Bamboo
Material properties & Market perspectives

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BAMBOO FOR EXTERIOR JOINERY

A research in material properties and market perspectives

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Written in commission of

SHR

The cover of this report is scanned from paper which consists of 100% bamboo fibers, hand-made in Asia. The leaf is from a winter-hardy bamboo in The Netherlands (species unknown).

The title page was printed on paper which consists for 90% of bamboo fibers, and 10% cotton (not digitally visible). It is produced as a sketching paper for artists by Hahnemühle in German Unfortunately, printing paper of bamboo is not available for consumers in Europe, and appears to be evenly rare in the rest of the world.

The bamboos on the title page are Moso (Phyllostachys pubescens) in the picture on the left, and Guadua (Guadua angustifolia) in the picture on the right.

The rest of this report was printed on 100% recycled paper, made from de-inked waste paper without any use of chlorine, OBA and other environmentally damaging chemicals.

Foreword

This report was written for my final thesis of the BSc ‘International Timbertrade’ at Larenstein University. The research project on bamboo combined many of my interests in the field of timber trade and forestry, especially material properties, renewable resources and sustainability; all of which served as inspirations during previous internships and assignments. Already during the start of the project I got grasped by the ‘bamboo-virus’, and my fascination for this versatile woody grass has grown ever since. By testing bamboo according to the requirements on timber for KOMO-certified exterior joinery applications, I now have a good understanding of the procedure for introducing a new timber species to the Dutch market; this I found very interesting. Furthermore, the market survey among the Dutch bamboo-sector gave me a good idea about the practical constraints with regard to the introduction of a relatively new material, but even more of the enormous opportunities.

I would like to thank Marina van der Zee (my external supervisor at SHR), for her help during the project was of great importance to me. And I also owe thanks to Ewald Pfeiffer, for thinking along on how to produce the test-specimens. Furthermore, I’d like to thank everybody at SHR for their help with countless little issues, and above all for the possibility for this thesis-placement.

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Abstract

In the Netherlands, industrially manufactured bamboo products are mostly used in indoor applications, and hardly in outdoor applications. However, there is an increased interest in using bamboo for outdoor applications, yet it remains a relative unfamiliar material. This report was written to explore the possibilities of bamboo for outdoor applications, focusing on exterior joinery applications (windows, doors, cladding). It is divided into a part which focuses on material properties, and a part which focuses on the perspectives for the material on the Dutch market.

The first research question was *'Is bamboo eligible for exterior joinery applications on the basis of its material characteristics, and are there differences between the common species used in industrial bamboo manufacturing'*. Phyllostachys pubescens (Moso) and Guadua angustifolia (Guauda) were chosen as test material, because they are the primary species used by the global industries. Their material properties were tested according to the standard for KOMO-certified exterior joinery (SKH publication 97-04, Dutch abbreviation BGS), which is the most commonly used standard for these applications in The Netherlands. The tests are performed on single, non-laminated strips, in order to obtain knowhow on the material in its natural condition. The results were that, although not all requirements in the BGS were researched, the material properties that were tested indicated that both bamboos meet the requirements, and do not deviate much from commonly used timber species. Furthermore, the suitability of treating bamboo (impregnation - full cell process) was tested. This indicated that dry bamboo strips are equally well treatable as Norway spruce and Scots pine, but certain parts of the material were left untreated. Therefore, treating dry bamboo by means of impregnation might not result in an adequate protection against degrading organisms. The major drawback with regard to the suitability of the tested bamboos for exterior joinery applications, is the natural durability. This was not tested in this project, but literature indicates durability is low.

The second research question was: *'Which applications in exterior joinery are possible on the basis of the material characteristics, and what are the perspectives for bamboo on the Dutch market for exterior joinery?* The possible applications for exterior joinery applications were drawn from the BGS, as well as from the opinions of the Dutch bamboo-sector by means of a market research. The market research was conducted among current traders and experts in the Dutch bamboo-sector, by means of a standardized, semi-open interview. The results were that, based on the tested material properties, it proves possible to use bamboo for all (KOMO-certified) applications in exterior joinery, namely windows, doors, cladding and glazing beads. However, according to the Dutch bamboo sector, laminated bamboo (in its natural condition) is not suitable for these applications, and has limited perspective; bamboo composite (strand woven bamboo) on the contrary, is regarded to have a very promising perspective for exterior applications. The general conclusion was that, although no official tests were performed, bamboo in its natural condition is not suitable for exterior joinery due to its low durability. However, if this is improved (which is possible), the material meets all the requirements in the BGS, and is in principle suitable for exterior joinery in The Netherlands. Furthermore, before laminated bamboo can be allowed for exterior joinery on the Dutch market, agreements on standardization of the material properties and control of the production process will have to be made.

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Chapter 1 INTRODUCTION

This thesis is on bamboo, a material which is renowned for its incredible versatility throughout history. It has proven itself suitable for a great number of purposes, from housing to paper and from food to clothing. Although officially bamboo is a grass, it forms a wood-like substance which exhibits properties similar to timber, and is of increasing interest to the timber industry. In a world where forests are under pressure for their timber, this highly renewable material offers interesting possibilities. Bamboo is mostly used for indoor products like flooring and paneling, and is still rather seldomly seen in exterior applications such as window frames and cladding. Whether bamboo is a suitable material for such applications will be investigated in this report.

Scope of research

This report was written during the author's last semester of the BSc major 'International Timbertrade' at the department of Forest and Nature Management, at University of Professional Education. This research project on bamboo formed the final thesis. It was also written for SHR (Centre for Wood Research) in Wageningen.

Problem analysis and definition

SHR is the main research centre on wood and timber products in The Netherlands. They experience an increased demand for 'bamboo know-how' by Dutch companies, especially on bamboo products in exterior applications. However, SHR is still rather unfamiliar with this material. In order to become a suitable partner in research and advice on bamboo, they wish to develop more in-depth expertise concerning material characteristics, as well as its suitability for exterior joinery and the market in general.

Bamboo might be a suitable material for exterior joinery, but whether its material characteristics are able to meet the stringent Dutch requirements on such applications remains uncertain. Furthermore, it is not known if there are differences between the few most widely utilized bamboo species in industrial manufacturing, which might affect their suitability for exterior joinery applications. Since most of the bamboo manufacturing industries rely upon those species, it is important for SHR to develop specific know-how on them. Because exterior joinery is exposed to harsh climate conditions, the materials have to be able to withstand these weathering effects. Besides providing the material with a coating, an effective and commonly used method for enhancing the durability of timber is impregnation with various substances. Therefore, knowledge on treatability and suitability for impregnation is necessary.

The first question in this project is:

'Is bamboo suitable for exterior joinery applications on the basis of its material characteristics, and are there differences between the common species used in industrial bamboo manufacturing'

The following sub-questions are derived from the first research question:

- Which demands need to be met by a wood species for it to be officially allowed in exterior joinery applications[1] on the Dutch market?
- What are the bamboo species that are commonly utilized in industrial manufacturing for construction related purposes[2] on the Dutch market?
- What are the material characteristics of these bamboo species, with regard to the demands which have to be met by a wood species to be allowed for exterior joinery applications?
- Is it possible to treat bamboo by means of impregnation?

[1]'Exterior joinery applications' in this report are: exterior window frames, exterior doors and cladding. The Dutch term for exterior joinery is 'geveltimmerwerk'.

[2]'Construction related purposes' in this report are: flooring and sheet material; load bearing applications are not included.

Several developments concerning bamboo in exterior joinery applications are to be noticed. However, Dutch research into the applications for which it might be suitable, based on its material characteristics, is still lacking. Also, an analysis of the perspectives for bamboo on the Dutch market for exterior joinery has not been performed yet.

This is why the second research question is:
‘Which applications in exterior joinery are possible on the basis of the material characteristics, and what are the perspectives for bamboo on the Dutch market for exterior joinery?

The following sub-questions are derived from the second research question:

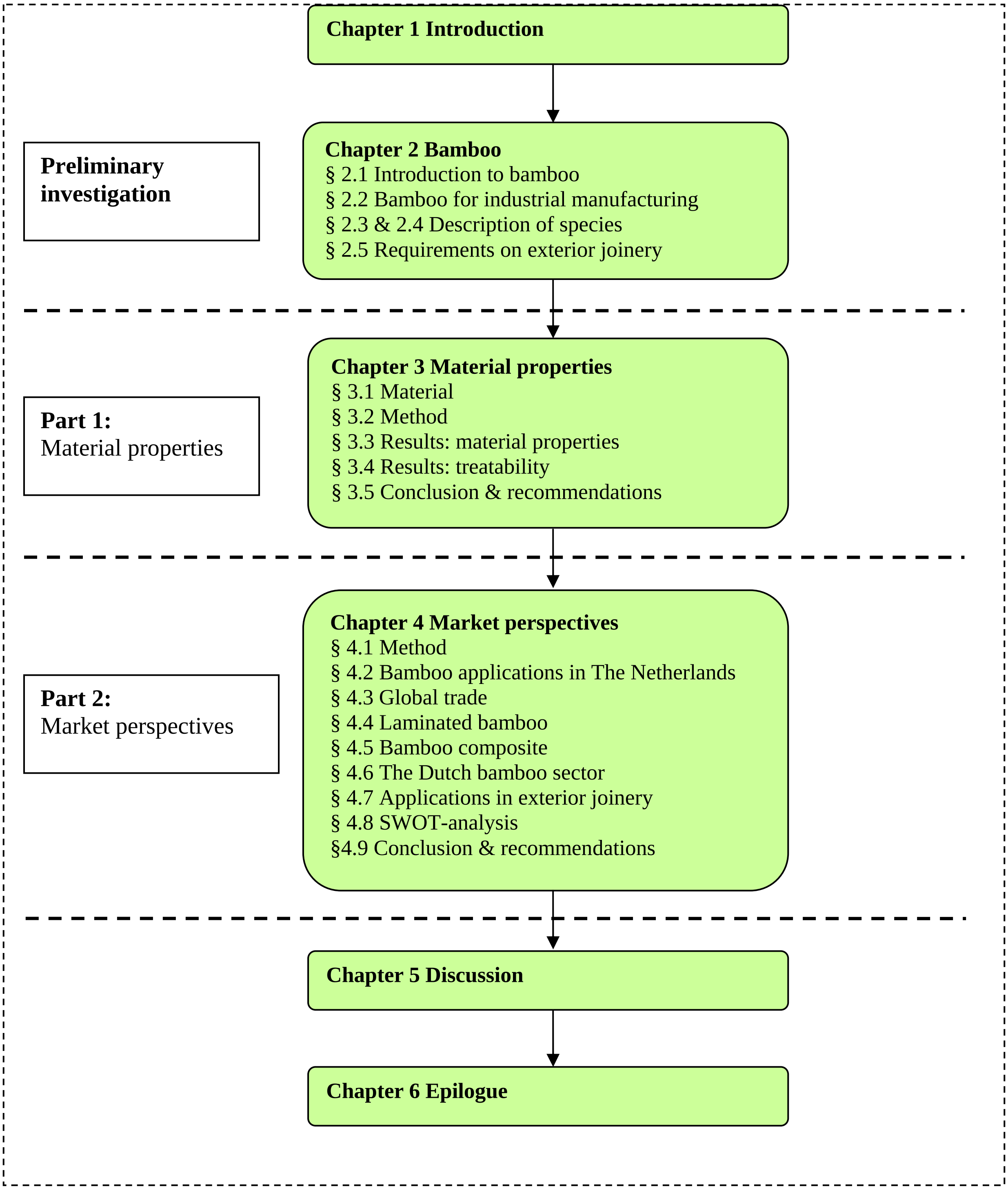
- Which applications in exterior joinery are possible on the basis of the material characteristics, and is there a difference between the tested bamboo species?
- What does the Dutch bamboo-sector look like, and what are the developments concerning bamboo in exterior joinery applications?
- What are the opportunities and threats, and strengths and weaknesses for bamboo in exterior joinery applications the Dutch market?

Goals

This project has the following goals. The first goal is to determine the material characteristics of the commonly utilized bamboo species in industrial manufacturing, and to check whether these meet the requirements of wood for exterior joinery applications in the Netherlands. The second goal is the identification of the perspectives for bamboo in exterior joinery applications on the Dutch market. Both goals were set as part of the overall goal, which is to provide SHR with specific know-how on bamboo.

Phasing & method

This project consisted of several phases, which were captured in the following diagram. The methods for obtaining the answers on the research questions, and the paragraph or chapter in which they are answered, are described on the following page. Specific parts of the methods are explained in greater detail in paragraphs §3.2 (material properties) and §4.1 (market research).



***** *Preliminary investigation (Chapter 1 and 2)*
Firstly the problem, research questions and goals were defined in the project plan. After this, the first two sub-questions of the first research question were answered, which are:

1) What are the bamboo species that are commonly utilized in industrial manufacturing for construction related purposes on the Dutch market? **(§2.2)**
2 Which demands need to be met by a wood species for it to be officially allowed in exterior joinery applications on the Dutch market? **(§2.5)**

The following methods were used to answer these sub-questions.

1) Literature and internet survey, as well as a short market survey among the leading present bamboo traders
2) Review of literature and internet on Dutch standards for exterior joinery applications, as well as interviews with experts on standards

** Part 1 Material properties (Chapter 3)*
The bamboos which were identified during the preliminary investigation, were tested on their material properties in the test facilities of SHR. These tests were performed according to the requirements of the standard which was identified in the first phase. Furthermore, the possibilities for treating bamboo were also investigated. For a detailed explanation of these test methods, see **§3.2.**

Firstly, the last two sub-questions of the first research question are answered, namely:

1) What are the material characteristics of these bamboo species, with regard to the demands which have to be met by a wood species to be allowed for exterior joinery applications? **(§3.3)**
2) Is it possible to treat bamboo by means of impregnation?**(§3.4)**

Secondly, the first research question is answered on the basis its sub-questions, namely:
'Is bamboo suitable for exterior joinery applications on the basis of its material characteristics, and are there differences between the common species used in industrial bamboo manufacturing' **(§3.5)**

** Part 2 Market perspectives (Chapter 4)*
The market perspectives for the tested bamboos were identified on the basis of the results of the material properties in phase 2, although primarily on the basis of interviews among present bamboo traders and experts. For a more detailed explanation of the applied methods, see **§4.1**.

