all components of the joint. To ensure the expected behaviour is 'reliably predictable', all other components of the joint should have a capacity 1.25 times that of the critical component of the joint. The failure mode of a joint must exhibit a ductility $\mu \geq 1.25$.

ISO 22156, Clauses 10.10–10.12 provide expected component capacities and detailing requirements of some well-established joint types as discussed in this chapter. Clause 10.3 requires that this approach be validated through complete-joint testing (Section 7.8 of this *Manual*), though the standard does not include how validation should be undertaken. Appendix A7.2 of this *Manual* proposes a possible method.

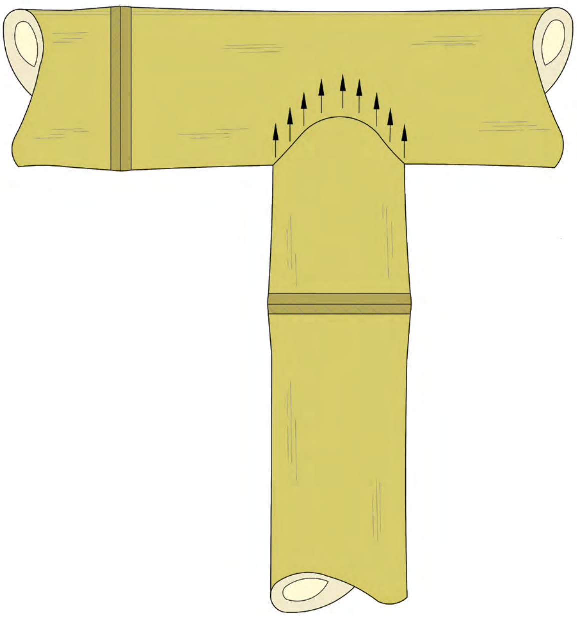
7.3.1 End bearing capacity of joints

End bearing is characterised as Group 1 behaviour (Appendix A7.1). Direct bearing on a flat base (Figure 7.1a) or bearing on the 'mouth' of a fish-mouth joint (Figure 7.1b) are common examples.

Figure 7.1: Joints affected by end bearing capacity



a) Bamboo column base bearing on flat surface



b) Fish-mouth joint resisting bearing over mouth of joint

Bearing capacity, P_b, is based on allowable bearing stress of the bamboo, f_c, and culm section area, A (ISO 22156, Clause 10.10):

$$P_b = C_{EB} f_c A \qquad \text{Equation 7.1}$$

Where:

C_{EB} = 0.8 for straight cuts bearing on a flat surface (Figure 7.1a).
C_{EB} = 0.4 for fish-mouth joints bearing onto another piece of bamboo (Figure 7.1b).

The reduced factor for fish-mouth joints accounts for incomplete or uneven bearing over the mouth and the greater likelihood that a fish-mouth may split longitudinally (i.e., be forced open by the culm around which the mouth bears).

7.3.2 Circumferential bearing capacity of joints

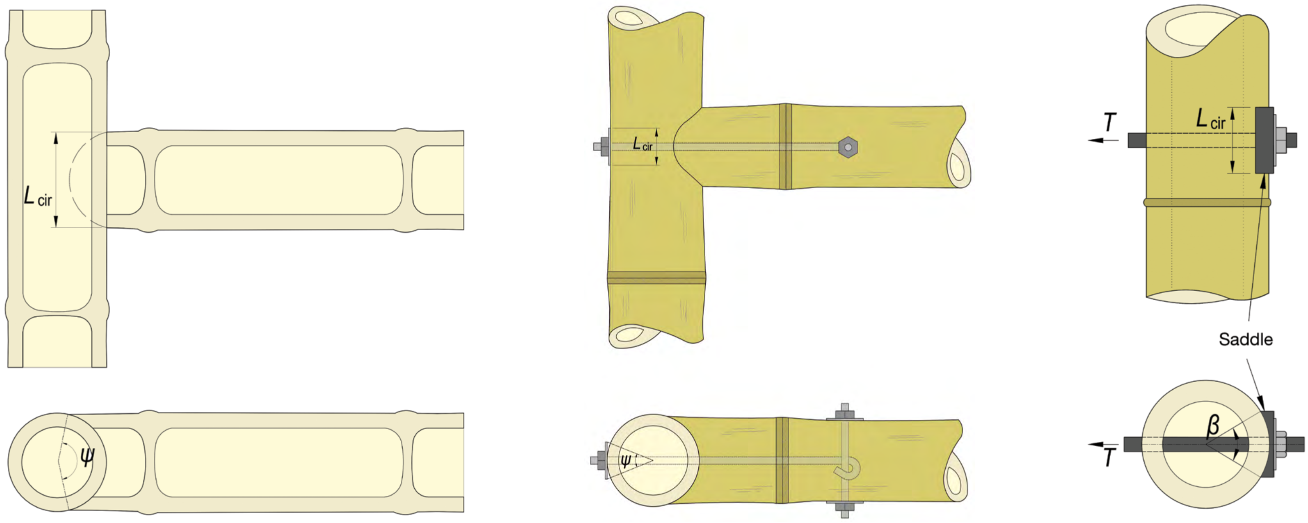
Circumferential bearing is characterised as Group 5 behaviour (Appendix A7.1). Such bearing may occur at the intersection of elements and may be efficiently engaged using fish-mouth joints — in this case, the bearing refers to the uncut culm around which the 'mouth' is placed (Figure 7.2a). A second common occurrence is at the bearing surface of a washer of a through-culm bolt or anchor in which the bolt is under tension. The bolt may be pretensioned (Figure 7.2b) or used as a hanger (Figure 7.2c).

The resultant bearing force, P_{cir}, shown in Figure 7.2d must be distributed over a region of the culm wall described by the arc $\beta \geq 45°$ and length, L_{cir}. The bearing region should be at least two culm diameters from the end of a culm and, if possible, one node should fall between the bearing region and end of the culm.

For an unfilled culm, the bearing shown in Figure 7.2d is resisted by allowable bending of the culm wall perpendicular to the fibres (i.e., through the wall thickness), characterised by f_{m90}. In ISO 22156, both Equation 32 and the values provided in Table 10 are incorrect. There was a typographic error in the equation and the approach taken to derive the equation was inappropriately conservative. The following is a recommendation for correcting Section 10.11 in ISO 22156. The derivation is based on the perpendicular bending resistance of the culm determined from fundamental mechanics[7.5]:

$$P_{cir} \leq \frac{4 f_{m90} t^2 (L_{cir} + 2D)\left(1 - \cos\left(\frac{\beta}{2}\right)\right)}{3\beta D K_M} \qquad \text{Equation 7.2}$$

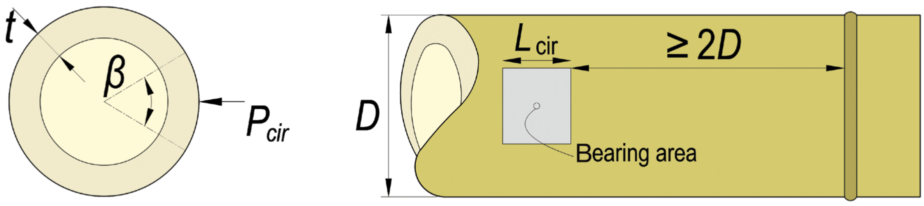
Figure 7.2: Joints affected by circumferential bearing capacity



a) Circumferential bearing in a fish-mouth connection

b) Prestressed fish-mouth joint; washer exerts circumferential bearing on culm through which it is placed

c) Bolt used as tension anchorage; saddle exerts circumferential bearing on culm



d) Geometry of circumferential bearing connections

The (L_{cir} + 2D) term is the effective length of the culm over which the moment resulting from P_{cir} is resisted — resistance is spread approximately D beyond either side of the L_{cir} bearing length.

The K_m factor accounts for variation in force distribution around the circumference of the culm as a function of β. K_M is given by Equation 7.3 and values of β are presented in Table 7.1:

$$K_m = \frac{1}{\pi\beta}\left[2\cos\left(\frac{\beta}{2}\right) - 2 - 2\pi\sin\left(\frac{\beta}{2}\right) + \beta\sin\left(\frac{\beta}{2}\right) + \pi\beta - \frac{\beta^2}{4}\right] \quad \text{Equation 7.3}$$

Table 7.1: K_m for different values of β

β (degrees)	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
β (radians)	0.785	1.047	1.309	1.571	1.833	2.094	2.356	2.618	2.880	3.142
K_M	0.023	0.039	0.059	0.081	0.105	0.130	0.156	0.181	0.206	0.229

Where:

$\frac{\pi}{4} \leq \beta < \pi$ is expressed in radians.

The bearing is limited by allowable compression strength of the bamboo, f_c:

$$P_{cir} \leq 0.5 L_{cir} t f_c \quad \text{Equation 7.4}$$

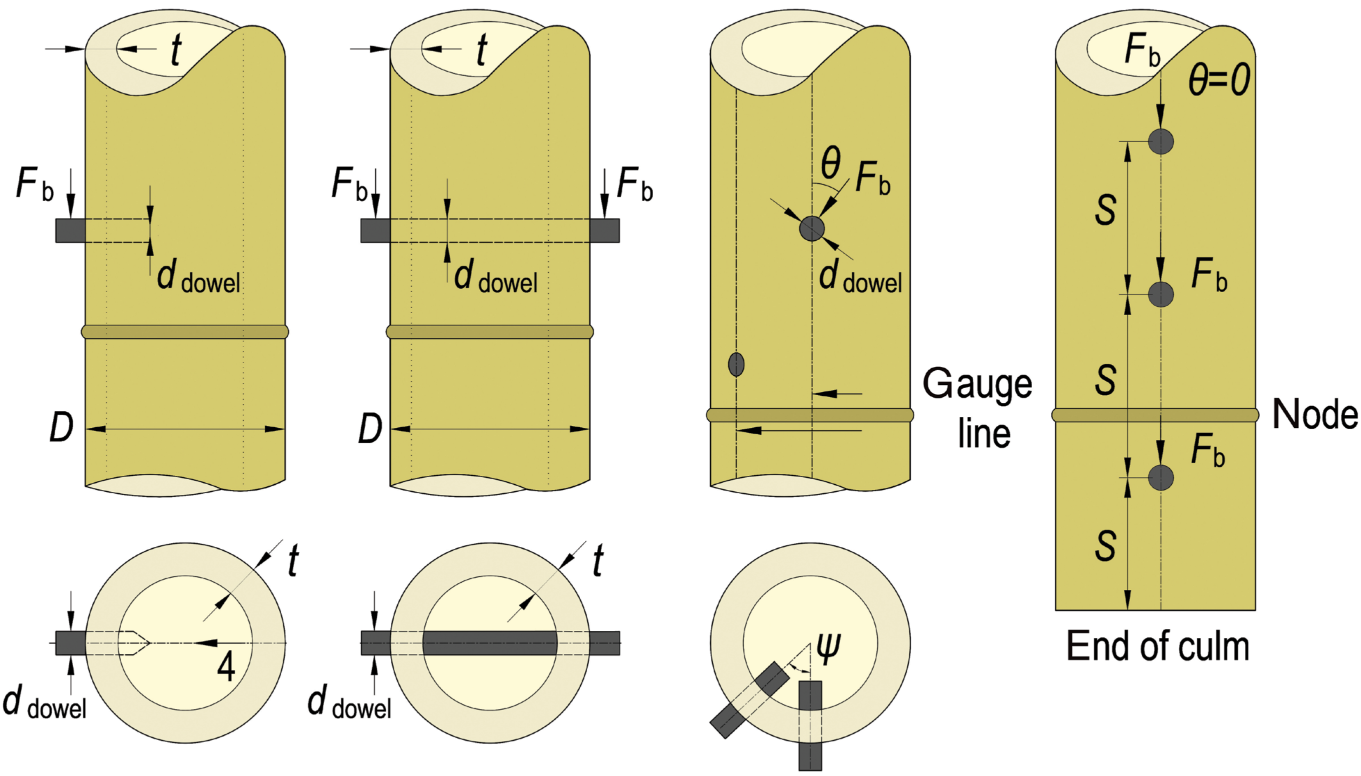
For a mortar-filled culm, ISO 22156 requires complete-joint testing. However, since in this scenario culm wall bending is mitigated, a lower-bound capacity can be estimated from Equation 7.4.

7.4 Dowel-type connections

Dowel-type connections, characterised by Group 3 behaviour (Appendix A7.1) are common simple means of connecting multiple bamboo culms. These may take a variety of forms including metal, wood, bamboo or plastic dowels or bolts; wood and/or machine screws are also permitted. A single dowel may pass through one culm wall (Figure 7.3a) or diametrically through the culm, engaging both walls (Figure 7.3b). Dowel-type connection capacities are described in Section 7.4.1. Dowel connection capacity, F_b, is given in terms of penetration through a single-culm wall (Figure 7.3a). For dowels passing through the culm (Figure 7.3b), capacity of each penetration is F_b, making the connection capacity $2F_b$.

Dowel connection theory was first described in 1949[7.6] and has evolved since to be known as the 'European Yield Model' (EYM). When ISO 22156 was published, little formal research of dowelled bamboo connections was available. As a result, ISO 22156 provisions described in Clause 10.12 are limited in scope and understood to be conservative in calculation of capacity. Subsequent studies have demonstrated that equations contained in ISO 22156 are conservative[7.7] when evaluated against EYM and experimental data. Therefore, complete-joint testing of dowel connections conducted in the context of the Johansen[7.6] criteria may be necessary to establish improved, less-conservative provisions.

Figure 7.3: Geometry of dowel connections



a) Dowel engaging single-culm wall

b) Symmetrically-loaded dowel engaging both culm walls

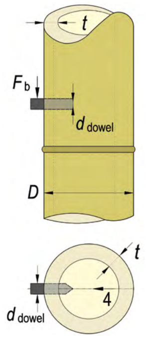
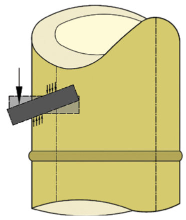
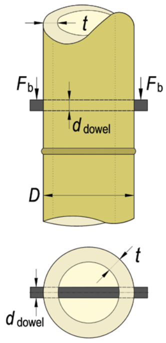
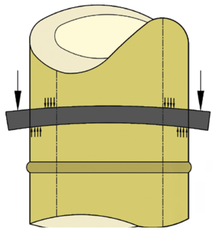
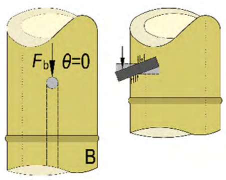
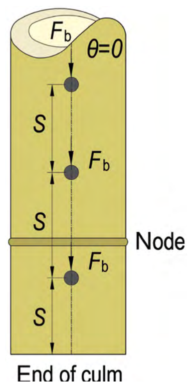
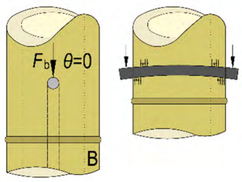
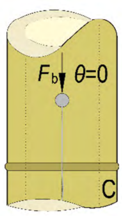
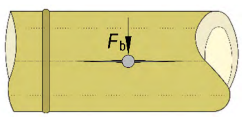
c) Radial spacing of dowel gauge lines

d) Dowel spacing (pitch) along single gauge line

7.4.1 Dowel-type connection capacity

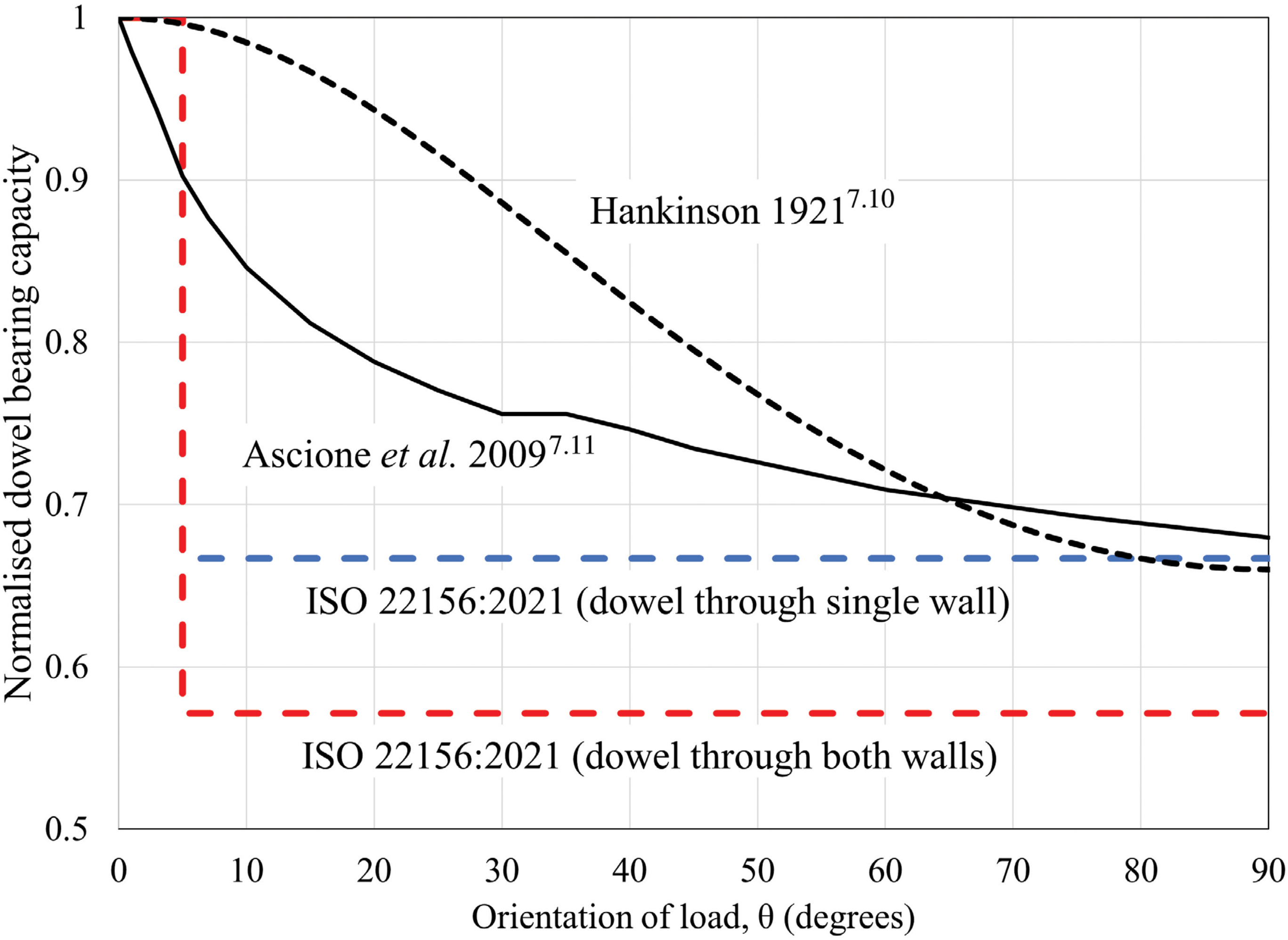
Dowels embedded in the culm wall may exhibit three failure modes, indicated A, B and C in Table 7.2; all are Group 4 force transfer mechanisms (Appendix A7.1). The allowable bearing capacity under a dowel is taken as the lesser of the capacities given in this table. Capacity is affected by the angle of applied load, θ, and the nature of dowel penetration. Single dowels passing through both culm walls (symmetric loading) are inherently stiffer and do not rotate as much within the culm wall.

Table 7.2: Dowel-bearing capacities included in ISO 22156

Failure mode	Schematic	Capacity	Notes
Mode A-a (asymmetric) bearing Dowel engaging single-culm wall only or asymmetrically-loaded dowel engaging both culm walls.		For $0° \le \theta < 5°$ $F_b = 0.3D_{dowel}tf_c$ For $\theta > 5°$ $F_b = 0.2D_{dowel}tf_c$	
Mode A-s (symmetric) bearing Symmetrically-loaded dowel engaging both culm walls.		For $0° \le \theta < 5°$ $2F_b = 1.4D_{dowel}tf_c$ For $\theta > 5°$ $2F_b = 0.8D_{dowel}tf_c$	
Mode B-a (asymmetric) Shear or 'tear out'.		$F_b = 1.6stf_v$	 Ensuring that spacing between bolts $s \ge 14D_{dowel}$ should mitigate this failure mode. This failure mode will not propagate across a node.
Mode B-s (symmetric) Shear or 'tear out'.		$2F_b = 3.2stf_v$	
Mode C Cleavage Dowel-induced splitting.		For $0° \le \theta < 5°$ $F_b \le \frac{\pi D_{dowel}tf_{t90}}{2\left(1-\frac{D_{dowel}}{D}\right)^2}$ For $\theta > 5°$ refer to Mode D	Malkowska et al.[7.7] demonstrated that this equation was excessively conservative. Radial clamping may mitigate this failure mode[7.8].
Mode D Transverse load-induced splitting Not included in ISO 22156.		$F_b = 0$	Radial clamping may mitigate this failure mode[7.9].

Bearing capacity is maximised at $\theta = 0°$ and falls as θ increases to 90°. This behaviour is similar to that of wood, described by Hankinson's formula[7.10]. However, bamboo has a greater degree of anisotropy than wood. In pultruded fibre polymer composites (FPCs) (also having a high degree of anisotropy), the transition in bearing capacity at $\theta = 0°$ to that at $\theta = 90°$ is more abrupt than the Hankinson equation predicts[7.11] (Figure 7.4). Owing to a lack of bamboo-specific data, in ISO 22156 the orientation of load applied to a dowel is transitioned at a loading angle of only 5° from the longitudinal culm axis. Nonetheless, the scalar factors shown in Table 7.2 of this *Manual* are understood to be conservative estimates of capacity. An additional factor of 1/1.25 is applied to failure modes B and C as these are potentially non-ductile modes.

Figure 7.4: Variation of dowel bearing strength with angle of load, θ



The Mode C equation presently given in ISO 22156 (and Table 7.2 of this *Manual*) was derived based on linear elastic fracture mechanics and results in very conservative values of capacity. This has been demonstrated for small diameter dowels ($D_{dowel} < 5$mm) loaded asymmetrically in the direction of the fibres[7.7] (Figure 7.3a with $\theta = 0°$). Furthermore, if spacing between dowels on the same gauge, s, is greater or equal to $14D_{dowel}$ and distance to the end of the culm exceeds $10D_{dowel}$, shear and cleavage failures are uncommon[7.12]. Therefore, Mode A capacity may be used without considering Mode B and C checks if:

- End distance between dowel and end of culm exceeds $10D_{dowel}$ and includes a node.
- For $D_{dowel} \leq 5$mm, multiple dowels placed in the same gauge line are spaced $s \geq 14D_{dowel}$. Dowels in adjacent gauge lines are spaced $s \geq 7D_{dowel}$ and gauge lines are staggered by an angle Ψ (Section 7.4.4 and Figure 7.3c).

- For $D_{dowel} > 5$mm, only one dowel is permitted in a gauge line. Dowels in adjacent gauge lines are spaced $s \geq 14D_{dowel}$ and gauge lines are staggered by an angle Ψ (Section 7.4.4 and Figure 7.3c).

For dowels satisfying these spacing limits, dowel capacity may be taken as:

For $\theta \leq 5°$ and symmetrical loading (Figure 7.3b): $F_b = 0.7D_{dowel}tf_c$

For $\theta \leq 5°$ and asymmetrical loading (Figure 7.3a): $F_b = 0.3D_{dowel}tf_c$

For $\theta > 5°$ and symmetrical loading: $F_b = 0.4D_{dowel}tf_c$

For $\theta > 5°$ and asymmetrical loading: $F_b = 0.2D_{dowel}tf_c$

Where:

f_c is the allowable bamboo strength parallel to the fibres.

Whenever a connection relies on a single dowel to transfer load from one element to another, a notional split analysis should be undertaken (Clause 5.3) to understand the effect this loss of capacity will have on the overall structure. If there is concern about the effect that a crack would have on the safety of a connection, it is advisable to use more dowels or use radial clamping.

A fourth dowel-induced failure mode, Mode D in Table 7.2 — splitting induced by dowels acting perpendicular to the fibres of the bamboo — has been omitted from ISO 22156. An analytical model for this failure mode has been postulated[7.9]. Mode D can potentially be mitigated, like Mode C, by the use of radial clamps, although this requires experimental validation.

7.4.2 Screw connections placed in tension (withdrawal capacity)

With the exception of the type of detail shown in Figure 7.2c, ISO 22156 does not permit dowels to resist tension perpendicular to the culm wall (i.e., causing a 'withdrawal force'). Recent studies have demonstrated that the screw withdrawal capacity of bamboo can be significant and, like timber, is a function of density. Characteristic values of screw withdrawal strength from *P. edulis*[7.13] and *G. angustifolia*[7.14] of about 30N/mm^2 and 22N/mm^2, respectively, are reported. The 'withdrawal' area is the screw diameter multiplied by the culm wall thickness, $D_{dowel} \times t$. These forces are adequate to secure a screwed dowel reliably.

7.4.3 Dowel requirements

Dowel diameter, D_{dowel}, should not exceed one eighth the culm diameter, $D/8$. For wood screws, D_{dowel}, is taken as 1.1x the root diameter of the screw; this value will be less than the nominal (threaded) diameter of the screw. Dowels should fully penetrate the culm wall and engage the culm wall with their full diameter at all locations. When screws are used, the smaller screw tip must pass through the culm wall so the largest diameter of the screw thread engages the entire culm wall thickness.

With the exception of wood screws, conventional dowels are inserted through predrilled holes that may not exceed 110% of the dowel diameter. Holes for press-fit dowels, such as drift pins or key wedges, should be marginally less than the dowel diameter, although the force required to fit the dowels should not cause damage or splitting to the culm walls. Press-fit dowels should have a modulus similar to the bamboo.

Dowels should be secured from 'slipping' out of their holes. Typically, bolts will be secured with washers and nuts. The nuts should only be 'finger tight' and include a means of ensuring that they cannot loosen with time (lock washers, double nutting, damaging the bolt thread, etc.).

To mitigate splitting the bamboo culm wall, wood and/or sheet metal screws should have pilot holes of 75–100% of the root diameter, which equates to about half to two thirds the nominal diameter. This range has been established experimentally[7.12–7.14] and differs slightly from the guidance contained in ISO 22156, Clause 10.12.2 which requires the pilot holes to be between one quarter and one half the nominal diameter of the screw. The authors of this *Manual* believe that the proposed guidance lessens the risk of splitting. Pilot holes should never exceed the root diameter of the screw. Self-drilling (auger-tip) wood screws not exceeding 6.3mm diameter (#14 screw) may be used without pre-drilling[7.13, 7.14] — larger wood screws will typically need pre-drilling. Large pitch or deep thread screws such as 'concrete screws' or 'thread-forming screws' should not be used[7.13]. The bamboo epidermis is very hard, so it can be difficult to start a self-drilling screw into a rounded culm surface accurately; pilot holes will facilitate easier installation. There are no known studies of screw connections in which the screw diameter exceeds 6.3mm. ISO 22156 does not permit use of driven nails or staples for load-resisting joints because of the high risk of splitting the bamboo culm wall. The only exception being composite bamboo shear walls where the matrix would be fixed with nails (Chapter 8).

As with all connection hardware, consideration of durability of the dowel must be made in design (ISO 22156, Clause 10.9). Chapter 5 of this *Manual* provides more guidance on this.

7.4.4 Dowel arrangement

To avoid potential splitting of the culm wall within a single internode, dowels loaded along the longitudinal axis of the culm (i.e., $0^{o} < \theta \leq 5^{o}$ as shown in Figure 7.3) should be distributed around the circumference of the culm. The radial spacing between parallel gauge lines (Ψ; Figure 7.3c) should exceed $\Psi \geq 115D_{dowel}/D$ (degrees) [$\Psi \geq 2D_{dowel}/D$ in radians].

7.4.5 Dowel connection capacity

ISO 22156:2021 addresses only the capacity of the dowel penetration through the culm wall. Failure modes of the dowel itself are not prescribed. Dowel dimension, material selection and dowel failure checks using other resources are required.

7.5 Splitting and radial clamping of bamboo joints

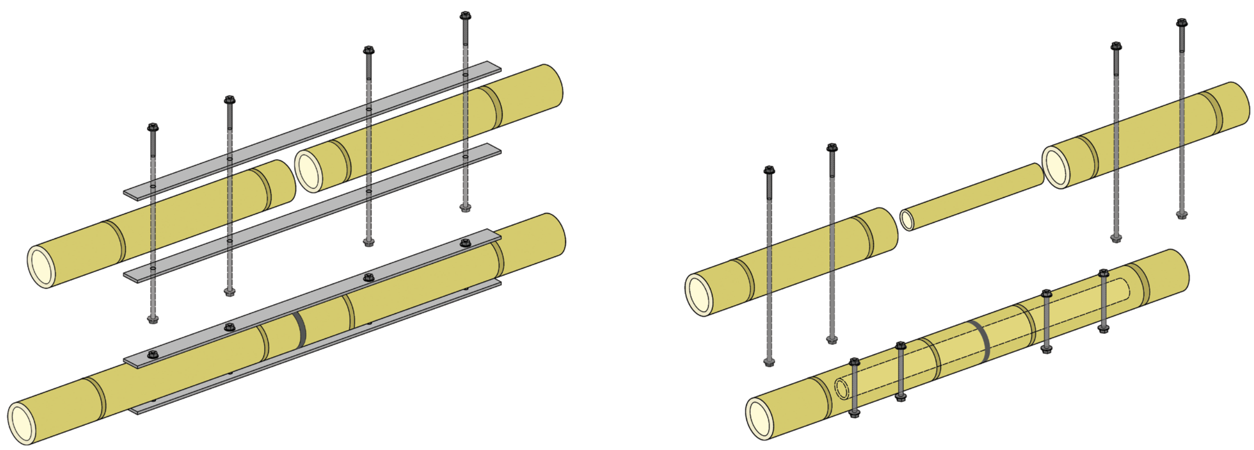
Culm splitting must be mitigated. Splitting is exacerbated by penetrations such as dowels and concentrations of forces at connections. In many joint types, adding radial clamping, characterised as a Group 6 (Appendix A7.1) joint, can 'toughen' a joint against splitting, and also provide residual capacity to connections in some instances if splitting does occur. Radial clamping can also help to engage Group 3 external friction.

Common examples of radial clamping include the use of pipe/hose clamps (jubilee clips), plastic (zip) ties and various forms of lashing. The clamping force is usually prestressed (as far as the clamps permit) but care must be taken not to damage the culm circumferentially. Often, radial clamping is integral to the performance of the connection; therefore, the clamping mechanism must meet the same requirements for durability as the remainder of the joint components. Consideration must be given to relaxation of the clamping force through loosening, drying or creep effects.

7.6 Splice joints

Bamboo splices are a special class of joint in which two culms are connected along their parallel longitudinal axes. Culms are usually spliced by placing elements coaxially and using internal splice spigots or external side plates (Figure 7.5) which are dowelled.

