DURABILITY OF WHOLE CULM BAMBOO: FACTS, MISCONCEPTIONS AND THE NEW ISO 22156 FRAMEWORK

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DURABILITY OF WHOLE CULM BAMBOO: FACTS, MISCONCEPTIONS AND THE NEW ISO 22156 FRAMEWORK

Sebastian Kaminski, Arup, UK, sebastian.kaminski@arup.com
Kent Harries, University of Pittsburgh, kharries@pitt.edu
Luis Felipe Lopez, Base Bahay, luis.lopez@base-bahay.com
David Trujillo, Coventry University, aa7170@coventry.ac.uk
Hector Archila, University West of England, hector.archila@bath.edu

ABSTRACT
Durability of bamboo is one of the most important aspects to consider when designing and building with this nature-based material. Durable structures with bamboo are resilient, cost-effective and have a lower whole life-cycle environmental impact. This paper firstly reviews the main causes of decay of bamboo: beetle, termite and fungal, and then discusses the efficacy of different treatments – both traditional and modern. Common misconceptions around the durability of bamboo and its preservation methods are corrected. Finally, the recently published framework for durability of bamboo within ISO 22156 – Bamboo Structures, based on Use Classes, is presented.

KEYWORDS
Bamboo; durability; preservation; codes; ISO

INTRODUCTION
Historically, bamboo as a building material has been lowly regarded for its poor natural durability, which is also one of the main reasons why bamboo structures fail in earthquakes (López et al., 2004; Drunen et al., 2016; Franco et al., 2017). Although durability is very well understood by communities who have traditionally worked with bamboo (Kaminski, 2017), in modern construction there is generally a focus on treatment against the more visible insect attack, rather than the longer term, but just as significant problem: rot. For this reason, many modern "permanent" bamboo buildings unfortunately have short lifespans, sometimes just 10-20 years (Kaminski, 2013). The root causes of this have been observed to be:

- Misconceptions of the various attack mechanisms of bamboo and the efficacy of preservation treatments (Kaminski, 2017);
- The drive to expose bamboo externally for aesthetics;
- The lack of standards and guidance for designing durable bamboo buildings.

Today, ISO 22156 – Bamboo Structures – Bamboo culms – Structural Design (ISO, 2021) is available. In addition to prescribing the structural load-bearing design of bamboo, this standard addresses durability of the resulting structures. This is the subject of this paper.

Wood and bamboo have comparable cellular structures and chemical compositions with similar cellulose, hemicellulose and lignin contents (Archila, 2015). Bamboo's bio-deterioration mechanisms and methods for improving durability are therefore largely identical to wood; hence, it is recommended to adopt the principles and approaches that modern timber design has developed.

Liese and Kumar (2003) report that bamboo is more susceptible to decay than wood, likely due to a lack of naturally-occurring 'toxins', along with generally higher levels of starch (Liese & Tang, 2015). Combined with its typically thin walls, this means that a small amount of decay in bamboo can cause a significant proportional change in structural capacity. There are three main causes of biotic decay in bamboo: fungal attack (rot), insects (primarily beetle and termite attack) and marine borers – these are covered in more detail in the following section.

BIOTIC ATTACK MECHANISMS

Fungal attack (rot)

Rot is caused by fungal attack, either to the cell contents in the form of mould and blue-stain fungi, or to the cell wall in the form of rot-fungi (Liese & Tang, 2015). For fungi to survive, the bamboo needs to be relatively wet with at least 20% moisture content (CEN, 2013), which essentially means that the bamboo must be exposed to rain or ground moisture for a period of time, without being allowed to dry (Ridout, 1999). Bamboo is therefore particularly vulnerable when exposed to water in the ground, driving rain, leaks in roofs or water traps in buildings. Unquestionably, warm tropical climates with high rainfall, where bamboo is often endemic, provide the harshest conditions (Figure 1); nevertheless, rot can still easily occur in cold temperate areas (cold countries can have rot risks associated with condensation).

a) Rotten bamboo columns which were exposed to driving rain (Colombia) (Kaminski, 2016)

b) Rotten bamboo chord of a bridge, where a bolt hole allowed driving rain to enter (Colombia) (Kaminski, 2016)

c) Rotten timber and bamboo inside the wall (Ecuador) (Kaminski, 2016)

d) Rotten bamboo where a beam was exposed and collected water (Costa Rica) (Kaminski, 2016)

Figure 1: Illustrations of rotten bamboo in different parts of structures

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 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 (Bravery et al. 2003; Lawrence & Ross, 2020). Because rot is not always obvious and may take some years to manifest itself, it is often an underestimated risk to bamboo buildings.