Firstly, the three sub-questions of the second research question were answered, namely:

1) What does the Dutch bamboo-sector look like, and what are the developments concerning bamboo in exterior joinery applications? **(§4.6 and 4.6.1)**
2) Which precise applications in exterior joinery are possible on the basis of the material characteristics, and is there a difference between the tested bamboo species? **(§ 4.7)**
3) What are the opportunities and threats, and strengths and weaknesses for these applications on the Dutch market? **(§4.8)**

The following methods were used to answer the sub-questions above:
1) Initially both internet survey and literature study, followed by interviews among selected companies and experts in the Dutch bamboo sector.
2) Primarily interviews among present bamboo traders and experts, but also a more in-depth comparison of the material properties to the standards on exterior joinery
3) A SWOT-analysis was performed, for which all the obtained information during the project served as input, although mainly based on the interviews among present bamboo traders and experts.

Secondly, the second research question is answered on the basis of sub-questions, namely: 'Which applications in exterior joinery are possible on the basis of the material characteristics, and what are the perspectives for bamboo on the Dutch market for exterior joinery? **(§4.9)**

Note that the conclusion and recommendations for the two research questions are given at the end of part 1 (Chapter 3 - Material properties) and part 2 (Chapter 4 – Market perspectives).
Furthermore, the first and second part of the report are discussed in chapter 5, followed by an epilogue in chapter 6 with a general conclusion and recommendations.

Preconditions
- This project focuses on bamboo in its natural condition by testing single, non-laminated bamboo strips.
- The precise origin of the bamboo culms is not know, as well as the lot(s) to which they belonged.
- Both bamboo species were treated prior to testing, and thus were not in their complete 'natural state'.

  Moso: the culms were fumigated (smoked) as a whole, which caused them to have a darker color, as well as a 'caramelized'-scent.

  Guadua: the culms were treated with boron via the Boucherie-process (Younge, 2010), which was established by laboratory tests (both bamboos were also tested for copper and fluor). Furthermore, Guadua was infected by blue stain fungi (determined by means of light-microscopy).
- Not all tests that are required by the BGS (see §2.5) were performed; it served as a guideline in obtaining the material characteristics. This because priority was given to the tests with the most 'indicative value', but also due to lack of time (durability) and capacity (machinability).
- The way the tests were performed sometimes deviated from the standard test procedure, which was mainly caused by the nature of the material. Depending on the type of test, this could have caused the results to be different from the actual properties (see Chapter 5 for a discussion on this issue).

Target audience
This report is written for SHR and Larenstein University, but whoever is interested in bamboo, exterior joinery, renewable resources, is most welcome to read it.

Note
The words 'sustainability' and 'durability' are in practice often mistaken for one another. Durability in this report means a material's resistance against degrading organisms like fungi. Sustainability means a material's impact on the persistence of the resource to the benefit of future generations when exploited.

Chapter 2 BAMBOO

§2.1 Introduction to bamboo
The tribe of the Bambuseae (member of the family of the Poaceae - grasses) encompasses many different genera and species, with an equal amount of different characteristics (see Figure 1). Although the precise taxonomy is not fully known, it is believed that there are 60-90 genera of bamboo, with some 1100 – 1500 species (INBAR, 2002 in Lugt, 2003)

Figure 1 Different bamboo species

Although bamboo is officially a grass, it exhibits similar properties to wood. It was used for centuries as a material for construction, an enormous variety of utensils, food (bamboo shoots), medicine, paper and even clothing. Many of its uses today are still based on the same craftsmanship as in past times. However, (large scale) industrial manufacturing has adopted bamboo as a suitable material for engineered products like flooring, kitchen ware and even laptop covers. It is estimated that nearly one billion houses on this planet are (partly) made of bamboo, and for many people especially in the poorer parts of the world, the material is of great importance.

Of all the bamboo in the world, only a relatively small number of species are suitable for construction related purposes, like flooring, paneling and laminated lumber etc. According to Janssen (2001, in Lugt 2003), about 50 bamboo species exhibit favorable properties for such applications. Especially the tall and fast growing 'giant bamboos' are of interest, because of their large dimensions and favorable yield.

§2.1.1 Plant characteristics
A bamboo plant consists of a root system and several culms (because bamboo is a grass, its 'stem' is called a culm). Different from trees, the width of the culm is already determined during its sprouting, and does not increase in diameter afterwards. Bamboos can be typified according to their root system into two types: sympodial (pachymorph, commonly called 'clumper') and monopodial (leptomorph, commonly called 'runner'), see Figure 2.Sympodial bamboos are native to Latin America, with a bush-like appearance with many culms close to each other. Monopodial bamboos are native to Asia, which form less dense bushes (Lugt, 2003). Bamboo culms have leaves, which can be attached directly to the culm, or on a branch (relative small compared to the branches of trees). Branches and leaves are usually only present at the higher part of the culm.

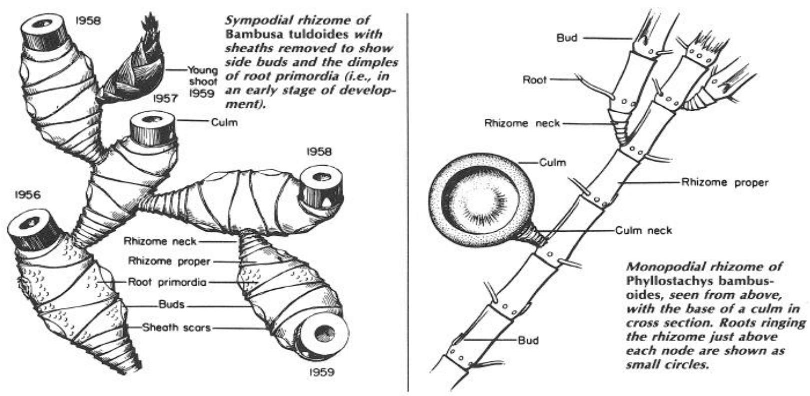


Figure 2 Sympodial roots (left) and monopodial roots (right) (Farelly, 1984)

§2.1.2 Bamboo plantations

Bamboo grows in several manners: naturally in the forest, in plantations or in a farmers yard, of which bamboo plantations provide the majority of bamboo for industrial purposes. In contrary to common practices in Scandinavian forests, bamboo plantations are not clear cut when the culms are mature; only part of the stems are cut each year. A well managed bamboo plantation consists of bamboo culms in various growth stages, ranging from sprouts to mature culms. Chinese farmers and foresters often mark a culm with the year it sprouted, which allows them to determine the suitable time for harvesting. A culm reaches its full length within several months, after which it takes about 5 years on average to reach maturity (culms that are not meant for construction can be harvested sooner). A major difference between bamboo and trees, is that bamboo continues to grow and produce after its 'stem' is removed, most trees are not able to do that (except for small shoots).

§2.1.3 Advantages of bamboo for the environment

The high yield per hectare (in a plantation) makes it a sustainable renewable material, which is by far more productive as an average production forest. A bamboo plantation produces about 3 to 4 times as much biomass as an average production forest. For example, Guadua yields 36 ton dry stems per year per heactare; Moso even more, 56 ton dry stems per year per hectare. Another advantage of this fast growth is its large carbon fixation capacity, which is about 2 - 2,5 times as high as an average production forest (Lugt, 2003). In addition to these major advantages, bamboo provides an excellent protection against erosion due to its large root network, and has several other environmental advantages like improvement soil structure, fertility etc.

§2.1.4 Global bamboo recourses

Bamboo grows in many countries throughout the world, especially in Asia, Africa and Latin America. A large thematic study on the world's bamboo resources was conducted by the FAO and INBAR (International Network for Bamboo and Rattan) in the framework of the 'Global forest resources assessment 2005' (Lobovikov et al., 2007). This provided the following data (see also Figure 3).

As a whole, it was found that the global bamboo resources surpasses 36 million hectares. Asia is the richest continent, with a total area close to 24 million hectares, followed by Latin America (over 10 million hectares) and Africa (2,7 million hectares).

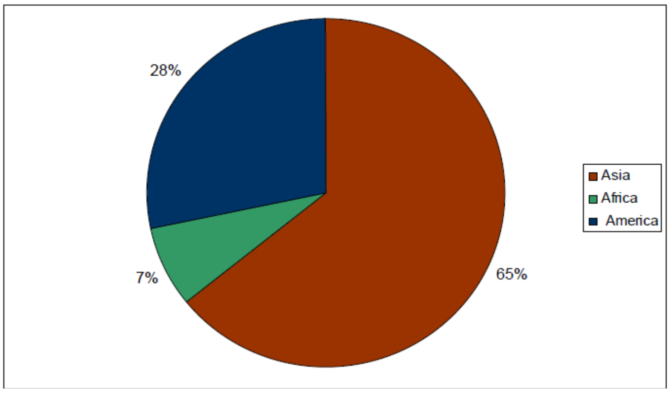


Figure 3 Contribution of world bamboo resources per continent (Lobovikov, 2007)

In Asia, the countries with the largest bamboo resources are India (11,4 million hectares) and China* (5,4 million hectares), followed by Indonesia (2 million hectares) and Laos (1,6 million hectares). Brazil (9 million hectares) has the largest bamboo resources in Latin America, followed by Chile (900.000 hectares); Colombia, Equador and Mexico have abundant bamboo resources as well. Most of the bamboo resources in Africa are found in Nigeria (1,5 million hectares) and Ethiopia (800.000 hectares).

These Figures were gathered between 2004 and 2007, and are probably different today. *China for example, has considerably enlarged its bamboo resources by reaforesting bare lands with Moso (*Phyllostachys pubescens*) (Lobovikov et al., 2007).

§2.2 Bamboo for industrial manufacturing

The EU and the USA are the largest importers of industrial manufactures bamboo products in the world. Over 95% of these bamboo products come from China (Lugt & Lobovikov 2008). The Chinese manufacturing industry primarily relies upon only one bamboo species, namely *Phyllostachys pubescens*, commonly known as Moso. This species occupies about 70% of the countrie's bamboo forestland, and about 80% of the total growing bamboo stock (Lobovikov et al., 2007). A short market survey among the leading present bamboo traders at the start of this thesis project, indicated that indeed all their industrial manufactured bamboo products came from China, and are produced from *Phyllostachys pubescens* (Younge 2010, Moso International 2010).

Next to Asia's economically most developed bamboo, it was chosen to test the economically most important species of Latin America (the continent with the second largest bamboo stock in the world), which is *Guadua angustifolia*, commonly known as Guadua.
Although it is not used for industrial manufactured bamboo products in the EU, it is Latin America's most important bamboo (Cleuren & Henkemans, 2003). The bamboo houses, both traditional and non-traditional, of South America are built exclusively of Guadua (Gutierrez, 2000). The following description sums it all up: 'Without doubt, Guadua angustifolia is the most extensively used and economically important bamboo native to the New World (Judziwicz et al. 1999 in Guiterrez, 2000). Furthermore, industrial activities concerning manufactured products of bamboo are picking up (Younge, 2010).

Conclusion

The sub-question was:
What are the bamboo species which are commonly utilized in industrial manufacturing for construction related purposes on the Dutch market?

In answer to this question the following can be concluded.
Phyllostachys pubescens (Moso) is the bamboo species which is most commonly utilized in industrial bamboo manufacturing in the world, China is the largest producer. Almost all products in the West are made from this species. *Guadua angustifolia* (Guadua) is hardly found in industrial manufactured products in the West (EU and USA), but since it is Latin America's most important bamboo, and industrial activities are picking up, it is of interest to develop know-how on this species.
By testing these two bamboos, SHR will acquire in-depth knowledge about the world's two most important giant-bamboo species.

§2.3 Characteristics of Phyllostachys pubescens (Moso)

Latin name: ***Phyllostachys heterocycla*** *var.* ***pubescens*** Mazel ex J.Houz.
Common synonym:
P. edulis (Carrière) J. Houz

Common names: (China) Moso bamboo, Mao Zhu

Figure 4 Moso forest

Characteristics

Length (average): 11-25m
Diameter (average): 6-18cm (breast height)
Growing speed: up to 119cm in 24 hours, and 24 m high in 40-50 days
Rhizome: monopodial (runner)
Other: cylindrical green internodes, length 25 cm on average. Leaves are 0.9-1.3cm wide and 5-8cm long
(Sources: Fu 2001, Farelly 1984)

Origin

Moso bamboo originates from China, from where it was introduced in various countries throughout the world, even in the south-east of the United States. Although it can be found in many countries, the vast majority of this species grows in China.

Uses

Moso was used for many centuries for a large variety of applications and products. Moso has another name in China: ‘Nan Zhu’; ‘Nan’ means very valuable hardwood. As a timber it was (and is) used for a great variety of applications, such as houses and bridges, boats, tools, kitchen ware and even as scaffolding for modern day skyscrapers that reach up to 40-storey high (Fu, 2001). Since industries developed processes for engendered products by using strips of bamboo, Moso was used for producing nearly everything, from flooring to furniture and from breadboard to laptop cover. In fact, one can be quite sure that a bamboo product bought in the West is made from Moso (see § 2.2). It is also used for an enormous variety utensils, like chopsticks, mats, baskets, lanterns, etc.

In addition to timber-like applications, Moso is also commonly used for food, for its young shoots are edible (its synonym botanical name is P. edulis, which means ‘edible’) – see Figure 5. The large size of the shoots makes Moso the central species in the bamboo-shoot business in both China and Japan. Although the quality of the mid-spring shoots is a bit below other Phyllostachys-species, the winter shoots are excellent, and an esteemed delicacy (Farelly, 1984). Besides timber and food, Moso is also used for pulp and paper production.