Figure 7.5: Splice joints



a) Coaxial splice joints with metal side plates

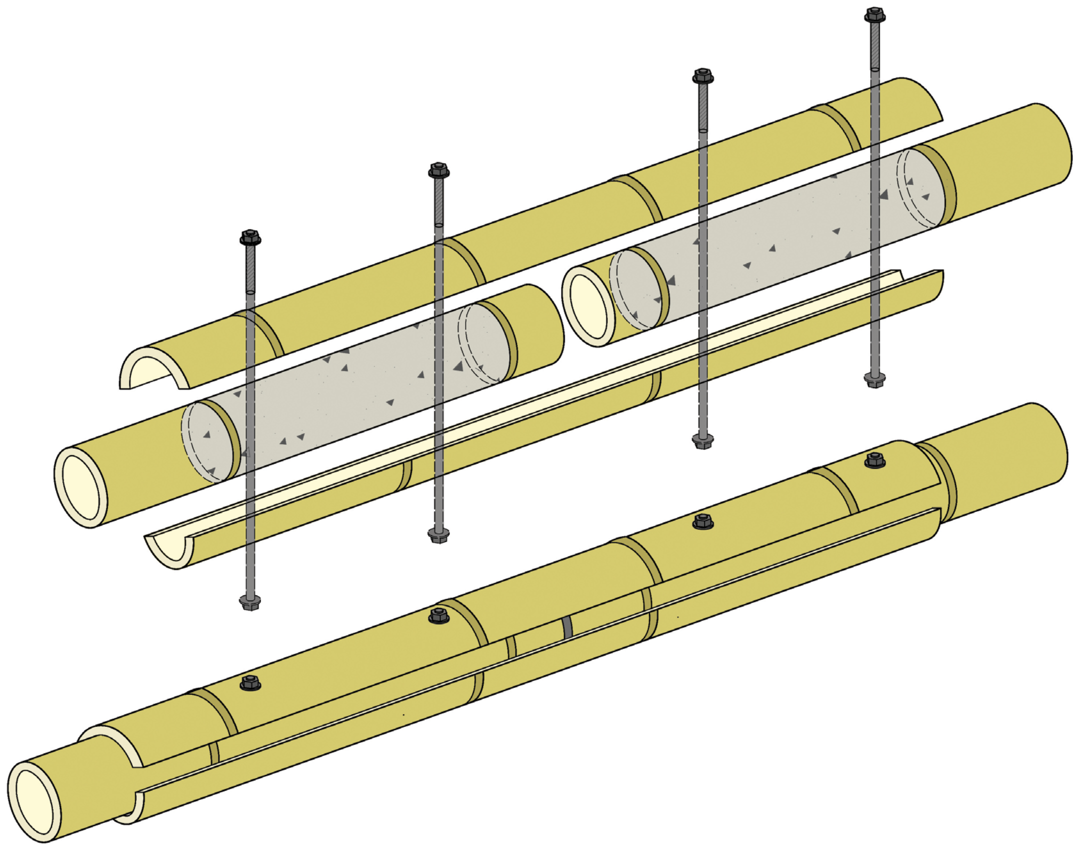
b) Coaxial splice joints with internal spigot

7.7 Mortar-filled culms

ISO 22156 does not specifically address the design of mortar or concrete-filled culm joints. However, these are commonly used and are described in the Colombian NSR-10 Code[7.15]. Filled-culm joints are classified as Group 2 (Appendix A7.1) and may be characterised by complete-joint testing (ISO 22156, Clause 10.2). Correal et al.[7.16] provide an extensive treatment of mortar-filled dowel connections in the context of European Yield Model failure modes.

Filling culms in the joint region is commonly used to enhance transverse bearing capacity of the culm (Group 5 and 6 capacities (Figure A7.1)). Filled joints (Figure 7.6) may also partially resist dowel forces, relieving the demand on the culm wall (Group 4 joints). In such a case, dowels are supported by mortar infill, and forces are transferred to the culm through friction on the inside of the culm and bearing on the internodal diaphragms.

Figure 7.6: Mortar-filled dowelled joint used as a coaxial splice

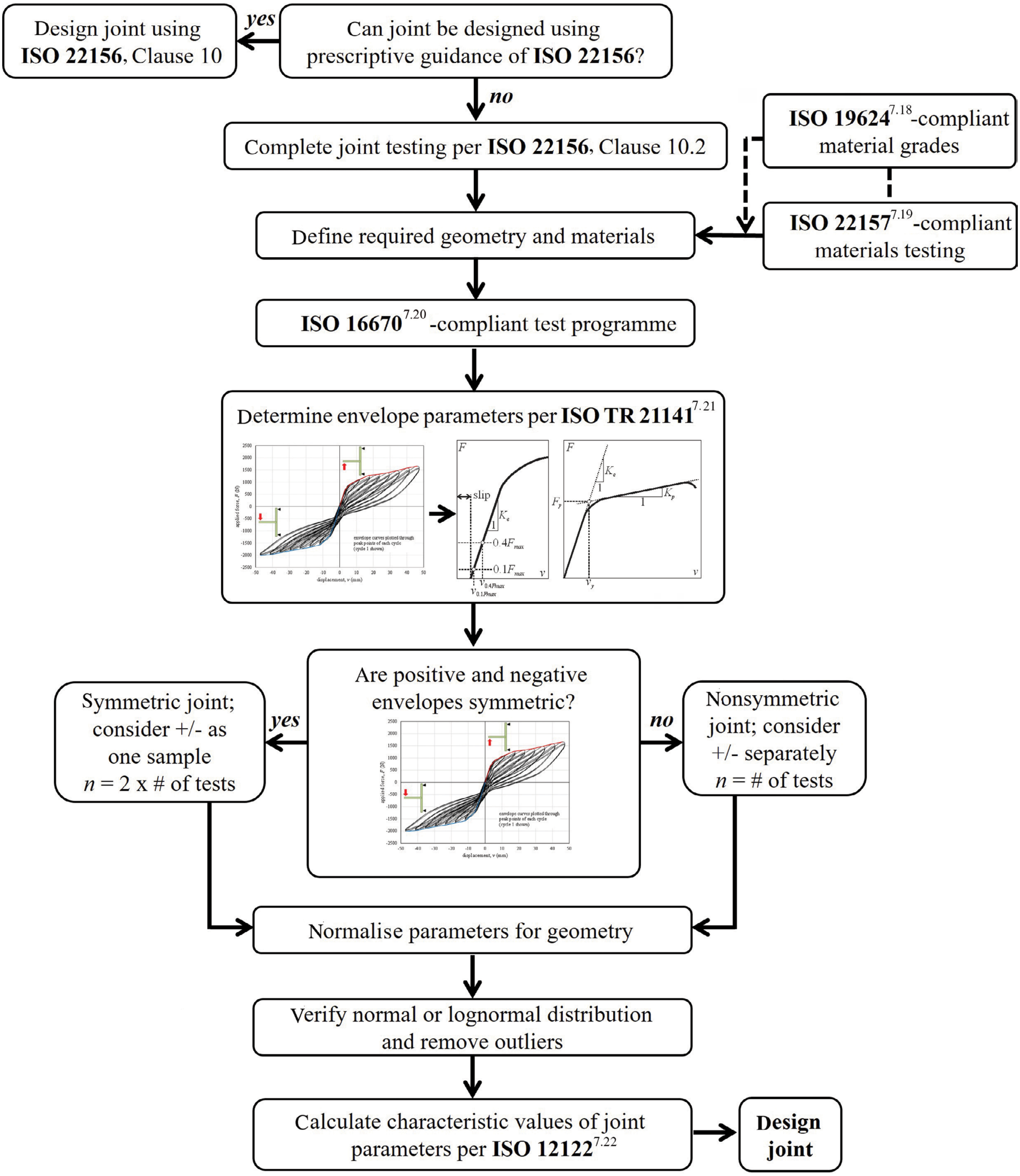


ISO 22156, Clause 10.9.2 provides guidance on the use of flowable infill material — typically a cementitious grout. Infill material must be selected to be dimensionally stable. Excessive shrinkage will diminish the expected performance of the infill as it pulls away from the culm wall. Excessive swelling could result in culm splitting. Ideally, a 'shrinkage-compensating' cementitious grout, having expected expansive strain no greater than 0.001, should be used.

7.8 Joint design by complete-joint testing

Complete-joint testing — defined by ISO 22156, Clause 10.2 — is intended to provide the design capacity and stiffness of the joint. Figure 7.7 summarises the necessary steps and provides the ISO standard references for each stage in a complete-joint testing protocol. Each step is elaborated in Sections 7.8.1–7.8.4. A more extensive discussion, including an example of a complete-joint testing protocol, is presented in Reference 7.17.

Figure 7.7: Flowchart for complete-joint testing protocol described in ISO 22156, Clause 10.2[7.17]



Complete-joint testing requires full-scale testing of joint assemblages having the same geometry, fastener elements and details, and connected bamboo element properties and/or grades as the joint being designed. Joints designed to resist moments should be tested in assemblies in which the connected bamboo members are loaded at their points of contraflexure — so maintaining correct moment-to-shear ratios present in the *in situ* joint.

7.8.1 Complete-joint test protocol

According to Clause 10.2, complete-joint tests should be carried out in accordance with the method prescribed by ISO 16670[7.20]. Few joints are subject to truly static loads. Transient loads and wind and seismic loads result in varying stresses — and often stress reversals in joints. Owing to the relatively light nature of bamboo construction, transient loads will often exceed permanent 'dead loads'. For this reason, the quantification of load characteristics based in quasi-static reversed-cyclic tests was adopted in ISO 22156.

ISO 16670 specifies a reversed cyclic loading protocol based on ultimate displacement (or rotation) of the statically loaded joint, v_c, which is used as a control displacement for cyclic testing (Figure 7.8). The parameter v_c is defined as v_u in ISO 16670; it has been revised here for consistency with ISO/TR 21141[7.21] terminology. The value of v_c is determined using the method described in ISO 6891[7.23]; an initial monotonic test of the same joint geometry. Single complete cycles (one excursion in the positive direction, followed by one in the negative direction) at displacement increments of $0.025v_c$ up to $0.10v_c$ are used to 'shake down' the test specimen. Following this, three complete cycles to $0.20v_c$ are conducted; these are continued at incremental displacements of $0.20v_c$ until failure of the joint. An example of a complete load-displacement or moment-rotation hysteretic response is shown in Figure 7.9.

Figure 7.8: Prescribed ISO 16670 test protocol

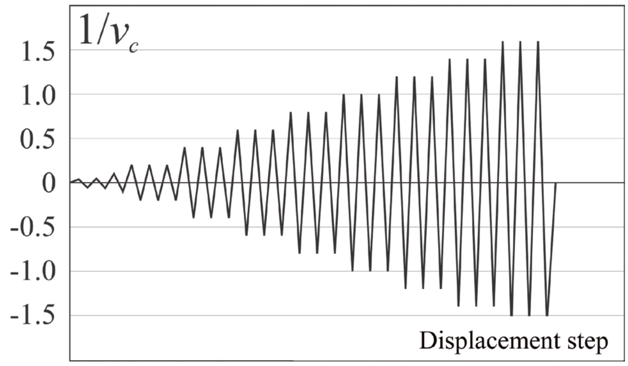
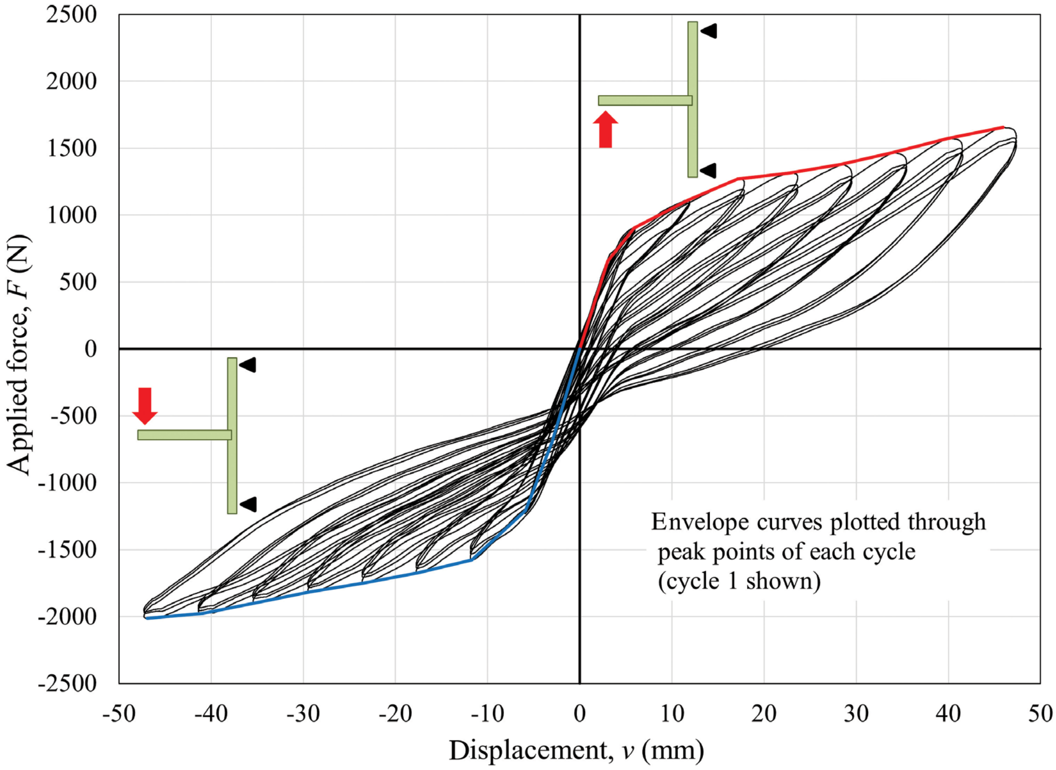


Figure 7.9: Hysteretic curve showing envelope drawn through both positive and negative peaks[7.17]



Since cyclic testing is complex and can be onerous, it is reasonable to argue that for connections that are likely to undergo only small levels of cyclic load, particularly those unlikely to undergo full load reversals (i.e., not change from tension to compression or from positive to negative or *vice versa*), a monotonic test procedure should be adequate, such as the method prescribed by ISO 6891.

7.8.2 Determining joint properties from complete-joint testing

Joint properties are determined based on ISO/TR 21141. Envelope curves (often called 'backbone curves') are drawn through the peaks of the first cycle at each displacement (Figure 7.9). From these envelope curves, properties of the joint are established using ISO/TR 21141.

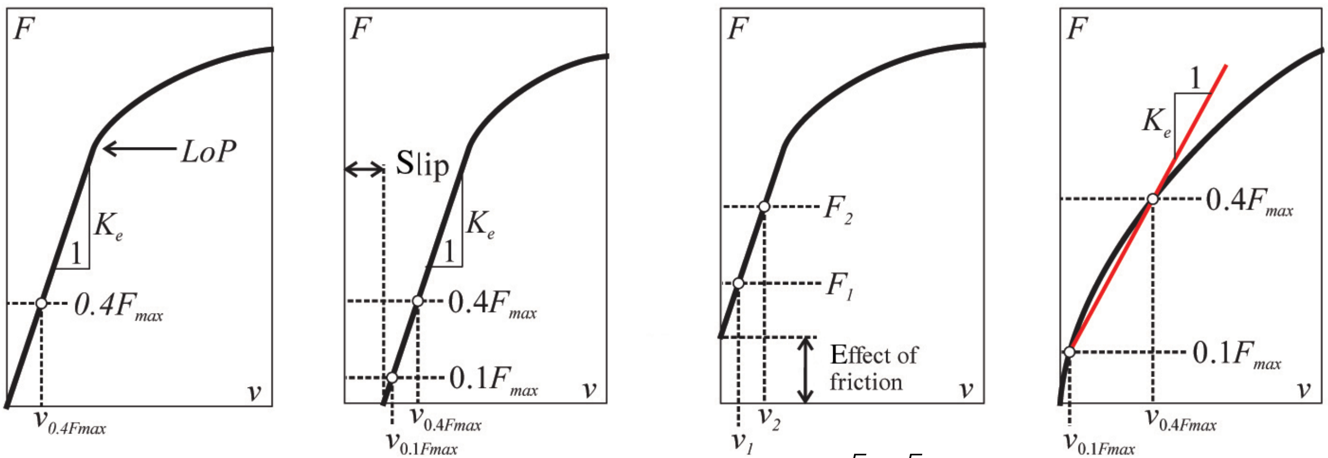
ISO/TR 21141 permits a number of different methods for calculating joint properties; the selection of which is dependent on the nature of the envelope curve (Figures 7.10 and 7.11). The concepts for derivation of these properties contained in ISO/TR 21141 are transferrable to monotonic tests undertaken in accordance with ISO 6891.

The **maximum load capacity** of the joint, F_{max}, is the greatest load resisted. The ultimate (or failure) load, F_u, and corresponding displacement, v_u, is determined as the point on the envelope at which the post-peak capacity falls to $0.8F_{max}$. For joints that fail in a brittle manner, v_u is determined at the load at which failure initiates, typically $F_u = F_{max}$.

For assemblies exhibiting 'excessive deformation', ISO/TR 21141 describes an alternative failure criteria corresponding to a "*displacement 30mm for joints and rotation or shear deformation angle 1/15 rad. for assemblies*".

Elastic stiffness of a joint, K_e, is determined differently depending on the nature of the envelope curve. Four methods are shown in Figure 7.10a–d.

Figure 7.10: Calculation of joint stiffness, K_e, based on ISO/TR 21141[7.17]



$$K_e = \frac{0.4F_{max}}{v_{0.4Fmax}}$$

a) Ideal linear behaviour through limit of proportionality (LoP)

$$K_e = \frac{0.4F_{max} - 0.1F_{max}}{v_{0.4Fmax} - v_{0.1Fmax}}$$

b) Linear behaviour following initial slip

$$K_e = \frac{F_2 - F_1}{v_2 - v_1}$$

$$F_2 - F_1 \geq 0.3F_{max}$$

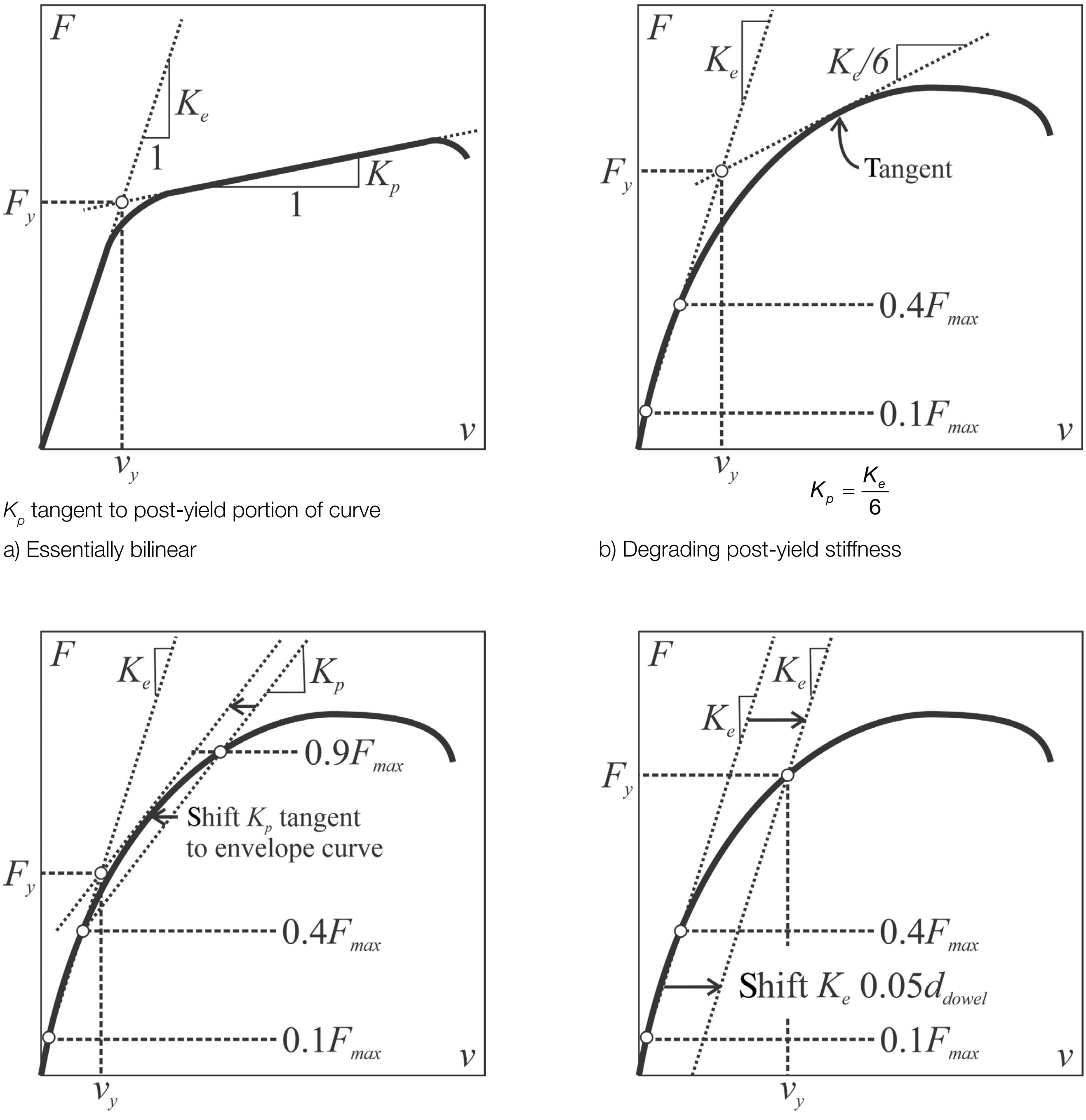
c) Linear behaviour with initial friction

$$K_e = \frac{0.4F_{max} - 0.1F_{max}}{v_{0.4Fmax} - v_{0.1Fmax}}$$

d) No linear behaviour

The **yield capacity** of a joint, F_y, is determined from the envelope curve as the intersection of a line having a slope equal to elastic stiffness of the joint, K_e, and a second line having an idealising post-peak stiffness, K_p, tangent to the post-yield portion of the curve. Three approaches are permitted as described in Figure 7.11a–c. For joints dominated by dowel-type fastener behaviour (Figure 7.11d), a 5% offset of the elastic stiffness defines F_y. The yield displacement, v_y, is that corresponding to F_y.

Figure 7.11: Calculation of joint yield point (F_y, v_y) based on ISO/TR 21141[7.17]



K_p tangent to post-yield portion of curve

a) Essentially bilinear

$$K_p = \frac{K_e}{6}$$

b) Degrading post-yield stiffness

$$K_p = \frac{0.9F_{max} - 0.4F_{max}}{v_{0.9Fmax} - v_{0.4Fmax}}$$

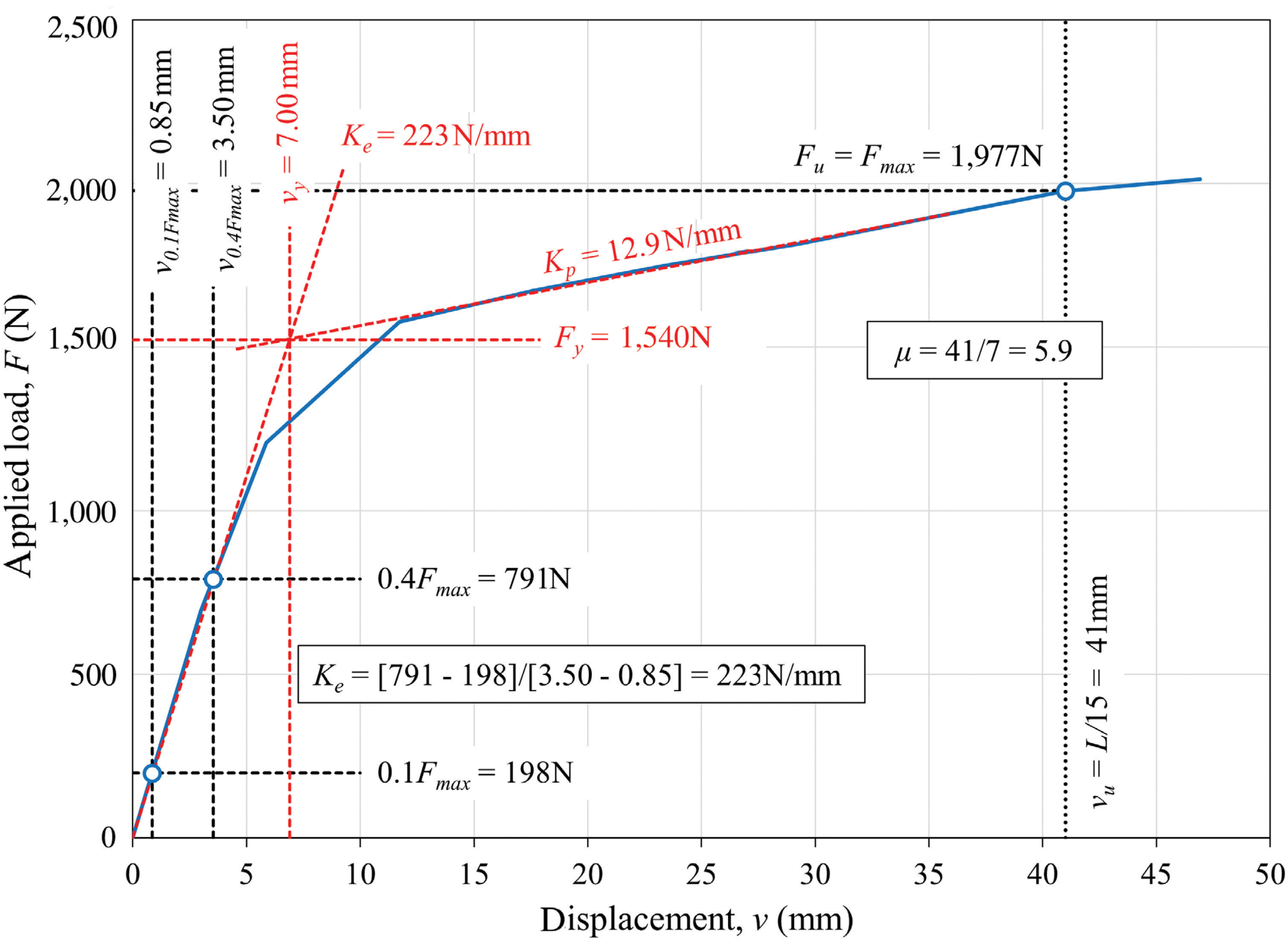
c) Degrading post-yield stiffness

d) Connection dominated by dowel behaviour

The **joint ductility factor** is given as the ratio of ultimate to yield displacement or rotation, $\mu = v_u/v_y$. ISO 22156, Clause 10.6 limits the use of marginally ductile joints. Joints in load-bearing structures should have $\mu \geq 1.25$ (i.e., exhibiting nominal ductility). Joints in moment-resisting connections should have $\mu \geq 2.0$ and those that are part of the main seismic lateral load-resisting system should have $\mu \geq 2.5$.

An example of determining joint properties from an envelope curve (negative cycles envelope shown in Figure 7.9) is shown in Figure 7.12. In this example, the envelope is essentially linear to its limit of proportionality (LOP) and conforms to the cases shown in Figures 7.10a and 7.11a. When determining envelope curve parameters, the original (native) data is used — applied load vs. displacement in the example shown. The envelope curves themselves should not be 'processed' to represent derived values such as moment and curvature.

Figure 7.12: Envelope curve of negative cycles shown in Figure 7.9 with necessary calculation parameters[7.17]. Joint parameters are: F_y = 1,540N, K_e = 223N/mm and μ = 5.9



7.8.3 Determining characteristic joint properties for design

Characteristic values of joint properties used for design are determined by the methods of ISO 12122-5[7.24] or ISO 12122-6[7.25] as appropriate. The calculation of characteristic values from resulting test data is prescribed by ISO 12122-1[7.22]. Characteristic capacities, F_{yk}, are defined as the 5th percentile characteristic value expressed with 75% confidence. Characteristic stiffnesses, K_{ek}, are defined as mean value expressed with 75% confidence. Discussion of the calculation of characteristic values is given in Appendix A3.3.

Conducting joint test programmes having large sample sizes (n > 30) are typically impractical. ISO 16670[7.20] recommends that a minimum of six replicate specimens should be tested. With this smaller sample size, the non-parametric approach of calculating characteristic values promulgated by ASTM D2915[7.26] (as cited in ISO 12122-1 and described in Appendix A3.3) should be used.

Additionally, there are some nuances of complete-joint testing to highlight:

- Test specimen geometry may be symmetric or nonsymmetric; that is joints may have different positive and negative behaviours of relevance when tested in a cyclic manner. If a joint is expected to have symmetric behaviour (such

as that shown in Figure 7.9) the positive and negative envelope curves may be considered separately (each test providing two data points), doubling the sample size. However, a statistical test, such as an unpaired t-test[7.27] should be conducted to verify that the behaviour is indeed symmetric (i.e., statistically the same in both directions).
- ISO 16670-compliant test protocols will report applied load vs. displacement results. Unless test specimen geometry is very tightly controlled, these may need to be normalised to account for the variation inherent in bamboo geometry; by converting to stresses the variability of the data is reduced. For example, moment applied to a joint is one order removed from applied load, being affected by specimen geometry. Extreme fibre stress is two orders removed, being affected by moment and culm geometry. By normalising by specimen dimension (measured lever arm length in this case) and culm geometry (measured culm diameter), a reduction in measures of experimental variability is likely[7.17].
- As in any experimental test programme, statistical outliers should be identified and assessed. Care should be taken to not simply exclude outliers without consideration of their source. Outliers may represent a rare but possible limit state that should not be excluded. Outlier tests (Grubb's test is likely sufficient[7.27]) should be conducted on normalised test data rather than the original applied load vs. displacement results.
- The definitions of characteristic properties assume that experimentally-determined values follow a normal (Gaussian) or lognormal distribution. This should be verified, typically at a significance level of 0.05. The Anderson-Darling test for normality[7.27] is easily conducted on smaller data sets, although the Kolmogorov-Smirnov[7.27] is recommended by ISO 12122-1[7.22]. Characteristic properties from samples not found to have normal or lognormal distribution can be determined using a parametric method (Appendix A3.3), although these typically require a larger sample size.

7.8.4 Joint design parameters

Like member design, joint design capacity, F_y, is determined from the characteristic capacity, F_{yk}, modified by the load duration factor, C_{DF}, described in Section A3.6. For joint design, the factor of safety, FS_j is a function of joint ductility, μ:

$$F_y = F_{yk}\frac{C_R C_{DF}}{FS_j} \qquad \text{Equation 7.5}$$

Where:

FS_j = 3.0 for $\mu < 1.5$; FS_j = 2.0 for $\mu \geq 4.0$ and FS_j = 2.5 otherwise.

When ductility is unknown, joints should be assumed to be nominally ductile; i.e., μ = 1.25. (ISO 22156, Clause 10.4). Ductility is defined as the ratio of ultimate to yield displacement or rotation: $\mu = v_u/v_y$

Similarly, joint stiffness is determined from the characteristic stiffness, K_{ek}, as:

$$K_e = K_{ek} C_{DE} \qquad \text{Equation 7.6}$$

Where:

C_{DE} = modification factor accounting for Service Class and the expected duration of load (Section A3.6).

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Appendices

A7.1 Classification of bamboo joints

This Appendix summarises the joint classification approach[A7.1] on which ISO 22156, Clause 10 was founded. This background is useful in guiding the qualification of joint types intended to comply with the requirements of ISO 22156.

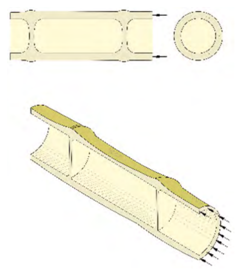
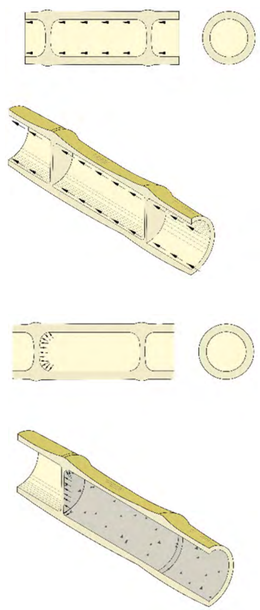
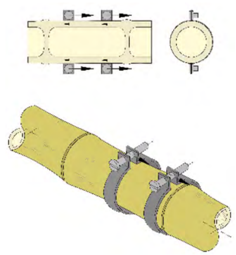
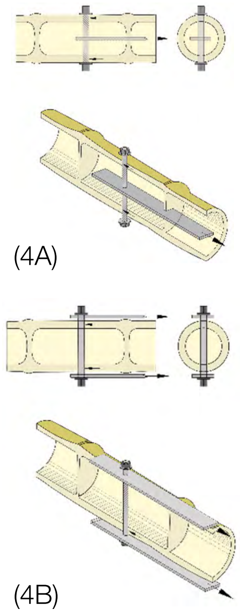
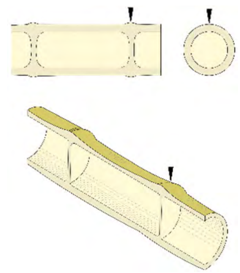
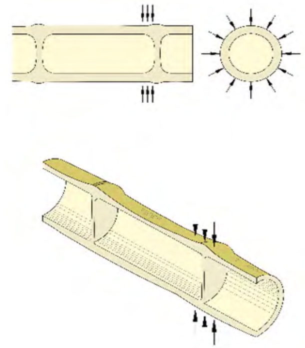
The method by which the connecting elements transfer force to the culm imparts different stress demands on the culm. These are classified based on:

- Method of force transfer: Compression along the fibres or perpendicular to the fibres, tension, friction, shear or bearing stress.
- Position of the connector: Attached to the outside of the culm or the inside of the culm cavity. Attached parallel or perpendicular to the fibres.
- A ‘connection’ is between one bamboo culm and its connector or supporting base, while a ‘joint’ is the collection of connections necessary to affect the desired flow of forces through the structure. For example, a joint between two bamboo culms can consist of one (bamboo 1 to bamboo 2) or two (bamboo 1 to connector A and connector A to bamboo 2) connections.