Since rot requires oxygen in addition to water, when bamboo is fully submerged and in an oxygen-free (anaerobic) environment, it will not rot (this is the reason the timber piles under Venice have lasted for so long – they are inserted below the waterline into the clay where there is little to no oxygen). In practice, this scenario is rare, as water normally contains sufficient oxygen to allow fungal attack. An equivalent scenario would be for bamboo to be submerged adequately in an appropriate anaerobic soil. For these reasons, bamboo piles generally will have a very limited useable life.

Insect attack

Introduction

The prevalence of individual insect species varies according to country, climate, soil, temperature and altitude, amongst other factors (CEN, 1994). Unless it is categorically known from specialists that insects which attack bamboo do not live in a specific region or they cannot survive there, it must be assumed that there is an insect risk (i.e. it is not adequate to simply assume that just because locally no insects have been seen anecdotally, 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 the risk of insect attack. The impacts of climate change should also be considered. Warmer, wetter summers and progressively shallower ground frost depths are resulting in termites surviving in more northerly climates. Therefore, prior 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.

Beetle attack

Certain beetles are attracted to the starch in bamboo and lay their eggs inside the culm. Upon hatching, the larvae eat along the inside culm (soft and less dense cell-tissue) and eventually through the culm walls to escape, leaving small round or oval exit holes (about 1mm–6mm diameter) (BRE, 2003), as seen in Figure 2. This attack effectively makes many holes inside the bamboo, weakening it by reducing the area available to carry the load.

Bamboo which is young (immature), green or when it is exposed to high humidity appears to experience greatest beetle attack (Liese & Kumar, 2003), however even mature and dry bamboo in air-conditioned environments can be attacked by certain species. Species with higher levels of starch such as bambusa vulgaris have reportedly higher levels of beetle attack ((liese & Kumar, 2003). There are many different types of beetles worldwide that can attack bamboo (BRE, 2003) found in most warm climates around the world; however, since the method of protecting against beetles remains the same, there is generally no need to distinguish between them. Evidence of beetle attack includes beetle exit holes and small piles of dust of a similar colour as the bamboo.

a) Beetle larvae inside bamboo (Bangladesh) (Kaminski, 2016)

b) Beetle exit holes visible on side of bamboo (Bangladesh) (Kaminski, 2016)

Figure 2: Beetle attack in bamboo

Termite attack

Termites are small ant-like insects which live in colonies and feed on plant material (Figure 3a). Termites are also attracted to the starch in bamboo, but unlike beetles, they have enzymes which enable them to break down cellulose (BRE, 1999). Because they live in large colonies they can cause significant and rapid damage. This attack makes longitudinal tunnels (known as "galleries") inside the bamboo, weakening it by reducing the area available to carry building load (Figure 3b).

a) Subterranean termite (Bangladesh) (Kaminski, 2016)

b) Significant termite damage to bamboo column (Costa Rica) (Kaminski, 2016)

Figure 3. Termite attack in 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 via mud tunnels, which provide protection against sunlight and predators (BRE, 1999). Drywood termites live in dry bamboo, but do not require contact with soil; they can also fly and live in generally smaller colonies. Dampwood termites live in damp wood/bamboo; thus, they are rarely found in bamboo buildings as these structures, under normal service conditions, would typically not be damp. Subterranean termites normally cause the most damage to bamboo structures because of their large colony size (Antonelli, 2002).

Termites are found on all continents (except Antarctica) and prefer warmer, wetter climates. In tropical countries attack appears 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 the termites eat the inside while leaving the thin protective, harder and highly fibrous outer layer). Evidence of subterranean termites includes termite external shelter tubes, and evidence of drywood termites is frass (termite droppings) which are normally dark in colour.

Marine borers

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

Thermal and UV

Although not strictly an attack mechanism, the cyclic action of sun and rain has been observed to lead to splitting of exposed bamboo, which not only breaks any external waterproofing coating (such as paint and varnish), but weakens the culm and any structural connections. At the same time, prolonged UV exposure can weaken the tougher outer, highly lignified and waxy layer of bamboo (cortex) and reduces the water-repellent characteristics of the bamboo cortex. These issues further increase the vulnerability of bamboo to insects and rot attack.