Figure 5 Young Moso shoots

§2.4 Characteristics of Guadua angustifolia (Guadua)

Figure 6 Mature Guadua culm

Latin name: **Guadua angustifolia** Kunth
Common names: Guadua, Giant American bamboo

Characteristics
Height: 20-30 m
Diameter: 10-15 cm
Growing speed: 21cm per day on average, maximum height is reached within first six months of growth
Rhizome: sympodial scattered (open-clumper)
Production: Guadua provides commercial (suitable for harvesting) after 4-5 years. The annual yield per hectare in a plantation is between 1200-1350 mature culms per year.
Other: the internodes are green with a characteristic white-colored strips that marks the nodes; they are cylindrical and 27cm long on average. The leaves are 10-20cm long and 6-12mm wide
(Sources: Farelly 1984 and GuaduaBamboo 2010)

Origin
The Guadua genus is native to Colombia, Ecuador and Venezuela, and was introduced to various other Latin American and Caribbean countries. The most important and economically developed species is Guadua angustifolia (Cleuren & Henkemans, 2003), which is cultivated in plantations in several countries throughout Latin America.

Uses
Since pre-Columbian times, Guauda was widely used for numerous applications in all countries where it occurred in South America (Cleuren & Henkemans 2003). All bamboo houses of South America are built exclusively of Guadua (Gutierrez, 2000). The construction industry in Colombia is the country's largest consumer of Guadua poles, consuming 70% of all Guadua in the country. They are used for supporting floors, as scaffolding and formwork; especially the latter saves much concrete and reinforcement material (Colorado 2001, Janssen 2000, in Cleuren & Henkemans 2003). In Colombia's coffee region for example, Guauda-bamboo is still part of the local culture; bridges, hillside houses over four stories tall, kitchen utensils, household objects, fences, stairways and drainage pipes are all made of Guadua (Vilegas 1989, in Cleuren & Henkemans 2003). Simon Velez (a Colombian architect) has renewed the world's interest in bamboo-structures, for which he often used Guadua. The development of proper joint-techniques made it possible to make uncommon structures, see Figure 7 for an example of the structural possibilities with bamboo culms.

Figure 7 The Phenomena building in Rotterdam, 1985/1986 (Janssen, 2000)

§2.5 Requirements on exterior joinery in The Netherlands

All constructions in The Netherlands have to meet legal requirements which were set by the Dutch government. These legal requirements are written down in The Dutch Building Regulation (Het Bouwbesluit in Dutch), and have to be met by all buildings, such as housings, office buildings, stores, hospitals and even rebuildings of a private household (VROM, 2010).

The Dutch Building Regulation sets requirements on the level of a building or a part of a building like a façade for example, which are all formulated on a 'high' and integral level (see example below). The requirements in The Dutch Building Regulation are public law, and concern security, health, user friendliness, energy efficiency and the environment.

For the fulfillment of these requirements, the Dutch Building Regulation refers to specific Dutch NEN-standards, or to European (EN) standards if they are already drafted.

> An example:
> The Dutch Building Regulation sets requirements on window frames. Take 'the prevention of moisture from the outside' with certain minimum values. In order to test whether or not a window frame is able to prevent moisture moving from the outside to the inside, the law refers to the specific Dutch standard NEN-2778.

Note

It is important to note that The Dutch Building Regulation states no specific requirements on the actual material to be used; a window frame may be made from aluminum, plastic or wood, as long as the product as a whole is able to meets the requirements. It is the product (at the lowest level), or the part of the structure in which it is applied, that has to fulfill the requirements. Because of a lack of correlation between a requirement and material characteristics, and a lack of specific requirements on material characteristics in The Dutch Building Regulation, it is difficult to establish if bamboo is able to meet the requirements of The Dutch Building Regulation (Bloom, 2010)

Besides testing a product according to the designated NEN-standards, the most common way to meet the requirements in The Dutch Building Regulation is to produce conform a 'quality statement'. Several stakeholders in the timber branch like FSC-The Netherlands, VVNH, Centrum Hout and the NBvT, took the initiative to develop their own sets of requirements, which were concluded in a 'quality statement' for KOMO-certification. In addition to the public requirements in The Dutch Building Regulation, a quality statement consists of private requirements that are forthcoming from the market. For example, The Dutch Building Regulation does not set any specific requirements on matters like durability, straightness, colorfastness, machinability etc. It may remain clear that these properties are very important.

The key document of a quality statement is a National Assessment Directive (Dutch: Beoordelingsrichtlijn – short: BRL), from here onwards abbreviated with the Dutch term BRL. This is an official document, which lists all the private and public requirements on a certain product. The Dutch government checks a BRL to see if it covers the requirements in The Dutch Building Regulation. If approved, it means that by meeting the requirements in a BRL, one automatically fulfills the public legal requirements as well.

Certification Institutes which are accredited by the government, check if a product meets the requirements in the BRL, and award the KOMO-certificate if it does. SKH and KIWA are the two main certification institutes in The Netherlands which certify wooden products, of which SKH does most. In the Dutch construction sector it is common practice to use KOMO-certificates; one can hardly enter the market without having their product certified according to KOMO (and thus the specific BRL).

There are four National Assessment Directives (BRL'en) that concern wood in exterior joinery applications. Each of these documents lists the requirements for a certain type of application:

- BRL 0801 'Wooden façade elements'
- BRL 0803 'Wooden exterior doors'
- BRL 0812 'Wooden glazing beads'
- BRL 4103 'Wooden and wood-based façade covering systems'

Not all timber species prove suitable for these applications. The timber species which are allowed by the National Assessment Directives above, have to meet certain requirements. These are listed in the 'Evaluation standard for wood species for application in timberwork', SKH-publication 97-04 (Dutch: Beoordelingsgrondslag houtsoorten voor toepassing in geveltimmerwerk'- BGS in short), from here onwards abbreviated with the Dutch term BGS. This document encompasses all the requirements on the different timber properties, and how to test them. These properties are:

- Hygroscopic properties
- Hardness
- Strength
- Durability
- Gluability
- Paintability
- Machinability
- Fire retardation

When a timber species was tested and meets all the requirements of the BGS, it can be added to the list of 'Allowed timber species' (SKH publication 99-05) and the KVT[1], and is allowed to be used for KOMO-certified application in exterior joinery. However, it is not necessary to add a wood species to this list; if it meets all the requirements in the BGS, it can also be used for certified exterior joinery (see also Chapter 5 for a discussion on this matter).

All National Assessment Directives refer to the BGS for the requirements on a wood species, except BRL 4103 on cladding. This is because there are less requirements on cladding than on the applications described in the other three National Assessment Directives. Nonetheless, a wood species which meets the requirements in the BGS, may also be used for cladding according to BRL 4103.

[1]The KVT is a quality guideline that was established by the NBvT (Dutch Association of Joinery Factories), and is widely used in this branch.

Conclusion

The sub question is:

'Which demands have to be met by a timber species for it to be officially allowed in exterior joinery applications on the Dutch market'

In answer to this question the following can be concluded.

The Dutch Building Regulation does not set specific requirements on material properties, and sets requirements on only some properties which are highly valued by the market. A BRL that concerns timber in exterior joinery applications however, does have a clear set of requirements. These are specified in the BGS. This document can be regarded as the threshold that has to be matched by a timber species, for it to be officially allowed, and to compete in exterior joinery applications on the Dutch market.

Exterior joinery applications of bamboo will need to compete in a market that is dominated by KOMO-certified construction products. Therefore, bamboo will be tested accordingly, and compared to the key-requirements that are posed on timber for KOMO-certified exterior joinery applications; which are described in the BGS.

PART 1

Material properties

The first part of the report (chapter 3) is on the material properties of Moso and Guadua, which were tested according to the requirements in the 'Evaluation standard for wood species for application in timberwork' (SKH-publication 97-04)

Reading guide
The material which was used for the tests on the material properties is described in paragraph §3.1, and the tests methods in §3.2. Paragraph §3.3 deals with general bamboo anatomy, macro- and microscopic features, the influences of starch on the properties, and the results of the tests on the material properties. The tests results on the treatability are presented in §3.4, and the conclusion and recommendations for the first research question in §3.5.

Chapter 3 MATERIAL PROPERTIES

§3.1 Material

The bamboo material which was tested is described below.
Bamboo culms (parts of the whole culm) were purchased at 'Bamboo information centre' in Schellinkhout, three culms of *Phyllostachys pubescens* (Moso), and two culms of *Guadua angustofilia* (Guadua).

Latin name:	***Phyllostachys pubescens*** Mazel ex J.Houz.
Common names:	Moso bamboo, Mao Zhu (China)
Origin:	Anji province, West-China
Remarks:	Culms were fumigated (smoked) for protection against wood degrading organisms (caramelized scent present). Diaphragms had been pierced. All the culm parts came from the lower part of the culm (just above ground level), no branches were present. Culms were about 4-5 year old after harvest.

See Figures 8, 9 and 10 for representative pictures of the Moso culms , and Table 1 for the sizes for each of the three culms.

Figure 8 Moso bamboo culm no. 1 - length 266 cm

Figure 9 Moso culm no. 1 - lower end (Ø 11cm)

Figure 10 Moso culm no. 1 - top end (Ø 9,5 cm)

Table 1 Moso sizes [cm]

Moso sizes [cm]				
		Culm 1	Culm 2	Culm 3
Diameter				
	Lower end	11	10,5	11
	Top end	9,5	9	8
Wall thickness				
	Lower end	1,5	1,5	1,5
	Top end	0,9	0,9	0,9
Total length		266	268	254
Internode length*				
(lower end)	1	10	11	10,5
	2	13	12	11
	3	14	15	13,5
	4	16	17	15
	5	18	19	16,5
	6	19	20,5	17,5
	7	21	22	19,5
	8	22	23,5	20,5
	9	23	25,5	22,5
	10	25	26,5	23,5
	11	26	27,5	25
(top end)	12	27	27,5	25
* Only non-disrupted internodes were measured				

Latin name:	**Guadua angustifolia** Kunth
Common names:	Guadua, Giant American bamboo
Origin:	Near Pereira (city), Colombia
Remarks:	Culms were treated with boron via the Bouchery-process (Younge, 2010), which was also established by laboratory tests. The diaphragms were pierced. Culms were infected by blue stain-fungi, see also Figure 14. All the test material of Guadua came from the middle/upper region of the culm, branches were present. The culms were at least 1-2 years old after harvest.

See Figures 11, 12 and 13 for representative pictures of the Guauda culms, and Table 2 for the sizes for each of the two culms.

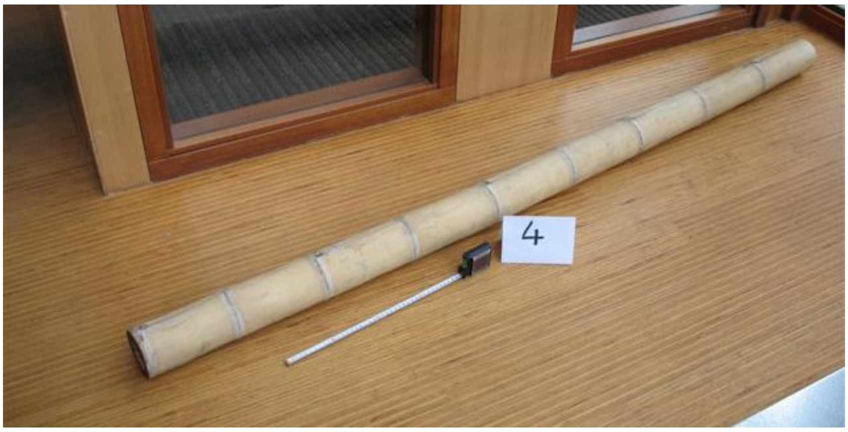


Figure 11 Guadua bamboo culm no. 4

Figure 12 Guauda culm no. 4 - lower end (Ø 9,5cm)

Figure 13 Guauda culm no. 4 - top end (Ø 9,5cm)


Figure 14 Blue stain fungi (note the distinct boundary)

Table 2 Guadua sizes [cm]

Guauda sizes [cm]		
	Culm 4	Culm 5
Diameter		
Lower end	9,5	9,5
Top end	9,5	9,5
Wall thickness		
Lower end	2	1,5
Top end	1,2	1
Total length	198	
Internode length*		
(lower end) 1	17	18
2	18	19
3	19,5	19,5
4	20,5	20
5	22	21
6	22	22
7	24	22,5
(top end) 8	24,5	23,5
* Only non-disrupted internode were measured		

§3.2 Test methods
The tests were performed according to the standards of the 'Evaluation standard for wood species for application in timberwork' (BGS) as much as possible (see preconditions). Certain test were performed according to the specific standard operational procedure (SOP) of SHR, which are internal documents.

The test pieces were produced in SHR's workshop, the production process is described below (see also Figure 15).

Firstly, the culms were sawn lengthwise into 8 strips using a circular saw (first in halves, then in quarters and finally in eights). Following this, the remaining parts of the diaphragms were removed with a band saw. Next, the strips were planed to the desired thickness by a planning machine. Finally, the strips were edged by planning one side on the joiner's bench, which allowed the other side to be edged by the circular saw.

Figure 15 Production of the test strips

The tests were performed on planed strips of ±7mm thickness on average, either edged or unedged, depending on the specific test.

In order to obtain in-depth knowledge about the variation in properties of the different part of the bamboo culm, most tests were performed on the following characteristic parts:

- Internode (section without a node, straight grain)
- Node (section with a node present, curly grain)
- Outside of culm-wall (tangential surface just below outer cortex, high vascular concentration of bundles which are small in diameter)
- Inside off culm-wall (tangential surface just below inner cortex, low concentration of vascular bundles which are diameter)

The specimens were conditioned in a 65% RH, and 20 °C climate, unless stated otherwise.

In order to provide a point of reference, the test results were compared to two wood species. Norway spruce and dark red meranti were chosen because they are commonly used on the Dutch market, and are often used for exterior joinery.