Based on these principles, bamboo connections can be divided into six main groups as shown in Figure A7.1. Most bamboo joints use a combination of these basic principles. Group 1 is primarily to transfer compression while Groups 2, 3 or 4 are used to transfer tension.

Most bamboo joints use a combination of connection types (Groups). Seventeen combinations of Groups 1–4 have been identified in known forms of bamboo connections[A7.1] (Figure A7.1). Group 5 cannot be readily combined with other connection types. Combinations including Group 6 are typically only practical with Group 3 and tend to rely on the enhancement of friction forces (Group 3) possible using the pretensioning effect of Group 6. Other combinations with Group 6 may work in parallel but are primarily two separate connections. Representative examples of many of these connection types are illustrated in Reference A7.1.

Figure A7.1: Bamboo joint classification informing ISO 22156

Group 1: Transferring compression through contact with the whole section	**Group 2:** Transferring force through friction on the inner surface or compression to the diaphragm	**Group 3:** Transferring force through friction on the outer surface	**Group 4:** Transferring force through bearing stress and shear to the bamboo wall from perpendicular elements (dowels) connected from inside (4A) or outside (4B) the culm	**Group 5:** Transferring force perpendicular to the fibres	**Group 6:** Transferring radial compression to the centre of the culm through shear and circumferential stress perpendicular to the fibres
					

A7.2 Validation of component capacities

ISO 22156, Clause 10.3 states that the component capacities approach should only be used for joint types that are "*well understood and can be reliably predicted*", and that "*this approach should be validated by complete-joint testing*". Recognising that at present the ISO 22156-prescribed component capacities can be conservative, this Appendix proposes an approach that avoids the need to undertake at least six tests for a connection to be validated. The steps are written assuming a dowelled joint (ISO 22156, Clause 10.12), but the principles also apply for other types of joint.

Step 1: Build a test specimen that is representative of the dowelled connection proposed. Record all relevant properties for the determination of F_b, e.g., D, D_{dowel}, t and s.

Step 2: Determine design value of the joint capacity, $F_{b,design}$, for the test specimen from Clause 10.12.1 assuming C_{DF}, C_T and C_R = 1.0 when determining f_c, f_v and $f_{t,90}$, but using the relevant FS_m (Chapter 3).

Step 3: Test the specimen in accordance with ISO 6891[A7.2] or ISO 16670[A7.3] and record F_y and μ as described in Section 7.8.2.

Step 4: Based on the experimentally-determined ductility, μ, determine the FS_j (this is the same relationship as used for Equation 7.5):

$$FS_j = 3.0 \text{ for } \mu < 1.5$$

$$FS_j = 2.5 \text{ for } 1.5 \leq \mu < 4.0$$

$$FS_j = 2.0 \text{ for } \mu \geq 4.0$$

Step 5: If Equation A7.1 is satisfied, the single test capacity is sufficiently greater than the component capacity and no further validation is required. If the ratio in Equation A7.1 exceeds 1.0 a full suite of complete-joint testing is required (i.e., six tests). In the latter case, characteristic joint capacity may be determined to exceed $F_{b,design}$.

$$\frac{F_{b,design}}{0.5F_y / FS_j} \leq 1.0 \qquad \text{Equation A7.1}$$

The $0.5F_y$ term in Equation A7.1 is equivalent to the characteristic strength calculated with K x COV = 0.5 in Equation A3.2.

References

A7.1 Widyowijatnoko A. and Harries K. A. 'Chapter 20: Joints in Bamboo Construction'. *Nonconventional and Vernacular Construction Materials*, 2020, pp561–596. DOI: https://doi.org/10.1016/B978-0-08-102704-2.00020-2.

A7.2 International Standards Organization. *ISO 6891:1983: Timber structures — Joints made with mechanical fasteners — General principles for the determination of strength and deformation characteristics*. Geneva: ISO, 1983.

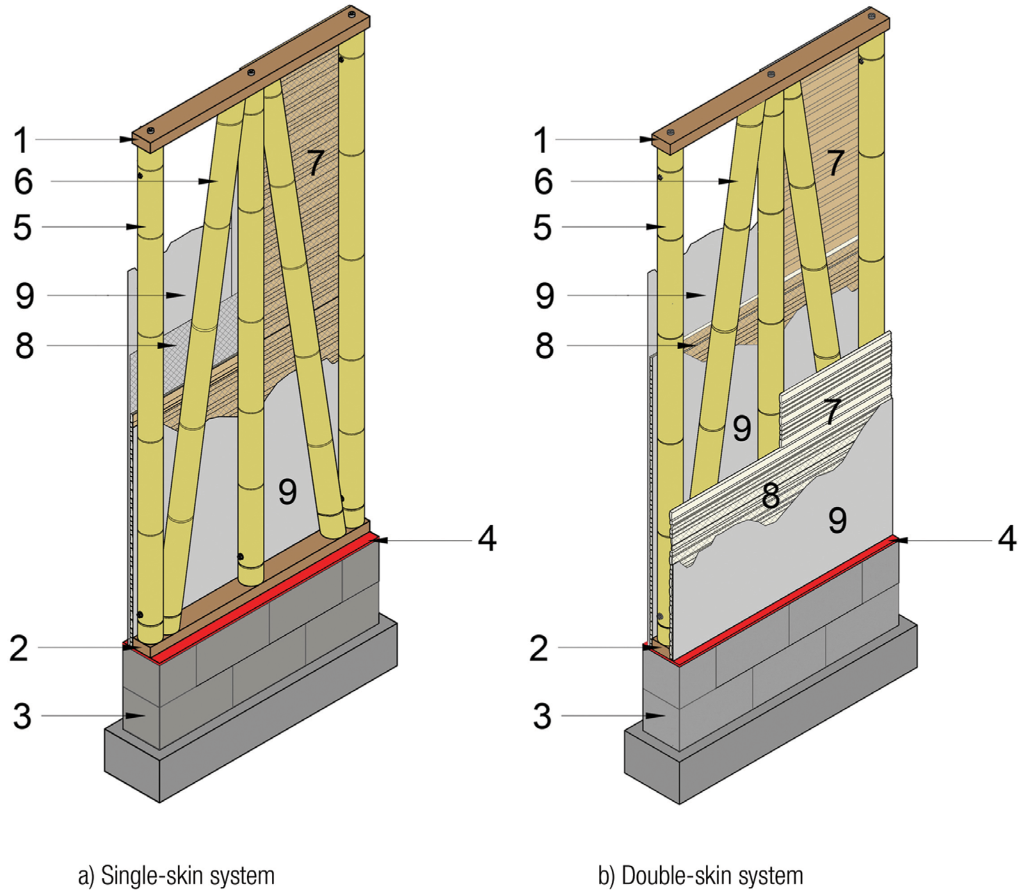
A7.3 International Standards Organization. *ISO 16670:2003: Timber structures — Joints made with mechanical fasteners — Quasi-static reversed-cyclic test method*. Geneva: ISO, 2003.

8 Composite bamboo shear walls

8.1 Introduction

Composite bamboo shear walls (CBSW) are a modern construction system consisting of a frame, a matrix and a finishing render. The system forms structural shear walls which can be used to resist gravity, wind and seismic loads. CBSW panels consist of a frame made of large diameter (≥75mm) bamboo and/or timber, onto which a matrix of different materials such as flattened bamboo (*esterilla*), bamboo laths, expanded steel mesh, small diameter bamboo or wild cane is fastened (Figure 8.1).

Figure 8.1: Typical composite bamboo shear wall components in both single- and double-skin systems



Key

1 Head plate (typically timber)
2 Sole plate (typically timber)
3 Upstand on concrete or masonry
4 Damp-proof membrane
5 Bamboo studs (timber can be used)
6 Bamboo bracing (bracing is optional)
7 Wall matrix (may consist of strip bamboo, flattened bamboo, small-diameter bamboo or cane, or galvanised metal lath)
8 Galvanised wire mesh (nailed or stapled to matrix)
9 Cement mortar or lime cement render

Walls are finished with cement render to form shear walls. Over the past 30 years, at least 10,000 one- and two-storey homes with modern CBSW panels have successfully been constructed in countries including Costa Rica, Colombia, India, Nepal, Ecuador, Peru, Mexico, El Salvador and the Philippines[8.1] (Figures 8.2 and 8.3). When properly designed and built, they have demonstrated their effectiveness as an affordable, hazard-resilient, low-carbon and durable form of housing. The system is now codified in the Colombian, Ecuadorian (formally adopted by the *Norma Ecuatoriana de la Construcción*) and Peruvian structural standards, as well as in ISO 22156[8.2–8.5]. Appendix A8.1 provides more details on different CBSW systems.

CBSW panels are an improved-vernacular system, based on the traditional Latin American earthen-based wattle-and-daub system known as 'bahareque' or 'quincha', but enhanced and made compliant to modern codified standards of durability and seismic performance, using modern materials and construction techniques. This is done by:

- Preservative-treating the bamboo (or timber) frame and wall matrix against insect attack.
- Replacing the mud plaster with a more durable and stronger cement-based mortar.
- Engineering the connection details[8.1].

Figure 8.2: Examples of CBSW homes around the world

a) CBSW house in Colombia, built in 2001

b) CBSW house in the Philippines, built in 2021

c) CBSW house in Costa Rica, built in the 1990s

d) CBSW house in El Salvador, built in 2012

Figure 8.3: Interior view of single-skin CBSW properties in the Philippines

Variations of this technology exist around the world, with different names. For example, in Colombia it is called '*bahareque encementado'* (cemented bahareque), while in the Philippines it is called 'cement bamboo frame technology' (CBFT). The umbrella name for the technology that encompasses all these variants is 'composite bamboo shear walls' (CBSW).

The system is currently most appropriate for contractor-built low-rise (typically one–two storey) housing projects in tropical and sub-tropical lower- and middle-income countries where bamboo grows, with a focus on rural and peri-urban areas. This is because urban areas typically require taller and denser housing, and there is very limited precedence for CBSW housing above two storeys.

This chapter provides an overview of CBSW technology and general design requirements in terms of durability, load path, structural limitations and determining capacities. Appendix A8.1 provides more detail, offering additional minimum material requirements.

8.2 General structural performance

This Section describes the structural performance of well-designed CBSW systems that satisfy ISO 22156 requirements[8.5].

8.2.1 Strength

Low-rise CBSW housing has been successfully designed to resist earthquakes and strong winds, even in the world's most hazardous-prone regions. The frame, matrix and cement mortar render have been shown to behave compositely, acting as a shear wall in-plane. The walls are also relatively light — with a mortar thickness of 25–40mm (depending on the matrix), the weight of the walls is typically less than 1kN/m^2 on elevation (which is around 1/4 to 1/5 of the mass of a conventional confined masonry wall). The resulting low seismic mass is advantageous in earthquakes. For high wind zones, the typical mass of CBSW housing is greater than a conventional light frame timber building, although strong foundation tie-downs are still likely to be required.

Average in-plane ultimate shear strengths determined from testing vary from 10–15kN/m (i.e., 10–15kN per linear metre of wall) for bamboo-framed systems with single-skin *esterilla* (flattened bamboo) (Figure 1.3), 20–30kN/m for systems with double-skin *esterilla* (on both sides of the frame) and 40kN/m for single-skin timber-framed systems with wild cane[8.6]. Design strengths would be lower, as the designer would need to determine the characteristic strength from the dataset and further reduce these by an appropriate factor of safety. In general, timber-framed systems have higher strengths than bamboo-framed systems, and systems which bond the cement mortar better to the matrix have higher strengths (such as those using wild cane or steel mesh, rather than *esterilla*). Diagonal bracing has been shown to increase the stiffness and post-yield in-plane strength of CBSW, however it reduces the ductility. Appendix A8.1 provides more details on different CBSW systems. More information on in-plane shear capacity is available in Appendix A8.2.

Out-of-plane, the studs and matrix can be designed to resist required demands, and when fixed back to the matrix, the render has been demonstrated not to spall[8.7].

8.2.2 Ductility and seismic performance

CBSW systems have been tested in-plane under monotonic and cyclic loading to destruction, and several full-scale shake-table tests have also been conducted. These tests suggest that the system may demonstrate a displacement ductility of at least 2–3, and up to 10 for some systems[8.7]. However, since in-plane shear test data is still relatively limited, CBSW systems designed following ISO 22156 are limited to a seismic modification/behaviour factor of 1.5; this corresponds to systems having nominal ductility (Chapter 4). CBSW systems designed and detailed in accordance with the *Norma Andina*[8.3] are permitted to have a response modification factor R = 2.0. The increased value is justified because the *Norma Andina* refers to one specific sub-system of CBSW and is more explicit regarding minimum detailing and design rules.

Where national building standards do not explicitly provide out-of-plane seismic demands, ASCE 7–22, Clause 12.11.1[8.8] can be used to determine the load applied to the wall.

8.2.3 Durability

Traditional bahareque housing has been shown to last over 100 years when well-designed and maintained. Modern CBSW housing can achieve a design life equal to well-designed and well-built conventional construction materials, such as reinforced concrete and steel. As discussed in Chapter 5, a 50-year design life is also recommended for CBSW systems and can be achieved through good design[8.9]. Chapter 5 requirements for durability should also be applied to all CBSW designs, specifically:

- All bamboo components should be treated with boron or another safe and appropriate chemical.
- All timber components should be equally treated or alternatively made from naturally durable wood species.
- Timber and bamboo must be kept dry through good design details.
- Steel connections should be painted, galvanised or of stainless steel.
- Special protection is required for CBSW panels in internal areas where water risks are high, such as adjacent to sinks and showers. Local protection against water such as ceramic tiling, in conjunction with allowing the inside of the wall to be ventilated, helps to reduce this risk. In general, no timber or bamboo should be exposed to showers or sinks, and the CBSW panels facing sinks and showers should be non-structural.

Bamboo forming part of external CBSW rendered on the outside and exposed to driving rain can be classified as Use Class 3.1 (Chapter 5), provided these recommendations are followed:

- The wall matrix must be fitted to the outside of the structural frame and not in-line (Figure 8.4).
- The cement render satisfies requirements of Appendix A8.1.3 and is painted (as paint significantly reduces permeability of mortar).
- The wall is detailed to avoid water traps. Render should be smooth with no concave surfaces where water could enter. Particular attention should be paid to architectural details and at the frame-to-upstand interface (Figure 8.5).
- The wall is situated on an elevated upstand at least 200mm high, ideally 400mm. This reduces moisture that the wall is exposed to from the ground, driving rain and splashback.
- A continuous durable damp-proof membrane (DPM) is provided at all interfaces between the structural upstand and the beginning of the timber/bamboo wall. The detail here should be carefully designed so that water does not pond on top of the DPM. Small penetrations through the DPM to permit shear and vertical fixings are permitted, provided these are kept to the minimal.
- Walls are regularly maintained, cracks infilled and repainted.
- The roof over the wall has an adequate slope (at least 15°, ideally 20°), is made from a durable material, has a low risk of leaks and is properly maintained.
- A downwards facing roof overhang (over the wall) of at least 0.5m, ideally 1m, is provided.
- The primary bamboo/timber frame is permitted to 'breathe' internally by either having it fully exposed internally (Figure 8.3), or having it exposed within a ventilated cavity (e.g., by an opening between each pair of studs, with a wire mesh to prevent insects entering).
- The houses are single storey. There is less precedence regarding long-term durability performance of two-storey CBSW housing, so it is more difficult to guarantee a 50-year design life for these. Additional details to reduce water exposure of the exposed external walls, such as by incorporating additional overhangs at floor levels (Figure 8.6) are likely to give the designer more confidence that two-storey housing can also achieve a design life closer to 50 years. The additional overhang also has the added benefit that it will result in a cooler internal environment.

Figure 8.4: The exterior wall matrix protects the bamboo from rain and sun, providing better in-plane shear strengths

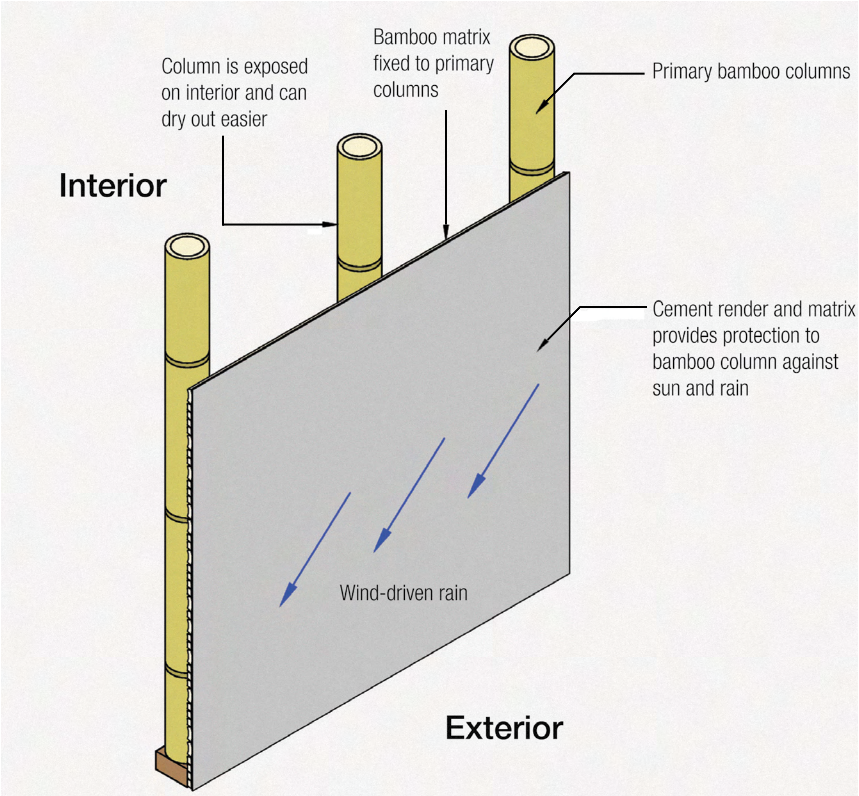


Figure 8.5: The wall must be carefully detailed to avoid water traps

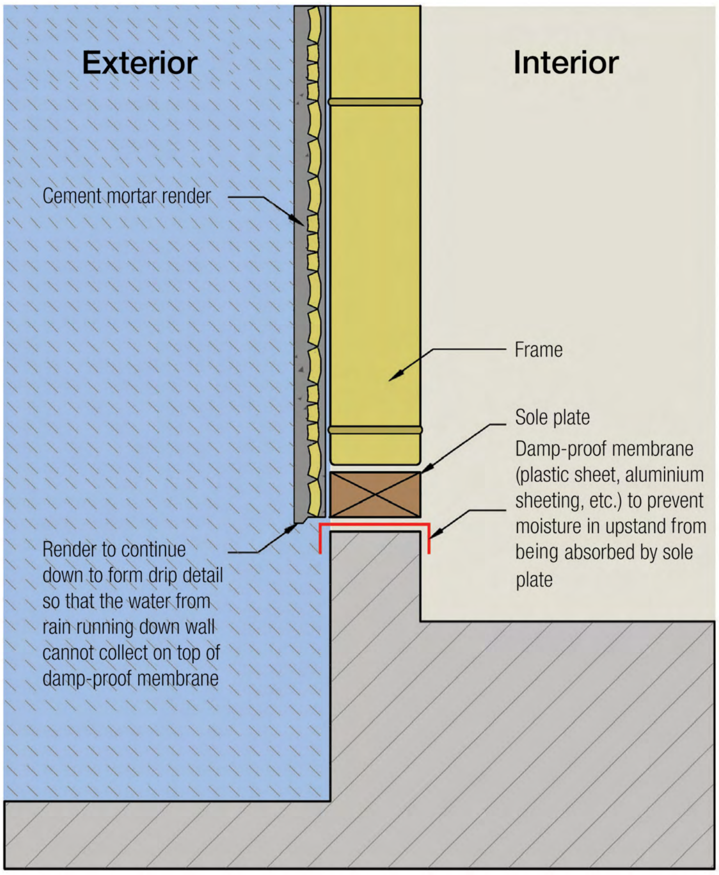
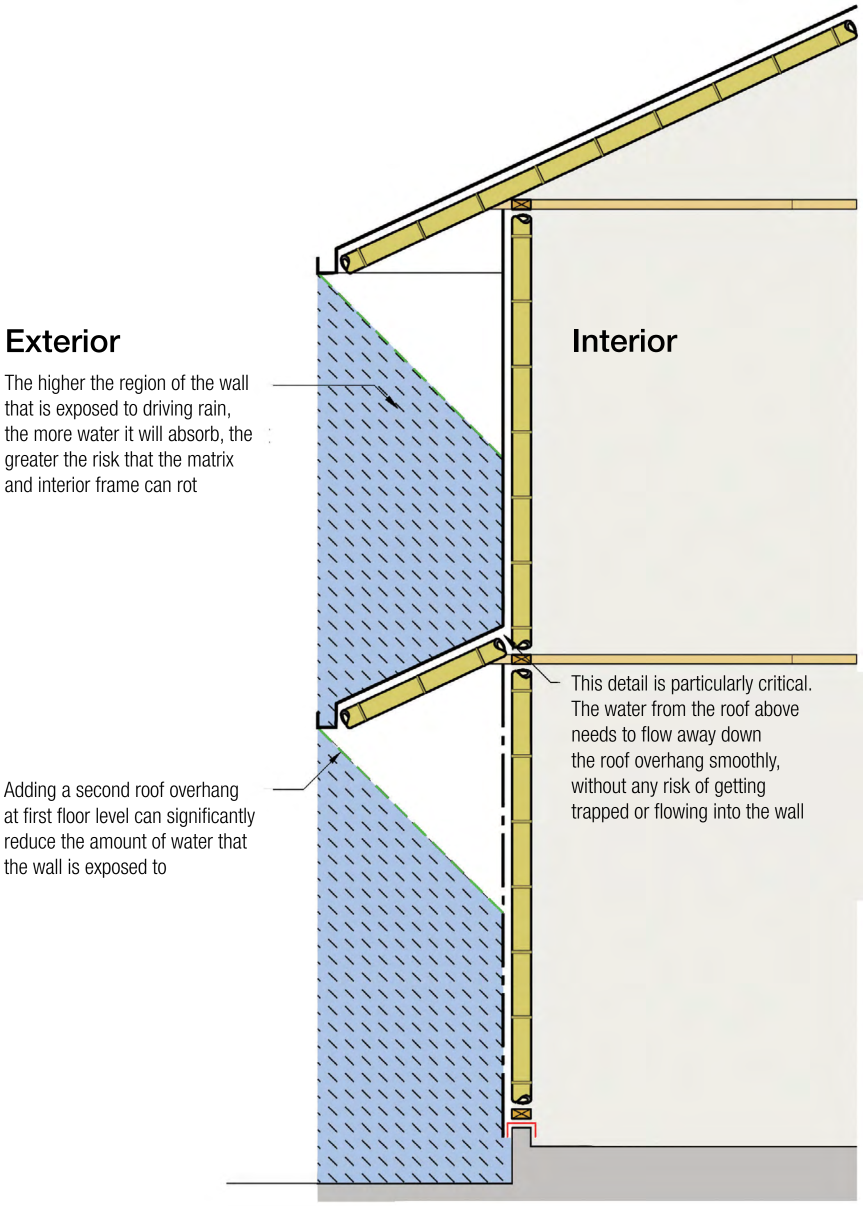


Figure 8.6: Additional considerations for two-storey housing



Where any of these recommendations are not met, it is more difficult to guarantee a 50-year design life, and it is possible that the bamboo elements within the external walls may need to be classified as Use Class 3.2. Recent evaluations of CBSW housing that does not properly consider all of this criteria have unfortunately demonstrated reduced design life.

8.2.4 Sustainability

CBSW housing has been shown to be superior to many other forms of modern permanent alternatives in terms of sustainability and environmental impact, especially housing using materials such as masonry and concrete[8.10, 8.11]. The two main reasons for this are that the bio-based materials used have significantly lower carbon footprints and emissions from production and transportation compared with conventional construction materials such as reinforced concrete, and because the use of bamboo and timber serves as a carbon sink[8.12]. A study of construction in the Philippines[8.13] assessed the environmental impact of CBSW systems and compared them to houses built to the same standard using conventional masonry. The results showed that CBSW have 45% of the embodied carbon of a conventional house, with the major contributors to the environmental impact being the concrete foundation and cement render. A similar study focusing on El Salvador[8.14] compared the environmental impact of timber-framed CBSW housing in El Salvador with conventional reinforced masonry, and found that the CBSW had 53% of the global warming potential of the masonry house when including biogenic carbon.

The environmental impact of any CBSW housing system can be minimised by sourcing materials locally, sustainably sourcing bamboo and timber and ensuring the design life of the house is as long as possible.

8.2.5 Behaviour in fire

The CBSW system provides a convenient way to protect the naturally-susceptible timber and bamboo from fire. Using 15mm of cement mortar render can provide a nominal level of protection, while increasing this to >25mm on one side (while leaving 15mm on the other side) may provide a 30-minute fire resistance rating against fire compartmentation[8.15]. Preliminary tests have also suggested that 20–25mm mortar both sides could potentially achieve 60 minutes[8.16], but further investigation is required to validate this.

In general, bamboo and timber elements should not be exposed to sources of naked flames. This can be achieved either by reducing or removing the hazard (e.g., promoting electric rather than gas hob cookers) or protecting exposed timber/bamboo with cement render or fire-rated gypsum plasterboard[8.15].

National building standard requirements should always be followed when considering designing for fire.

8.3 Structural limitations

These structural limitations should be followed for all CBSW systems. They are based on a combination of precedence, good practice seismic design requirements, good practice timber design requirements and engineering judgement:

- Wall and column transfers in CBSW buildings are not permitted — i.e., all columns and walls must be continuous from roof to foundation level (Figure 8.7).
- Panels should have a height-to-length ratio of no greater than 3:1 (greater than this and the wall flexural stiffness is likely to be very low) (Figure 8.7).
- Minimum lengths of individual structural CBSW panels that contribute to in-plane loading are 1m (Figure 8.7). Lengths below this are permitted, but should not be assumed to contribute structurally.
- Braced CBSW systems should not exceed three storeys and 9m in height. Unbraced CBSW systems should not exceed two storeys and 7m in height. This is because precedence of building with these systems is limited and bracing provides more redundancy and higher stiffness.
- The wall matrix is fixed to the outside of the primary frame and is continuous across adjacent panels (Figures 8.4 and 8.7). This provides a much stronger matrix-to-frame connection, and is the basis for all testing and validation of this system following ISO 22156 and the Colombian and Ecuadorian building codes[8.2,8.3]. In addition, for external walls, fixing the matrix to the outside of the primary frame protects the frame against rain and sun. Matrices that are placed in the centreline (i.e., between culms) of the frame are not permitted, as the frame is exposed to the sun and rain. This system is also untested and the matrix has no reliable connection to the frame for in-plane shear.
- The wall matrix panel may be single-skin (matrix applied to one side of studs only) or double-skin (matrix applied to both sides of studs). The mortar render may be applied to one or both sides of the matrix.
- On every floor on plan, in each orthogonal direction (Figure 8.8):
    - In-plane walls should be evenly distributed throughout the building to avoid torsional irregularities on plan.
    - At least two individual shear walls are required.
    - At least two parallel lines of shear walls are required.
    - A minimum total length of 6m of in-plane shear wall is required.
- The perpendicular spacing between individual lines of structural CBSW panels is limited by the diaphragm design — i.e., the diaphragm needs to be stiff and strong enough to span the structural CBSW panels and therefore this may limit the perpendicular spacing of structural CBSW panels.
- Structural systems with walls at angles other than the two orthogonal directions (e.g., hexagonal or triangular systems) are permitted, provided the decomposed/resultant CBSW lengths in the two orthogonal directions satisfy the requirements detailed (Figure 8.9).
- Structural systems with CBSW panels in one orthogonal direction and another permitted lateral load-resisting system in the other orthogonal direction are permitted, provided their stiffnesses and the diaphragm stiffness are compatible.
- In seismic areas, in any one direction, dual systems (mixed systems consisting of CBSW panels and other structural systems, e.g., confined masonry) which are designed to share the lateral load, are not permitted. CBSW panels may instead be used as non-structural infill walls, provided their impact on the local and global behaviour of the structure is considered (e.g., torsion, short column effects, etc.).