Summary

In summary, bamboo should be considered very susceptible to rot, termite and beetle attack. Following EN 350 (CEN, 2016), bamboo should be considered "not durable" to attack by decay fungi (DC5), wood-boring beetles (DC S), termites (DC S) and marine organisms (DC S).

INTRODUCTION OF KEY CONCEPTS: DESIGN LIFE AND EFFICACY

Design life

Design life is the minimum lifespan of the materials used for the primary structure in a building. During its design life, the building is expected to perform its intended purposes, and be serviceable with minimum maintenance, and without major repair being necessary. Building codes do not tend to define what is "minimum maintenance", but broadly speaking, this is considered to include façade repair, repair of leaks and associated damage due to water ingress, painting and replastering. It is not generally intended to include repair or replacement of primary structural elements.

The concept of a design life of structural elements is implicit within most international structural design codes, but not always expressed overtly or clearly, and with subtle differences between codes and materials. EN 1990 provides probably the clearest recommendations of design life internationally, requiring a "design working life" of 50 years for building structures and other common structures (CEN, 2002).

For bamboo structures, the authors recommend a minimum design life of 50 years, which matches major international standards for all the mainstream building materials: steel, reinforced concrete, masonry and timber. In any case, it is worth stressing that the requirements provided in this paper and in ISO 22156 for achieving a minimum design life would be largely identical if the intended design life was lower, for example 30 years compared to 50. This is because there are no realistic effective solutions that provide a 30-year design life, but not a 50 year design-life. This is best illustrated in Table 5 of BS 8417 (BSI, 2014), which provides largely identical recommendations for design and treatment of timber using boron for a service life of 15, 30 and 60 years.

Bamboo is often proposed in humanitarian and developing world contexts by donors, designers and implementing agencies, sometimes for temporary solutions that 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 and when they fail. However, in many cases this may not be the case, and therefore this assumption may not always be appropriate to make, because of the following:

- The end-user may forget or not be aware of the importance of this, or they move out and someone else occupies the building;
- The end-user is often simply not informed clearly;
- The end-user may not have the resources or the technical expertise to do this;
- The replacement of key structural elements may be challenging, due to the design not adequately catering 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 their building would have a design life equal to "next door's masonry house", which is normally 50 years.

For these reasons, in humanitarian and developing world contexts, with the exception of humanitarian emergencies, transitional buildings constructed as part of properly managed reconstruction programs or construction programs utilising vernacular systems that the end-user is already very familiar with, the recommended minimum design life for "permanent" bamboo structures is 50 years.

Efficacy of preservation methods

Efficacy is an unbiased scientific assessment of how effective any method of improving the durability of bamboo in structures really is. Anecdotal evidence is generally inadequate to provide efficacy, since the actual efficacy of a method can depend on many different factors, many of which may not be immediately obvious.

When reviewing any new preservation method of bamboo for efficacy, remember:

1. Conduct impartial inspections of the treated bamboo after multiple years of use (5, 10, 15, 20 etc), observing the condition of the bamboo and the aggressiveness of the exposure to sun, water and insects. Inspections should be conducted by an appropriately experienced person (Bravery et al. 2003; Lawrence & Ross, 2020).
2. There should be a large sample size of treated bamboo in different exposure conditions and different communities.
3. There already exists significant traditional knowledge on how to slightly improve the durability of bamboo. Formal construction is looking for methods which provide reliable efficacy for 50+ years.

METHODS OF PROVIDING DURABLE BAMBOO STRUCTURES

This section discusses the various ways of improving durability of bamboo in structures for a design life of 50 years. They can be grouped into 12 categories:

1. Using more naturally durable species.
2. Selecting mature bamboo.
3. Harvesting at appropriate times.
4. Traditional methods of reducing sugar content.
5. Smoke or fire treatment.
6. Other traditional methods of preservation.
7. Surface coatings.
8. Seasoning (drying).
9. Modern chemical treatments: boron-based.
10. Modern chemical treatments: chemically-fixed.
11. Modern chemical treatments: others including bio-based alternatives.
12. Durability by design.

Each of these is discussed in detail in the following sub-sections. In practice a mixture of these is always required. There are no effective and appropriate ways to improve durability against marine borers (Liese & Kumar, 2003) – in general, bamboo placed in marine environments will not last long and hence should be avoided.