The simplified data sheets of the tests contain information on the standard deviations (stdev) and variation (V%), see annexes on pages 69-75.

§3.2.1 Microscopic features
Transversal, radial and tangential coupes of ±20 μ thickness were cut from internodes (straight grain) of the culms. Pictures were taken from representative parts (vascular bundles from the centre of the culm wall) of the micro-structure, to obtain characteristic information about the species. Before cutting the coupes, the material was boiled in an autoclave at 1 bar for 4 hours. Next, the specimens were stored in 70% alcohol for over two weeks. This procedure is accordance with the method described by Grosser (Grosser, 1971).

The coupes were stained with safranin, embedded in glycerol and examined under a light microscope.

§3.2.2 Density
The density was measured of specimens with a node in the centre, and without a node. The density was established for the equilibrium moisture content belonging to 65% RH and 20 °C.
Size of all specimens: 5 x 20 x 130 mm

The number of tested specimens for the two different situations (with or without node) is shown in the table below.

	Moso	**Guadua**
With node	10 x	10 x
Without node	10 x	10 x

The specimens were conditioned in a climate chamber at 65% RH and 20 °C. Dimensions and weight were recorded after an equilibrium was established. Weight was recorded a second time after 24 hours drying at 103 °C.

The density was calculated by means of the following formula.

$$\rho = \frac{m \cdot 10^6}{b_1 \cdot b_2 \cdot t}$$

m = mass in gram
b_1 = width in mm
b_2 = length in mm
t = thickness in mm

The EMC was calculated with the same formula as used for the EMC-test (see §3.2.3).

The 5% quantile value was calculated for all specimens together (with and without node) by means of the following formula. This in order to compare bamboo to strength classes for timber, which requires a 5% quantile value for the density and the MOR, and an average value of the MOE.

Density (5% quantile) = average density – (stdev * students coeffficient[1])

[1]The students coefficient belonging to 20 test specimens is 1.73

§3.2.3 Equilibrium moisture content
The equilibrium moisture content (EMC) was determined according to SHR SOP 47. The EMC was determined for the climates referred to in the BGS, thus for 50%, 65%, 80%, 95% RH and water-saturated; 25% RH was added to this sequence to provide additional information.

The different relative climate conditions were created in regular climate chambers, as well as by salt regulated chambers (saltbox), which are specified in the table below.

Relative humidity [RH] at 20 °C	**Climate chamber or saltbox**
25%	Potassium acetate (CH_3COOK)
50%	Regular climate chamber
65%	Regular climate chamber
80%	Ammonium chloride (NH_4Cl)
95%	Potassium nitrate (KNO_3)
Water saturated	Submersion in water under vacuum

Size* for all specimens: 5 x 20 x 5 mm. Note that this is very small.
* Due to the nature of the tested material, the sizes deviated from the SOP for wood (minimum 20 x 20 x 5-10 mm).

Number of specimens (both Moso and Guadua): 10x

The EMC was calculated by means of the following formula.

$$EMC_i = \frac{m_{ci} - m_{od}}{m_{od}}$$

EMC_i: equilibrium moisture content at RH i.
m_{ci} : mass after conditioning in climate i.
m_{od}: mass after drying in oven

The specimens reached their EMC within 6 days on average.

§3.2.4 Dimensional stability: swelling
Swelling was determined according to SHR SOP 49. Shrinkage was not determined, since only the swelling characteristics would provide a sufficient indication of the dimensional stability. The measurements were made on the same specimens which were used for determining the EMC. See the previous paragraph (§3.2.3) for the size and number of specimens, and conditioning sequence.

The swelling was calculated by means of the following formula.

$$S_{swell,j} = \frac{d_j - d_{od}}{d_{od}}$$

$S_{swell, j}$: swelling of the wood at equilibrium moisture content (EMC) j
d_j: dimension of the wood at EMC j (in radial or in tangential direction).
d_{od}: dimension of the wood after oven drying

§3.2.5 Janka Hardness
The Janka hardness was tested according to ASTM D 143-83.
Due to the nature of the material, the sizes deviated from the standard; both bamboo species were tested as unedged strips, measuring:

- Moso 7 x 30 x 1000 (±) mm
- Guadua 10 x 30 x 1000 (±) mm

The spots of indention were spaced at a minimum of at least 50 mm from each other. Every strip was placed on top of another strip of the same material, in order to compensate for the limited thickness, hereby avoiding differences in compression behavior of the underground. Janka hardness was measured with different parts of the culm placed upwards (towards the indention device): the outside of the culm-wall up, the inside of the culm-wall up, and for node- and internode sections.

The number of indentions per different situation is shown in the table below.

	Moso		**Guadua**	
	Inside wall up	Outside wall up	Inside wall up	Outside wall up
Internode	10 x	12 x	11 x	10 x
Node	5 x	6 x	5 x	5 x

Machine: Universal pressure bench, type Zwick Z020. Load-cell 20 kN
Indentation device: Steel ball with a diameter of 11,284 mm
Other parameters: Pre-load 5 N, test speed 6 mm/min

§3.2.6 Strength
A four-point bending test was performed according to NEN-EN 408. The test results were calculated according NEN-5498, and compared to strength classes for timber according to NEN-5498/A1 and NEN-EN 338. The specimens were placed with the inside of the culm-wall up (inside of culm wall loaded in compression), the outside of the culm-wall up (outside of culm wall loaded in compression) and with or without a node in the center.

Size[1] of specimens (both Moso and Guadua): 5 x 20 x 130 mm
[1]The specimen sizes are conform NEN-EN 408 (length minimum 19 times the depth (thickness) of the section) and NEN-5498. However, according to NEN 5498 , the value of the depth has to be modified with a certain modification factor before calculating the MOR, if the depth is less than 200 mm and a minimum of 75 mm. The depth of the bamboo specimens was much less than the minimum of 75 mm. Therefore, no modification factor could be applied without loosing the indicative value of the results.

The number of specimens per different situation is shown in the table below.

	Moso		**Guadua**	
	Inside wall up	Outside wall up	Inside wall up	Outside wall up
Internode	5 x	4 x	5 x	5 x
Node	5 x	6 x	5 x	5 x

Machine: Universal pressure bench, type Zwick Z020. Load-cell 20 kN
Span between bending points: 90mm
Span between one bending point and adjoining pressure point: 31,5mm
Other parameters: MOE was calculated between 20 and 40% of MOR, test speed 15mm/min

Calculation: MOE was calculated as an average value. MOR was calculated as average value, and also 5%-quantile value for the total (total = average value of all specimens) bending strength (the so called 'characteristic value'). The 5% quantile value of the MOR was calculated according to the formula below, using all test data for each species.

MOR (5% quantile) = average MOR – (stdev * students coeffficient[1])
[1]The students coefficient belonging to 20 test specimens is 1.73

§3.2.7 Water uptake and loss

The water uptake was determined according to SHR SOP 122. In order to research the effect of a node on the water uptake, halve of the specimens had a node - all at different heights above the water level (described as low, middle and high above water level).

Number of specimens: Moso 10x, of which 6 had a node (1 high, 2 low, 3 middle)
Guadua 10x, of which 7 had a node (1 high, 1 low, 5 middle)

Size of all specimens: ±9 x 20 x 150 mm

The number of weighing moments and duration of the water uptake sequence was more than what is normally done for wood, namely five weeks instead of three. The last weighing moment during the water loss sequence was after 13 days instead of 14.
For the weighing sequence, see Annex 6.

The water uptake and loss was calculated by means of the following formula.

$$M - \%_t = \frac{m_t - m_{od}}{m_{od}}$$

M (moisture)-$\%_t$:	moisture content at time t
m_t	mass at time t
m_{od}:	mass after drying in oven

The specimens were conditioned at 85% RH before they were placed in the water, this because small surface droplets appeared on the surface in a 95% RH climate, indicating more water was soaked up than allowed before the test commenced. This is done in order to prevent the specimens from taking up moisture from the air, instead of only from the water. The specimens were placed with their cross section into ±1 cm water in a covered container after conditioning. The water uptake was measured as the weight gain (related to the cross sectional surface). The water loss was measured by measuring the weight changes of the specimens in a climate of 65% RH. As the climate conditions differed between start (uptake) and drying (loss), the curve of the water loss is partly displayed negatively.

In order to compare the results with wood (dark red meranti and Norway spruce), the average water uptake was calculated into mg/mm^2. This comparison could not be made for the water loss, because of the large difference in size and therefore in surface for water evaporation.

§3.2.8 Gluability

The gluability (tensile shear strength of a glue) was tested according to NEN-EN 205. This in order to obtain information about bamboo’s suitability for gluing. The results were compared to NEN-EN 204, as well as SHR internal test record of the used glues.

The specimens were glued with two outsides of the culm wall together, and also with two insides together. See the table below for the number of tests (for all glues the same)

	Moso	**Guadua**
Inside culm wall together	6 x	6 x
Outside of culm wall together	6 x	6 x

The size of the specimens was adjusted according to NEN-EN 205 – Annex A
Size of specimens for each of the two halves (for Moso and Guadua): 5 x 20 x 80 mm (overlap 1cm)

Three types of glue were used for testing, a poly urethane (PU-glue), a poly vinyl acetate (PVAC-glue) and an emulsion polymer isocyanate (EPI-glue). All glues are known for performing well, and are commonly used in practice. The glued surfaces were pressed together by means of a 1 kg weight (pressing away the excess glue), this seemed to be sufficient pressure for the surface-size to obtain a thin filmed glue bond (pressure 0.05 N/mm^2). The tensile shear strength was tested after conditioning cycle 1 (7 days drying in standard atmosphere), which is the standard for D4-glues (exterior) according to NEN-EN 204.

The percentage of fiber fracture was determined under a microscope.

Machine: Universal pressure bench, type Zwick Z020. Load-cell 20 kN
Clamping device: two self-locking steel clamps, sample was aligned in a way the tensile force was exerted in the same plane as the glue bond
Other parameters: pre-load 20N, test speed 25 mm/min

§3.2.9 Paint adhesion
The paint adhesion was tested according to ASTM D 3359A-93 (X-cut) and SKH publication 05-01. Dry and wet adhesion was tested, for a normal (covering) primary coating system (Sigma Sigmalith WBA primer – white), and a transparent coating system (Sikkens Cetol WF 955 - brownish). The first paint is an alkyd-emulsion, the second an acrylate-dispersion. See the table below for an overview.

Brand name	Main composition	Color	KOMO-certified
Sigma Sigmalith WBA primer	alkyd-emulsion	Opaque white	yes
Sikkens Cetol WF 955	acrylate-dispersion	Transparent brownish	yes

Both systems are known as good quality paints for wood, and are commonly used for KOMO applications. Because the aim was to research the adhesion between the coating and the bamboo-surface, only one layer of paint was sprayed, measuring ±180 µ wet (±80 µ dry) for both coating systems – hereby deviating from the guideline for coatings in BRL 0801- Annex 5, which requires at least two layers and a thickness of 100 µ. The adhesion is classified in 6 classes, class 0 = 100% adhesion, class 5 = less than 35% adhesion). The adhesion is tested by making a cross cut through the coating, after which tape is applied and pulled away. The amount of paint which is pulled away is classified.

The adhesion (dry and wet) was tested for the in- and outside of the culm wall, on nodes and internodes. For the number of adhesion tests, see the table below.

	Moso		**Guadua**	
	Inside wall	Outside wall	Inside wall	Outside wall
Internode	3 x	3 x	3 x	3 x
Node	2 x	2 x	2 x	2 x

The drying time for both paint was two weeks. The wet adhesion for the acrylate-dispersion (Sikkens Cetol WF 955) was tested a second time after 6 weeks drying, this in order to eliminate the influence of drying time on the results.

Size of specimens
Unedged strips, width of plained surface at least 25mm in width (same as width of testing tape), thickness 7mm for moso and 10mm for Guadua, lengths variable (around 1000mm).

Other parameters: X-cuts were spaced at a minimum of 50mm from each other.

§3.2.10 Treatability
In order to research the pathways through which the solution would be impregnated into the material, the cross-sections (ends) of the specimens were sealed with an epoxy resin in various ways. The different ways of sealing, and the amount of specimens are shown in the table below.

Way of sealing	**Guadua**	**Moso**
Both cross-section ends sealed	5x	5x
One cross-section end sealed, one open	5x	5x
One cross-section end sealed, on open with a node just behind the open end	5x	5x

Both species were impregnated with a 1% copper ($CuSO_4$) solution in water. The treatment cycle consisted out of ½ an hour vacuum, followed by 1 ½ hours pressure (8 bar) in an autoclave; the so called 'full-cell process'. The specimens were submerged in the copper solution during the process. Before the treatment, the specimens were conditioned in a climate of 65% RH and 20 °C.
After the treatment, the specimens were weighed a second time and eventually dried at 60 °C.
A statistical probability test (Students T-test) was conducted to research the effects of the different pathways on the amount of solution that was able to ingress into the material.

After this, small sections of the treated specimens of 10mm length were cut at 30mm behind the open end, for both the specimens with and open end with of without a node. A 10mm long cross section was cut from the centre of the specimens with both ends sealed, as well as a longitudinal section by cutting the entire specimen in halves. The 'fresh' cross- and longitudinal cuts were treated with a reagent to detect copper (a violet color indicates copper). Following this, the cuts were examined under a light microscope. Pictures were taken of the characteristic features.

§3.3 Results - Material properties
This paragraph is on the general anatomy of bamboo, the influences of starch on its application, the macro- and microscopic features, and the results of the tests on the material properties according to SKH publication 97-04.