Figure 8.7: Key structural limitations and rules for CBSW housing

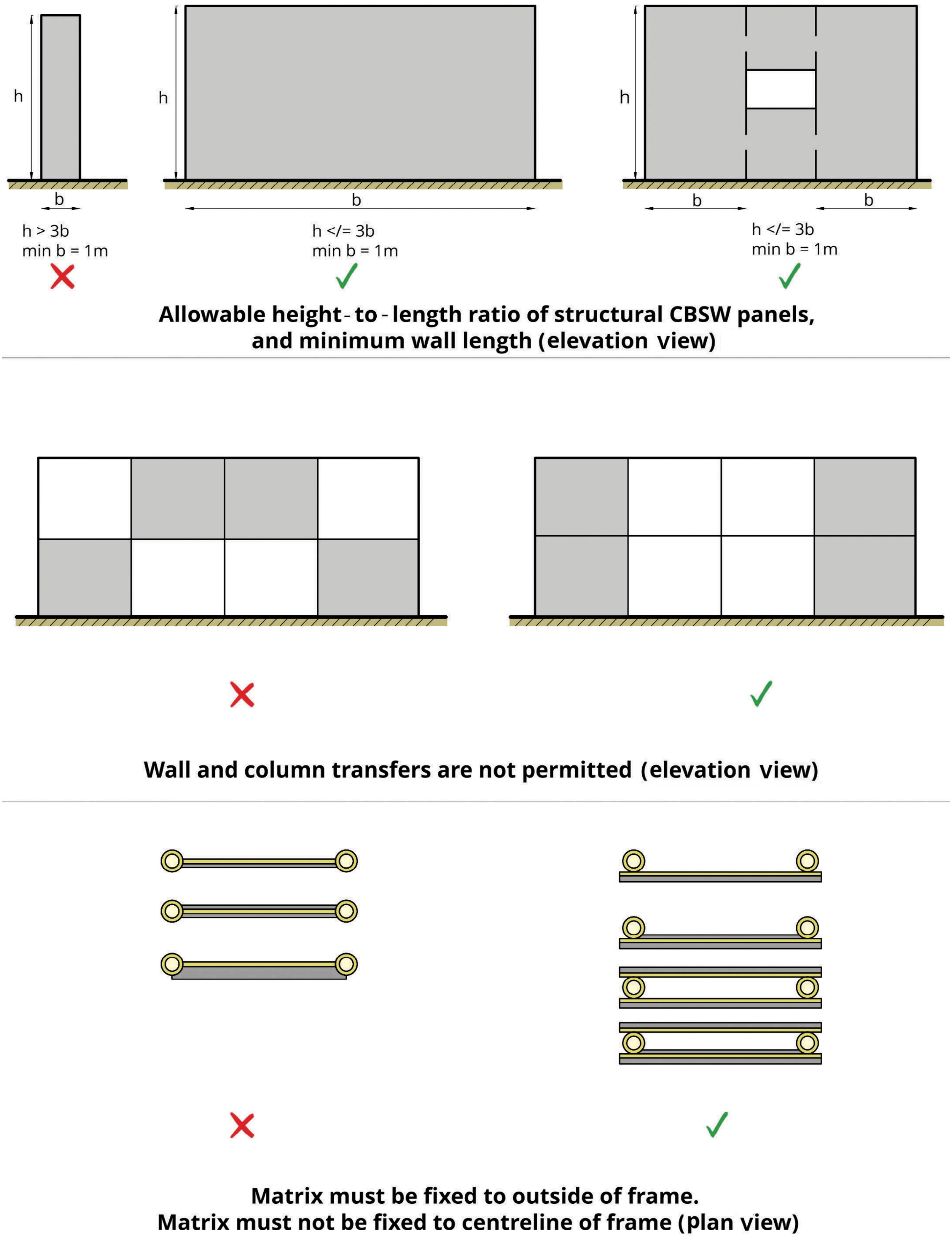


Figure 8.8: Key structural limitations and rules for CBSW housing (plan view: structural columns – yellow, CBSW – grey)

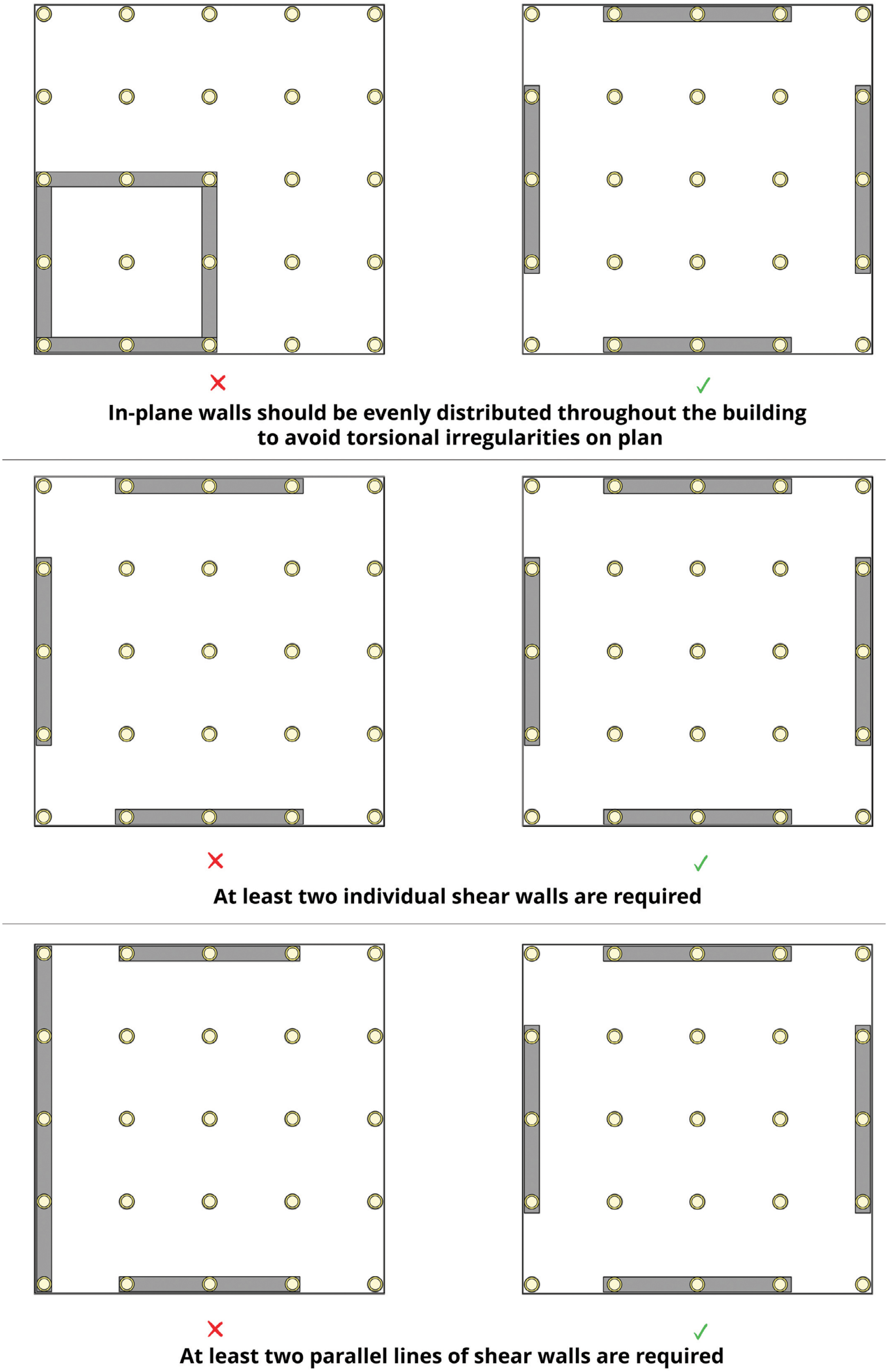
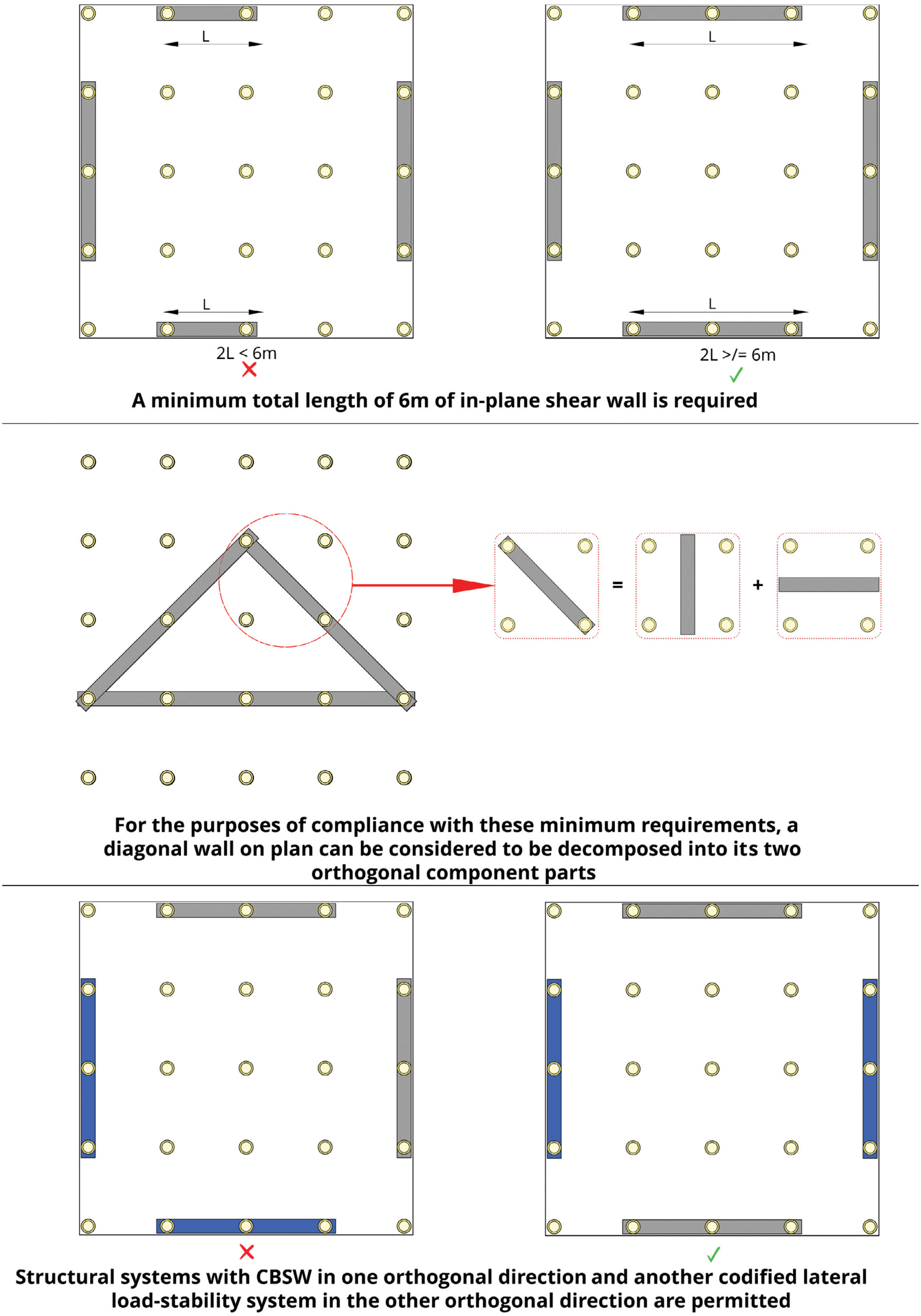


Figure 8.9: Key structural limitations and rules for CBSW housing (plan view: structural columns – yellow, CBSW – grey)

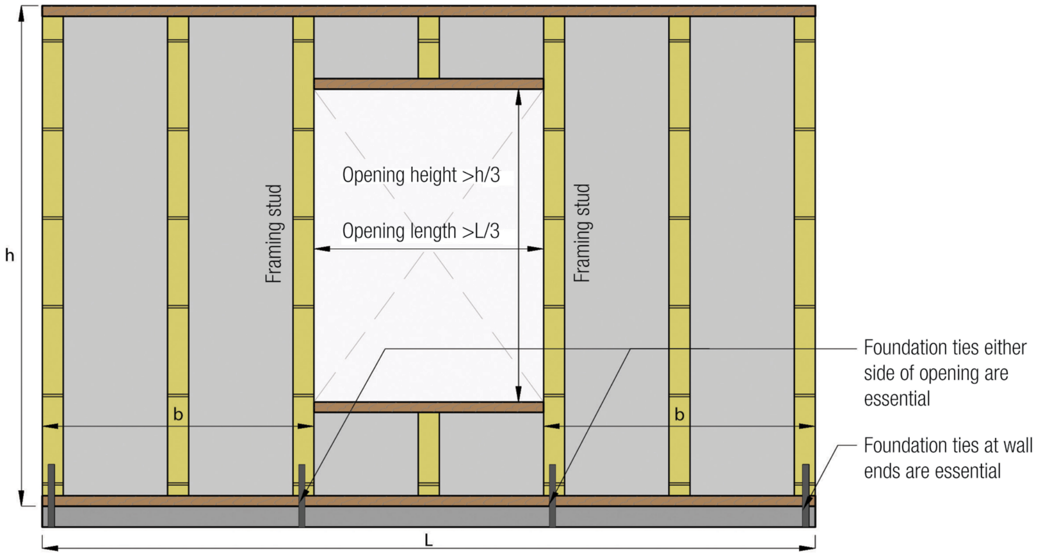


8.4 Openings in panels

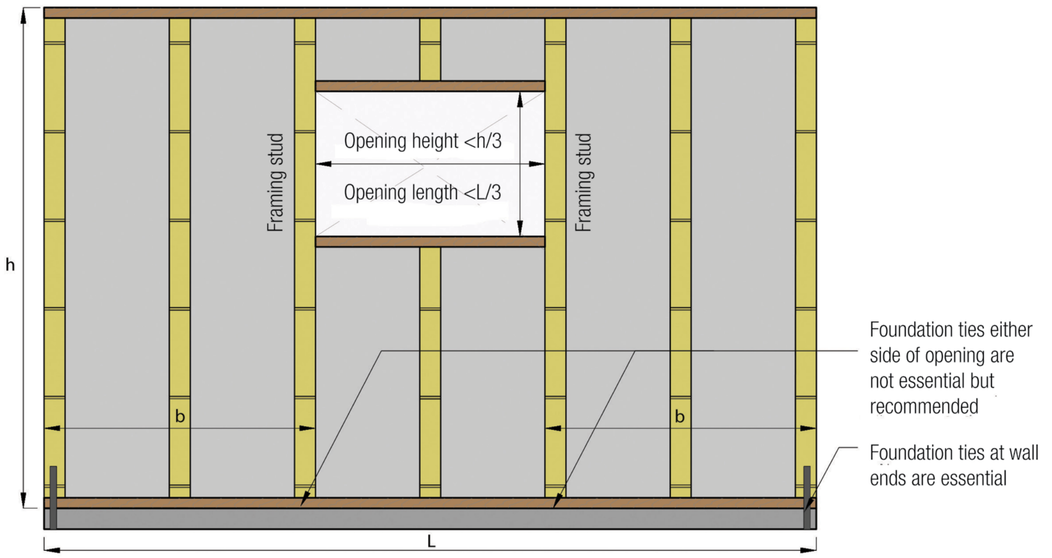
CBSW systems are permitted to include openings for windows and doors, provided one of the following conditions is met (Figure 8.10):

1. The panel is considered as two separate panels located either side of the opening, with vertical studs and foundation tie-downs either side of the opening, and no contribution from the panel directly above or below the opening considered in the overall in-plane wall capacity calculations. Each panel either side of the opening must individually satisfy the criteria in Section 8.3. This is the preferred approach and is necessary for door openings.
2. The opening is less than 1/3 of both the length and height of the panel, the opening is framed on all four sides, the vertical studs either side of the opening are continuous from sole to head plate, and the entire panel including opening is tested in-plane and the resulting strengths used for design.

Figure 8.10: Panel with an opening showing framing studs and tie-down (tension) connectors



Option 1: Panel considered as two separate panels located either side of the opening. Requires vertical studs and foundation tie-downs either side of the opening.



Option 2: Entire panel tested and results used for design. Requires that opening is less than 1/3 of both length and height of panel, opening is framed and vertical studs are continuous. Foundation tie-downs adjacent to window not essential, but still recommended.

8.5 Design of load path

CBSW panels can be designed to resist vertical loads (gravitational or wind), as well as horizontal (seismic or wind) in-plane and out-of-plane loads.

8.5.1 Determination of loads

All gravity, wind and seismic loads should be determined and combined, having consulted relevant national building standards.

For seismic design:

- The CBSW building must be designed assuming that wall panels remain elastic in the design earthquake (i.e., a ductility factor of 1 is assumed, which is equivalent to a response modification factor R = 1.5, or a behaviour factor q = 1.5, compatible with the ASCE 7[8.8] and Eurocode 8[8.17] frameworks respectively). If following the Ecuadorian or Colombian codes, a higher R factor of 2 can be used.
- An equivalent static approach should be used for derivation of the design loads.
- Regardless of building height, when deriving the base shear, the building should always be assumed to be on the peak plateau of the response spectrum. This is because CBSW buildings are inherently relatively stiff.
- Out-of-plane seismic loads should be considered to be transferred to the floor and roof diaphragms. The floor and roof diaphragms in turn transfer load to the in-plane walls and down to the ground.

8.5.2 Vertical loads

CBSW panels can be designed to resist vertical loads, such as those from gravity and winds. These requirements should be followed:

- Vertical framing elements (studs) spanning between the head and sole plates should be designed to resist loads in their entirety (Chapter 6). The mortar and matrix should not be assumed to contribute towards vertical load-carrying capacity nor towards out-of-plane buckling of studs, although the studs can be assumed to be restrained against in-plane buckling by the cemented matrix.
- The matrix can contribute self-weight against net upward wind loads.
- The mortar infill inside the bamboo stud can be considered beneficial against uplift. If used, refer to Example 2 in Chapter 10 for an alternative.
- The head plate should be designed in accordance with Chapter 6 for gravity loading, assuming it spans horizontally between studs and that the matrix below provides no vertical support.
- Net upward vertical loads should be transferred directly to studs via ties, which in turn should have dedicated tie-downs at their base (Chapter 7).
- The panel should not be assumed to be capable of transferring vertical upward or downward wind or gravity loads from one individual stud to the next, through the matrix (unless they are placed next to each other and positively connected, e.g., using bolts).

8.5.3 Out-of-plane loads

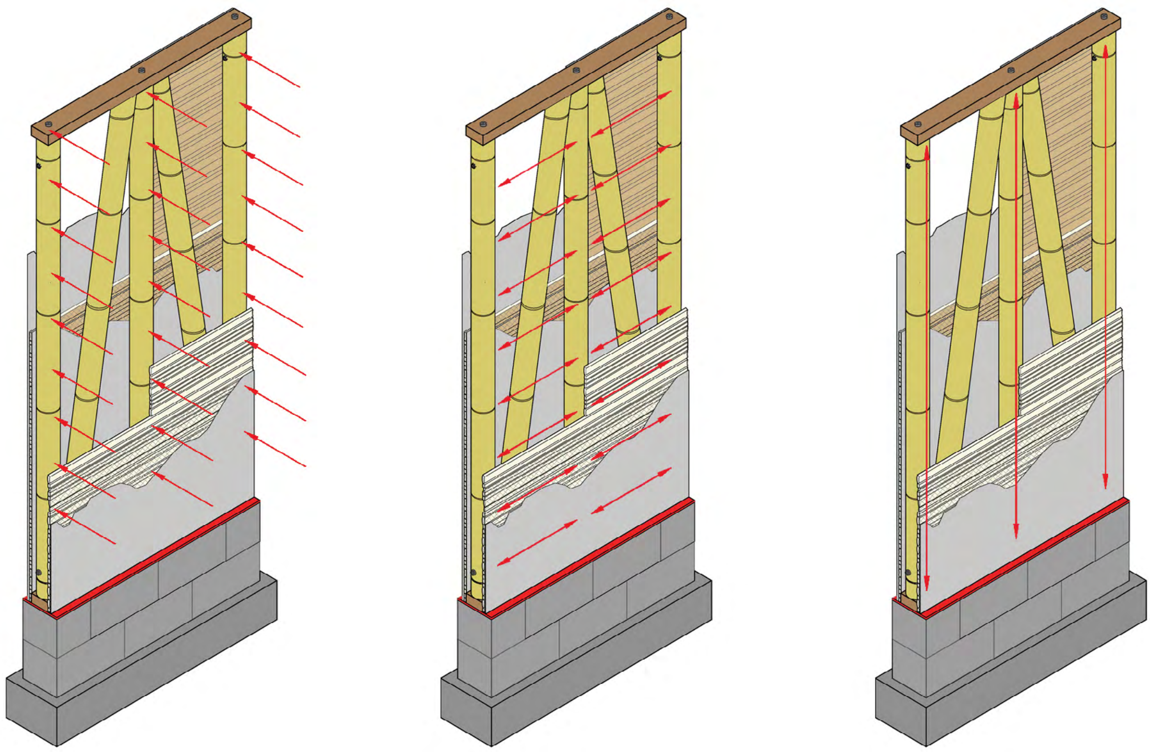
CBSW can be designed for horizontal out-of-plane loads from winds or earthquakes. The load path (Figure 8.11) should be assumed as:

- Render loads matrix.
- Matrix spans horizontally in flexure between vertical studs.
- Studs span vertically in flexure between head and sole plates.
- Sole plate on ground floor is connected directly to a reinforced masonry or reinforced concrete upstand. Sole plates on upper floors, and all head plates are connected to the diaphragm.

Under no circumstances should CBSW be designed as free-standing cantilevers out-of-plane.

The vertical studs should be checked, assuming simply-supported members subjected to a uniformly-distributed load spanning from head to sole plate (Chapter 6). If the studs are simultaneously subjected to compression or tension forces, these should also be considered (Chapter 6). No contribution from the matrix or mortar should be considered (i.e., studs should be considered non-composite out-of-plane). The shear connection between studs and head and sole plate should be checked (Chapter 7).

Figure 8.11: Out-of-plane load path for CBSW panels



a) Out-of-plane loads

b) Matrix spanning horizontally between vertical studs

c) Studs spanning vertically between sole and head plates

The horizontally-spanning matrix should be checked experimentally or analytically. If checked analytically:

- Assume a uniformly-distributed load and pinned supports.
- Horizontal continuity of matrix over internal pinned supports (studs) can be considered where it exists.
- The matrix should not be assumed to be able to span vertically.
- The render should not be assumed to contribute towards the out-of-plane capacity, neither by itself nor compositely with the matrix.
- The connection capacity between the matrix and the vertical studs should be checked (Chapter 7), considering the matrix pulling away from the studs.

Where the recommended minimum wall matrix properties of Appendix A8.1.1 are met, the resistance to out-of-plane loads of the horizontally-spanning wall matrix and its connections back to the studs can be assumed to be satisfied for loads defined in Appendix A8.1.1. This is based on precedence and testing already conducted. The vertical studs, stud to sole/head plate shear connections, sole/head plates and their connections, will all still need checking from first principles, following this *Manual*.

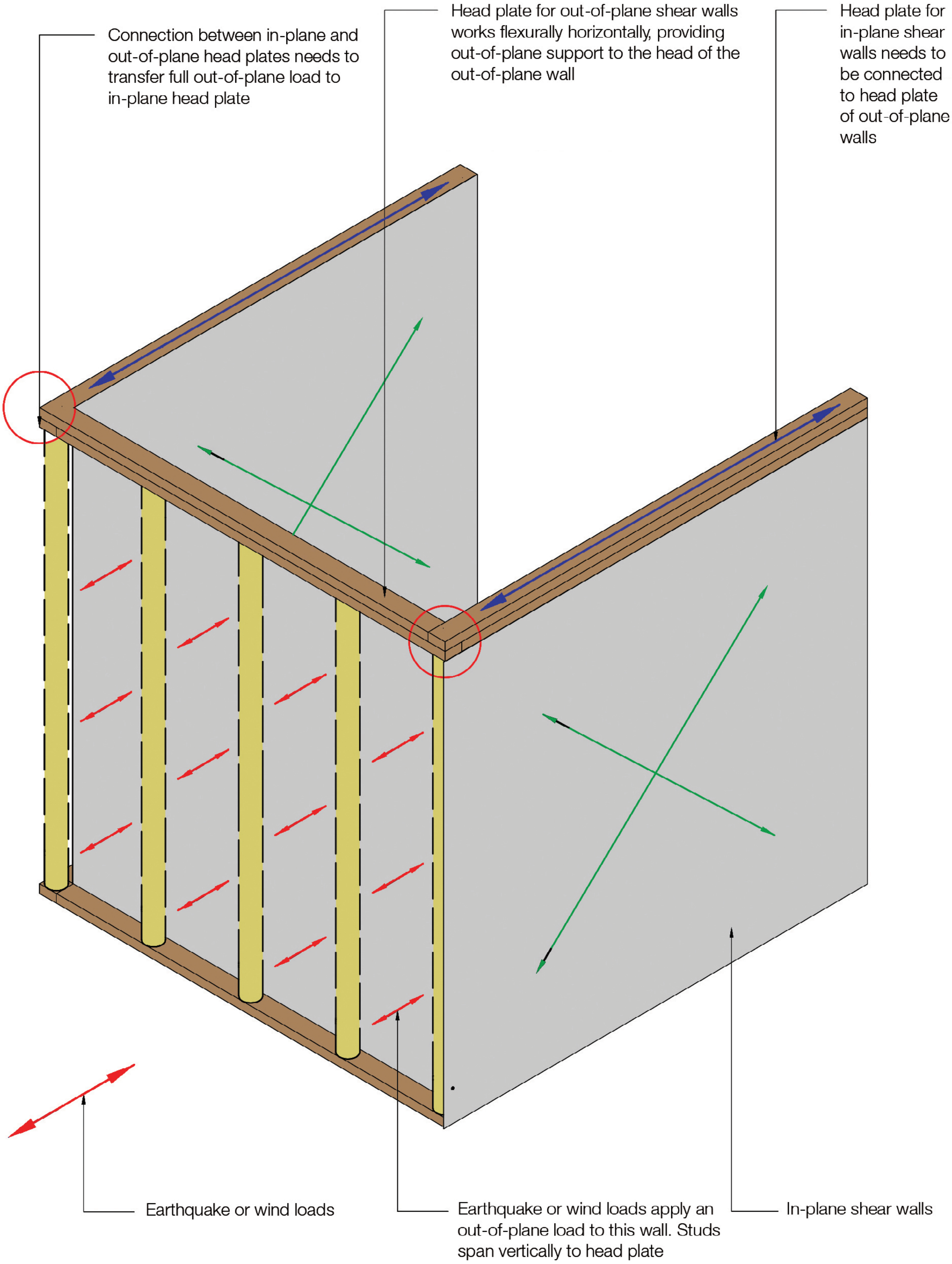
8.5.4 Structural diaphragms

Structural diaphragms are required to pick up the roof and out-of-plane wind and seismic loads and transfer them to the in-plane shear walls. Structural diaphragms should be designed for shear, bending and axial stresses resulting from these forces. Two options are available:

- The diaphragm consists of a continuous planar structural material, such as structural plywood fixed to floor joists, which are connected to all the head plates of the CBSW panels (refer, for example, to the guidance published by the APA for timber diaphragms[8.18]). Here, the diaphragm and its connections should be designed for transferring the loads to the in-plane shear walls acting as a conventional diaphragm. Such diaphragms should normally be considered flexible, unless they are explicitly designed to be stiff and strong enough to satisfy the 'rigid diaphragm' requirements in the national building standard used for design. Chords and their splices around the perimeter of such diaphragms should be designed for design axial compression and tension loads.

- The diaphragm consists of only the head plate spanning between return walls, without a continuous planar structural material. In this scenario, the head plate acts as a beam, and should be designed for flexure and shear (Figure 8.12). The connection between the head plate and return wall should be designed for transferring the full load to the in-plane shear walls. The head plate must consist of one continuous timber or bamboo element without splices. Such diaphragms are limited to cellular construction with shear walls spaced at centres no greater than 4m. These diaphragms should be considered flexible in all cases.

Figure 8.12: Possible load path for CBSW buildings without a continuous planar diaphragm

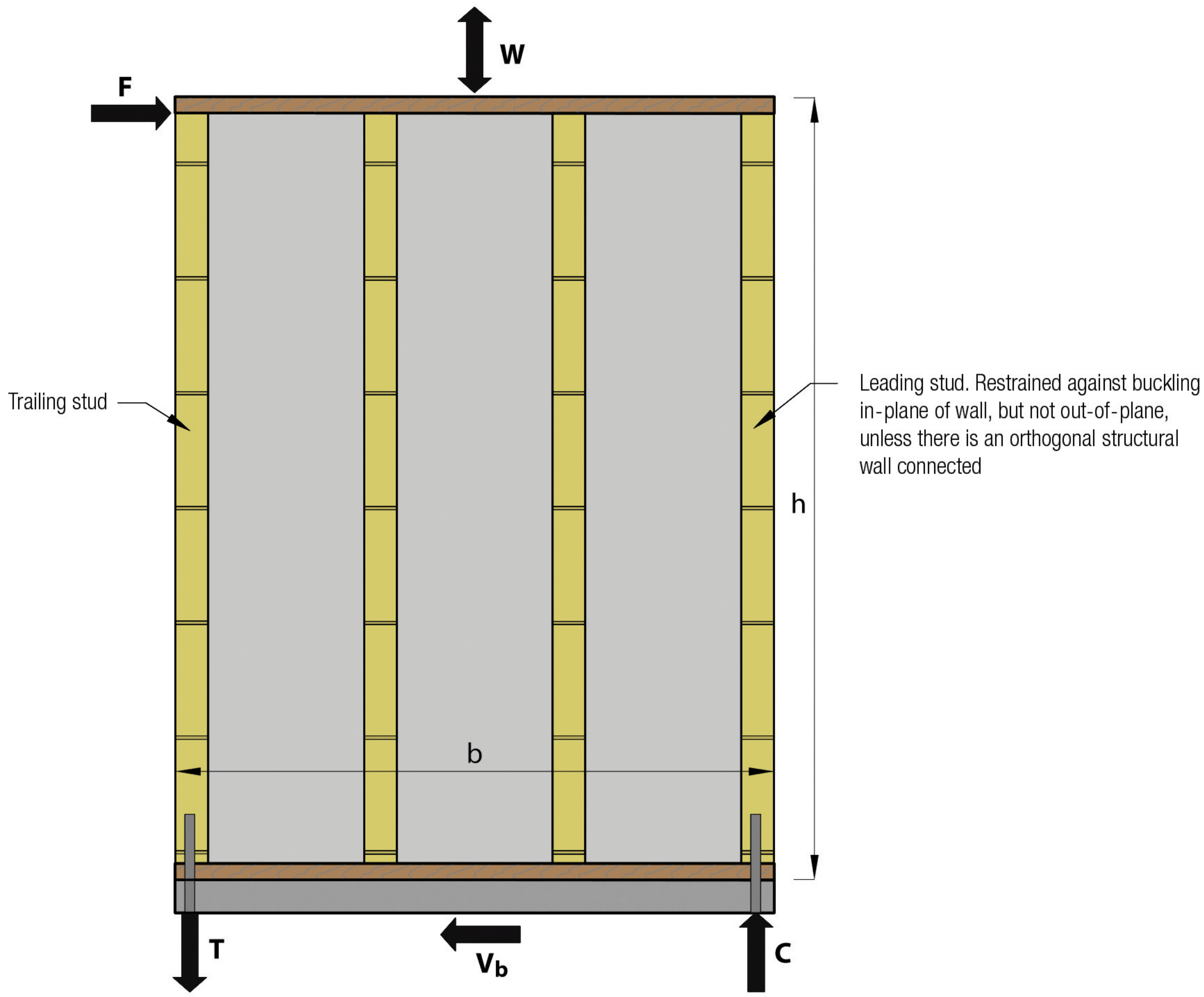


8.5.5 In-plane loads

CBSW can be designed for horizontal in-plane loads from winds or earthquakes. The load path and assumptions bear similarities to how light frame plywood/OSB timber stud walls are typically designed. It should be assumed that:

- Loads are transferred to the walls by the floor diaphragms. The proportion of load that each wall carries depends on the diaphragm design (Section 8.5.4). Flexible diaphragms should be assumed to load the in-plane shear walls in proportion to their tributary area. Rigid diaphragms should be assumed to load the in-plane shear walls in proportion to their in-plane stiffness, which in the absence of more information, can be assumed to be proportional to their respective length. The diaphragms load the wall itself via the head plate. The diaphragm to head plate connection should be designed for in-plane loads.
- CBSW should be designed as vertical cantilevers in-plane, transferring shear and and the resulting axial couple to the foundations.
- Coupled CBSW panels have a higher initial strength and stiffness than a comparative uncoupled wall, however the coupling beam breaks down relatively quickly under higher deformations. Section 8.4 offers more information. In general, it is recommended to ignore the additional stiffness that a coupling beam provides.
- Shear forces are resisted solely by the composite mortar and matrix system plus any diagonal in-plane bracing present. The shear capacity of the composite mortar and matrix system, plus any diagonal in-plane bracing present, should be determined (Section 8.8).
- Axial forces (compression and tension) generated by in-plane flexure should be resisted solely by the end stud members, accounting for simultaneous vertical forces from gravity, wind and earthquake. A typical distribution of in-plane and vertical forces on a CBSW panel is shown in Figure 8.13.