Using more naturally durable species

All species of bamboo should be considered very susceptible to rot, termite and beetle attack. Although minor variations in natural durability do appear between species (Liese & Kumar, 2003), in particular for beetle attack, in formal modern construction the difference is not considered to be significant, especially for termite attack and rot. Therefore, it is not generally considered important to select a specific bamboo type which anecdotally may have greater natural resistance – there are normally much more important factors which influence durability. In addition, proper identification of bamboo in the wild can be difficult even for specialist botanists, and therefore communities may sometimes be mixing species and local names anyway.

Selecting mature bamboo

Bamboo should be harvested when it is mature as this is when it is strongest and most durable (Liese & Kumar, 2003). Although maturity does slightly affect durability, even mature bamboo should still be considered very susceptible to insect attack, rot and marine borers (Arup, 2018).

Harvesting at appropriate times

Bamboo should be harvested at appropriate times of the year following local practice when its starch and/or water content are lowest, and to avoid damaging the plant. However, it is important to note that even optimally-harvested bamboo can still be susceptible to beetle attack, and remains very susceptible to termite attack, rot and marine borers (Arup, 2018). In some countries, bamboo is harvested at very specific times of the month and even day. Although some studies have shown the starch content to vary even in these short durations, the variation is unlikely to be significant enough to have a big effect on the durability of the bamboo (Liese & Kumar, 2003).

Traditional methods of reducing sugar content
There exist a number of 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 fungi attack (Liese & Kumar, 2003; Arup, 2018).

Smoke or fire treatment
This method involves exposing bamboo to fire or smoke for a period ranging from 30 minutes to several hours. This method may provide some protection, however the level of this is questionable, and the heat tends to damage and weaken the bamboo fibres (Liese & Kumar, 2003; Arup, 2018).

Other traditional methods
Other traditional methods exist that may anecdotally provide some protection to bamboo. However, these tend to have limited or unproven efficacy, certainly scientifically, and some can be dangerous to humans (Arup, 2018).

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 outer toxic protective barrier. However, they only provide partial protection to the outside of bamboo, and are largely ineffective against insect and fungal attack on the inside of bamboo. None are therefore considered entirely effective methods of protection by themselves. Many also have other disadvantages such as toxicity to humans or requiring frequent reapplication (Arup, 2018).

Seasoning (drying)
Seasoning of bamboo involves reducing its water content to be in equilibrium with the surrounding air (Arup, 2018). Seasoning of bamboo reduces the risk of insect and rot attack, increases its strength and significantly reduces the risk of splitting in service. Seasoning should be considered a must for all bamboo, regardless of the chemical treatments used.

Modern chemical treatments: boron based
Boron based preservatives are relatively cost-effective, low-tech, widely available, have a low-toxicity and have a high efficacy against both termites and beetles. They also have efficacy against fungal attack, however because they are readily soluble in water, they are easily leached out of the bamboo in water or even driving rain, and therefore can only be used effectively where the bamboo is completely protected. Boron is the most common method of treating bamboo internationally (Arup, 2018).

Modern chemical treatments: chemically fixed
Modern chemically-fixed treatments are those that are fixed into the bamboo such that 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), and they can be very effective against insects and rot (Lebow, 2004; Arup, 2018). Because of their higher cost they are not currently widely used with bamboo.

Modern chemical treatments: others
There are many other modern preservatives such as copper sulphate, copper-chrome arsenic (CCA), creosote, dursban, creosote and sodium pentachlorophenate. While some of these can be effective, most of them are either expensive, complex to apply or carry significant health risks during application and at end of life (Arup, 2018). As such, many of these are now illegal in many countries, or only permitted for heavy industry, and certainly not homes or community infrastructure.

There also existing some modern "bio-based" or "sustainable" methods that anecdotally provide some protection to bamboo (e.g. Gauss et al., 2020). However, to date these tend to have limited or unproven efficacy, and some can be dangerous to humans.

Durability by design

The most effective single method of reducing the risk of attack is by reducing or removing the hazard altogether – this is known as “durability by design”. All bamboo designs should specify some form of durability by design. Durability by design involves:

1. Keeping the bamboo dry.
2. Allowing the bamboo to breathe.
3. Disrupting subterranean insect paths.

Summary

When combining all of 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 certainly vulnerable to termite and rot attack. While the combination of all of 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 here is 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.