§3.3.1 General bamboo anatomy
Bamboo's material structure is similar to wood, although no rays and other radial cell elements exist, and hardly any knots (Figure 16 - 4) are present. The bamboo culm (see Figure 16) is hollow, and built up of sections. The inside cavity is called a lacuna, which is present in almost all bamboos, although there are some which have solid internodes (Liese, 1998).The straight grained sections are internodes (Figure 16 -1), which are separated from each other by a diaphragm at the lower and upper end (Figure 16 -3). This diaphragm has an out-growth, which can be seen as a ring around the culm, called a node (Figure 16 -2). The outside of the culm wall is formed by a thin cortex which has a high silica content (an important barrier against water and degrading organisms), and is covered by a thin layer of wax. The inner side of the culm wall is mostly protected by heavily thickened and lignified parenchyma cells, called the pith ring. In some species, the pith ring is covered by a paper thin membrane called the the pith cavity membrane (present in *Phyllostachys pubesces* for example).

For a more detailed explanation of the different cell types and microscopic features, see §3.5

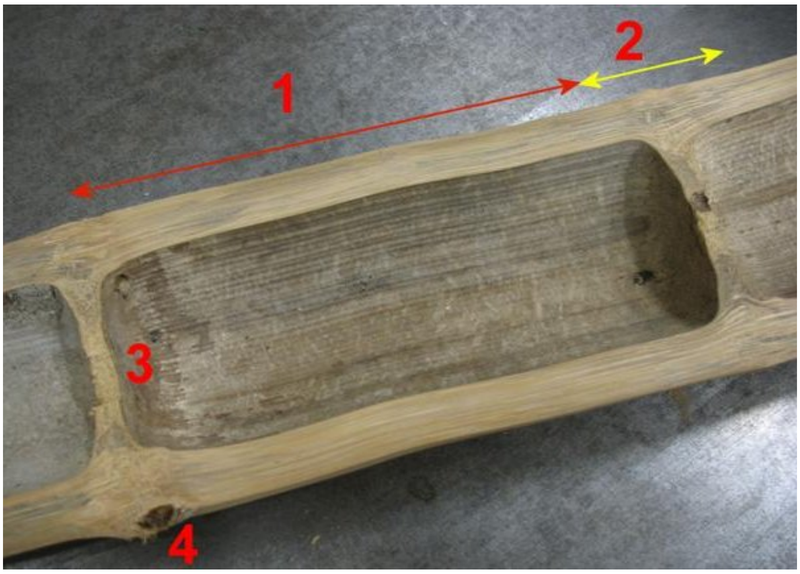


Figure 16 Bamboo culm (Guauda) split in halves; 1 internode, 2 node, 3 diaphragm, 4 branch (knot)

§3.3.2 Macroscopic features

Latin name:	***Phyllostachys pubescens*** Mazel ex J.Houz. Common synonym: *P. edulis* (Carrière) J. Houz
Common names:	Moso bamboo, Mao Zhu (China)
Origin:	China (Asia)
Remarks:	The material has a darker color because the culms were smoked.

Moso has a reasonably fine grain, finer than Guauda due to its smaller vascular bundles. The nodal regions are small (due the small diaphragm), and do not result in a coarse surface after planing. Similar to Guadua, the concentration of the vascular bundles near the outside of the culm wall is high (Figure 17), resulting in more 'stripes' on the tangential surface near the outside of the culm wall than on the inside (see difference between Figure 18 and 19).

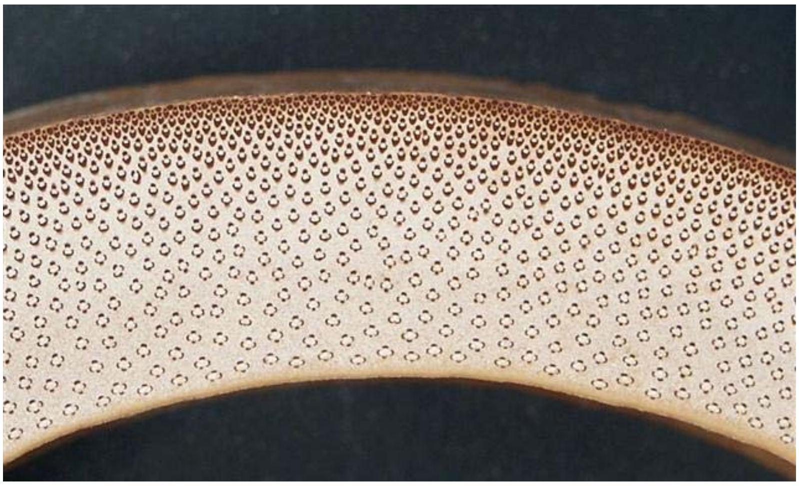


Figure 17 Moso - transverse surface

Figure 18 Moso - tangential surface, outside of culm wall (1 stripe equals 1 cm)

Figure 19 Moso - tangential surface, inside of culm wall, with node (1 stripe equals 1 cm)

Latin name:	**Guadua angustifolia** Kunth
Common name:	Guadua, Giant American bamboo
Origin:	The region of Colombia, Equador and Venzuela
Remarks:	Parts of the material is infected by blue stain fungi, which cause the grayish gloom (visible in Figure 22)

Guauda has a relatively coarse grain, due to its large vascular bundles (Figure 20). These appear not to run strictly axial (wavy pattern), see Figure 21. The nodal region is relatively large (Figure 22), due to the large thickness of the diaphragm, and results in a coarse surface after planning. Just as for Moso, note the difference between the outside and inside of the culm wall.

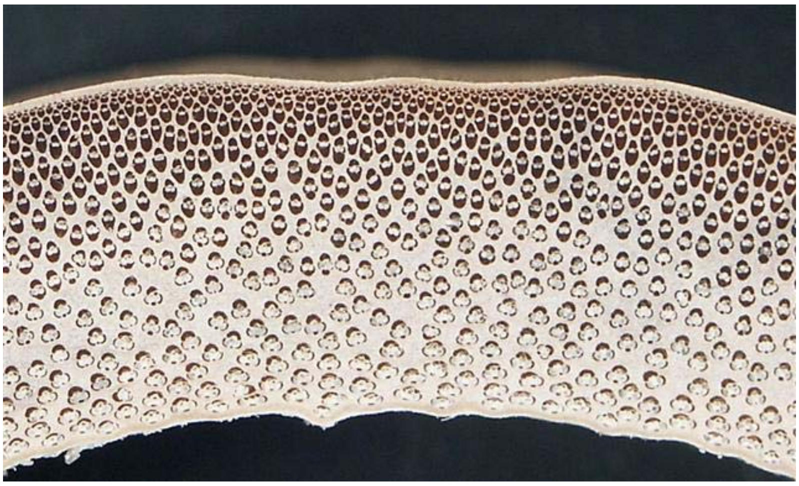


Figure 20 Guadua - transverse surface of culm wall

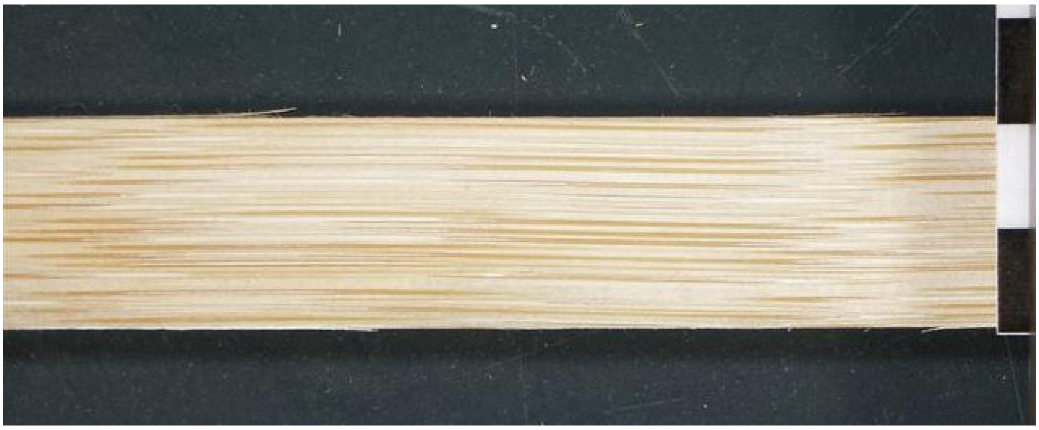


Figure 21 Guadua - tangential surface, outside of culm wall (1 stripe equals 1 cm)

Figure 22 Guadua - tangential surface, inside of culm wall, with node (1 stripe equals 1 cm)

§3.3.3 Microscopic features

The ground tissue of a culm consists of parenchyma cells, with embedded vascular bundles composed off metaxylem vessels, sieve tubes with companion cells, and fibers. Bamboo tissue is approximately composed of 52% parenchyma, 40% fibers (sclerenchyma sheaths and separate fiber strands) and 8% conducting tissue (tubes) (Liese, 1998). The concentration of the vascular bundles on the outside of the culm wall is high, and low on the inside (see Figures 17 & 10 in §3.3.2). Therefore, the percentage of fibers (sclerenchyma or separate fiber strands) decreases towards the inside of the culm wall. Furthermore, the numerous vascular bundles near the outside of the culm wall are small in diameter, where the ones in the centre and near the inside of the culm wall have a large diameter. Due to the presence of fibers, vascular bundles determine the strength of a culm. The cells are all strictly axially orientated within an internode, except the vascular bundles seize to run straight in a node where some of them bow off into the horizontal diaphragm.

The microscopic features of a vascular bundle are described in Figure 23, note that these features are not present in every bamboo species.

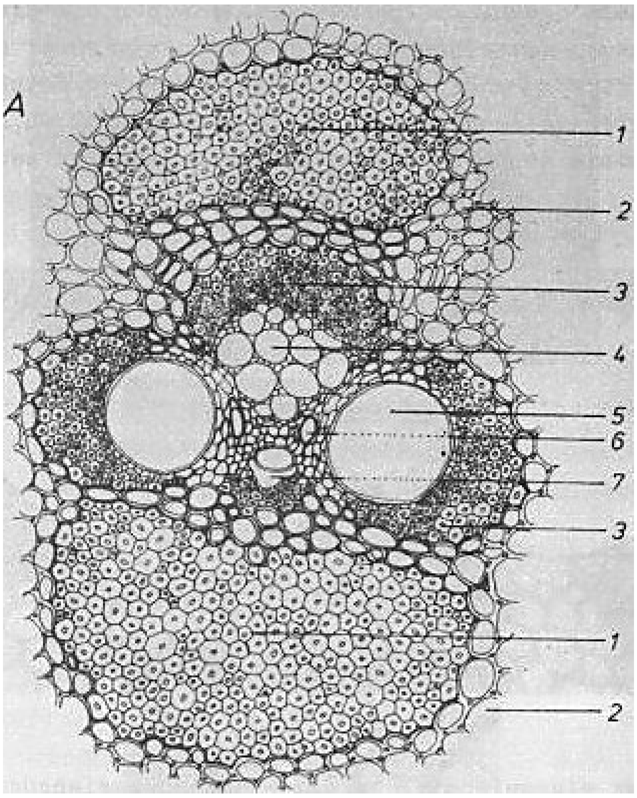


Figure 23 Composition of a bamboo vascular bundle (Grosser, 1971)

Details of vascular bundle
1 – Fiber strand
2 – Parenchyma
3 – Sclerenchyma sheaths
4 – Phloem (sieve tubes with companion cells)
5 – Metaxylem (vessel)
6 – Smaller metaxylem element
7 – Intra-cellular pathway, strengthened by the remainder of the original tube-element (protoxylem)

Figures 24 and 25 are meant to characterize the micro structure of both bamboo species. Only features of the centre of the culm-wall were photographed, because this region exhibits most characteristic features. The description (and pictures) of the macroscopic features for Moso accounts for culm parts from the lower region of the culm (the used internodes from Moso are within 2 meters above ground level). For Guadua, the description accounts for the middle/upper region of the culm (branches were present).

It proved to be difficult to cut a coupe in transverse direction for Guadua, what most likely is caused by the toughness of the vascular bundles which are large in diameter; sclerenchyma cells have an extremely thick cell wall.

The diagnostics description of bamboos is restricted to only the cross-section, while radial and tangential sections do not exhibit any special features (Grosser, 1971). See Annex 1 for pictures of tangential and radial surfaces.

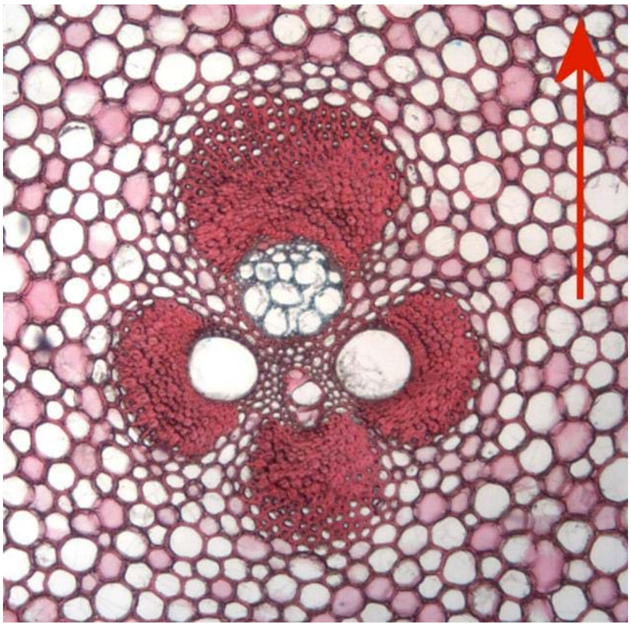


Figure 24 Moso - vascular bundle, transversal surface, centre of culm wall, arrow points towards outside of culm wall (40x)

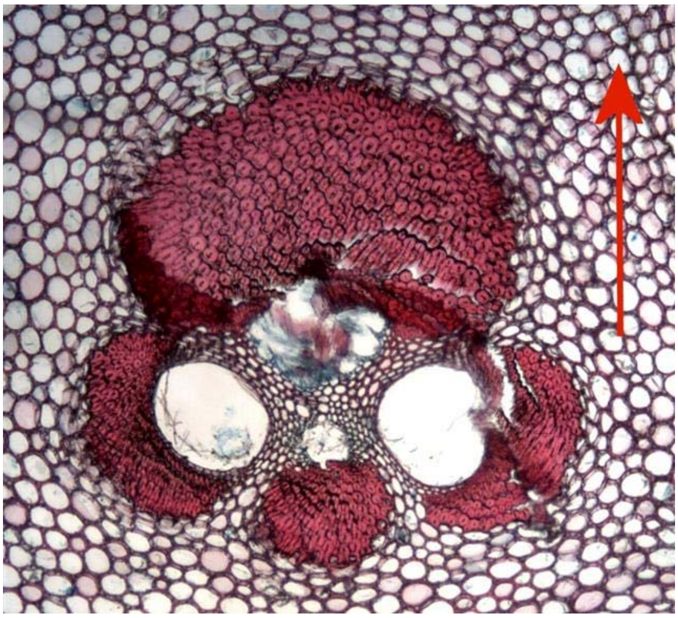


Figure 25 Guadua - vascular bundle, transversal surface, centre of culmwall, arrow points towards outside of culm wall (40x)

Moso and Guadua both have in common that phloem and xylem (conducting tissue at the heart of a vascular bundle) are surrounded by sclerenchyma sheats; no separate fiber strands are present. Moso has four sclerenchyma sheets which are fairly eaqual in size. Thylosis is noticeable inside the intra-cellular pathway. Guadua also has four sclerenchyma sheets, of which two (left and right) are of equal size. The sclerenchyma sheat which surrounds the intra-cellular pathway is much smaller, and the sheat that surrounds the phloem is remarkably thick. No thylosis was observed.