Figure 8.13: Distribution of in-plane forces within a CBSW panel



Tension, *T*, and compression, *C*, onto the leading and trailing studs should be determined from Equation 8.1:

$$T = C = \frac{F \times h}{b}$$ Equation 8.1

Where:

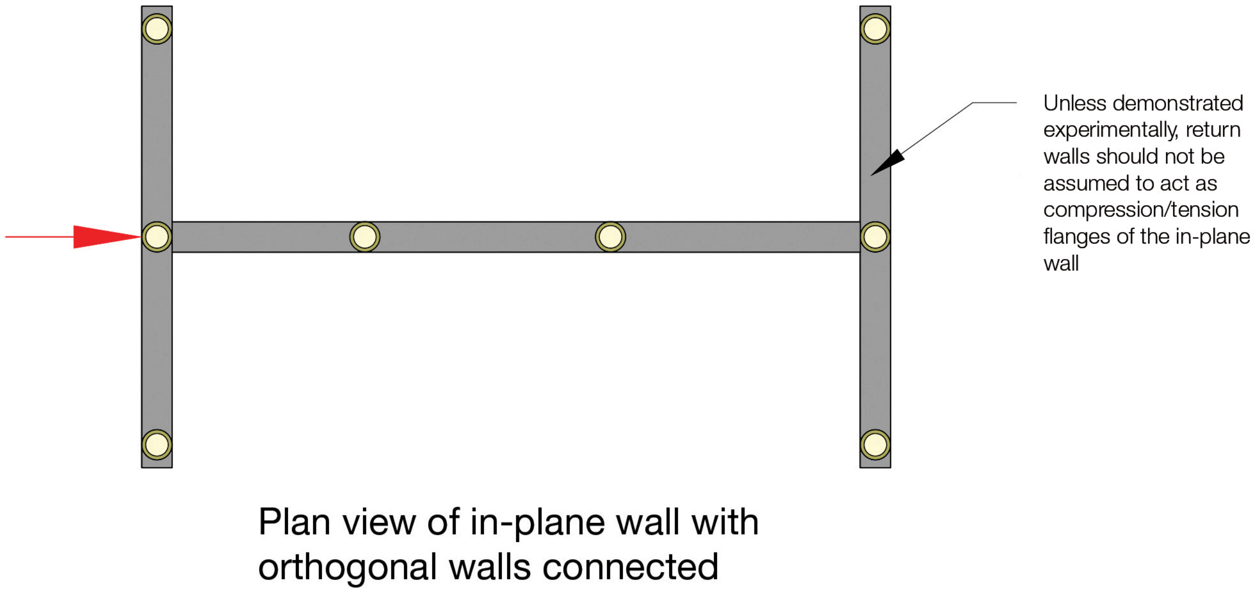
F = horizontal in-plane force acting at top of wall panel.
h = vertical distance from point of application of in-plane load (typically top of wall) to base of wall panel.
b = horizontal distance from centre of leading stud group that resists compression, to trailing tie-down.
V_b = horizontal in-plane force acting at base of wall panel.
W = gravity load from above applied onto wall, considering any vertical seismic or wind loads, and in addition self-weight of wall.

  a. For compression:
    i. Studs can be assumed to be restrained against buckling in the plane of the wall. Intermediate studs (i.e., those not at the extreme ends) in an in-plane CBSW panel should not be assumed to contribute to resisting forces resulting from overturning.
    ii. The perpendicular crushing capacity of the sole and head plates when subjected to vertical loads from the studs should be checked.
    iii. The maximum downward load from all other loads applied to the same end stud should be applied simultaneously (e.g., gravity).
  b. For tension:
    i. Studs that need to transfer net tension between floors should have a direct connection between the member above and below the floor (e.g., a tension tie fixed to both members).
    ii. Studs that need to transfer net tension into the foundations should have a direct connection between the member and the foundation (e.g., a tension hold-down).
    iii. The maximum upwards load from all loads applied to the same end stud should be applied simultaneously (e.g., wind minus gravity).
- When checking for net uplift due to overturning:
  a. The beneficial self-weight of the wall panel itself can always be included; although most national design load standards will require that this contribution be reduced.
  b. It is often simpler and conservative to neglect the beneficial effects of gravity loads from above.
  c. When including the beneficial effects of gravity loads from above, ensure that the wall panel and/or any head plate/binder has the vertical stiffness and vertical strength between tie-downs to redistribute the vertical gravity loads along the wall length. This can be obtained by one of the following:
    i. Having stud tension tie-downs at spacings not exceeding 1.2m.
    ii. Designing the head plate/binder to redistribute these loads along the length of the wall.
    iii. Full-scale testing of the wall panel itself.
- CBSW panel studs should have stud tension tie-downs:
  a. At all wall ends and corners.
  b. In regions without typhoons/hurricanes (<119km/h one minute gust in open sea), at horizontal spacings not exceeding 3m (including requirements for tie-downs adjacent to openings such as windows).
  c. In regions with typhoons/hurricanes (≥119km/h one minute gust in open sea), at horizontal spacings not exceeding 1.2m (including requirements for tie-downs adjacent to openings such as windows).
  d. So that all wall panel aspect ratios height-to-length are not less than 0.5.
  e. At all vertical joints along the wall where the complete wall matrix and mortar are not continuous across panels.
- Where structural return walls are present, the end studs can be assumed to be restrained against buckling in both directions.
- Where structural return walls are present, unless demonstrated experimentally, the return wall panel should not be assumed to be capable of transferring vertical upward or downward loads along the length of the return wall panel (i.e., the return walls should not be assumed to act as compression/tension flanges of the in-plane wall) (Figure 8.14). This is because the current height limit of the buildings of two storeys means that when considering shear lag, very little width of the flanges will be mobilised in practice.
- The sole plate to head plate connection at upper floors, the sole/head plate to diaphragm connection and the sole plate to foundation connection should all be designed for in-plane loads.
- The in-plane sliding capacity at the ground floor sole plate to reinforced masonry/concrete upstand should be checked, considering any reduction in shear friction and cohesion due to any damp-proof membrane present.

- Full-body overturning of the wall and foundation should be checked, considering the weight of the wall and foundation and the bearing capacity of the soil below.
- If checking horizontal displacements against prescribed national building standard drift limits, the average cracked in-plane stiffness of the complete wall panel assembly shall be used in analyses. Appropriate in-plane stiffnesses should be taken from testing or from existing published data (Appendix A8.2).
- Simultaneously acting in-plane and out-of-plane loads on CBSW panels should be checked using structural engineering principles. This could be conducted by ensuring that the wall remains elastic in-plane under the design loads, so the out-of-plane shear capacity is not significantly affected.
- The vertical studs provide out-of-plane restraint against buckling of the wall panel under in-plane shear loads (e.g., equivalent strut analogy). This second-order effect needs to be checked experimentally or analytically.

All bamboo elements should be checked following the requirements in this *Manual*. Timber elements and connections should be designed as detailed in Section 8.6.

Figure 8.14: Limitations on composite action of CBSW with flanges of return wall when in flexure



8.6 Design of timber elements in CBSW buildings

The design of sawn timber elements in CBSW buildings must meet the requirements of the appropriate national building standard. Where a national building standard for structural design of timber is not available, or considered outdated, it is recommended to use the European structural timber design code[8.19].

8.7 Requirements of CBSW panels

Minimum requirements for CBSW panels are provided in Appendix A8.1. Where any of these requirements are not satisfied, full-scale testing will typically be required to determine behaviour and strength of the wall system. Alternatively, walls can be treated as non-structural.

8.8 Determination of in-plane shear capacity of CBSW panels

The shear capacity of the structural system between the head plate and the sole plate cannot currently be easily determined from first principles nor analytically, so must therefore be determined experimentally.

Some published data for the shear capacity of different CBSW panel systems exists and can be found in Appendix A8.2. Where existing data is not considered adequate for the CBSW structural system proposed, full-scale testing will be required.

The in-plane shear strength of CBSW panels should be determined in accordance with ISO 21581:2010[8.20]. Cyclic tests are preferred to monotonic tests as they provide a better understanding of the performance of the shear wall under load reversal. Cyclic tests should be conducted following ISO 21581, Clause 6.2. Panel properties should be determined following ISO/TR 21141:2022[8.21]. Characteristic and design in-plane shear strengths should be determined following BS EN 1990:2023[8.22] or ISO 12122-6:2017[8.23].

More information on testing and determination of in-plane shear capacity of CBSW panels is provided in Appendix A8.2.

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Appendices

A8.1 Requirements of CBSW panels

Appendix A8.1 provides minimum requirements for CBSW panels. Where any of these requirements are not satisfied, full-scale testing will typically be required to determine the behaviour and strength of the wall system. Alternatively, the walls can be used non-structurally.

A8.1.1 Wall matrix

The wall matrix (the material that spans between vertical studs) can consist of:

- Cut narrow strips of large-diameter bamboo or 'splits' (Figures 1.4 and A8.1c).
- Flattened bamboo (also known as *esterilla* in Spanish (Figures 1.3 and A8.1a).
- Whole-section small-diameter bamboo or cane (Figure A8.1b). (Note that 'cane' is a separate lineage of giant grass from bamboo, although it has many similarities).
- Galvanised expanded metal lath (e.g., rib-lath) (Figure A8.1d).

The wall matrix can be applied to one side (single-skin) or both sides of the frame (double-skin). Double-skin wall matrices conceal studs and plates, and can act as an encapsulation for fire resistance, providing potential fire compartmentation between rooms. Double-skin wall matrices need ventilation holes where there is a risk of moisture — the effect of such holes on the fire performance of the panels needs to be considered (Figure A8.2).

Figure A8.1: Typical wall matrices for CBSW panel systems

a) Flattened large-diameter bamboo (*esterilla*)

b) Small-diameter bamboo/cane

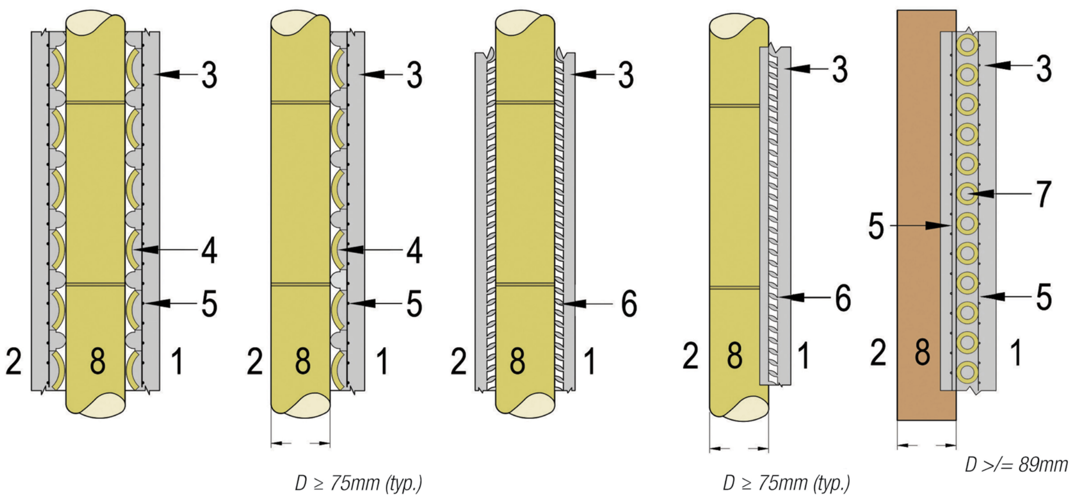
(Continued)

Figure A8.1: *Continued*

c) Cut strips of large-diameter bamboo

d) Galvanised expanded metal lath

Figure A8.2: Typical sections through CBSW panels with different matrices



a) Section through double-skin (left) and single-skin (right) CBSW panel with strip or flattened bamboo matrix

b) Section through double-skin (left) and single-skin (right) CBSW panel with expanded metal lath matrix

c) Section through CBSW panel with small-diameter bamboo or cane matrix

Key

1 Exterior facade
2 Interior facade
3 Cement mortar render
4 Strip or flattened bamboo
5 Galvanised wire mesh
6 Expanded metal lath
7 Small-diameter bamboo or cane
8 Vertical CBSW member (stud)

The requirements of the wall matrix are that:

- It must be able to span horizontally between vertical studs to transfer wind and seismic out-of-plane loads.
- It must have sufficient gaps and roughness to create a durable and reliable bond with the render, so that the matrix and render behave compositely in-plane.
- It must be able to work as part of the in-plane shear wall.
- It must be fixed to one side of the studs.
- The fixing from the wall matrix to the studs must not cause splitting of the stud. With bamboo studs, this typically requires nails no greater than 3mm diameter at centres no less than 100mm, and staggered. With timber studs, this typically requires nails no greater than 3mm diameter at centres no less than 30mm, and staggered.

Table A8.1 provides the allowable combinations of wall matrices, maximum stud spacing and connections of matrix to frame, that are both permitted to ISO 22156[A8.1] and also satisfy the following out-of-plane loads:

- A factored design wind pressure of 2kN/m^2 at ultimate limit state (or an allowable wind pressure of 1.7kN/m^2).
- The seismic out-of-plane loads that a CBSW building that satisfies the requirements of Chapter 8 and Appendix A8.1 of this *Manual* would experience if designed for a peak ground acceleration of 0.5g.

Table A8.1: Permitted combinations of wall matrices, stud spacing and connections of matrix to frame

Matrix type	Matrix material specification	Matrix spacing required to ensure good connection with mortar	Maximum stud spacing	Mechanical connection of matrix to frame
Bamboo strips or flattened bamboo mat Galvanised wire mesh also required	Minimum thickness = 8mm Minimum width of bamboo strips 50mm (so that nails are at no less than 100mm centres)	5–20mm gaps between matrix elements	0.6m centres	3mm diameter 20mm long nails at 100mm centres into bamboo/timber studs with a minimum wall thickness = 7mm
Galvanised expanded metal lath (e.g., rib-lath) — metal to be mild steel or stronger	Minimum lath weight = 1.4kg/m^2	~3–10mm	0.6m centres	3mm diameter 20mm long nails at 100mm centres into bamboo/timber studs with a minimum wall thickness = 7mm
Small-diameter bamboo or cane Galvanised wire mesh also required	Minimum diameter = 15mm Minimum cane/bamboo wall thickness = 3mm	5–20mm gaps between matrix elements	1m centres	Timber studs: 2.5–3mm diameter 75mm long nails (bamboo studs not permitted as requires very close nails)

Additional requirements:

- If the nails fixing the matrix to the studs are driven into bamboo studs, their location should be staggered vertically to minimise risk of splitting/cracking.
- If the matrix consists of flattened bamboo mats, in addition to the nails, 1mm diameter (gauge 18) galvanised wire should be run between nail heads and wrapped around each, prior to fully driving the nails. The wire ensures that the matrix remains in place should a crack/fissure be induced in the flattened bamboo.
- The matrix must also be fixed to the head and sole plates in the same way as it is fixed to the studs.

The better the bond between the matrix and the render, the higher the elastic and ultimate shear capacities and stiffness of the wall.

A8.1.2 Structural mortar render reinforcement

Unless metal lath is used in the wall matrix, render reinforcement is required in each rendered skin and on both sides of the matrix where render is applied on both sides (Figure A8.3). The render reinforcement must also be fixed onto the head and sole plates.

Render reinforcement should consist of galvanised wire mesh with an American Wire Gauge (AWG) of approximately 19–22 (1.00–0.70 mm diameter), and a maximum mesh size of 20mm. Such wire mesh is often known as ‘chicken wire’.

The reinforcement should be fixed taut to the frame with screws, staples or nails, taking care not to split the studs. The reinforcement should also be fixed to the matrix as follows:

- For cut narrow strips of large-diameter bamboo, 10mm-wide steel staples.
- For flattened bamboo, 10mm-wide steel staples.
- For whole-section small-diameter bamboo or cane, steel wire ties at 100mm centres on elevation connecting the two meshes together either side of the matrix.

Figure A8.3: Render reinforcement

a) Chicken wire mesh on flattened bamboo

b) Chicken wire mesh either side of small-diameter cane

A8.1.3 Structural mortar render

A mortar render is essential to provide shear strength to structural walls. The mortar render should satisfy the following:

- For cut narrow strips of large-diameter bamboo or whole-section small-diameter bamboo or cane, the render must be applied to both sides of the matrix, with each render skin extending from the face of the bamboo at least 15mm thick and no more than 40mm thick.
- For flattened bamboo, the render can be applied to either one side or both sides of the matrix, with each render skin (where present) extending from the face of the bamboo at least 15mm thick and no more than 40mm thick.
- For galvanised metal lath, the render must be applied to both sides of the matrix, with the outer render skin extending from the face at least 30mm thick, and the inner render skin at least 10mm thick.

The render should consist of cement-sand or cement-lime-sand mortar, with a 28-day cube compressive strength of at least 4MPa (however 6MPa is typically recommended). Renders without cement are not permitted, as cement is essential to providing corrosion resistance to the steel connections and components within the wall, and because cement reduces the porosity of the wall. Although cement increases the embodied carbon of the system, it is one of the key aspects which enables a 50-year design life of CBSW systems with little to no maintenance, and it still results in buildings with a significantly lower embodied carbon compared to conventional materials (Section 8.2). Research into cement replacements (e.g., geopolymers) would enable the embodied carbon of CBSW systems to fall further. A suitable cement replacement should result in CBSW panels with similar strength and durability performance as cement.

The render mix should have adequate workability, minimal porosity and provide an alkaline environment once cured, especially when used in perimeter walls. The render must be durable enough to provide corrosion protection to any embedded steel reinforcement for the design life of the structure. Higher render strengths are less porous and naturally result in reduced cracking, improving the durability of the walls. Polymer dispersions may be incorporated in cement mortar mixes to improve bond strength, resistance to rain penetration and durability, although they are not normally used. Care should be taken to use only polymers that are suitable for exterior use.

Mortar ratios that satisfy the requirement of 4MPa include:

- Cement: lime: sand = 1: 0.5: 4.
- Cement: sand = 1: 4.

Ratios with lower concentrations of cement are unlikely to achieve the correct requirements for strength, durability and porosity.

The render must be forced through the gaps in the matrix, and must bond with the render on the other side where present. Rendering is typically undertaken in 2–3 layers, allowing for a day or two between layers. The previous layer should be well-roughened and well-moistened prior to the application of a new layer. Render should be cured with water spraying for at least seven days. The render must also extend over and onto the head and sole plates.

A8.1.4 Vertical framing members/studs
Vertical framing members should consist of bamboo or sawn timber studs. Bamboo studs should have a diameter no smaller than 75mm and are usually no larger than 120mm. Sawn timber studs should be at least 38 × 89mm with the larger dimension orientated perpendicular to the length of the panel.

The maximum centre-to-centre spacing of studs should be 0.6m. The maximum spacing may be increased to 1m if both of the following conditions apply:

- The matrix uses solid bamboo or cane with a minimum diameter of 15mm and a minimum wall thickness of 3mm.
- The studs are sawn timber.

The studs should be positively connected to the head and sole plates preferably using self-drilling screws or bolts (nails are also possible, but should be considered a last resort). At least two nails or self-drilling screws should be used per stud to sole/head plate connection. These connections should be designed to fully resist the out-of-plane loads on the panels. Each stud to sole/head plate connection must also be designed to resist a total minimum (divided by the number of fasteners per connection) of:

- 1.5% of the in-plane shear demand on the entire panel (e.g., a 3m long shear wall may have a total in-plane shear demand of 90kN, which would mean the connections need to be designed for 1.4kN). This is intended to ensure that the connections are able to provide an out-of-plane buckling resistance of the panel under in-plane shear loads.
- 1kN.

For the connection between the vertical studs and sole/head plates under in-plane loads:

- For studs in net vertical tension, there should be a direct reliable connection between the stud and the member above or below (e.g., a steel tension tie). Nails and screws must not be relied upon in withdrawal to transfer tension.
- For intermediate studs, the studs inevitably contribute to overall in-plane shear capacity of the panel. Therefore, the shear connection used for the in-plane shear wall tests should be replicated in the construction (Chapter 7). Nails and self-drilling screws may be used for this shear connection.

A8.1.5 In-plane vertical bracing
In-plane vertical bracing is permitted but not essential. Where present, bracing should consist of bamboo, timber or a steel plate. Bamboo bracing should have a similar diameter to the vertical studs (Section A8.1.4). Sawn timber bracing should have a similar size to the vertical studs, with the larger dimension orientated perpendicular to the length of the panel.

Steel plates 3mm thick x 20mm wide have been used successfully. Steel plates need to be protected from corrosion (Chapter 5). Steel plates should be robustly connected to the head and sole plates, and be connected to all studs they cross.

Bracing members can be designed to resist only tension, only compression or both tension and compression. Where bracing is used, at least two active bracing elements must be installed along each shear wall line.

Bracing can provide greater post-cracking stiffness and strength, however tends to result in panels with less ductility. Bracing is therefore generally most important in panels where the unbraced shear strength is relatively low and/or less reliable.

A8.1.6 Head and sole plates

Head and sole plates should consist of timber or bamboo members. Bamboo head and sole plates should be at least equal in size to the vertical studs, although preferably slightly larger to permit a well-fitting fish-mouth connection. Sawn timber elements should be at least equal in size to the vertical studs, although if using bamboo studs, preferably slightly larger to deal with the variable diameters of the bamboo studs. Sawn timber elements should have the larger dimension orientated perpendicular to the length of the panel. Timber head and sole plates are preferred, as they are less prone to local crushing and are easier to connect to.

Head and sole plates should be continuous, spanning between out-of-plane restraints or return walls. Where no continuous diaphragm is present, they should be designed to resist the out-of-plane loads in flexure and transfer them to the in-plane walls. End connections should be designed for the full out-of-plane load.

Head and sole plates should be capable of resisting in-plane loads applied to them by the vertical studs and braces. This is especially important at the end of panels where vertical elements resist gravity, tension and compression forces associated with overturning, and bracing may also connect to the head and sole plates. Head and sole plates consisting of bamboo elements are particularly vulnerable to local crushing from vertical loads from both gravity and overturning — as a minimum, the internodal region in the crushing zone of the head/sole plate should be infilled with cement mortar.

Sole plates should bear directly onto a reinforced masonry or concrete upstand. Shear connections should be provided connecting the sole plate to the upstand at a spacing not exceeding 1.2m. Shear connections could be centrally-placed holding-down shear bolts, or steel plates/angles that wrap around the sides of the sole plate and are mechanically fixed to it. If sawn timber sole plates are used, there are a wide range of commercially available tie-downs and shear transfer devices available.

Where the end stud in a panel is required to resist net tension from overturning, the stud should be directly connected to the foundation with a tie-down or steel plate. For bamboo studs, one of the most common connections used is to cast a reinforcing bar into the centre of the studs with a mortar/grout. Such a connection should always pass through at least two nodes. It is not permitted to transfer a net tension upward load into the sole plate that then relies on the sole plate in upwards flexure to transfer the load back into a tie-down situated further along the panel.

A8.2 Determination of in-plane shear capacity of CBSW panels

A8.2.1 Introduction

As described in Section 8.5.5, under in-plane loads, the following capacities can be determined from first principles using this *Manual*:

- Shear connection capacity between diaphragm and head plate.
- Shear connection capacity between sole plate and foundation.
- Rigid body overturning capacity of wall and foundation.
- Compression buckling capacity of leading stud and its connection to the sole plate.
- Tension capacity of trailing stud and its connection to the foundation.

The individual stiffnesses of these connections may be more challenging to determine and may require full-scale individual component testing.

The shear capacity of the structural system between the head plate and the sole plate cannot currently be easily determined from first principles nor analytically, and must therefore be determined experimentally. Such testing will also identify the risk of out-of-plane buckling under in-plane shear loads.

There is published data for shear capacity of different CBSW panel systems:

- *Preliminary strengths, stiffnesses and ductilities for various composite bamboo shear wall systems*[A8.2] provides data, although these are average values, since insufficient data was available to determine characteristic values.

- The Ecuadorian code *Norma Andina para diseño y construcción de casas de uno y dos pisos en bahareque encementado*[A8.3] provides allowable in-plane shear capacities for a specific CBSW panel system.
- The Colombian code *NSR-10: Reglamento Colombiano de construcción sismo resistente*[A8.4] provides allowable in-plane shear capacities for a specific CBSW panel system. The original data is taken from a thesis[A8.5] and is also available in *Boletin Technico No. 56: Comportamiento sísmico de bahareque encementado de guadua y madera*[A8.6].

It can be assumed that the aforementioned data is compatible with Service Class 1 and 2 environments. Appropriate corrections may be required if designing for a Service Class 3 environment.

Where existing data is not considered adequate for the CBSW structural system proposed, full-scale testing will be required. Prior to beginning any full-scale testing, it is recommended to use existing guidance and standards to determine the demands and capacities of as many of the individual components of the CBSW system as possible, in order to reduce the uncertainties in the wall (so that fewer components fail too early or are overdesigned). This will reduce the number of tests that are required. Note that 'capacity-design' in this context is meant in the classic earthquake engineering sense, and not as described elsewhere in this *Manual* as 'capacity-based design'.

Shear responses in engineered bahareque shear walls tend to be more ductile than flexural failure modes and are therefore preferred. The designer may wish to consider 'capacity-designing' more brittle failure modes to force a more ductile shear response. Note that 'capacity-design' in this context is meant in the classic earthquake engineering sense, and not as described elsewhere in this *Manual* as 'capacity-based design'.

A8.2.2 Full-scale testing

A review of existing full-scale testing of CBSW panels and subsequent recommendations for future tests is provided in References A8.2, A8.7 and A8.8, presenting detailed documented results on testing methodology and results.

Test specimens should be representative of actual construction in the field, taking into account likely local quality assurance.

Step 1: Select testing regime

The in-plane shear strength of CBSW panels should be determined in accordance with ISO 21581[A8.9]. Two distinct testing regimes are available, Methods I and II, and the engineer should select the most appropriate testing regime for the chosen system:

- **Method I:** The boundary conditions of the test are designed to assess only the shear response of the wall panel, and therefore testing should ensure that the full shear capacity of the wall is achieved. This method requires that all other possible element and connection strengths and stiffness have been determined separately. This method will probably also require pretensioning down the trailing stud to avoid overturning.
- **Method II:** The boundary conditions are designed to reflect the intended actual construction details of joints connecting the wall to bottom and top boundaries, and therefore the test should produce the actual overall response (which could be rocking or combined shear-rocking).

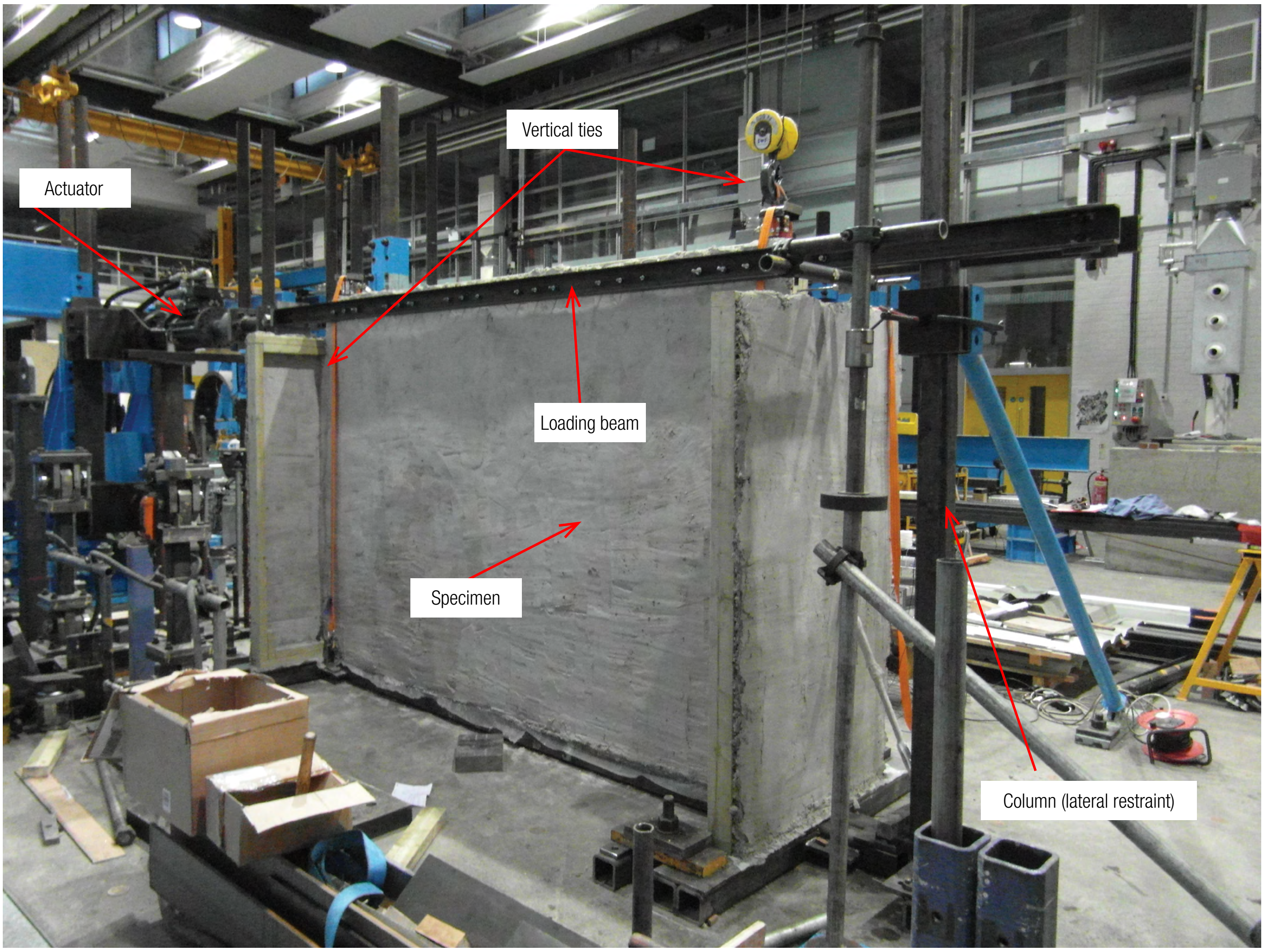
Method I is generally preferred where possible, as it will typically result in better shear strength data for fewer tests. Method II is useful to understand more general flexure and shear performance of the wall, and especially where there are more internal components of the wall with unknown stiffness and capacity. However, it will probably require significantly more tests to obtain sufficiently reliable shear strength capacities.

An adequate number of identical specimens need to be tested to derive reliable mean stiffnesses and characteristic strength values for design. A minimum of three repetitions would provide an initial dataset with statistical relevance that could be used for design. However, ideally six or more repetitions should be conducted to reduce the penalisation of the characteristic value that is inevitable with very small datasets (refer to Section 7.8.3).

Step 2: Test set-up

Specimens should be representative of the final construction, and should consider any variations in wall length, gravity loads, wall heights, wall build-ups and whether any openings are present. Boundary conditions should be representative of actual boundaries. Figure A8.4 shows an example test set-up for Method I.

Figure A8.4: Example test set-up for Method I



Step 3: Monotonic test

Cyclic tests are preferred to monotonic tests as they provide a better idea of the overall performance of the wall under load reversal. Where cyclic tests are not possible because of limitations in the set-up, monotonic tests can be conducted instead. Where cyclic tests are to be conducted, it is necessary first to conduct one monotonic test to failure. This allows the test protocol for the cyclic tests to be properly planned, and also provides a better idea of the wall behaviour in advance of the more complex cyclic tests. Monotonic tests should be conducted in accordance with ISO 21581, Clause 6.1[A8.9].

Step 4: Cyclic tests

Cyclic tests should be conducted in accordance with ISO 21581, Clause 6.2. It is important to conduct a sufficient number of testing cycles at low displacement to determine elastic stiffness and yield point with confidence.