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

KEY PRINCIPLES OF DURABILITY BY DESIGN

Keeping the bamboo dry

Sources of water include rain, flooding, condensation and moisture in the ground. Rain does not only fall vertically, so consider all exposed bamboo that falls within a 45-degree angle of the corner of the roof overhang as vulnerable. In some instances, driving rain can also splash off a hard surface surrounding a structure and dampen the lower parts of walls. All fungal growth and many bamboo destroying insects require bamboo moisture content greater than 20%. By ensuring the moisture content remains below this value, the risk of attack can be significantly reduced. This is best achieved by keeping all bamboo within the weather line and separating ground floor columns and walls from foundations with damp-proof membranes. Externally exposed bamboo must be avoided, and the hazard can be reduced by:

- Providing protection in the form of a roof overhang or veranda.
- Sacrificial facades.
- Elevating the columns from the ground.
- 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 (Figure 4).
- Ensure the bamboo is completely protected on the outside (Figure 4), although ideally the bamboo will still be able to “breathe” on the inside face.

By following these rules, the damage to bamboo from cyclic sun and rain, and from UV, can also be mitigated.

Provide good ventilation / Allow the bamboo to ‘breathe’

Accidental wetting can occur when weather barriers or water distribution networks leak or during extreme weather. In addition, some buildings are constructed with bamboo that is still green and unseasoned. Bamboo should ideally always be allowed to “breathe” inside the waterproof envelope, even if there is no obvious risk of water. Flat roofs are particularly vulnerable to undetected leaks in waterproofing membranes and should ideally contain a ventilation cavity to allow any water penetration to evaporate. Bamboo should never be cast into concrete (Archila et al., 2018) – concrete is hygroscopic, meaning it will absorb nearby water, and create perfect conditions for rot.

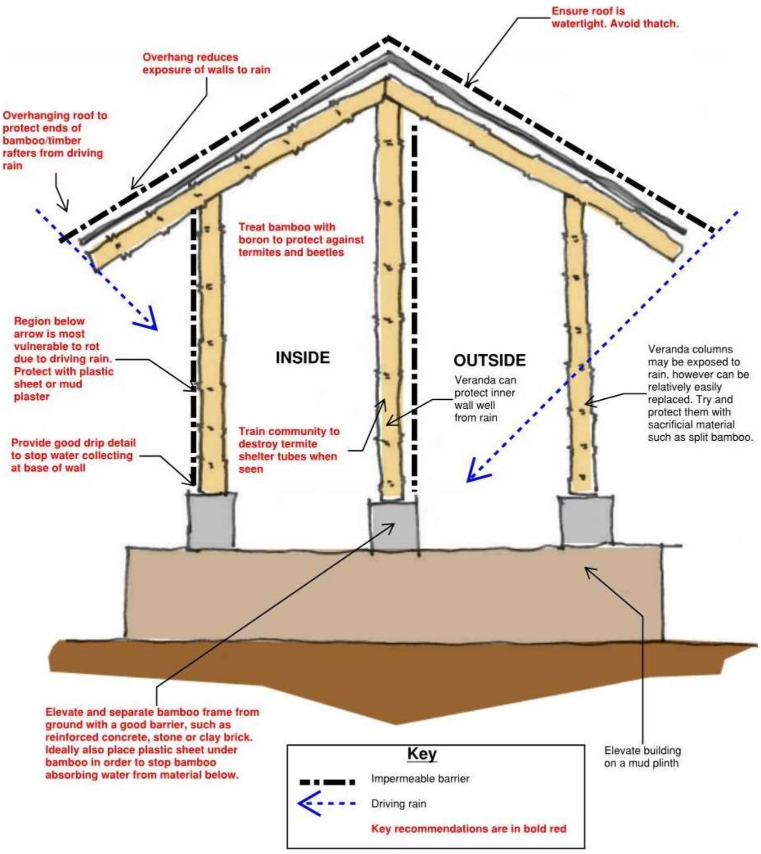

Figure 4: Author’s summary of key recommendations for “durability by design”

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 the foundations to prevent termite attack (termites can pass through cracks in concrete as small as 0.8mm) (University of Tennessee Agricultural Extension Service, 2001). Additional measures include bait boxes.