Note
The variation in micro-structure of the vascular bundles is high for both transverse (across the culm-wall) and longitudinal direction (differences between lower and upper parts of the culm) (Liesse, 1998) See Annex 1 for an example of a vascular bundle near the inside of the culm wall (for Moso), and an vascular bundle near the outside of the culm wall (for Guadua).

Conclusion
Both bamboos have microscopic features which are quite different compared to wood. These features should make the material suitable for determination. However, a determination key which comprises all bamboos is not known yet; although several attempts have been made (Liese, 1998).

§3.3.4 Inclusions: starch

Bamboo tissue contains several organic and inorganic inclusions (extractives), which are deposited within cell walls as an encrusting material, in cell lumina, as a cortex apposition or inside lacunae. One of the inclusions which is often discussed with regard to the durability of bamboo is the starch content. The starch content of the parenchyma cells influences to a larger extent the susceptibility to attack by fungi, especially blue stain fungi, and beetles. Starch grains occur abundantly in the parenchyma cells that form the ground tissue (see Figure 26), and in parenchyma in the vascular bundles. Even fibers may contain starch. Starch serves as an energy resource for the production of new shoots. The amount is influenced by several factors: 1 – the season. For example, Sulthoni (1987, in Liese 1998) reported a fluctuation in the starch content in culms from java – *Bambusa vulgaris* had 0.24% in January (rain season) and 7.97% in November (dry season); 2 – the culm's age. Virtually no starch is present during the first year of growth, and gradually increases when the culm becomes older; 3 – the position along the height of the culm, and across the culm wall. The lower part of the culm has a higher durability as middle and top parts due to the lower concentration of starch in the bottom parts, and the inner part of the culm wall has a lower durability than the outer part, which is attributed to the higher content of nutritious parenchyma in the inner part. Furthermore, there is a considerable difference in starch content among the different bamboo species (Liese, 1998).

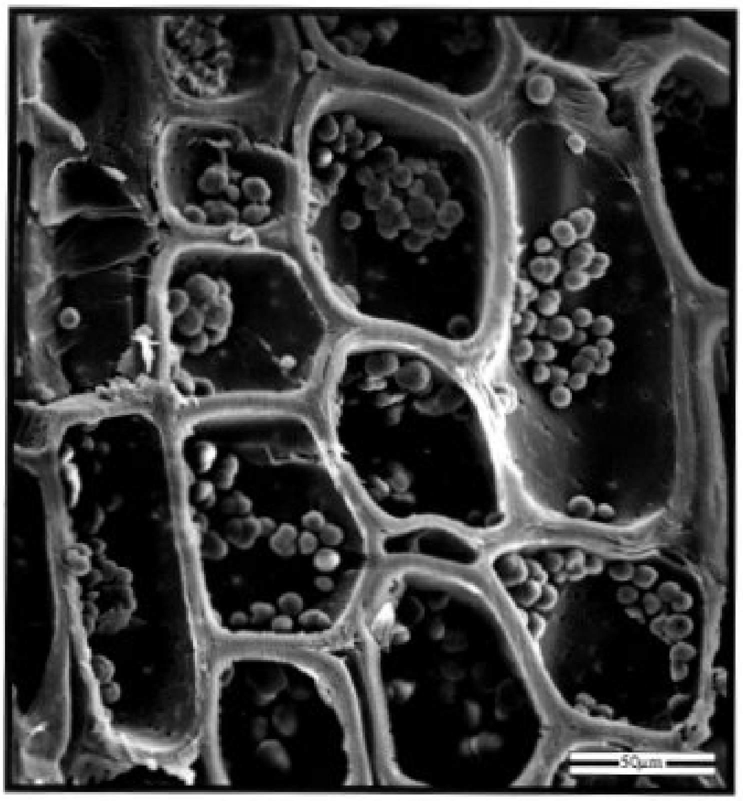


Figure 26 Parenchyma cells (ground tissue) filled with starch granulae in *Phyllostachys viridiglaucescens* (Liese, 1998)

§3.3.5 Density
The density of both bamboos is shown in the chart below (Figure 27), see Annex 2 for the data (simplified version). The density was measured for Moso at a moisture content of 10.3%, and for Guauda 12.6%. Literature values of Norway spruce and dark red meranti were added for a comparison.

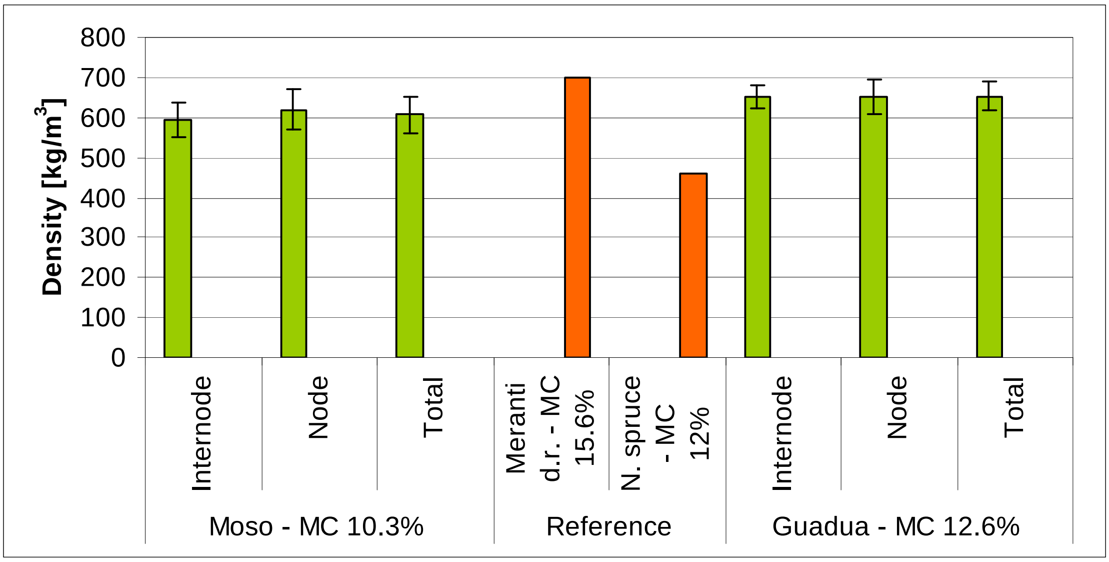


Figure 27 Density of bamboo, at equilibrium MC with 65% RH and 20 °C
Source of literature values for timber: Wiselius, 2005

Both bamboo species have quite similar densities; Guadua is denser than Moso, what most likely is caused by its higher moisture content. Although nodes have a higher density than internodes in both species, the difference is not significant. The density of both bamboos seems less than dark red meranti (note the higher MC), but higher than Norway spruce.

Guadua levels out at an EMC of 12.6% in a climate of 65% RH and 20 °C. Moso levels out at an EMC of 10.3% in the same climate.

The 5%-quantile values of the average density (nodes and internodes together) are shown in the chart below (Figure 28).

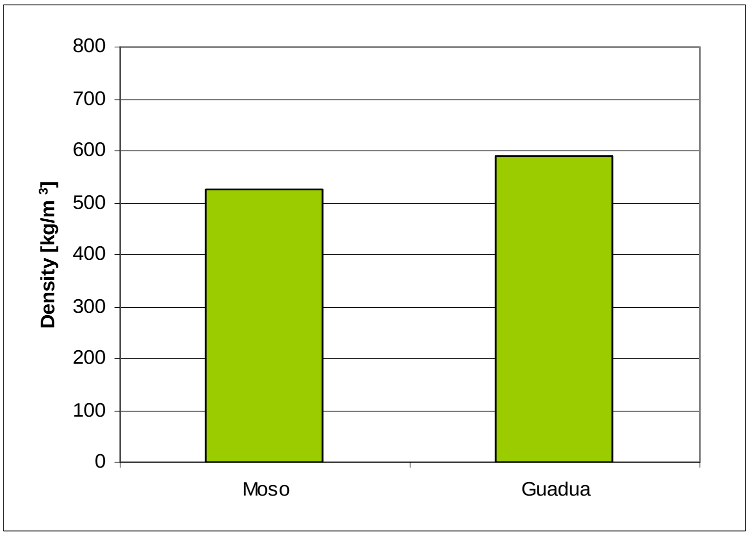


Figure 28 5%-quantile value of total density

These values are calculated in order to compare the properties of bamboo to strength classes for timber (together with the MOE and MOR - see also §3.3.9)

§3.3.6 Equilibrium moisture content

The relation between the relative humidity and moisture content (equilibrium moisture content) is shown in the Figures below (Figures 29 and 30). See Annex 3 for the data (simplified version). For a comparison, literature values for Norway spruce and dark red meranti are given (Figure 31).

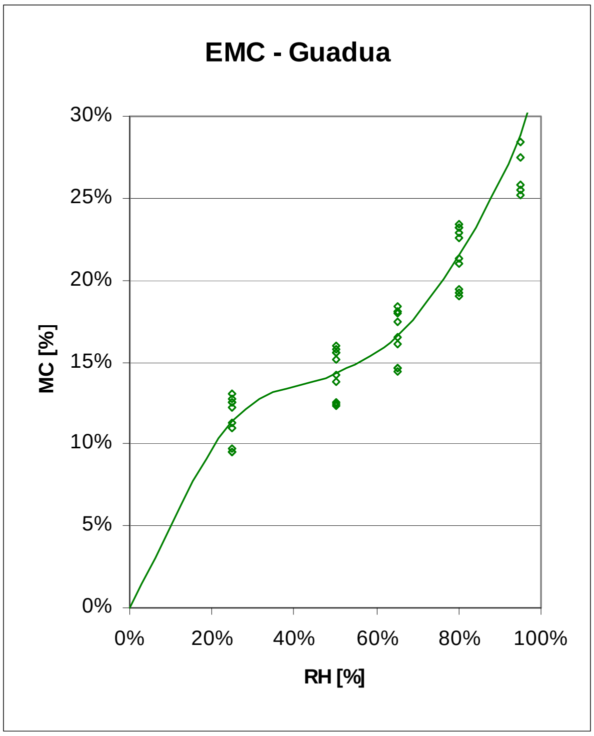


Figure 29 Equilibrium moisture content Guadua

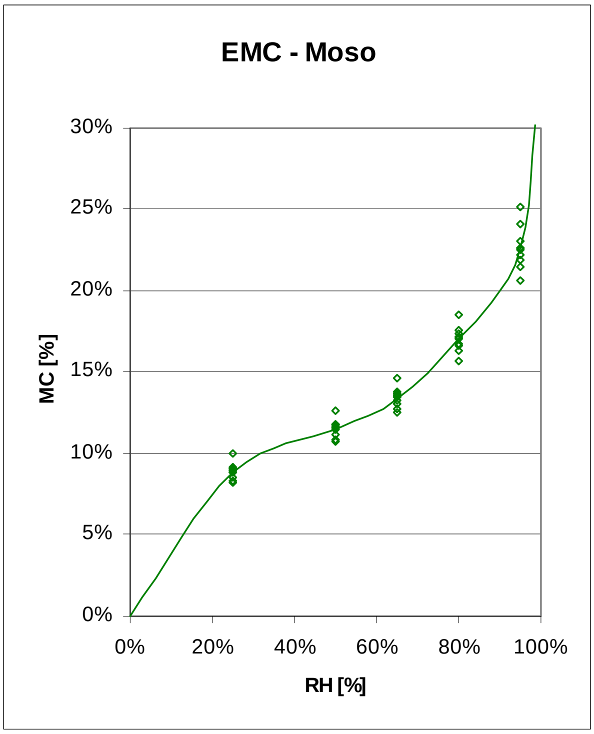


Figure 30 Equilibrium mositure content Moso

The fiber saturation point was not measured. In order to graphically display the absorption curve, the fiber saturation point for both bamboos was estimated at 35% MC. See Table 3 for the EMC at 95% RH and water-saturated, which gives an indication of the fiber saturation point.