Step 5: Interpret testing

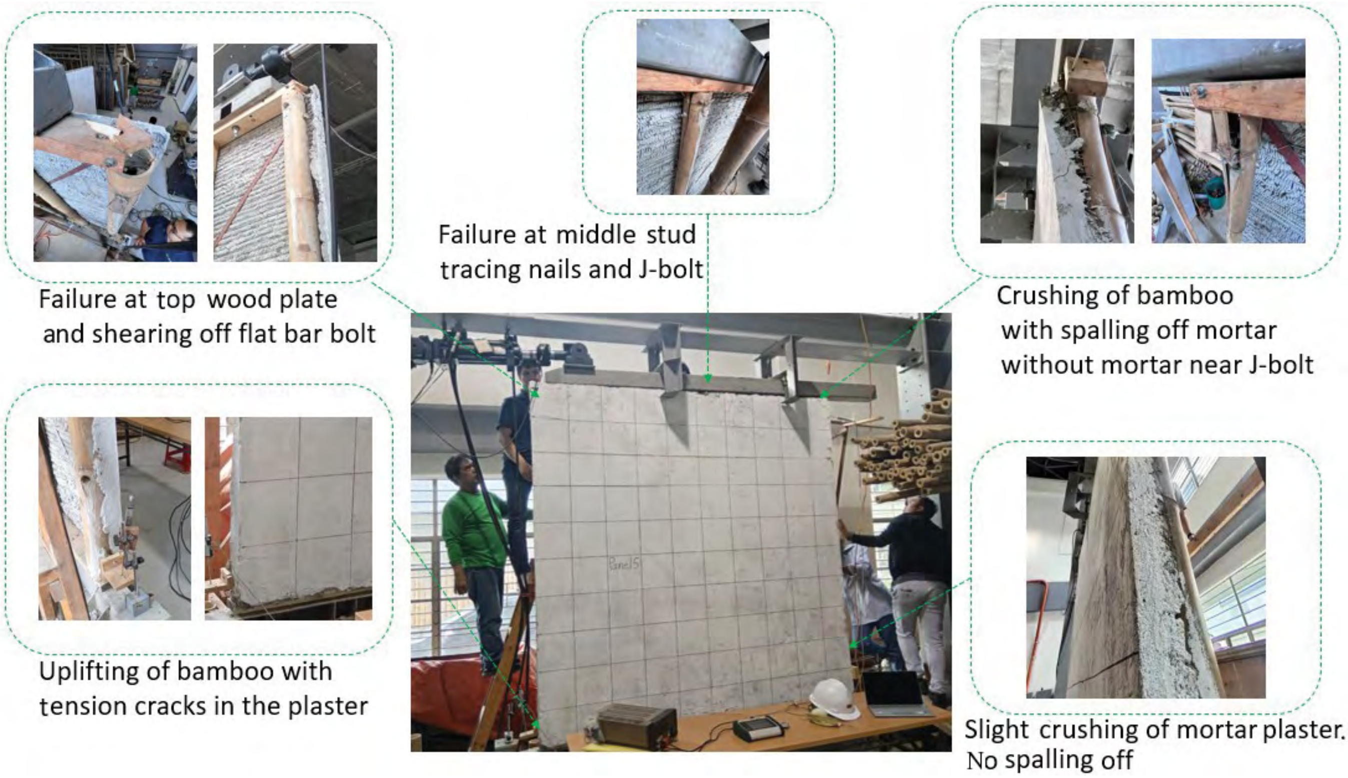
Panel properties should be determined in accordance with ISO/TR 21141[A8.10]. To determine the yield point, it is recommended to use Method A1 when the load-displacement curve presents two well-defined linear parts, and Method A3 when it does not (Section 7.1 in ISO/TR 21141). Figure A8.5 shows some typical damage mechanisms seen in CBSW panels.

Step 6: Determine characteristic and design values

Characteristic and design in-plane shear strengths should be determined according to BS EN 1990[A8.11] or ISO 12122-6[A8.12] or equivalent. BS EN 1990 provides two methods for determining the design value:

- **Direct assessment of the design value for ULS verifications.** This method permits the ULS design value to be directly assessed from the data. The value $V_{x,\,unknown}$ should typically be used.

Figure A8.5: Typical damage mechanisms seen in CBSW panels



- **Assessment of the characteristic value.** This method allows the characteristic value to be assessed, however an appropriate partial material factor of safety must also then be separately determined, to establish the design value. A recommended minimum partial material factor of safety is 1.5.

In both cases, if an 'allowable strength' is sought rather than a 'limit state design strength', a further reduction factor, typically 1.5, needs to be applied.

References

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A8.5 Silva, M. and López, L. *Comportamiento sismo-resistente de estructuras en bahareque*. Final year project, Universidad Nacional de Colombia Sede Manizales, Facultad de Ingeniería y Arquitectura, Ingeniería Civil. Manizales, Colombia, December 2000 [in Spanish].

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A8.7 Elghazouli, A. Y. *et al*. *Seismic Testing of Sustainable Cane and Mortar Walls for Low-cost Housing in Developing Countries*. London: Institution of Civil Engineers, 2013.

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A8.11 British Standards Institution. *BS EN 1990:2023: Eurocode. Basis of structural and geotechnical design*. London: BSI, 2023.

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9 Research and development gaps and needs

9.1 Introduction

ISO 22156:2004[9.1] was an intent-signifying document which guided the development of ISO 22156:2021[9.2]. The latter remains the first version of an international design standard for bamboo structures. Although informed by a considerable body of research in recent decades (as evidenced by this *Manual*), ISO 22156:2021 has many gaps and placeholder provisions to be confirmed and completed in future revisions of ISO 22156. Some of those placeholder provisions were, it seems, drafted based on overly conservative assumptions and calculations. ISO 22156, Sections 5.11.3 and 10.2 — the 'design by testing' permissions — provide means for a motivated designer to improve upon the conservativeness inherent in ISO 22156 or, indeed, to fill in some of the gaps.

This chapter identifies some of these gaps and areas that require research to make ISO 22156 a more complete and efficient document in future revisions. The discussion of gaps and research required provided in this chapter is by no means exhaustive. It is an attempt to highlight some of the critical gaps and requirements that will result in the greatest improvement in subsequent revisions of ISO 22156.

A related 'gap and research needs' analysis, was conducted in late 2021[9.3].

9.2 Bamboo species

As described in ISO 22156, Annex A, provisions are ultimately based on research and experience with relatively few bamboo species, representing limited geographic diversity. For bamboo construction to be viable, it must utilise local materials. Well-curated studies of bamboo from around the world are needed to validate ISO 22156 provisions across a broader range of bamboo.

It has been proposed in some forums that — beyond grading — bamboo species may be classified into structural 'groups' similar to wood resources ('softwood' and 'hardwood', or more detailed designations such as 'spruce-pine-fir'). To accomplish such an objective, extensive studies and well-curated databases are required. As an example, like wood, bamboo density (and more simply, linear mass) is emerging as a promising surrogate for multiple material properties[9.4]. Validation of the impact of density for multiple species could lead to better bamboo classifications and simplification of many ISO 22156 provisions. Coordinated international research efforts are needed in this area.

9.3 Grading

Just as classifying species will help to universalise bamboo design, improved grading techniques are required. Presently, bamboo is graded visually. This procedure requires two levels of conservativeness. Firstly, through the derivation of characteristic material properties (Appendix A3.3) and secondly through the creation of diameter-based grade (Appendix A3.4). The compounding effect of these could be overcome by inferring the load-bearing capacity of elements through 'machine-grading' techniques suitable for bamboo. Machine grading will also allow for improved uniformity of product and greater product volume to be utilised efficiently. Correal et al.[9.5] present a compelling example of how this approach may be applied.

9.4 Composite behaviour of multiple-culm bamboo members

Owing to lack of available guidance, ISO 22156 does not permit an assumption of composite behaviour in the design of multiple-culm members. The authors believe that partial composite action can be attained and has been demonstrated both anecdotally and in literature. Nonetheless, guidance is required on the degree of composite action that can both be attained and relied upon. Although it may not be possible to rely on partial composite behaviour at the ultimate limit states, composite behaviour may significantly improve serviceability modes of performance, allowing bamboo culms to be utilised more efficiently.

9.5 Connections

The greatest gaps in ISO 22156 relate to the design of connections. At present, many connection types will require some degree of testing to implement efficiently. Prescriptive design provisions for common connection types are needed. Indeed, the format of ISO 22156, Section 10 was designed to allow new connection types to be added easily.

ISO 22156 Clause 10.2 '*Design properties by complete joint testing*', provides a methodology for thorough investigation of a connection type. Harries et al.[9.6] demonstrate the entire process prescribed by Clause 10.2 for an example connection type. Using such an approach, connection capacity tables may be developed to supplement ISO 22156 provisions. A rational objective could be entirely prescriptive design provisions for some simple connection types.

An additional concern that affects the interpretation and use of complete-joint testing data is establishing the correct relationship between maximum (F_{max}) and yield (F_y) design capacities for connections exhibiting better-than-nominal ductility. In some instances, it is likely to be uneconomical (and exceedingly conservative) to design using characteristic yield capacity ($F_{y,k}$) as it is presently defined in ISO 22156 (5th percentile with 75% confidence)[9.6].

Confirmation and necessary adjustments to European Yield Model formulas for dowel-type connections[9.7–9.9] in full-culm bamboo should be a priority, since these simple connections are common, and provisions for their design in ISO 22156 presently have some conservative placeholders.

Ductility in bamboo structures must come from the connections. Design and testing of connection types having improved ductile modes of behaviour are needed. Details aimed at mitigating bamboo splitting should be emphasised.

9.6 Fire performance

Fire performance of bamboo is known to be poor (Section 4.6). Means of ensuring adequate fire performance — and validation of these through fire testing — is critical to ensure that the life safety and structural adequacy objectives of building standards are met. Lack of fire performance data and/or fire performance ratings for bamboo structural systems is a significant roadblock to their adoption in many jurisdictions and for more building types.

9.7 Splitting

Bamboo culms have a tendency to fissure or split. ISO 22156 has addressed this phenomenon indirectly through:

- The requirement to use dry bamboo since most cracking occurs during the drying process (grading should be undertaken with dry bamboo to comply with ISO 19624[9.10]).
- The requirements for redundancy (Clause 5.4 of ISO 22156 and Section 6.3 of this *Manual*).
- The adoption of higher FS_m values for failure modes most sensitive to the effects of cracking (shear and tension perpendicular to the culm).
- The requirements for inspectability and replaceability (Clause 5.9).

Splitting is directly addressed through Clause 10.7 — requirements that connections be robust against splitting. Future versions of ISO 22156 should revisit these requirements as a better understanding of splitting emerges. In particular, the mechanics of bamboo cracking and splitting, the effects fissures have on load-bearing capacity, thresholds at which fissures are tolerable in a structure and whether extant cracks can be repaired, remain open areas of investigation.

9.8 Durability

Means and methods of improving bamboo durability in ways that are inexpensive, non-toxic and sustainable will enhance the 'green credentials' of bamboo construction and potentially permit its use in a broader range of Service and Use Classes (ISO 22156, Sections 5.6 and 5.7.1, respectively). Important objectives are:

- To determine load duration factors (C_{DF} and C_{DE}).
- To assess service class and temperature modification factors (C_T) for Service Class 3.
- To refine these factors based on bamboo treatment method provided.

Further research into minimum retention levels of boron to provide adequate and durable protection against beetles and termites is needed. Current guidance is based on timber treatment and inferred to be the same, however further laboratory and *in situ* testing is required to confirm this.

9.9 Design and modelling tools

Digital design tools — from algorithmic design (AD) through to building information modelling (BIM) — aimed across the spectrum of architects, engineers and contractors is becoming ubiquitous. In parallel with improving our understanding of building with bamboo, we must communicate this to users in a manner consistent with other building materials. Developing 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 example of this approach is described by Naylor[9.11], in which the potential for extending the service life of bamboo through algorithmic design approaches is addressed.

Finally, the potential role that material informatics[9.12] and machine learning[9.5] may have on grading, design and adoption of bamboo in building construction is yet to be adequately explored.

9.10 Seismic behaviour

With the exception of composite bamboo shear walls, few full-scale laboratory tests of bamboo lateral load-resisting systems have been conducted. Further in-plane cyclic testing of different bamboo lateral load-resisting systems, such as braced frames and portal frames, would be useful to understand their hysteresis, and eventually determine appropriate ductility factors for seismic design.

9.11 Composite bamboo shear walls

Composite bamboo shear walls have shown excellent potential as ductile lateral load-resisting systems for seismic and typhoon-prone areas. Further testing is required to:

- Optimise their in-plane strength, stiffness and ductility.
- Determine more reliably their in-plane strength, stiffness and ductility, and ultimately derive appropriate factors of safety for design and ductility factors for seismic design.
- Determine more reliably their out-of-plane strength.
- Improve their durability to rot.

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10 Worked examples

The concepts presented in this *Manual* converge into three examples with worked calculations. Example 1 shows the relatively simple design of a floor joist, Example 2 expands to the more involved process of designing a composite bamboo shear wall, and Example 3 finishes with the design of a connection using the two methods outlined by ISO 22156 — component capacities and complete-joint testing.

Example 1: Floor joist

The Institution of Structural Engineers	Job No. 1	Sheet 1 of 6	Drawing No:
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	Component:		

Project: **Example 1: Floor joist**

REF	CALCULATION	OUTPUT

Problem:

Description of problem

A series of floor joists are required to span 3m. They can be assumed to be simply-supported. The permanent (dead) area load, q_{dead} = 0.3kN/m^2; the floor imposed (live) area load, q_{live} = 1.5kN/m^2. The joists do not have a plaster or plasterboard ceiling to the underside. The joists are located in a Service Class 2 environment. The joists will be made from *Dendrocalamus asper*.

Characteristics of bamboo culms

The findings from the geometric, physical and mechanical initial evaluation (characterisation) in accordance with ISO 19624[10.1] and ISO 22157[10.2] of the *Dendrocalamus asper* plantation to be used in this project are:

- Culms with a diameter = 125mm at the base are sufficiently common. — Output: D_b = 125mm
- The mean external taper of the culms is α_e = 0.2% (Cl. 6.2.3.5, ISO 19624).
- The mean internal taper of the culms is α_i = 0.01% (Cl. 6.2.3.6, ISO 19624).
- The mean *D/t* ratio at the base of the culms = 7.
- The characteristic bending strength, $f_{m,k}$ = 50N/mm^2.
- The characteristic shear strength, $f_{v,k}$ = 5N/mm^2.
- The mean modulus of elasticity (at 75% confidence), E_k = 20,000N/mm^2.

$f_{m,k}$, $f_{v,k}$, E_k determined according to ISO 22157 and derived according to ISO 12122-1[10.3]

Solution:

Geometry

On this basis, the geometric characteristics of the culm will be:

D_b = 125mm

> Note: 125mm should be the minimum acceptable diameter at the base of the culms. This information needs to be conveyed to the contractor.

Wall-thickness at the base: $t_b = D_{max} \div D/t = 125\text{mm}/7 = 17.9\text{mm}$ — Output: t_b = 17.9mm

Equation 1 ISO 19624 — Diameter at top: $D_t = D_b - \alpha_e L = 125\text{mm} - 0.2\% \times 3{,}000\text{mm} = 119\text{mm}$ — Output: D_t = 119mm

Equation 2 — Wall-thickness at the top: $t_t = t_b + \dfrac{\alpha_i L - D_b + D_t}{2} = 17.9 + \dfrac{0.01\% \times 3{,}000 - 125 + 119}{2}$

ISO 19624 — $t_t = 17.9\text{mm} - 2.85\text{mm} = 15.1\text{mm}$ — Output: t_t = 15.1mm

Cl. 6.4.1 — Check variation of culm diameter along length: $\dfrac{D_b - D_t}{D_b} = \dfrac{125\text{mm} - 119\text{mm}}{125\text{mm}} = 4.8\%$

ISO 22156[10.4] — $$\frac{D_b - D_t}{D_b} = 4.8\% < 10\%$$

Check variation of culm wall thickness along length: $\dfrac{t_b - t_t}{t_b} = \dfrac{17.9\text{mm} - 15.1\text{mm}}{17.9\text{mm}}$

$$\frac{t_b - t_t}{t_b} = 15.6\% > 10\%$$

Therefore, for calculations adopt D_{mean} and t_t in accordance with Clause 6.4.1.

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	Component:		

Project: Example 1: Floor joist

REF	CALCULATION	OUTPUT

Where:

$$D_{mean} = \frac{(125+119)}{2} = 122\text{mm}$$

OUTPUT: D_{mean} = 122mm

REF: Annex A.3

Check that top of section complies with recommendation that D/t < 12

$$D_t/t_t = 119/15.1 = 7.88$$

OUTPUT: D/t ∴ OK

Geometric properties of the section

Cross-sectional area: $A = \frac{\pi}{4}(D_{mean}{}^2 - (D_{mean} - 2t_t)^2)$

$$A = \frac{\pi}{4}(122^2 - (122 - 2 \times 15.1)^2) = 5{,}071\text{mm}^2$$

Elastic section modulus: $S = \frac{\pi}{32D_{mean}}(D_{mean}{}^4 - (D_{mean} - 2t_t)^4)$

$$S = \frac{\pi}{32 \times 122}(122^4 - (122 - 2 \times 15.1)^4) = 1.21 \times 10^5\text{mm}^3$$

Moment of inertia: $I = \frac{\pi}{64}(D_{mean}{}^4 - (D_{mean} - 2t_t)^4)$

$$I = \frac{\pi}{64}(122^4 - (122 - 2 \times 15.1)^4) = 7.39 \times 10^6\text{mm}^4$$

REF: Table 4.1 of this *Manual*

Joist spacing

Estimate the total uniformly-distributed load (UDL) onto a single culm according to span and diameter from Table 4.1 of this *Manual*

For **D = 125mm** and **L = 3,250mm**, total **UDL = 1.00kN/m, for D = 125mm** and **L = 2,600mm**, total **UDL = 1.25kN/m.**

Table 4.1: Floor beams — spans (mm)

D_{mean} (mm)	Total uniformly-distributed load (dead + live) in kN/m										
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
50	**1,700**	1,000	650	500	400	300	250	250	200	200	150
75	**3,000**	2,300	1,500	1,150	900	750	650	550	500	450	400
100	**4,400**	**3,450**	2,750	2,050	1,600	1,350	1,150	1,000	900	800	700
125	**5,950**	**4,700**	**4,100**	3,250	2,600	2,150	1,850	1,600	1,400	1,250	1,150
150	**7,600**	**6,000**	**5,200**	4,600	3,750	3,100	2,650	2,350	2,050	1,850	1,650

By interpolating for L = 3,000mm, UDL = 1.1kN/mm

Spacing of joists can be estimated from:

Spacing = total UDL/area load $s = \frac{UDL_{total}}{(q_{dead} + q_{live})} = \frac{1.1\text{kN/m}}{(0.3+1.5)\text{kN/m}^2} = 611\text{mm}$

Assume spacing, s = 600mm c/c

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	Component:		

Project: **Example 1: Floor joist**

REF	CALCULATION	OUTPUT

Load combination and corresponding allowable strengths

Two load combinations considered:

Permanent (dead) load only = $w_{perm} = s \times q_{dead} = 0.6\text{m} \times 0.3\text{kN/m}^2 = 0.18\text{kN/m}$

Transient (dead + live) loads = $w_{transient} = s \times (q_{dead} + q_{live})$

$$= 0.6\text{m} \times (0.3 + 1.5)\text{kN/m}^2 = 1.08\text{kN/m}$$

> Note: By inspection the transient load combination is more critical, yet here both will be tested for completeness. Observe that loads are not factored because this is an allowable stress standard. For load combinations, refer to national standards.

Adjustment factors

Cl. 6.4

C_R = 1.1 because compliance with Cl. 5.4.2 may be assumed (i.e., more than four joists)

C_T = 1.0 because temperature in a floor is unlikely to exceed 38°C > three hours

C_{DF} = 0.55 for permanent loads in Service Class 2

C_{DF} = 0.65

For transient loads in Service Class 2

FS_m = 2.0 for bending

FS_m = 4.0 for shear

Cl. 6.4 Formula 2

$$f_i = f_{i,k} \times C_R \times C_{DF} \times C_T \left({}^{1}\!/_{FS_m} \right)$$

For shear:

$$f_{v,permanent} = 5\text{N/mm}^2 \times 1.1 \times 0.55 \times 1.0/4.0 = 0.756\text{N/mm}^2$$

$$f_{v,transient} = 5\text{N/mm}^2 \times 1.1 \times 0.65 \times 1.0/4.0 = 0.894\text{N/mm}^2$$

For bending:

$$f_{m,permanent} = 50\text{N/mm}^2 \times 1.1 \times 0.55 \times 1.0/2.0 = 15.1\text{N/mm}^2$$

$$f_{m,transient} = 50\text{N/mm}^2 \times 1.1 \times 0.65 \times 1.0/2.0 = 17.9\text{N/mm}^2$$

Because transient load is 6x larger than the permanent load, and strength values only 18% larger, undoubtedly the transient load combination is more critical.

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	Component:		

Project: **Example 1: Floor joist**

REF	CALCULATION	OUTPUT

Shear and moment capacity checks

> Note: Shear capacity is generally more critical than bending, so check shear first.

Cl. 8.3.2.1 — Shear capacity check

(for simply-supported beam subject to uniformly-distributed load)

$$V = \frac{w_{transient} \times L}{2} = \frac{1.08\text{kN/m} \times 3.0\text{m}}{2} = 1.62\text{kN}$$

Table 6.2 of this *Manual*

$$V_r = f_{v,transient} \times \frac{A}{2} = 0.894\text{N/mm}^2 \times 5{,}071\text{mm}^2 \div 2 = 2.27\text{kN}$$

$$V = 1.62\text{kN} < V_r = 2.27\text{kN}$$

Utilisation ratio = 1.62/2.27 = 71%

OUTPUT: Shear ∴ OK

Cl. 8.3.2 — Moment capacity check

(for simply-supported beam subject to uniformly-distributed load)

$$M = \frac{w_{transient} \times L^2}{8} = \frac{1.08\text{kN/m} \times (3.0\text{m})^2}{8} = 1.22\text{kNm}$$

Formula 12

$$M_r = f_{m,transient} \times \sum S = 17.9\text{N/mm}^2 \times 1.21 \times 10^5\text{mm}^3 = 2.17\text{kNm}$$

$$M = 1.22\text{kNm} < M_r = 2.17\text{kNm}$$

Utilisation ratio = 1.22/2.17 = 56%

OUTPUT: Bending ∴ OK

Bearing capacity check

ISO 22156 does not include a procedure to undertake bearing checks. It is customary to fill the end of bamboo culms with mortar, which makes the risk of bearing failure minimal.

Deflection check

> Note: Deflection limits are not prescribed in ISO 22156. These are generally defined by jurisdiction. This example follows the approach adopted in the UK for timber beams. Deflection limits for timber beams are given by Table NA.5 from the UK National Annex to Eurocode 5[10.5]. The limit stipulated is L/150 for net final deflections for elements without plasterboard or plaster ceilings. Net final deflections combine instantaneous deflections with long-term creep effects. Long-term creep effects are calculated by adding a percentage of the live load (referred to as ‘quasi-permanent’ loads) to the dead load. Table NA.A1.1 from the UK National Annex to BS EN 1990[10.6] requires that 30% of the live load is considered quasi-permanent. In the UK there is no requirement to check for short-term deflections.

For simply-supported beam subject to uniformly-distributed load:

$$\text{Deflection, } \delta = \frac{5wL^4}{384EI}$$

> Note: This equation does not include the shear component of deflection. ISO 22156 accounts for shear deflections through the modification factor accounting for shear deformations, C_v, which is calculated next. If C_v = 1.0, the contribution to the overall deflection from shear deformations is negligible.

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Project: Example 1: Floor joist

REF	CALCULATION	OUTPUT
	ISO 22156 requires:	
Cl. 8.4.2 Formula 16	$EI = E_d \times \sum I \times C_v$	
	Where:	
Cl. 8.4.1 Formula 15	$C_v = 0.5 + 0.05 \times \left(\frac{a}{D}\right) \leq 1.0$ Where: a is the shear span (L/2 in this instance); a = 1,500mm $D = D_{mean}$ = 122mm Hence: $C_v = 0.5 + 0.05 \times \left(\frac{1{,}500}{122}\right) = 1.11 > 1.0$ therefore take C_v = 1.0 And:	
Cl. 6.6 Formula 6	$E_d = E_k \times C_{DE} \times C_T$ Where: E_k = 20,000N/mm^2 — mean value with 75% confidence. C_T = 1.0 because temperature in a floor is unlikely to exceed 38°C > 24 hours. Note: Clause 8.4.3 requires that the deflections caused by permanent and transient loads need to be calculated separately, with different appropriate E_d values used and then summed together.	
Cl. 6.5 Table 7	C_{DE} = 0.45 for permanent loads in Service Class 2 — in this example interpreted to mean dead load + quasi-permanent load. C_{DE} = 0.95 for transient loads in Service Class 2 — in this example interpreted to mean remaining live load only (i.e., after subtracting the quasi-permanent load). Note: If the instantaneous deflection needs to be checked in isolation, take C_{DE} = 1.0 for all load types. Therefore: $(EI)_{long-term} = (20{,}000\text{N/mm}^2 \times 0.45 \times 1.0) \times 7.39 \times 10^6\text{mm}^4 = 6.65 \times 10^{10}\text{Nmm}^2$ $(EI)_{short-term} = (20{,}000\text{N/mm}^2 \times 0.95 \times 1.0) \times 7.39 \times 10^6\text{mm}^4 = 14.0 \times 10^{10}\text{Nmm}^2$ Note: The terms 'long-term' and 'short-term' have been adopted here to avoid confusion with transient and permanent load combinations used in the strength calculations.	

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Project: **Example 1: Floor joist**

REF	CALCULATION	OUTPUT

The long-term loads consist of total permanent plus the quasi-permanent component of the live load.

$$w_{long-term} = 0.18\text{kN/m} + 0.3 \times 1.08\text{kN/m} = 0.50\text{kN/m}$$

The short-term part of the live load will therefore be:

$$w_{short-term} = 0.7 \times 1.08\text{kN/m} = 0.76\text{kN/m}$$

$$\delta_{long-term} = \frac{5w_{long-term}L^4}{384(EI)_{dead}} = \frac{5 \times 0.50 \times 3{,}000^4}{384 \times 6.65 \times 10^{10}} = 7.9\text{mm} = L/378$$

$$\delta_{short-term} = \frac{5w_{short-term}L^4}{384(EI)_{live}} = \frac{5 \times 0.76 \times 3{,}000^4}{384 \times 1.40 \times 10^{11}} = 5.7\text{mm} = L/523$$

$$\delta_{final} = \delta_{long-term} + \delta_{short-term} = 7.9 + 5.7 = 13.6\text{mm} = L/220$$

Net final deflection limit

$$\frac{L}{150} = 3{,}000 \div 150 = 20\text{mm}$$

Deflection ∴ OK

Deflection check

$$\delta_{final} = 13.6 < \frac{L}{150} = 20$$

Utilisation ratio = 13.6/20 = 68%

End of checks

Observations

- All ISO 22156 checks have been completed. This does not preclude that vibration checks may be required in some jurisdictions. As ISO 22156 does not include vibration, it is deemed beyond the scope of this *Manual.*
- Table 4.1 (from this *Manual*) provided a conservative estimate, as would be expected from a concept design resource.
- It should be noted that the governing failure mode was shear (i.e., greatest 'utilisation ratio'). This is common for beam design to ISO 22156 owing to the large FS_m used for shear.
- The largest utilisation ratio was 71%. Where possible, aim for utilisation ratios above 80%.

Example 2: Composite bamboo shear wall

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Project: Example 2: Composite bamboo shear wall

REF	CALCULATION	OUTPUT
Problem:	**Description of problem**	

A 1.2m × 2.4m composite bamboo shear wall (CBSW) of a one-storey house is required to resist dead and wind loads. The house has a lightweight roof supported by trusses and purlins made of bamboo. Located in a high-wind region and being built using lightweight materials, the house is designed to have composite bamboo shear walls that must be able to withstand net lateral, downward and uplifting forces. The house is considered to be in a Service Class 2 environment.

The CBSW panel consists of a top head plate and bottom sole plate made from sawn softwood (50 × 100mm), *Guadua angustifolia* bamboo studs placed at 600mm centres, an expanded metal lath mesh fixed to a single side of the bamboo and rendered with 40mm cement mortar plaster (Figure 10.1). The wall does not have any additional vertical bracing. Above each CBSW panel is a head binder plate made from a bamboo culm that interconnects all the panels, so the dead load from the roof can be assumed to be distributed evenly onto the panel.

The following loads are to be considered for the design of the wall panel:

Dead load from roof
w_{sdl} = 1.4kN/m (superimposed)

Wind loads

$F_{wind\text{-}h}$ = 1.80kN (lateral)
$W_{wind\text{-}v(up)}$ = 2.55kN/m (uplift)
$W_{wind\text{-}v(down)}$ = 2.10 kN/m (downward)

Table 17 from the Andean Standard[10.7] provides an allowable shear capacity for the above system per unit length = 3.45kN/m for a single cladding wall.

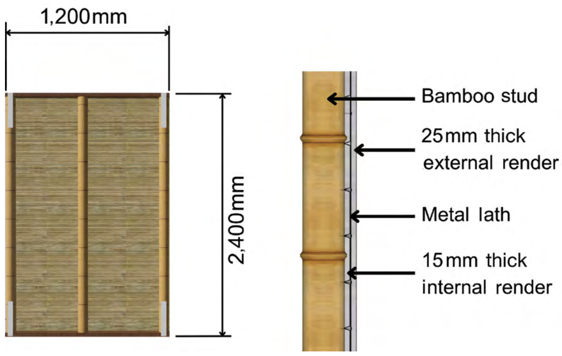

Figure 10.1: Elevation of CBSW and wall construction detail

Characteristics of bamboo culms

The bamboo culms should be made from *Guadua angustifolia* Kunth with the following geometric and mechanical properties:

- The diameter of the culms within the plantation are 90–120mm at the base.
- The mean external taper of the culms is α_e = 0.15% (Cl. 6.2.3.5, ISO 19624[10.1]).
- The mean internal taper of the culms is α_i = 0.00% (Cl. 6.2.3.6, ISO 19624).
- The mean D/t ratio for culms = 9.5.
- Members will be graded to ensure $b_0 \leq$ 0.67%.
- The characteristic compression strength parallel to fibres, $f_{c,k}$ = 45N/mm^2.
- The characteristic shear strength, $f_{v,k}$ = 6.6N/mm^2.
- The 5th percentile modulus with 75% confidence, $E_{k,0.05}$ = 13,500N/mm^2.

$f_{c,k}$, $f_{v,k}$, $E_{k,0.05}$ is determined according to ISO 22157[10.2] and derived from ISO 12122-1[10.3]

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Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT

Solution:

Loads

Dead load

Self-weight of the wall panel is derived considering the weight of each component. Above the wall is a uniformly-distributed superimposed dead load from the weight of the roofing, trusses, purlins and other components in the roof.

Self-weight of wall

Timber plates:	0.04kN
Bamboo studs:	0.15kN
40mm cement mortar render:	2.30kN
Rib lath:	0.03kN
Miscellaneous:	0.05kN
Total self-weight:	**2.57kN**

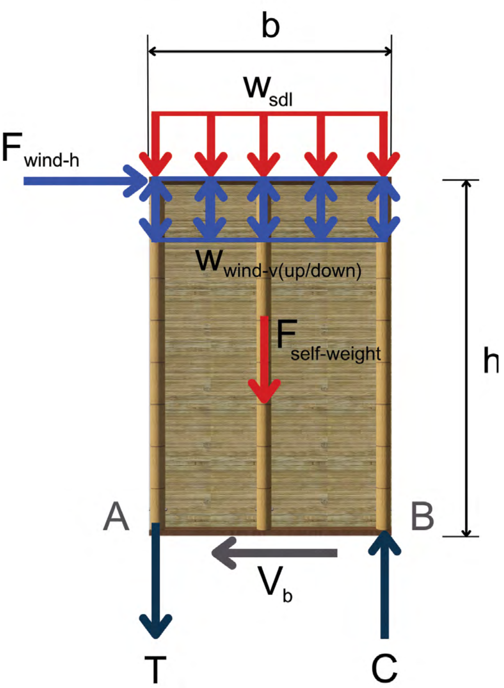
Superimposed from roof above

w_{sdl} = 1.4kN/m

Wind load

Wind loads are transferred to the shear wall through the roof diaphragm and onto the top plate as a concentrated lateral force $F_{wind,h}$. Wind pressures also can generate downward and uplift loads on the structure, given here as uniformly-distributed loads, $w_{wind\text{-}v(up)}$ and $w_{wind\text{-}v(down)}$ (Figure 10.2).

Figure 10.2: Free-body diagram showing forces acting on wall



As given:
$F_{wind\text{-}h}$ = 1.80kN (lateral)
$w_{wind\text{-}v(up)}$ = 2.55kN/m (uplift)
$w_{wind\text{-}v(down)}$ = 2.10kN/m (downward)

Load combination

Load combination to be used for the design shall be:

$LC1 = 0.6D + 0.6W$ (for uplift check)

$LC2 = D + 0.6W$ (for downward check)

Note: ISO 22156[10.4] does not specify load combinations; this is specified by the respective building standard. In this instance, two representative load combinations for allowable strength design (ASD) were taken from ASCE 7 *Minimum design loads for buildings and other structures*[10.8] and assumes wind loads are already in ultimate load format. This combination is deemed to produce the most critical demand for the panel. Note that this combination is also used by several other countries.