CLASSIFYING THE EXPOSURE

ISO 22156 draws on the principles of “Use Classes”, adopted in international codes and described in EN 335 (CEN, 2013) and ISO 21887 (ISO 2007), to provide a simple to use matrix of service conditions to guide the designer. Each Use Class corresponds to a different environment in terms of water and sun exposure. Table 1 presents the efficacy and likely design lives of bamboo in a high beetle, termite and/or marine borer risk zone, in different Use Classes – this is effectively a simple summary of the earlier sections within paper.

The range of likely and possible design lives stated are approximate and are based on the personal observations of the authors having conducted structural condition surveys of existing bamboo structures across Latin America, Africa and Asia (e.g. Kaminski, 2013), interviews and focus groups with communities living in bamboo houses (Kaminski, 2017), and independent published guidance (Liese & Kumar, 2003; Practical Action, n.d.). It is worth emphasising that many treatment facility workers and vendors have an unrealistically positive view of the efficacy of their methods (Kaminski, 2017).

Table 1: Use classes and potential treatment chemicals in high beetle, termite and/or marine borer risk

Use class	Service conditions	Typical uses	Efficacy of chemical treatment against biological agents	
			Boron	Safe chemically-fixed treatments such as copper
1	Interior, dry	Framing, pitched roof members	Effective permanently against insects and won't wash out. 50+ year design life	Effective permanently against insects and won't wash out. 50+ year design life
2	Interior, occasional damp (possibility of condensation)	Framing, roof members, ground floor joists, framing built into exterior walls		
3.1	Exterior, above ground protected from driving rain and UV radiation	Protected exterior joinery and framing		
3.2	Exterior, above ground not protected from weathering	Unprotected exterior framing and joinery including cladding, vertical load bearing members, exposed unprotected culm ends	Effective temporarily but will wash out eventually. Also bamboo likely to split with sun. Likely 5-15 year design life.	Effective temporarily but may wash out eventually. Also bamboo likely to split with sun. Likely 10-30 year design life but little precedence exists
4.1	In contact with ground or in-ground	Sole plates or columns at ground, columns built into ground, piles	Effective very temporarily but will wash out eventually. Also bamboo likely to split with sun. Possible 1-5 year design life.	Effective temporarily but will wash out eventually. Also bamboo likely to split with sun. Possible 5-20 year design life
4.2	In-ground severe, fresh water	Piles	Effective very temporarily but will wash out eventually. Possible 0.5-2 year design life.	Effective very temporarily but will wash out eventually. Possible 0.5-5 year design life
5	Marine or brackish water	Marine piles including splash zone	Effective very temporarily but will wash out eventually. Possible 0.5-1 year design life.	Effective very temporarily but will wash out eventually. Possible 0.5-2 year design life

Upon reviewing Table 1, the following observations can be made:

- In order to achieve a 50-year design life, bamboo can only be used in Service Classes 1, 2 and 3.1.
- Service Class 3.2 can achieve a design life of no more than 5 years.
- Services Classes 4.1, 4.2 and 5 cannot achieve any useful design life, except for temporary informal structures.
- 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 Service Classes 3.2, and 4.1 because the bamboo is exposed to the sun, it is likely to split under cyclic sun and rain, and it is more likely to experience surface UV deterioration.

ISO 22156 presents a simplified version of Table 1, replicated here as Table 2. Following the summary within Table 1, the requirements in ISO 22156 go on to state the following:

- Only Use Classes 1, 2 and 3.1 are permitted for permanent bamboo structures.
- Use Class 3.2 is only permitted for temporary structures with a design life of less than 5 years.
- Use Class 4.1, 4.2 and 5 are not permitted.

These requirements are largely identical to the design requirements for a timber with little natural durability treated with boron, following Table 5 of BS 8417 (BSI, 2014). The permitted Use Classes are an effective way of forcing good practice "durability by design" principles to be adopted by the designer.

Annex B in ISO 22156, which is informative rather than mandatory, provides the following additional recommendations:

- B.2 provides general good practice "durability by design" guidance, which are self-explanatory.

- Boron retention levels should be at least 4kg/m^3. In the absence of significant rigorous published research on bamboo, this is taken from experience with timber (Lloyd, 1997), which is likely to be similar to bamboo. In more detail:
    - At least 4-5 kg/m3 is likely to give enough protection against most termites and beetles (some termites may require >6 kg/m3).
    - 2-3 kg/m3 is likely to give enough protection against beetles, but may be inadequate for termites.
    - <2 kg/m3 is unlikely to provide sufficient protection against beetles or termites.
- 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 UV radiation.
- 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.