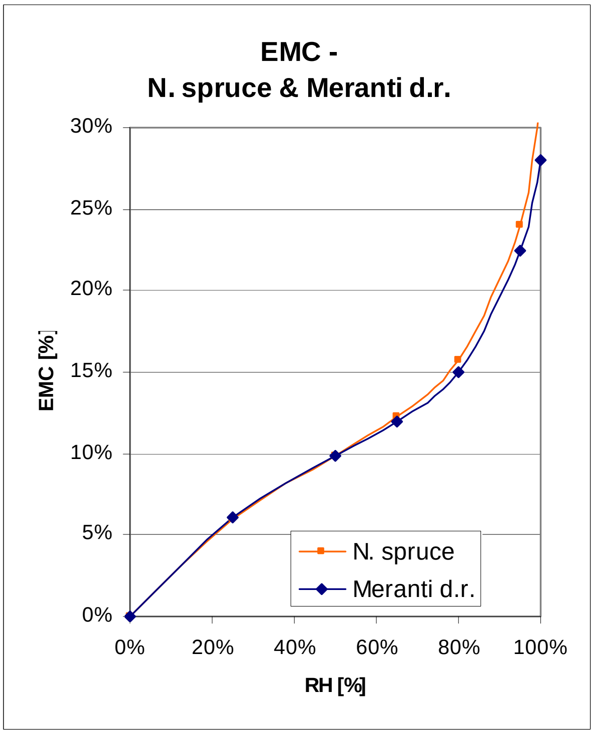


Figure 31 EMC Norway spruce & dark red meranti
Source: Laming et al. 1978

Table 3 MC for 95% and water-saturated

	95% RH	Water-saturated
Moso	22,6%	70,1%
Guadua	28,8%	82,9%

Guadua has a considerably higher EMC than Moso. Compared to both wood species, the EMC for Moso is of a similar order of magnitude. Guadua's EMC however, is much higher.

Note

The EMC's which are presented in this paragraph provide only a rough indication, since the small size of the specimens caused a deviation (see chapter 5 for a discussion of this issue). The EMC's for a climate of 65% RH and 20 °C in §3.3.5 are more accurate.

Conclusion

On the basis of the EMC in relation to the relative humidity, it is possible to determine the MC which bamboo needs to have with regard to the specific application (indoor/exterior, product type).These results are not very accurate however.

§3.3.7 Dimensional stability: swelling
The results of the swelling characteristics (tangential and radial) are shown in the Figures below for both bamboos (Figures 32 and 33). See Annex 3 for the data (simplified version).
The scattered data-points provide an indication on the variation between the specimens.

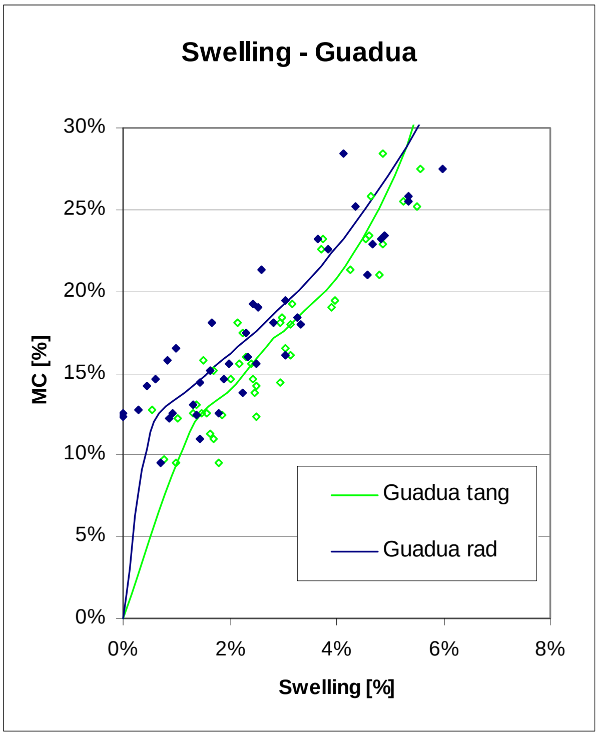


Figure 32 Swelling Guadua

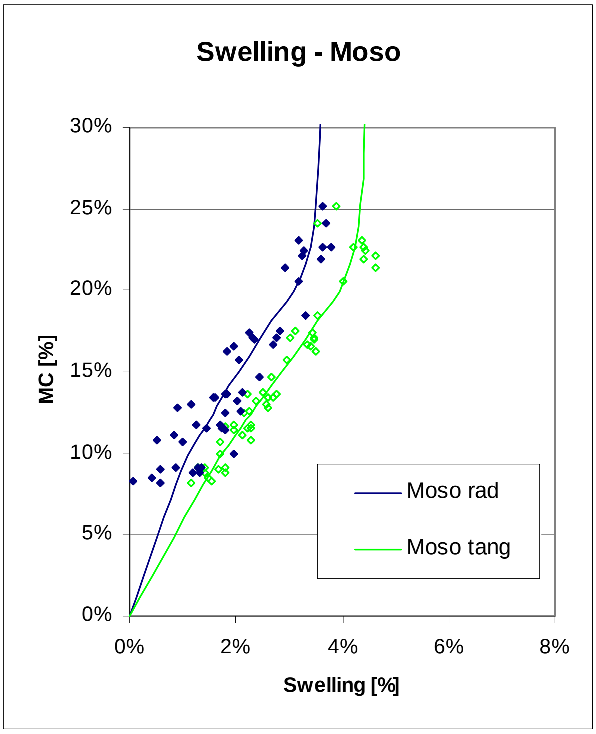


Figure 33 Swelling Moso

Note
The swelling was measured for internodes, not for nodes. Due to a different arrangement of the cells (especially the vascular bundles), the swelling might be different in the nodes.

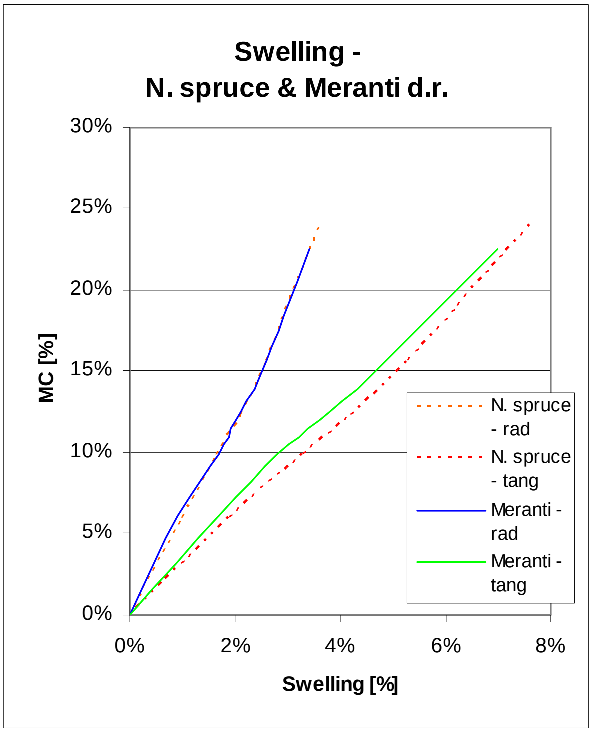


Figure 34 Swelling Norway spruce & dark red meranti
Source: Laming et al. 1978

Both bamboo species have a different swelling behavior with respect to the different sections (radial and tangential) through the culm wall. Just like wood, the swelling is higher in tangential direction than in radial direction. However, the swelling of both bamboos is almost equal in both tengential and radial direction (similar to some tropical timber species).

For a comparison, literature values of Norway spruce and dark red meranti were added (Figure 34).

Note
The swelling curves of both timber species were manually copied, which causes slight deviations in the curve's shape; they serve an indicative purpose.

The swelling which is presented in this paragraph provides only a rough indication, since the small size of the specimens caused a deviation (see chapter 5 for a discussion of this issue).

The average swelling between 50% and 95% RH, is shown in Table 4. Values for Norway spruce and dark red meranti were added for comparison (Laming et a., 1978).

Table 4 Average swelling between 50% and 95% RH

	Tangential	Stdev	Radial	Stdev
Moso	2,2%	0,3%	2,0%	0,3%
Guadua	3,2%	0,5%	4,0%	0,8%
Norway spruce	4,30%		1,95%	
Meranti, d.r.	4,20%		1,70%	

Note that the average swelling of Guadua in the radial direction larger is than in the tangential direction.

The longitudinal swelling is shown in Table 5. Because the longitudinal swelling is so low, it was not objectively measurable for the stretch between 25% and 80% RH.

Table 5 Longitudinal swelling & moisture content

Moso				Guadua		
RH	EMC	Swelling		RH	EMC	Swelling
25%	8,9%			25%	11,41%	
50%	11,50%			50%	14,34%	
65%	13,41%			65%	16,64%	
80%	17,00%	0,06%		80%	21,54%	
95%	22,64%	0,36%		95%	28,83%	0,10%
100%	70,11%	0,57%		100%	82,86%	0,28%

Conclusion

The BGS requires the tangential swelling to be between 50% and 95% RH not to be more than 4% (standard deviation not to be larger than 1%). Moso and Guauda both have a swelling in the tangential direction that is less than 4%. However, Guauda has an average swelling in the radial direction of 4%.

Even though the specimens had a higher swelling due to the high moisture absorption of the small specimens (see Chapter 5), both bamboo species were still able to meet the requirements in the BGS. Therefore, the actual swelling will turn out to be even lower.

§3.3.8 Hardness (Janka)
The test results of the Janka hardness test are shown in the graph below (Figure 35). See Annex 4 for the data (simplified version). The hardness was measured for both internode and nodes, and for the outside and inside of the culm wall. For a comparison, literature values for Norway spruce and dark red meranti are given.

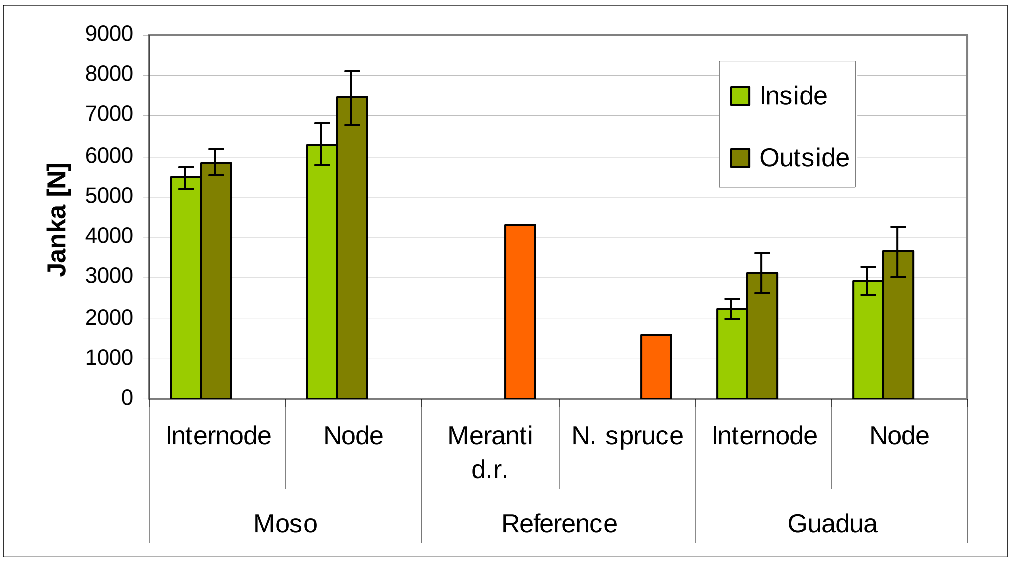


Figure 35 Janka hardness
Source of literature values for timber: Wiselius, 2005

For both species, the outside of the culm wall proved to be harder than the inside of the culm-wall. A similar difference is observed for node and internode sections. The hardness of Moso is about twice as high as the hardness of Guadua, and can be compared to the hardness of European Oak (6280 N). Whereas Moso is harder than dark read meranti as well Norway spruce, Guadua is less hard than hard than the meranti but harder than Norway spruce.

Conclusion
The hardness of Moso makes it a suitable material for applications which need to be resistant against indentions (door frames for example), Guauda seems not to be a first choice material for applications which face a high risk of indentions.

§3.3.9 Strength
The test results of the 4-point bending test are shown in the graphs below. The modules of elasticity (MOE) is shown in Figure 36, the modulus of rupture (MOR - bending strength) is shown in Figure 37. See Annex 5 for the data (simplified version).

The MOE and MOR were measured for both internode and nodes, and with the outside and inside of the culm wall alternately placed upwards (loaded in compression). For a comparison, literature values for Norway spruce and dark red meranti are given.

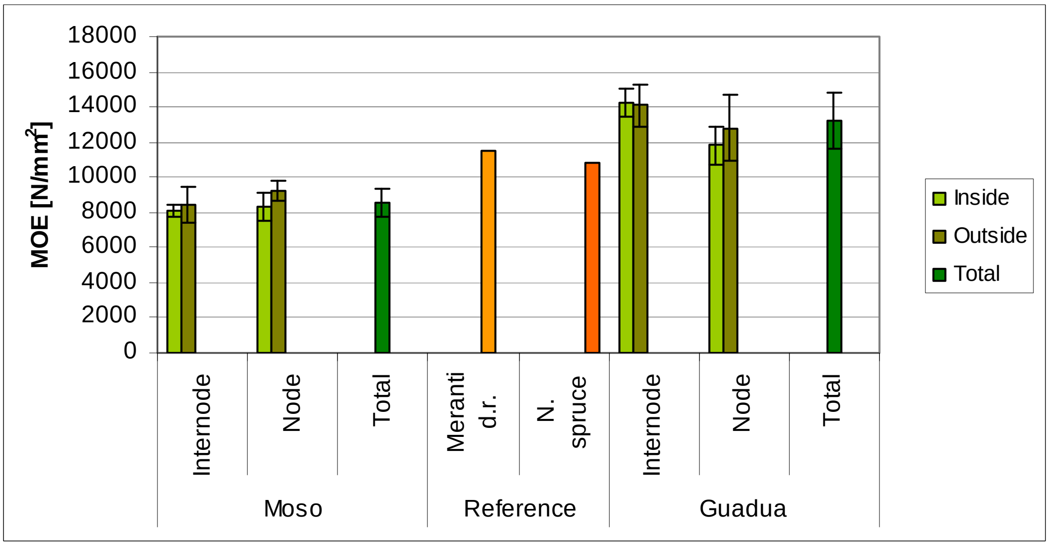


Figure 36 Modulus of elasticity (MOE) – average values
Source of literature values for timber: Wiselius, 2005

Guadua has the highest modules of elasticity (MOE), significantly higher than the MOE of Moso, and is even more stiff than dark red meranti as well as Norway spruce. The sections with a node are less stiff as node-less sections, the difference in positioning of the in- and outer culm wall seems of little influence on Guadua's MOE. Moso has a relatively low MOE compared to Guadua, and is less stiff than both dark red meranti and Norway spruce. Contrary to Guadua, sections with a node have a higher MOE than those without. There is a small difference in MOE depending on the positioning of the in- and outside of the culm wall; the MOE is a bit higher when Moso's outer culm wall faces upwards (loaded in compression).