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Project: Example 2: Composite bamboo shear wall

REF	CALCULATION	OUTPUT

Shear capacity check for wall

Cl. 12.2.2 ISO 22156 — Check wall to withstand wind-induced shear force.

> Note: ISO 22156 does not contain shear wall capacities. Some national standards do contain values, such as the referenced Andean Standard[10.7]. In other contexts, these capacities will need to be determined experimentally as outlined in Chapter 8.

Allowable shear wall capacity per m length = 3.45kN/m

Allowable shear capacity of the whole wall

$$V_{cap} = (3.45\text{kN/m})(1.20\text{m})$$

$$V_{cap} = 4.14\text{kN}$$

Applied shear force

$$V_{wind} = 0.6(1.8\text{kN}) \quad \textit{(from load combination)}$$

$$V_{wind} = 1.08\text{kN}$$

Check

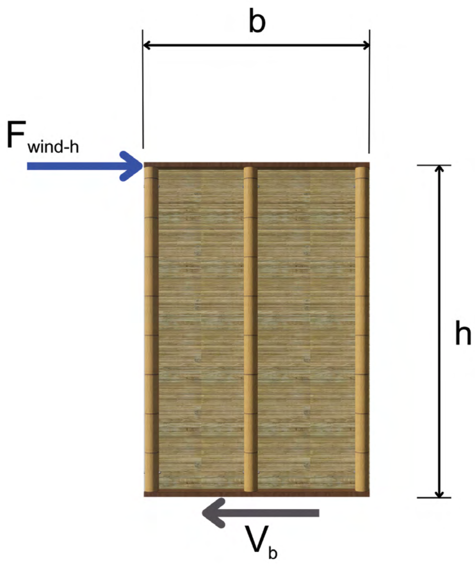
$$V_{wind} \le V_{cap}$$

$1.08\text{kN} < 4.14\text{kN} \therefore$ OK

Utilisation ratio

$$UR = \frac{1.08\text{kN}}{4.14\text{kN}} = 26\%$$

Figure 10.3: Horizontal forces acting on wall



OUTPUT: ∴ *OK*

Wall overturning check

Cl. 12.2.2 Figure 5 — As outlined in Clause 12.2.2 and Figure 5 from ISO 22156, shear walls can be modelled as a vertical cantilever, where the outer studs act in tension and compression (referred to as ‘trailing’ and ‘leading’ stud, respectively). The forces acting on these studs are determined through equilibrium (Figure 10.3). Dead loads will be included in the equilibrium equations according to the two load combinations.

In order to determine the maximum tensile reaction at A, $LC1 = 0.6D + 0.6W$ shall be used considering the uplift wind load.

$$\sum M_B = 0$$

$$0.6(F_{wind-h})(h) + 0.6(w_{wind-v(up)})(b)\left(\frac{b}{2}\right) - 0.6(F_{self-weight})\left(\frac{b}{2}\right) - 0.6(w_{sdl})(b)\left(\frac{b}{2}\right) - T(b) = 0$$

$$0.6(1.80\text{kN})(2.4\text{m}) + 0.6(2.55\text{kN/m})(1.2\text{m})\left(\frac{1.2\text{m}}{2}\right) - 0.6(2.57\text{kN})\left(\frac{1.2\text{m}}{2}\right)$$

$$-0.6(1.40\text{kN/m})(1.2\text{m})\left(\frac{1.2\text{m}}{2}\right) - T(1.2\text{m}) = 0$$

T = **1.80kN** acting on A

OUTPUT: T = 1.80kN

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Project: Example 2: Composite bamboo shear wall

REF	CALCULATION	OUTPUT

To obtain the maximum compression reaction at B, $LC2 = D + 0.6W$ shall be used considering the downward wind load.

$$\sum M_A = 0$$

$$0.6(F_{wind-h})(h) + 0.6(w_{wind-v(down)})(b)\left(\frac{b}{2}\right) + (F_{self-weight})\left(\frac{b}{2}\right) + (w_{sdl})(b)\left(\frac{b}{2}\right) - C(b) = 0$$

$$0.6(1.80\text{kN})(2.4\text{m}) + 0.6(2.10\text{kN/m})(1.2\text{m})\left(\frac{1.2\text{m}}{2}\right) + (2.57\text{kN})\left(\frac{1.2\text{m}}{2}\right)$$

$$+ (1.40\text{kN/m})(1.2\text{m})\left(\frac{1.2\text{m}}{2}\right) - C(1.2\text{m}) = 0$$

C = **5.04kN** acting on B

OUTPUT: $C = 5.04\text{kN}$

Geometric properties of the studs

REF: Table 8 ISO 22156

First, estimate the size of the studs using the compression force **C = 5.04kN**, using Table 4.3 from this *Manual*. Length of bamboo studs, L = 2,400 – 2 x 50mm = 2,300mm (subtracting top and bottom plates). From Table 6.1 in this *Manual*, K = 1.0 for stud walls. Therefore, KL = 2,300mm. As interpolation is not permitted in this table, use KL = 2,500mm, and round up C to 5.7kN.

REF: Table 4.3 of this *Manual*

Table 4.3: Columns — maximum (unfactored) loads (kN) (interpolation is NOT permitted)

D_b (mm)	Effective length (KL) of column (mm)									
	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	5,500	6,000
50	**1.7**	**0.9**	**0.5**	**0.3**	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.0**
63	4.2	2.3	1.4	0.9	0.6	0.4	0.3	0.2	0.2	0.1
75	**8.5**	**4.9**	**3.0**	**2.0**	**1.4**	**1.0**	**0.8**	**0.6**	**0.5**	**0.4**
88	15.0	9.0	5.7	3.9	2.7	2.0	1.5	1.2	0.9	0.7
100	**23.5**	**15.1**	**9.9**	**6.8**	**4.8**	**3.6**	**2.7**	**2.1**	**1.7**	**1.3**
113	33.4	23.4	15.8	11.0	7.9	5.9	4.5	3.5	2.8	2.3
125	**44.6**	**33.9**	**23.7**	**16.7**	**12.2**	**9.2**	**7.1**	**5.6**	**4.5**	**3.6**
138	56.9	45.9	33.7	24.4	18.0	13.6	10.6	8.4	6.7	5.5
150	**70.2**	**59.4**	**46.1**	**34.1**	**25.5**	**19.5**	**15.2**	**12.1**	**9.8**	**8.0**

Hence adopt a section with D_b = 88mm, round up to D_b = 90mm for convenience.

OUTPUT: $D_b = 90\text{mm}$

Note 1: Table 4.3 does not substitute a full calculation. It is solely applicable for concept design and hence caters for a range of bamboo species. *Guadua* is amongst the strongest and stiffest, so it is expected that the solution will provide a greater capacity than predicted by the table.

Note 2: 90mm is the minimum acceptable diameter at the base of the culms. This information needs to be stipulated in structural drawings.

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Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT
	<u>Bamboo wall thickness at base</u> $t_b = D_{max} \div D/t$ $t_b = 90mm/9.5$ $t_b = 9.5mm$	$t_b = 9.5mm$
Eq. 1 ISO 19624	<u>Diameter at top</u> $D_t = D_b - \alpha_e L$ $D_t = 90mm - 0.15\% \times 2{,}300mm$ $D_t = 86.6m$	$D_t = 86.6mm$
Eq. 2 ISO 19624	<u>Bamboo wall thickness at top</u> $t_t = t_b + \frac{\alpha_i L - D_b + D_t}{2}$ $t_t = 9.5mm + \frac{0.00\% \times 2{,}300mm - 90.0mm + 86.6mm}{2} = 7.8mm$	$t_t = 7.8mm$
Cl. 6.4.1 ISO 22156	<u>Check variation of culm diameter along length:</u> $\frac{D_b - D_t}{D_b} = \frac{90.0mm - 86.6mm}{90.0mm} = 3.8\% < 10\%$ Check variation of culm wall thickness along length: $\frac{t_b - t_t}{t_b} = \frac{9.5 - 7.8}{9.5} = 17.9\% > 10\%$ Therefore, for calculations use D_{mean} and t_t Where: $D_{mean} = \frac{(90.0 + 86.6)}{2} = 88.3mm$ $D_{mean} = 88.3mm$	
Annex A.3 ISO 22156	<u>Check that top of section complies with recommendation that D/t < 12</u> $D_t/t_t = \frac{86.6mm}{7.8mm}$ $D_t/t_t = 11.1$	$D_t/t_t \therefore OK$
	<u>Cross-sectional area</u> $A = \frac{\pi}{4}({D_{mean}}^2 - (D_{mean} - 2t_t)^2)$ $A = \frac{\pi}{4}(88.3^2 - (88.3 - 2 \times 7.8)^2)$ $A = 1{,}973mm^2$	$A = 1{,}973mm^2$

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Project: Example 2: Composite bamboo shear wall

REF	CALCULATION	OUTPUT

Moment of inertia

$$I = \frac{\pi}{64}(D_{mean}{}^{4} - (D_{mean} - 2t_t)^4)$$

$$I = \frac{\pi}{64}(88.3^4 - (88.3 - 2 \times 7.8)^4)$$

$$I = 1.61 \times 10^6 \text{mm}^4$$

OUTPUT: $I = 1.61 \times 10^6 \text{mm}^4$

Cl. 6.4
ISO 22156

Adjustment factors

C_R = 0.9 for element compression of bamboo (because compliance with Cl. 5.4.2 cannot be assumed)
C_R = 1.1 for local screw failures where there are four or more screws in total and load is capable of being redistributed
C_T = 1.0 because temperature in a wall is unlikely to exceed 38°C > three hours
C_{DF} = 0.85 for instantaneous loads (wind) in Service Class 2
FS_m = 2.0 for connections in compression

Capacity in tension of trailing stud connection

The proposed detail to either side of the end studs (i.e., two straps per stud) is a steel strap made of 3mm thick steel plate fastened to the bamboo with screws (Figure 10.4).

Connection detail

Steel plate

$t_{plate} = 3\text{mm}$

Fasteners

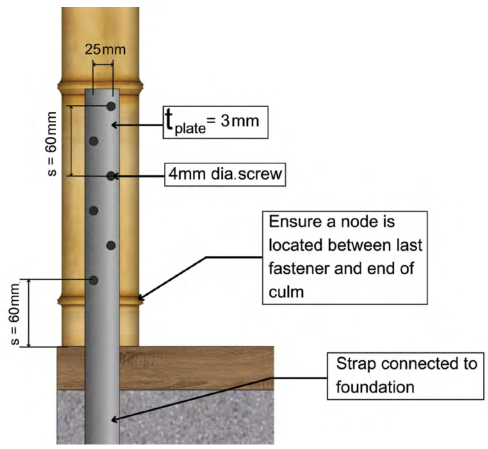
$n = \textit{six screws}$

$\textit{Threaded diameter} = 4\text{mm}$

$\textit{Root (shank) diameter} = 2.85\text{mm}$

$s = 60\text{mm}$

Figure 10.4: Detail of tension connection



Note: Clause 10.12.1 from ISO 22156 does not allow for the addition of multiple fasteners into a single culm without tests to determine reduction factors for multiple fasteners. However, given the similarity of the proposed configuration to that in *Study of screwed bamboo connection loaded parallel to fibre*[10.9], it will be assumed that this configuration is adequate. However, some confirmatory testing would still be required.

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Project: Example 2: Composite bamboo shear wall

REF	CALCULATION	OUTPUT
Cl. 10.12.1 ISO 22156	Check using component capacities (Cl. 10.3) Three failure modes within the connection need to be assessed: • $F_{b,A}$: bearing — Formula 34. • $F_{b,B}$: shear — Formula 35. • $F_{b,C}$: cleavage — Formula 36.	
Table 11 ISO 22156	<u>Bearing check of dowel connection</u> $F_{b,A} = D_{dowel} \times t \times f_c \times C_\theta$ Where: $D_{dowel} = 1.1 \times \text{root}(\text{shank})\text{diameter} = 1.1 \times 2.85\text{mm} = 3.1\text{mm}$ $t = t_t = 7.8\text{mm}$ (check for narrowest wall thickness) $C_\theta = 0.3$ for $\theta = 0°$ and fastener engaging only one wall f_C is the allowable compression strength, determined by: $f_C = (f_{ck})(C_R)(C_{DF})(C_T)\left(\frac{1}{FS_m}\right)$ $f_C = (45\text{N/mm}^2)(1.1)(0.85)(1.0)\left(\frac{1}{2.0}\right)$ $f_C = 21.0\text{N/mm}^2$ Therefore: $F_{b,A} = (3.1\text{mm})(7.8\text{mm})(21.0\text{N/mm}^2)(0.3)$ $F_{b,A} = 152\text{N} = 0.152\text{kN}$	$F_{b,A} = 0.15\text{kN}$
Cl. 10.12.1 ISO 22156	<u>Shear check of dowel connection</u> $F_{b,B} = 1.6 \times s \times t \times f_v$ Where: $s = 60\text{mm}$ $t = t_t = 7.8\text{mm}$ f_v is the allowable shear strength, determined by: $f_v = (f_{vk})(C_R)(C_{DF})(C_T)\left(\frac{1}{FS_m}\right)$ $f_v = (6.6\text{N/mm}^2)(1.1)(0.85)(1.0)\left(\frac{1}{4.0}\right)$ $f_v = 1.54\text{N/mm}^2$	

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Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT

Therefore:

$$F_{b,B} = 1.6 \times 60\text{mm} \times 7.8\text{mm} \times 1.54\text{N/mm}^2$$

$$F_{b,B} = 1{,}150\text{N} = 1.15\text{kN}$$

OUTPUT: $F_{b,B} = 1.15\text{kN}$

REF: Cl. 10.12.1 ISO 22156

<u>Cleavage check of dowel connection</u>

> Note: As outlined in Section 7.4.1 of this *Manual*, this check is excessively conservative. As proposed, Mode B and C checks can be omitted if:
>
> *"For $D_{dowel} \leq 5$mm, multiple dowels placed in the same gauge line are spaced $s \geq 14D_{dowel}$. Dowels in adjacent gauge lines are spaced $s \geq 7D_{dowel}$ and gauge lines staggered by an angle Ψ." Section 7.4.4 sets out the spacing requirements for* Ψ: $\Psi \geq 115D_{dowel}/D$ (degrees) [$\Psi \geq 2D_{dowel}/D$ in radians].
>
> Mode B check has been included above for completeness.

In this instance $D_{dowel} = 4.0\text{mm} < 5\text{mm}$, and dowels (i.e., screws) along the same gauge line are spaced vertically at 60mm from each other which is greater than $14D_{dowel} = 56\text{mm}$, hence compliant. Dowels that are staggered in adjacent gauge lines are spaced at 30mm along the line of the fibres, which is greater than $7D_{dowel} = 28\text{mm}$, hence also compliant.

Finally, $\psi_{(rad)} = \dfrac{\textit{distance between gauge lines}}{\left(\frac{D}{2}\right)} = \dfrac{25\text{mm}}{\left(\frac{90\text{mm}}{2}\right)} = 0.56\,\textit{radians}$

Which is greater than $\dfrac{2D_{dowel}}{D} = \dfrac{2 \times 4\text{mm}}{90\text{mm}} = 0.09\,\textit{radians}$

Therefore, Mode C check can be omitted, although a notional split analysis as outlined in Clause 5.3 should still also be undertaken.

OUTPUT: *∴ Mode C check may be omitted*

$$F_b = \textit{smallest}\begin{cases} F_{b,A} = 0.15\text{kN} \\ F_{b,B} = 1.50\text{kN} \\ F_{b,C} = \text{N/A} \end{cases}$$

$$F_b = 0.15\text{kN}$$

> Note: From these values, it is evident that Mode B was 10x higher than Mode A, which confirms that if spacing and edge distance requirements are met, it is unlikely for shear to occur.

As $T = 1.80$kN and $F_b = 0.15$kN, determine the minimum number of fasteners n from

$$n = \frac{T}{F_b}$$

$$n = \frac{1.80\text{kN}}{0.15\text{kN}}$$

$$n = 12 \text{ screws}$$

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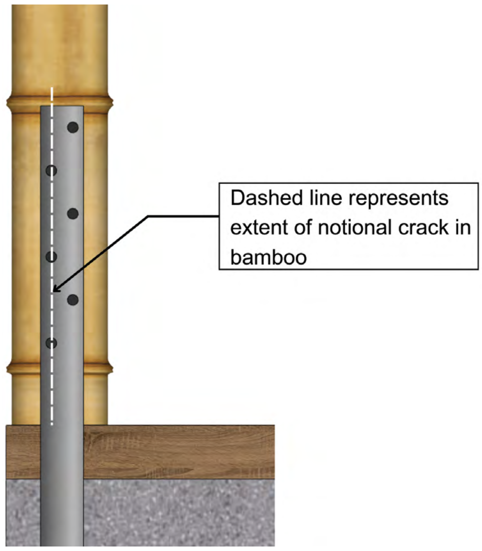
Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT
	Place 12 screws, six to either side of the culm	
	Utilisation ratio $UR = \frac{F_{per\ screw}}{F_b} = \frac{0.15kN}{0.15kN} = 100\% \therefore OK!$	$\therefore OK$
Cl. 5.3 ISO 22156	Notional crack check of dowel connection Clause 5.3 requires that the effects of a notional split/crack on a connection are considered. In this instance, it is assumed that a split (crack) has occurred along one line of screws (Figure 10.5). It can be assumed that this crack will negate the contribution from three of the 12 screws (six at either side of the stud) acting at the joint, reducing the joint capacity by 25%. This satisfies the 75% residual capacity requirement of Clause 5.3.	

Figure 10.5: Detail of connection showing notional crack



Note: Checking for notional splitting is especially important for two reasons:

- There is no alternative load path for tension loads other than the connection.
- Mode C failure mode check was omitted.

Capacity in end bearing of bamboo culm leading stud base connection

Allowable strength

$$f_C = (f_{ck})(C_R)(C_{DF})(C_T)\left(\frac{1}{FS_m}\right)$$

$$f_C = (45N/mm^2)(0.9)(0.85)(1.0)\left(\frac{1}{2.0}\right)$$

$$f_C = 17.2N/mm^2$$

End bearing capacity

$$P_b = (C_{EB})\,(f_C)\,(A)$$

$C_{EB} = 0.80$ (for straight cuts bearing onto a flat surface)

$$P_b = (0.80)(17.2N/mm^2)(1{,}973mm^2)$$

$$P_b = 27{,}100N$$

Output: $P_b = 27.1kN$

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Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT

Check

$C \leq P_b$

$5.04\text{kN} < 27.1\text{kN}$

Utilisation ratio

$$UR = \frac{5.04\text{kN}}{27.1\text{kN}} = 19\% \quad \therefore OK!$$

OUTPUT: $\therefore$ *OK*

REF: Eq. 6.1 of this *Manual*

Characteristic compression capacity

$$N_{cr,k} = \frac{P_{c,k} + P_{e,k}}{2c} - \sqrt{\left(\frac{P_{c,k} + P_{e,k}}{2c}\right)^2 - \frac{P_{c,k}P_{e,k}}{c}}$$

> Note: Remember that this is a modification of Formula 20 from ISO 22156 (Section 6.4.2 of this *Manual*).

Where:

C = 0.8

$P_{c,k}$ = characteristic crushing capacity calculated by:

REF: Eq. 6.2 of this *Manual*

$$P_{c,k} = f_{c,k} \times \sum A$$

$P_{e,k}$ = characteristic buckling capacity calculated by:

REF: Eq. 6.3 of this *Manual*

$$P_{e,k} = \frac{n\pi^2 E_{k,0.05} I C_{bow}}{(KL)^2}$$

Characteristic crushing capacity

$$P_{c,k} = f_C \times \sum A$$

$$P_{c,k} = 45\text{N/mm}^2 \times 1{,}973\text{mm}^2 = 88.8\text{kN}$$

Buckling capacity

$$P_{e,k} = \frac{n\pi^2 E_{k,0.05} I C_{bow}}{(KL)^2}$$

OUTPUT: KL = 2,00mm

Where:

n = number of culms, one in this instance

$E_{k,0.05}$, I, and KL have been previously explained

OUTPUT: $E_{k,0.05}$ = 13,500N/mm^2

> Note: The expression $E_{k,0.05}$ is not present in ISO 22156. It is proposed in this *Manual* as a more conservative way to calculate buckling capacity (Section 6.4.2).

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Project: **Example 2: Composite bamboo shear wall**

REF	CALCULATION	OUTPUT

$$c_{bow} = 1 - \frac{b_o}{0.02}$$

$$c_{bow} = 1 - \frac{0.0067}{0.02}$$

$$c_{bow} = 0.665$$

OUTPUT: $c_{bow} = 0.665$

Therefore:

$$P_{e,k} = \frac{\pi^2 (13{,}500\text{N/mm}^2)(1.61 \times 10^6 \text{mm}^4)(0.665)}{(1.0 \times 2{,}300\text{mm}^2)}$$

$$P_{e,k} = 26{,}970\text{N}$$

$$P_{e,k} = 27.0\text{kN}$$

Therefore:

$$N_{cr,k} = \frac{(88.8\text{kN}) + (27.0\text{kN})}{2(0.80)} - \sqrt{\left[\frac{(88.8\text{kN}) + (27.0\text{kN})}{2(0.80)}\right]^2 - \frac{(88.8\text{kN})(27.0\text{kN})}{2(0.80)}}$$

$$N_{cr,k} = 25.0\text{kN}$$

OUTPUT: $N_{cr,k} = 25.0\text{kN}$

REF: Eq. 6.5 of this *Manual*

Find the allowable column capacity, N_{cr}

$$N_{cr} = \frac{N_{cr,k} \times C_r \times C_T \times C_{DF}}{FS_m}$$

> Note: This equation is a modification of those contained in Clause 9.3 of ISO 22156. Section 6.4.2 of this *Manual* provides a justification for its use.

$$N_{cr} = \frac{25.0\text{kN} \times 0.9 \times 1.0 \times 0.85}{2.0} = 9.56\text{kN}$$

Check

$C \leq N_{cr}$

5.04kN < 9.56kN ∴ OK

OUTPUT: ∴ *OK*

Utilisation ratio

$$UR = \frac{5.04\text{kN}}{9.56\text{kN}} = 53\% \quad \therefore \textit{OK!}$$

> Further checks
>
> - Compression perpendicular to grain for timber softwood plates due to bearing of bamboo stud.
> - Shear check of timber softwood plates to structure below (connection detail not shown but typically bolts embedded in the foundation) and structure above (also typically bolts).
> - Capacity check of metal fasteners.
> - Tensile checks of steel hold-down plate.

Example 3: T-joint capacity using two methods

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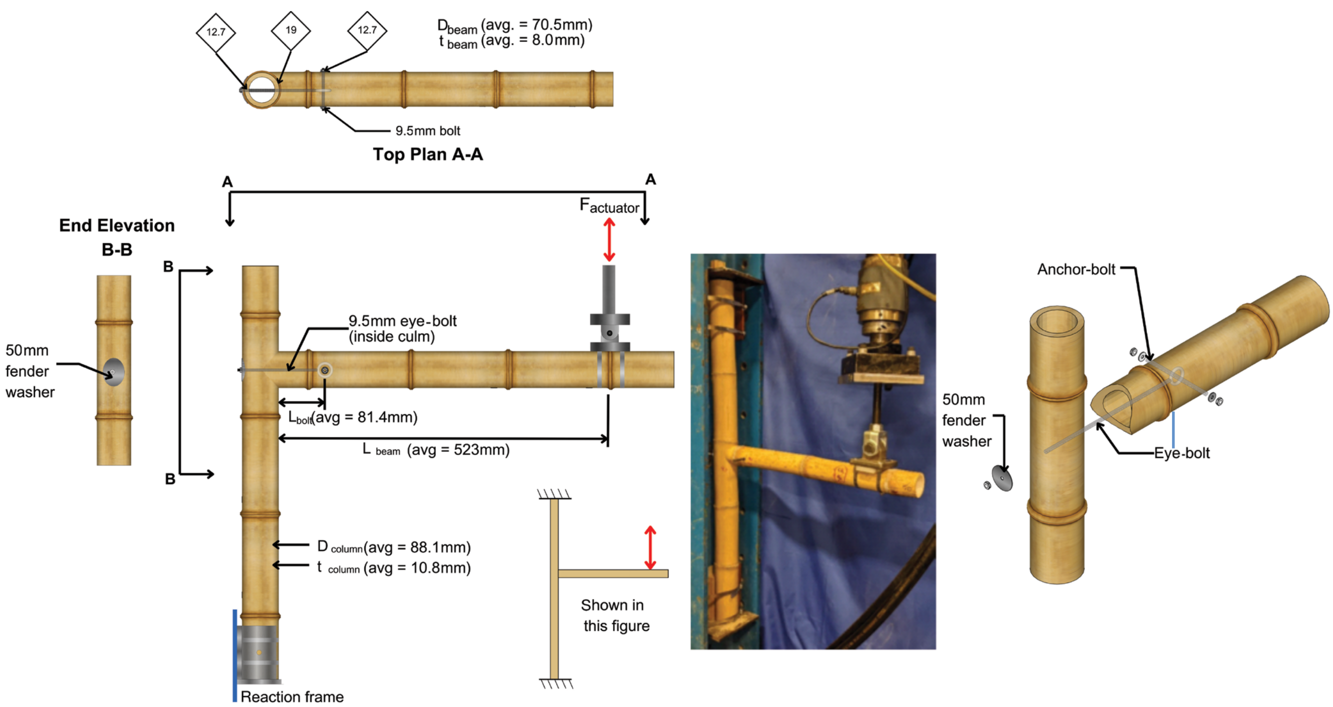
Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT
Introduction:	ISO 22156 offers two approaches to design bamboo connections. The first approach is joint design by component capacities which is explained in Section 7.3 of this *Manual* and is also presented in Example 2 of Chapter 10). The second approach is joint design by complete-joint testing which is explained in Section 7.8. Example 3, here, will explore both methods; Example 3a and Example 3b. The data used in this example is presented in *Bamboo joint capacity determined by ISO 22156 'complete joint testing' provisions*[10.10]. The joint examined has a small load-bearing capacity, which is not the case for all bamboo joints. This joint was selected for this example because it adopts the procedures in ISO 22156 for complete-joint testing.	
Problem:	**Description of problem** The capacity of a T-shaped moment-resisting connection is to be determined using the two approaches supported by ISO 22156. Summary of data: 20 joints of the type shown in Figure 10.6 were subject to cyclic testing in accordance with ISO 16670[10.11], joint characteristics were interpreted according to ISO/TR 21141[10.12] and characteristic values were derived according to ISO 12122-1[10.3]. The characteristic capacities (for the force applied at the actuator, referred to as $F_{actuator}$ hereafter) for the 20 joints were determined to be: $F_{actuator,y,k} = 115\text{N}$ $F_{actuator,max,k} = 693\text{N}$	

Figure 10.6: Test arrangement and details of T-shaped connection



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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT

Joints were not tested to destruction but limited to a 3.8° (1/15 rad) rotation (as prescribed by ISO/TR 21141 for assemblies having 'excessive deformation').
This example will focus on finding alternative means to predict the characteristic capacity that was not explored in *Bamboo joint capacity determined by ISO 22156 'complete joint testing' provisions*[10.10].

Characteristics of bamboo culms

The bamboo used was *Guadua angustifolia* Kunth with the following characteristics:

- D_{column}: Mean = 88.1mm, range: 76.2–99.8mm.
- t_{column}: Mean = 10.8mm, range: 7.0–19.2mm.
- D_{beam}: Mean = 70.5mm, range: 58.4–80.8mm.
- t_{beam}: Mean = 8.0mm, range: 6.5–10.7mm.

The characteristic confidence material properties are:

- Compression strength parallel to fibres, $f_{c,k}$ = 32N/mm^2.
- Bending strength perpendicular to fibres, $f_{m.90,k}$ = 7.8N/mm^2.
- Shear strength, $f_{v,k}$ = 8.0N/mm^2.

Characteristics of joint

- L_{beam}: Mean = 523mm, range: 467–567mm.
- D_{washer}: 50mm.
- L_{bolt}: Mean = 81.4 mm, range: 44.5–114.3mm.

Solution:

Nomenclature

For clarity, the following nomenclature will be adopted:

- Force applied onto the actuator, $F_{actuator}$.
- Resulting tensile force acting on the eye-bolt, $F_{eye\text{-}bolt}$.
- Preload tensile force applied on the eye-bolt, F_{torque}.

Assumed mechanism (Figure 10.7)

The application of $F_{actuator}$ results in a moment at the beam-to-column joint equal to the product $F_{actuator} \times L_{beam}$. This moment is resisted by the couple comprised of the tension in the eye-bolt, $F_{eye\text{-}bolt}$, and compression at the beam-to-column 'fish-mouth' cut.

Therefore, $F_{eye\text{-}bolt}$ can be calculated by:

$$F_{eye-bolt} = \frac{F_{actuator} \times L_{beam}}{D_{beam}/2}$$

$F_{eye\text{-}bolt}$ exerts a tensile force onto the 50mm fender washer where it bears against the rear side of the column. $F_{eye\text{-}bolt}$ also loads the 9.5mm anchor-bolt in the beam. The anchor-bolt is a symmetric dowel connection loaded at its centre — the anchor-bolt is therefore in flexure and is reacted by the culm walls in bearing. The connection-specific possible failure modes are:

- Bearing failure of bamboo column under the fender washer.
- Compression failure either in the bamboo column or beam at the beam-to-column joint.

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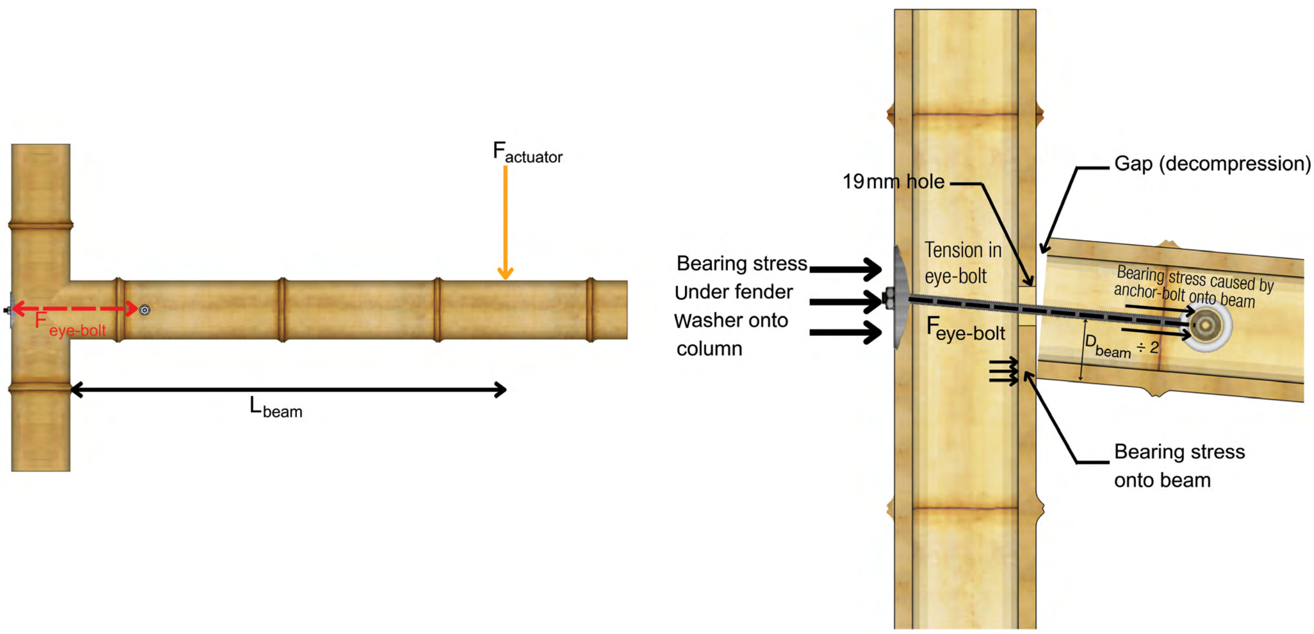
Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT

Figure 10.7: Details of assumed mechanism



- Bearing, splitting or shear failure of the bamboo beam at the anchor-bolt penetrations.
- Bending failure of the anchor-bolt (not explicitly addressed in ISO 22156).
- Tensile failure of the eye-bolt (not explicitly addressed in ISO 22156).
- Bending of the fender washer (not explicitly addressed in ISO 22156).