Table 2: Use classes and durability considerations (ISO 22156-21)

<table>
<tr><th rowspan="2">Use class</th><th rowspan="2">Service conditions</th><th rowspan="2">Typical uses</th><th colspan="4">Protection against biological agents</th></tr>
<tr><th>Fungal</th><th>Beetles</th><th>Termites</th><th>Marine borers</th></tr>
<tr><td>1</td><td>Interior, dry</td><td>Framing, pitched roof members</td><td>Not required as no water exposure</td><td rowspan="6">Required where risk of beetle attack exists (common in most warm countries)</td><td rowspan="6">Required where risk of termite attack exists (found in all continents)</td><td rowspan="6">Not required as no risk</td></tr>
<tr><td>2</td><td>Interior, occasional damp (possibility of condensation)</td><td>Framing, roof members, ground floor joists, framing built into exterior walls</td><td>Not generally required provided bamboo can dry rapidly</td></tr>
<tr><td>3.1</td><td>Exterior, above ground protected from driving rain and UV radiation</td><td>Protected exterior joinery and framing</td><td>Not generally required provided bamboo can dry rapidly</td></tr>
<tr><td>3.2</td><td>Exterior, above ground not protected from weathering</td><td>Unprotected exterior framing and joinery including cladding, vertical load bearing members, exposed unprotected culm ends</td><td>Required</td></tr>
<tr><td>4.1</td><td>In contact with ground or in-ground</td><td>Sole plates or columns at ground, columns built into ground, piles</td><td>Required</td></tr>
<tr><td>4.2</td><td>In-ground severe, fresh water</td><td>Piles</td><td>Required</td></tr>
<tr><td>5</td><td>Marine or brackish water</td><td>Marine piles including splash zone</td><td>Required</td><td>Not generally required as water prevents attack</td><td>Not generally required as water prevents attack</td><td>Required</td></tr>
</table>

When the recommendations within ISO 22156 are followed (in particular durability by design and 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. However, where these form part of the local traditions or value chain, there is normally no harm in letting them continue. The exception is smoke or fire treatment, which is not environmentally friendly, can weaken the bamboo and can be harmful to the workers, and therefore is discouraged.

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

SUMMARY OF COMMON MISCONCEPTIONS

1. **Painting bamboo with coal tar/bitumen/used engine oil is effective against insects and rot.** This method is ineffective against completely preventing insects and rot – the toxic chemicals only provide a thin layer on the outside of the bamboo, however the inside remains largely unprotected.
2. **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. The concrete also prevents the bamboo from "breathing", often leading to rot.
3. **Once bamboo is treated with boron, it can be exposed to rain.** Boron treated bamboo cannot be exposed to rain because the boron gets washed out over time.
4. **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.
5. **The type of 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 have been seen to be 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 fed this misconception.
6. **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. The most reliable reviewer of the efficacy of a treatment method is the end user. A comprehensive research study of bamboo housing in India (Kaminski, 2017) confirmed that community knowledge of durability and the efficacy of different traditional methods was extensive, however treatment facility workers and vendors tended to have an unrealistically positive view of the efficacy of their methods.

SUMMARY
All species of bamboo should be considered very susceptible to rot, termite and beetle attack. Some species are reported to be more naturally resistant, especially to beetles, primarily due to differences in starch content. However, any difference is not considered to be significant, especially for termite and rot resistance, and becomes largely insignificant once the bamboo has been harvested properly, seasoned and used in construction with proper detailing. The difference becomes unimportant once bamboo is properly chemically treated.

The following methods are required for adequate durability of bamboo in all scenarios, in order of application in the construction process (and not necessarily efficacy):

1. Select mature bamboo.
2. Harvest at appropriate time of year.
3. Seasoning.
4. Modern chemical treatments – boron is generally the most appropriate chemical here.
5. Durability by design, in particular, only use bamboo in Service Class 1, 2 and 3.1.

By employing the above five methods correctly, bamboo can achieve a design life of over 50 years. If any of these steps are not implemented properly, the lifespan of the structure is likely to be shortened significantly.

CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY
No data was assembled for the production of this paper.

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