The latter three failure modes relate to steel elements, so are not explicitly addressed in ISO 22156, nor are they covered by this example. This list is not exhaustive, as it does not include failure modes of the beam or column elements related to application of the joint moment. It should also be noted that joints were tested to the ISO/TR 21141-prescribed deflection limit of $L_{beam}/15$ but were not tested to destruction, hence governing ultimate failure mode was not established. However, bearing damage to the bamboo beam in contact with the anchor-bolt was observed.

As discussed in the introduction, two different approaches to connection design will be presented.

Example 3A: Joint design by component capacities to Cl. 10.3 – first approach

The capacity of a single specimen will be predicted using the clauses given in Figure 10.8. For each check characteristic strength will be used.

> Note: The procedures for joint design by component capacities normally result in an **allowable design capacity** (**Example 2)**. However, in this example the characteristic strength will be used, as it makes it easier to appreciate the level of safety of the solution prior to application of factors of safety.

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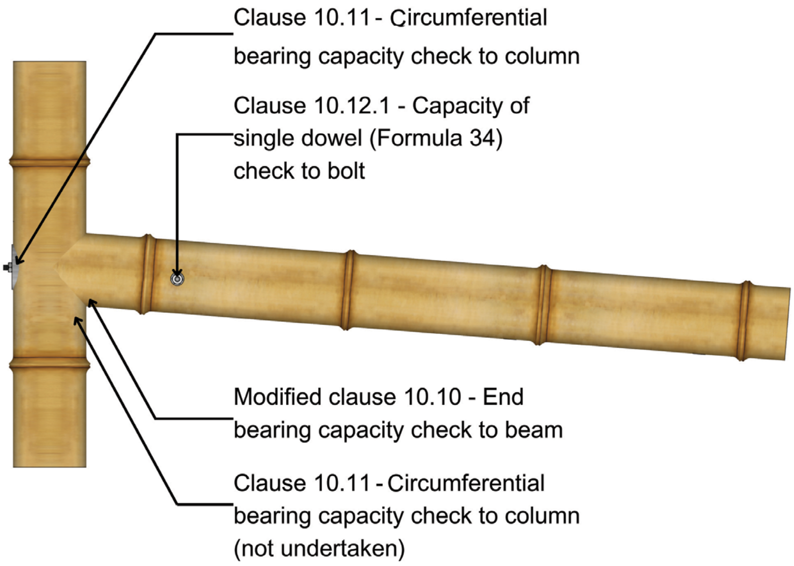
Project: Example 3: T-joint capacity using two methods

REF	CALCULATION	OUTPUT

Figure 10.8: Checks undertaken in the first approach



Specimen characteristics (specimen 16[10.10]):

- D_{column}: 88.9mm.
- t_{column}: 10.6.
- D_{beam}: 73.9mm.
- t_{beam}: 8.6mm.
- L_{beam}: 524mm.
- L_{bolt}: 76.2mm.

Cl. 10.11 ISO 22156

<u>Circumferential bearing capacity of column under washer</u>

> Note: The procedure for this check was presented in this *Manual*. Section 7.3.2 gives the justification. Figure 7.2 provides a definition of β.

Eq. 7.5 of this *Manual*

$$P_{cir} = \frac{4f_{m,90,k}(L_{cir} + 2D)t_{col}^{\ 2}\left(1 - \cos\left(\frac{\beta}{2}\right)\right)}{3\beta D_{col}K_m}$$

Where:

L_{cir} = diameter of washer = 50mm

$$\beta = \frac{L_{cir}}{(D_{column}/2)} = \frac{50\text{mm}}{(88.9\text{mm}/2)} = 1.125\,rad \quad (64.5°)$$

Eq. 7.6 of this *Manual*

$K_M = (1/\pi\beta) \times [2\cos(\beta/2) - 2 - 2\pi\sin(\beta/2) + \beta\sin(\beta/2) + \pi\beta - \beta^2/4] = 0.045$

Replacing the previous terms

$$P_{cir} = \frac{4 \times 7.8 \times (50 + 2 \times 89) \times 10.6^2 \times (1 - \cos(0.563))}{3 \times 1.125 \times 89 \times 0.045} = 9{,}122\text{N}$$

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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT
	This capacity should not exceed that given by Formula 33	
Formula 33	$P_{cir} \leq 0.5 L_{cir} t_{col} f_{c,k}$	
	With all terms defined previously, hence:	
	$P_{cir} \leq 0.5 \times 50 \times 10.6 \times 32 = 8{,}480\text{N}$, which is less than 9,122N	
	Therefore, $P_{cir,k}$ = 8,480N, and therefore <u>$F_{eye\text{-}bolt}$ should not exceed this capacity</u>	
	Note: The pretension applied to the eye-bolt should not exceed approximately 90% of P_{cir}, to avoid damaging the culm.	
Cl. 10.12.1 ISO 22156	<u>**Capacity of single dowel (per culm wall of the beam)**</u>	
	Three failure modes need to be assessed: $F_{b,A}$: bearing — Formula 34 $F_{b,B}$: shear — Formula 35 $F_{b,C}$: cleavage — Formula 36	
	<u>Bearing check</u> (bearing of anchor-bolt against beam wall)	
	$F_{b,A,k} = D_{dowel} \times t \times f_{c,k} \times C_{\theta}$	
	Where:	
	$D_{dowel} = 9.5\text{mm}$	
	t = 8.6mm	
Table 11 ISO 22156	C_{θ} = 0.7 for $\theta = 0°$ and fastener engaging both walls symmetrically $f_{c,k}$ is the characteristic compression strength	
	Note: As discussed at the beginning of this example, the procedure contained in ISO 22156 normally would require using **allowable compression strength**. However, this example will use characteristic strength (i.e., 5th percentile with 75% confidence without any factors of safety) so that the overall level of safety of the solution is better appreciated.	
	Therefore:	
	$F_{b,A,k} = 9.5\text{mm} \times 8.6\text{mm} \times 32\text{N/mm}^2 \times 0.7$	
	$F_{b,A,k} = 1{,}830$	
	The total characteristic bearing capacity of the dowel = 2 × $F_{b,A,k}$ = 3,660N	
	Note: F_b should be multiplied by two because the equations contained in Clause 10.12.1 are per culm wall, and in this instance two walls have been engaged.	
	<u>Shear check</u>	
	$F_{b,B} = 1.6 \times s \times t \times f_v$	
	Where:	
	s ≈ L_{bolt} = 76.2mm	
	t = 8.6mm	

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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT

$f_{v,k}$ is the characteristic shear strength

> Note: The earlier note regarding the use of characteristic strength instead of allowable strength applies here also.

Therefore:

$$F_{b,B,k} = 1.6 \times 76.2\text{mm} \times 8.6\text{mm} \times 8\text{N/mm}^2$$

$$F_{b,B,k} = 8{,}400\text{N} \text{ (per culm wall)}$$

The total characteristic shear capacity of both culm walls = 2 × $F_{b,B,k}$ = 16,800N

Cleavage check

> Note: As outlined in Section 7.4.1, Formula 36 from ISO 22156 results in an excessively conservative value. The alternative approach presented in this example instead uses spacing and end-distance checks. The adequacy of this approach is validated by the fact that cleavage was not reported in *Bamboo connection capacity determined by ISO 22156 'complete joint testing' provisions*[10.10].

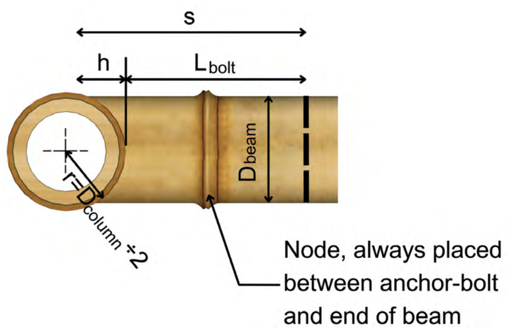
Section 7.4.1 of this *Manual*

Check for cleavage may be omitted if distance between end of culm and bolt exceeds, $s \geq 10D_{dowel}$ and includes a node. Nodes were always placed at the end of beams as can be seen in Figure 10.6. The distance to the end, s, is calculated $s = L_{bolt} + h$ (Figure 10.9).

Where:

h is the *sagitta* of circular segment formed by the fish-mouth cut.

Figure 10.9: Horizontal section of joint identifying key dimensions



A *sagitta* is calculated:

$$h = R - \sqrt{R^2 - \frac{c^2}{4}}$$

Where:

R is the radius of the circle containing the segment, in this instance D_{column} ÷ 2c is the length of the chord, in this instance D_{beam}

$$h = \frac{89.9\text{mm}}{2} - \sqrt{\left(\frac{89.9\text{mm}}{2}\right)^2 - \frac{(73.9\text{mm})^2}{4}} = 19.4\text{mm}$$

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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT

Therefore:

s = 76.2mm + 19.4mm = 95.6mm

As D_{dowel} = 9.5mm; 10D_{dowel} = 95mm < 95.6mm ∴OK!

Assessment of the capacity of single dowel

$F_{b,k}$ is taken as the smallest between $F_{b,A,k}$ and $F_{b,B,k}$ i.e., 1,830N

Assessment of $F_{eye\text{-}bolt}$ capacity

Therefore $F_{eye\text{-}bolt}$ should not exceed the smaller between $P_{cir,k}$ and 2 × $F_{b,k}$.

$$F_{eye-bolt} = min\begin{cases} P_{cir} \\ 2 \times F_{b,k} \end{cases} = min\begin{cases} 8{,}500\text{N} \\ 3{,}600\text{N} \end{cases} = 3{,}600\text{N}$$

By rearranging

$$F_{eye-bolt} = \frac{F_{actuator} \times L_{beam}}{D_{beam}/2}$$

For $F_{actuator}$, we obtain:

$$F_{actuator} = \frac{F_{eye-bolt} \times D_{beam}/2}{L_{beam}} = \frac{3{,}600\text{N} \times 73.9\text{mm}/2}{524\text{mm}} = 250\text{N}$$

Cl. 10.10 ISO 22156

End bearing capacity check to the beam (Figures 10.7 and 10.8)

Formula 31 may be used to assess the end bearing capacity of a fish-mouth cut.

When subjected to a compressive load:

$$P_{b,k} = C_{EB} \times f_{c,k} \times A$$

Where:

A is the cross-sectional area of the culm

$f_{c,k}$ is the characteristic compression strength

> Note: As discussed under bearing check, usually this would be **allowable compression strength.**

C_{EB} is a factor to account for the type of cut made to the bamboo; for fish-mouth cut = 0.4

However, because a moment instead of a compressive force is present, it is proposed that Formula 31 can be rewritten for moment as:

$$M_b = C_{EB} \times f_c \times S$$

Where:

S is the elastic section modulus calculated:

$$S = \frac{\pi}{32D_{beam}}(D_{beam}{}^4 - (D_{beam} - 2t_{beam})^4) = \frac{\pi}{32 \times 73.9}(73.9^4 - (73.9 - 2 \times 8.6)^4)$$

S = 25,900mm^3

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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT

Therefore:

$$M_b = 0.4 \times 32 \times 25{,}900 = 332{,}000\text{Nm}$$

> Note: This is a conservative approach. Given that in compression bamboo exhibits some plasticity, some level of redistribution could be assumed. A reasonable compromise would be to adopt 1.15 × *S*. However, this example will adopt the fully-elastic approach for simplicity.

$F_{actuator}$ can therefore be determined :

$$F_{actuator} = \frac{M_b}{L_{beam}} = \frac{332{,}000\text{Nmm}}{524\text{mm}} = 633\text{N}$$

From the checks undertaken (end bearing of beam and $F_{eye\text{-}bolt}$), the smallest $F_{actuator}$ = 250N, and the expected failure mechanism is the dowel bearing into the beam wall. As all the strength values inputted were characteristic values, it is proposed that this capacity is also characteristic. If the intention was to use this value for design, it would need to be converted into an allowable capacity. To do this, multiply $F_{actuator,k}$ by C_{DF} and divide by FS_j as outlined in Clause 10.4 from ISO 22156. For instance, if the joint were to be used in Service Class 2 to resist instantaneous loads (e.g., wind), C_{DF} = 0.85. *Bamboo connection capacity determined by ISO 22156 'complete joint testing' provisions*[10.10] reported an average ductility, μ = 5.6, therefore FS_j can be taken as 2.0, in accordance with Table 9 from ISO 22156.

OUTPUT: $F_{actuator,k}$ = 250N

$$F_{actuator,allowable} = C_{DF} \times \frac{F_{actuator,k}}{FS_j} = 0.85 \times \frac{250\text{N}}{2.0} = 106\text{N}$$

> Note 1: The allowable capacity for this joint is very small and is unlikely to be of significant practical value. The purpose of this example is to demonstrate how ISO 22156 can be used to determine connection design capacities.

> Note 2: This capacity can be compared to the experimental findings in *Bamboo connection capacity determined by ISO 22156 'complete joint testing' provisions*[10.10]. It is proposed that:
>
> - Characteristic yield capacity for all connections (i.e., $F_{actuator,y,k}$) = 115N.
> - Yield capacity for the specific specimen tested (specimen 16): 110N and 580N (each connection had two results from the upward and downward cycle).
>
> However, this does not clarify whether the method is appropriate.
>
> An alternative way to appreciate the level of safety of the solution contained in this example is to plot the experimental observations vs. the predicted characteristic values (Figure 10.10). This results in all but two data points being located above the black-dashed line. Data above the dashed black lines is safe (i.e., the prediction is smaller than the observed value). This suggests that overall this is a safe solution,

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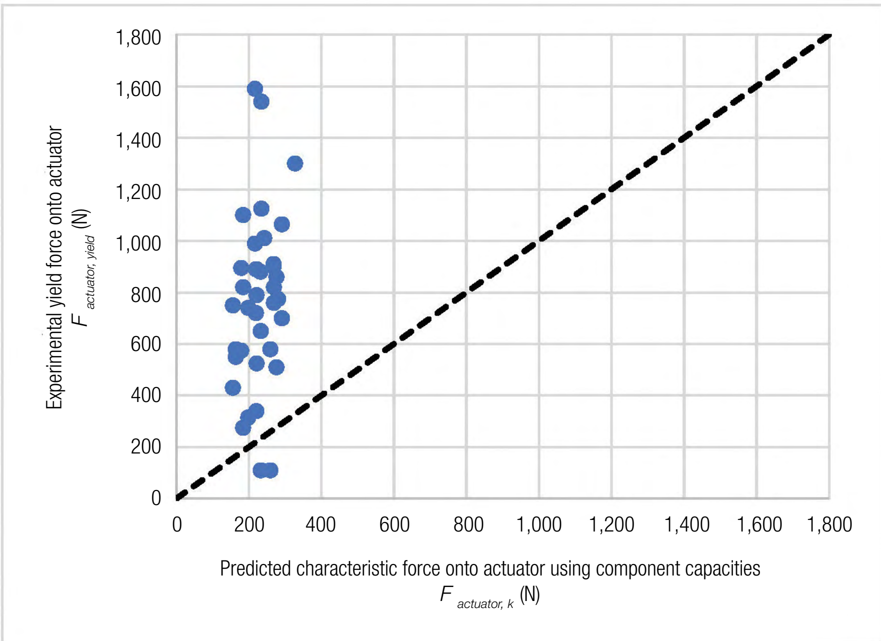
Project: Example 3: T-joint capacity using two methods

REF	CALCULATION	OUTPUT

as ≈ 5% of the specimens had experimental capacities smaller than predicted. Levels of safety would increase once the allowable capacity was determined (i.e., multiply by C_{DF} and divide by FS_j).

It should also be noted that the data does not cluster around the black dashed line, so suggests that the proposed model does not accurately reflect all real phenomena present in this connection type.

Figure 10.10: Plot comparing experimental data with prediction using Example 3a



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Project: **Example 3: T-joint capacity using two methods**

REF	CALCULATION	OUTPUT
	Example 3B: Complete-joint testing to Cl. 10.2 — second approach	

Bamboo connection capacity determined by ISO 22156 'complete joint testing' provisions[10.10] details a complete-joint test that was undertaken, and presented a characteristic capacity for the joint. It was observed that normalisation by geometry is necessary and justifiable to reduce the variability of the results. *This* example takes the normalisation further, as it will hypothesise a failure mode and normalise on this basis. This example adopts the 'resistance model' approach outlined in Clause 9.3 of ISO 12122-6[10.13]. Using this approach, it will be demonstrated that proposing a realistic failure mode and using this as a basis for normalisation, results in safe yet less conservative results. The basis for normalisation will be the bearing/embedment of the anchor-bolt into the walls of the bamboo beam as this was the governing failure mode. It is acknowledged that this is a simplification of a complex phenomenon. The approach described uses ISO 12122-6, which contains a procedure similar to Annex D from BS EN 1990[10.14].

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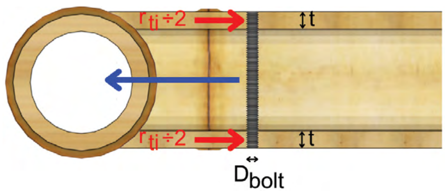
<u>ISO 12122-6 — resistance model approach</u>

Step 1: Develop a resistance model (r_{ti}) (Figure 10.11).

In this instance the force required to cause embedment failure at the anchor-bolt beam interface is hypothesised to be:

$$r_{ti} = 2 \times D_{bolt} \times t_{beam,i} \times f_{h,mean}$$

Figure 10.11 Proposed resistance model, r_{ti}



Where:

D_{bolt} = 9.5mm
$t_{beam,i}$ is the wall thickness of each bamboo beam (a variable)
$f_{h,mean}$ is the mean embedment strength for the bamboo calculated using Equation 8.32 from BS EN 1995-1-1[10.15], but using ρ_{mean} in place of ρ_k. It is hypothesised that this equation provides a reasonable prediction.

Eq. 8.32 Eurocode 5

$$f_{h,0,k} = 0.082(1 - 0.01D_{bolt})\rho_k$$

Eq. 8.32 Adapted

$$f_{h,mean} = 0.082(1 - 0.01D_{bolt})\rho_{mean}$$

If ρ_{mean} *for the sample = 757kg/m*^{3}

Therefore:

$f_{h,mean}$ = 56.2N/mm^2

And:

$$r_{ti} = 1{,}068N / mm \times t_{beam,i}$$

Step 2: Compare theoretical with experimental values

In this instance, the experimental values $r_{ei} = F_{eye\text{-}bolt} + F_{torque}$ when $F_{actuator} = F_{max}$

> Note: This approach uses the maximum load applied onto the actuator, F_{max}, instead of the load onto the actuator at yield, F_y, because the former has more consistent values. *Bamboo connection capacity determined by ISO 22156 'complete joint testing' provisions*[10.10] reports F_y having a coefficient of variation (CV) = 48%, while CV for F_{max} = 29%.

The values for r_{ti} and r_{ei} are presented in Table 10.1.

Where:

$$r_{ti} = 1{,}068\text{N/mm} \times t_{beam,i}$$

$$r_{ei} = F_{eye\text{-}bolt} + F_{torque}$$

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Table 10.1: Compilation of values from Steps 1 and 2

Test ref.	t_{beam} (mm)	r_{ti}	r_{ei}	$r_{ei}r_{ti}$	r^2_{ti}	Test ref.	t_{beam} (mm)	r_{ti}	r_{ei}	$r_{ei}r_{ti}$	r^2_{ti}
1+	8.46	9,049	31,306	283,293,508	81,888,423	11+	7.85	8,397	23,018	193,278,742	70,510,046
1-	8.46	9,049	22,459	203,233,510	81,888,423	11-	7.85	8,397	24,616	206,704,596	70,510,046
2+	7.14	7,636	29,578	225,860,038	58,310,489	12+	6.55	7,011	22,180	155,506,640	49,155,651
2-	7.14	7,636	34,589	264,125,861	58,310,489	12-	6.55	7,011	22,699	159,145,487	49,155,651
3+	6.53	6,984	22,058	154,051,495	48,775,338	13+	8.36	8,941	33,818	302,352,558	79,932,949
3-	6.53	6,984	42,518	296,940,690	48,775,338	13-	7.80	8,343	31,288	261,022,030	69,600,249
4+	6.81	7,283	22,549	164,219,014	53,040,014	14+	8.74	9,348	31,090	290,637,781	87,387,824
4-	6.81	7,283	25,518	185,845,482	53,040,014	14-	8.74	9,348	19,419	181,532,552	87,387,824
5+	7.14	7,636	27,772	212,072,456	58,310,489	15+	9.53	10,191	41,848	426,453,802	103,847,627
5-	7.14	7,636	26,644	203,459,944	58,310,489	15-	9.53	10,191	25,321	258,032,411	103,847,627
6+	7.59	8,125	26,061	211,753,565	66,020,136	16+	8.61	9,212	28,694	264,332,828	84,865,942
6-	7.59	8,125	23,656	192,208,407	66,020,136	16-	8.61	9,212	36,280	334,221,070	84,865,942
7+	6.71	7,174	26,920	193,126,870	51,468,545	17+	7.75	8,288	28,190	233,647,435	68,696,359
7-	6.71	7,174	35,908	257,610,941	51,468,545	17-	7.75	8,288	32,849	272,263,551	68,696,359
8+	10.21	10,924	21,994	240,273,153	119,340,031	18+	7.95	8,506	29,633	252,045,909	72,347,365
8-	10.21	10,924	23,680	258,684,199	119,340,031	18-	7.95	8,506	29,916	254,453,706	72,347,365
9+	8.05	8,614	32,385	278,974,969	74,208,314	19+	10.74	11,495	38,135	438,363,987	132,134,059
9-	8.05	8,614	39,173	337,456,248	74,208,314	19-	10.74	11,495	33,726	387,676,798	132,134,059
10+	8.18	8,750	40,049	350,444,826	76,567,732	20+	7.01	7,500	17,589	131,923,949	56,253,844
10-	8.18	8,750	39,593	346,453,093	76,567,732	20-	7.01	7,500	22,377	167,829,578	56,253,844

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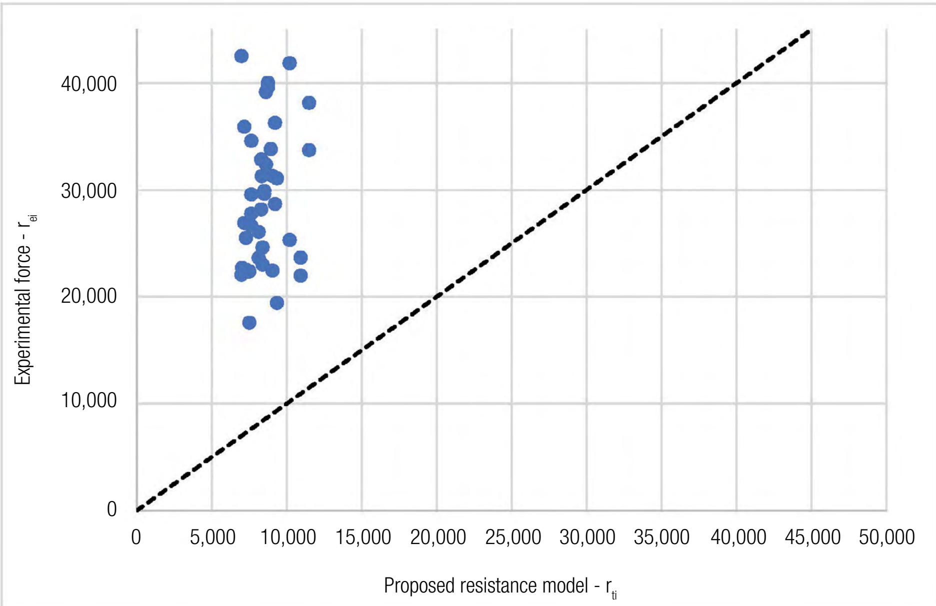
REF	CALCULATION	OUTPUT

Step 3: Estimate the mean value correction factor, *b*

$$b = \frac{\sum r_{ei} r_{ti}}{\sum r_{ti}^2} = \frac{10{,}031{,}513{,}678}{2{,}975{,}789{,}653} = 3.371$$

Note: Figure 10.12 shows that the relationship between r_{ti} and r_{ei} is weak. It also shows that r_{ti} significantly underpredicts the real capacity of the joint. This is not necessarily a problem, but demonstrates that the model for r_{ti} does not need to be perfect to arrive at a safe solution.

Figure 10.12: Plotting r_{ei} vs. r_{ti}



Step 4: Estimate the coefficient of variation of the errors

$$\delta_i = \frac{r_{ei}}{b r_{ti}}$$

Values presented in Table 10.2.

Step 5: Analyse compatibility. Despite the high scatter, no way to reduce the scatter has been identified, and creating sub-samples is not deemed beneficial. Proposed model and sample remain unaltered

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Project: **Example 3: T-joint capacity using two methods**

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Table 10.2: Compilation of values from Step 4

Ref	δ_i	δr_t
1.1	1.026	9,287
1.2	0.736	6,662
2.1	1.149	8,774
2.2	1.344	10,261
3.1	0.937	6,543
3.2	1.806	12,613
4.1	0.918	6,689
4.2	1.039	7,570
5.1	1.079	8,238
5.2	1.035	7,904
6.1	0.951	7,731
6.2	0.864	7,017
7.1	1.113	7,986
7.2	1.485	10,652
8.1	0.597	6,525
8.2	0.643	7,024
9.1	1.115	9,607
9.2	1.349	11,621
10.1	1.358	11,880
10.2	1.342	11,745

Ref	δ_i	δr_t
11.1	0.813	6,828
11.2	0.870	7,302
12.1	0.938	6,580
12.2	0.960	6,734
13.1	1.122	10,032
13.2	1.113	9,281
14.1	0.987	9,223
14.2	0.616	5,761
15.1	1.218	12,414
15.2	0.737	7,511
16.1	0.924	8,512
16.2	1.168	10,762
17.1	1.009	8,362
17.2	1.176	9,744
18.1	1.033	8,790
18.2	1.043	8,874
19.1	0.984	11,313
19.2	0.870	10,005
20.1	0.696	5,218
20.2	0.885	6,638

Step 6: Determine the coefficients of variation, V_{xi}, of the basic variables (Table 10.3)

> Note: Coefficient of variation is the ratio between the standard deviation and the mean.

Table 10.3: Summary of values

	r_{ti}	δ_i	δr_{ti}
Mean	8,538	1.026	8,655
Standard deviation	1,237	0.244	1,947
Coefficient of variation	0.145	0.238	0.225

V_{rt} is the coefficient of variation of r_{ti} values = 0.145

V_δ is the coefficient of variation of δ_i values = 0.238

V_r is the coefficient of variation of δr_{ti} values = 0.225

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Step 7: Determine the characteristic value, r_k, of the resistance. In this instance, r_k is the characteristic value for $F_{eye\text{-}bolt}$ when $F_{actuator} = F_{max}$

Equation 16 from ISO 12122-6 can be rewritten:

$$r_k = b \times (2 \times D_{bolt} \times t_{beam} \times f_{h,mean}) \times e^{(-k_\infty \alpha_{rt} Q_{rt} - k_n \alpha_\delta Q_\delta - 0.5Q^2)}$$

Where:

$$Q_{rt} = \sqrt{ln(V_{rt}{}^2 + 1)} = 0.144$$

$$Q_\delta = \sqrt{ln(V_\delta^2 + 1)} = 0.235$$

$$Q = \sqrt{ln(V_r{}^2 + 1)} = 0.222$$

$$\alpha_{rt} = \frac{Q_{rt}}{Q} = 0.649$$

$$\alpha_\delta = \frac{Q_\delta}{Q} = 1.057$$

Table 1 ISO 12122-6

$k_\infty = 1.64$

$k_n = 1.73$ taken for ≥ 30 (but not ∞) values assuming V_x is unknown

$$F_{eye-bolt,k} = r_k = 3.371 \times (2 \times D_{bolt} \times t_{beam} \times f_{h,mean}) \times 0.545$$

$$= 3.67 \times D_{bolt} \times t_{beam} \times f_{h,mean}$$

As D_{bolt} = 9.5mm and $f_{h,mean}$ = 56.2N/mm², the equation can be further simplified to:

$$F_{eye-bolt,k} = r_k = 1{,}962\text{N/mm} \times t_{beam}$$

This expression can then be used to find a theoretical $F_{actuator,max}$ for any of the specimens tested to observe the level of safety of the solution.

The theoretical $F_{actuator,max}$ is determined by:

$$F_{actuator,max} = \frac{(1{,}962\text{N/mm} \times t_{beam} - F_{torque}) \times D/2}{L_{beam}}$$

This can be plotted as shown in Figure 10.13.

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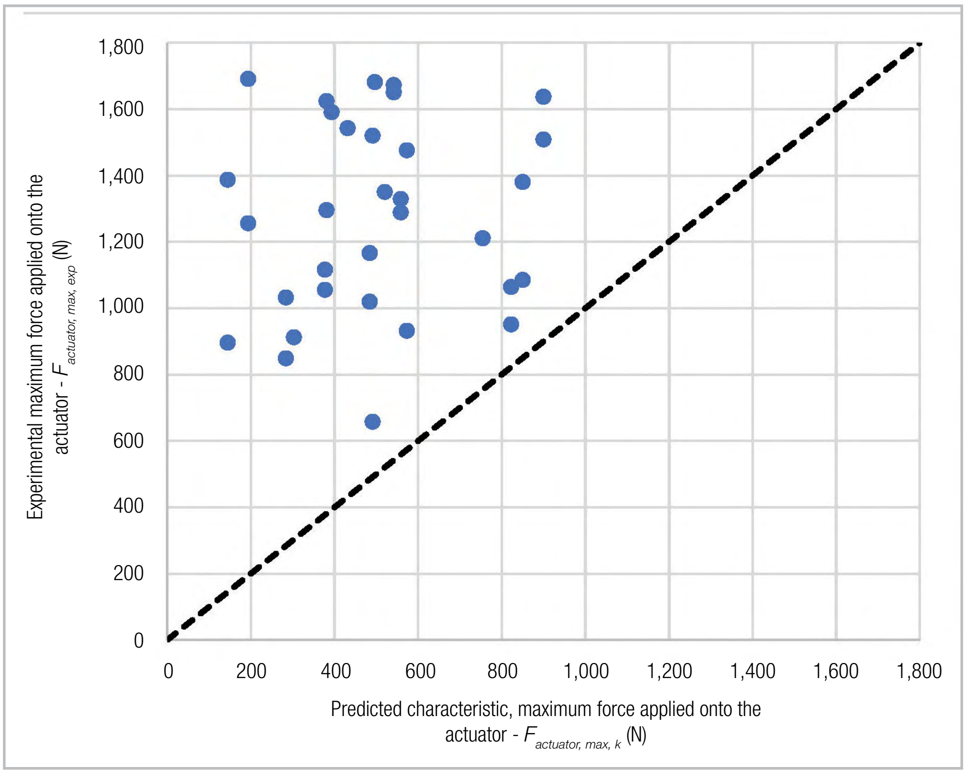
Figure 10.13: Predicted vs. experimental values for $F_{actuator,max}$



Note: Two observations can be made:

1) All the data points are above the black dashed line, which indicates that the prediction is **safe**.
2) The data points do not cluster along the black-dashed line, which indicates that the model does not accurately predict the mechanism of failure. Despite its inaccuracy, the solution can be used for a safe design provided input data is within range of the test parameters.

To convert this solution into an allowable capacity, multiply $F_{actuator,max,k}$ by C_{DF} and divide by FS_j as outlined in Clause 10.4 and:

$$F_{actuator,allowable} = C_{DF} \times \frac{F_{actuator,k}}{FS_j} = C_{DF} \frac{\frac{(1{,}962\text{N/mm} \times t_{beam} - F_{torque}) \times D/2}{L_{beam}}}{FS_j}$$

End of checks

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