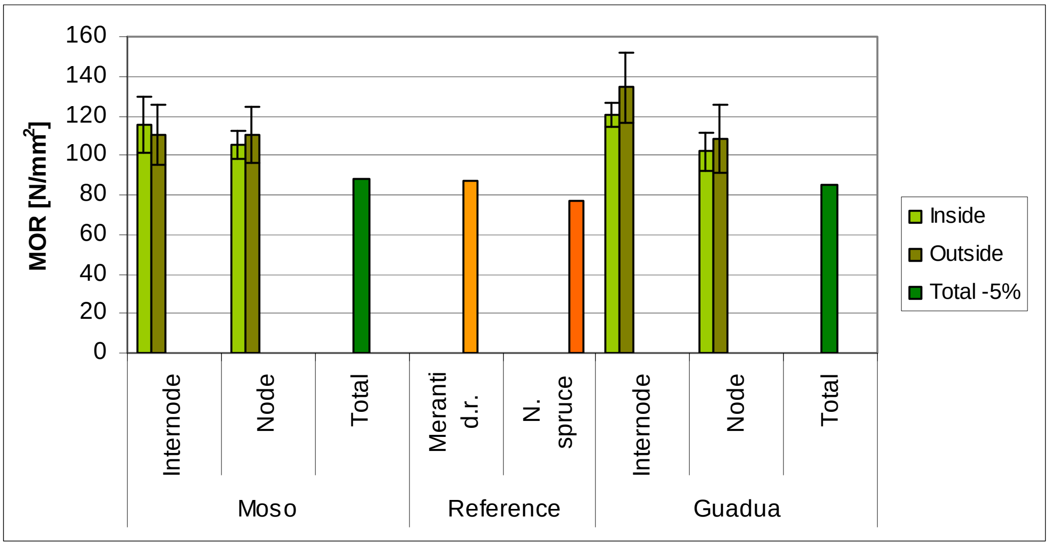


Figure 37 Modulus of rupture (MOR) - inside and outside are average values; total is a 5%-quantile value (total of the average of all specimens)
Source of literature values for timber: Wiselius, 2005

Both Moso and Guadua have a similar bending strength (MOR), which equals the MOR of dark red meranti and is higher than Norway spruce. Guadua has a higher bending strength when the outside of the culm-wall is placed up (loaded in compression), and sections with a node are able to stand less force as node-less sections. Moso has a fairly homogeneous bending strength, there is no large difference between a node and an internode, as well for the influence of positioning of the in- and outside of the culm-wall on the MOR.

When the strength properties of both species are compared to strength classes for timber (using the average MOE and the 5%-quantile values for the MOR and density), Moso would belong in strength-class C16, and Guadua in strength-class C35.

Conclusion

Both bamboos have a bending strength (MOR) that is superior to some timber species which are commonly used in the Dutch construction sector. The relation between Guadua's MOR and MOE makes the material suitable for load bearing applications; it is likely to stay stiff enough in order to not deform and cause a construction to loose its shape. Moso has a relative low MOE in relation to its MOR, which will cause a laminated beam which is used in a load bearing construction to bend faster than an often used timber such as Norway Spruce would do.

§3.3.10 Water uptake and loss
The results of the water uptake and loss test are shown in the graphs below (Figures 38 and 39). See Annex 6 for the data (simplified version).
The presence of a nodal-region is indicated with an N, and their situation in the specimen above water level is indicated with low, middle or high; clear means no nodal region was present.

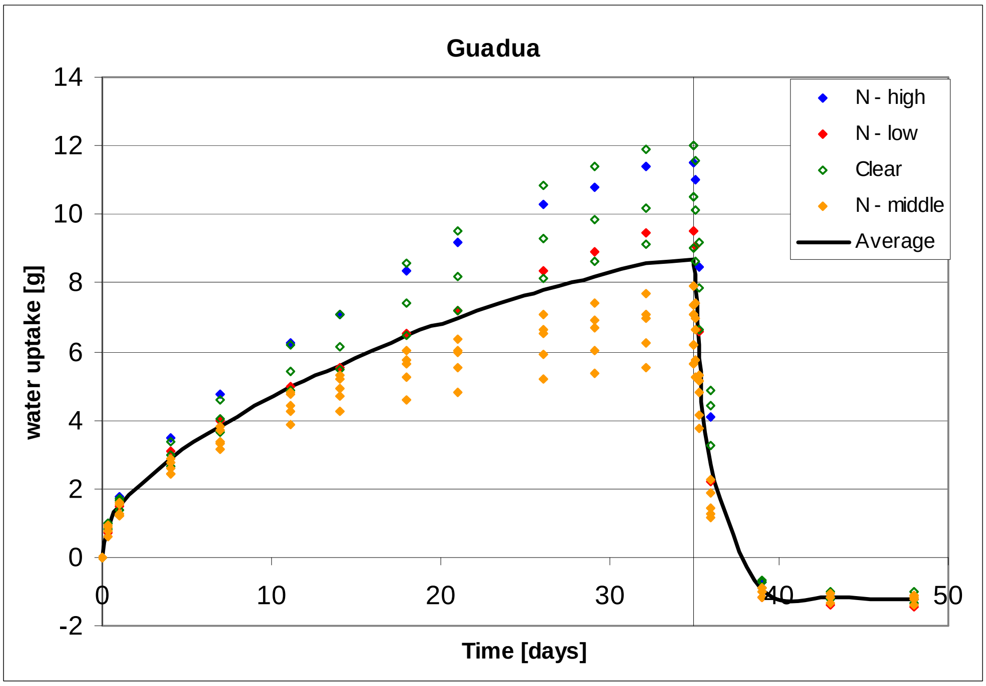


Figure 38 Water uptake and loss Guadua

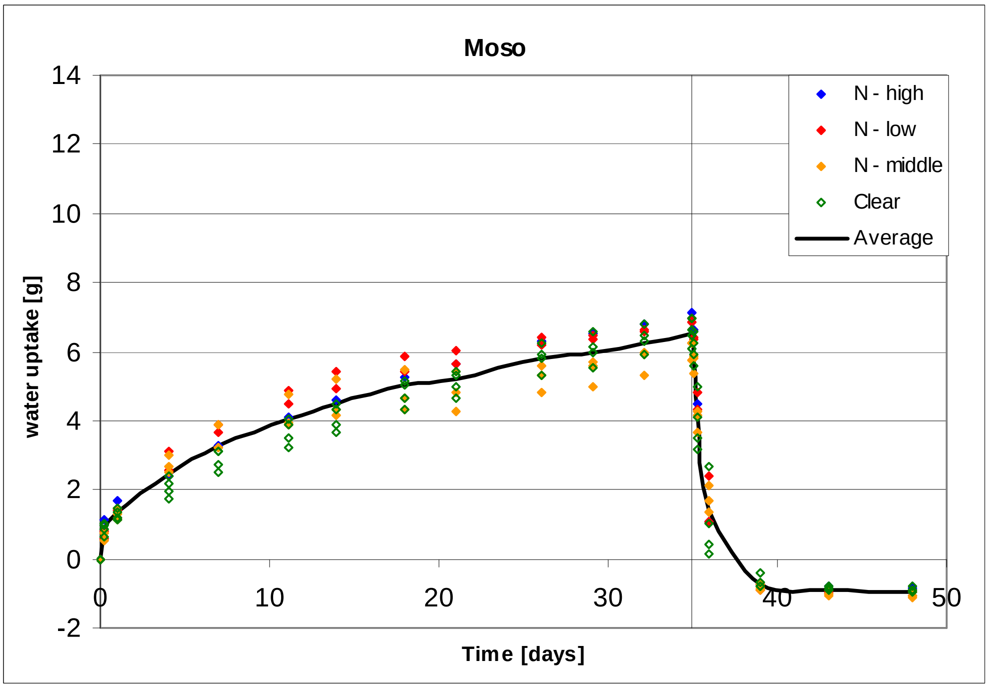


Figure 39 Water uptake and loss Moso

Note: Before the water uptake test commenced, the specimens were conditioned at 85% RH. The water loss was measured in a climate of 65% RH. Therefore the curve of the water loss is partly displayed negatively.

Both bamboo species demonstrated a similar water uptake and loss behavior as wood: fast in the first 24 hours after which the absorption rate decreased. Guadua absorbed more water than Moso over the full length of the test, and was still increasing after 5 weeks (the variation between the specimens is quite high, see chapter 5 for a discussion on this matter). The nodal regions which were located in the middle of the specimens had a significant influence on the water uptake for Guauda, the specimens with a nodal region at the lower and upper end did not have a significant influence on the water uptake. Moso's absorption rate flattened out earlier than Guauda's, and the variation between the specimens is low. For Moso, no significant influence of a nodal region on the water uptake was found. In Moso as well as Guauda, a nodal region did not have an influence on the water loss. The water loss of both bamboos went quickly, and reached a constant MC in less than a week.

The graphs below (Figures 40 and 41) provide a reference of the water uptake of bamboo compared to wood (Norway spruce and dark red meranti). The water uptake of bamboo was measured for small specimens with a cross cut surface of ±2 cm^2, whereas the water uptake of wood is measured for large specimens with a cross cut surface of ±4 cm^2. In order to compare bamboo to timber, the water uptake in grams was recalculated into mg/mm^2. This was not done for the water loss, because it would not serve an accurate comparison.

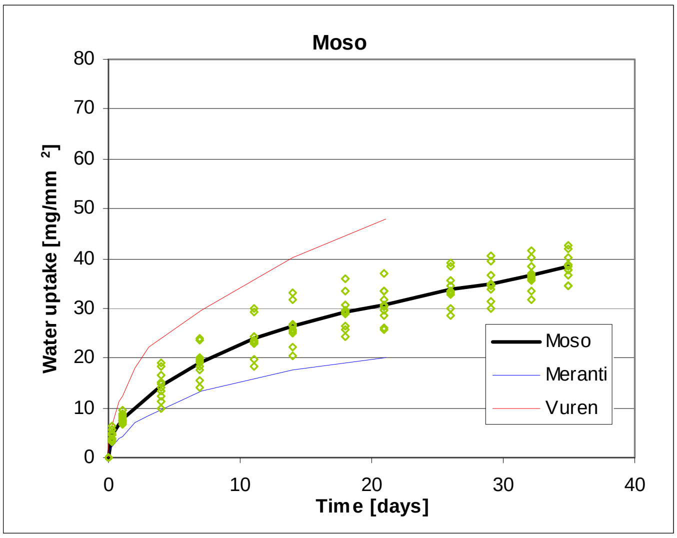


Figure 41 Water uptake Guadua compared to timber. Source of values for timber: 'Water uptake behavior' (Overeem, 2010)

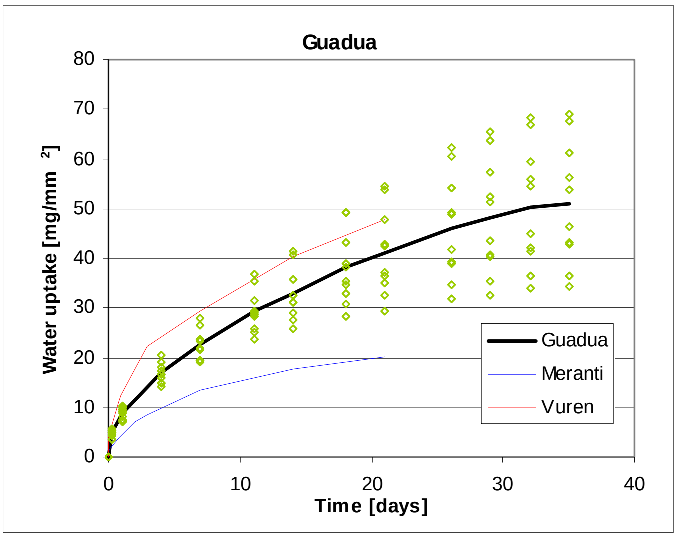


Figure 40 Water uptake Guadua compared to timber. Source of values for timber: 'Water uptake behavior' (Overeem, 2010)

Both bamboos have an average water uptake which is higher than dark red meranti, but lower than Norway spruce.

The average water uptake in mg/mm^2 for bamboo and wood after 24 hours and 21 days is shown in Table 6.

Table 6 Water uptake [mg/mm^2]

	1 day	21 days
Guadua	8,7	41,2
Moso	7,8	30,6
N. Spruce	12,2	47,9
Meranti d.r.	4,1	20,2

Conclusion

Guadua has a higher water uptake as Moso, which is similar to the water uptake of Norway Spruce; it also has a large variation between the individual specimens (see chapter 5 for a discussion of this matter). This is not a favorable characteristic with regard to its low natural durability, and could require additional protective measures. Moso´s water uptake increases less fast.Both bamboos do not reach their maximum water uptake within 14 days, which is required by the BGS; Norway spruce and dark red meranti however, has also not reached its maximum water uptake within 14 days, but is allowed for (KOMO) exterior joinery (SKH publication 99-05). The water loss of both bamboo species is very fast, and a steady moisture content is reached within 1 week (required by BGS).

§3.3.11 Glubility

The results of the glubility are shown in the charts below (Figures 42, 43 and 44). See Annex 7 for the data (simplified version). The tensile shear strength of the bond between the glue and the bamboo surface are shown in the charts on the left. The percentages of fiber fracture are shown in the charts on the right.

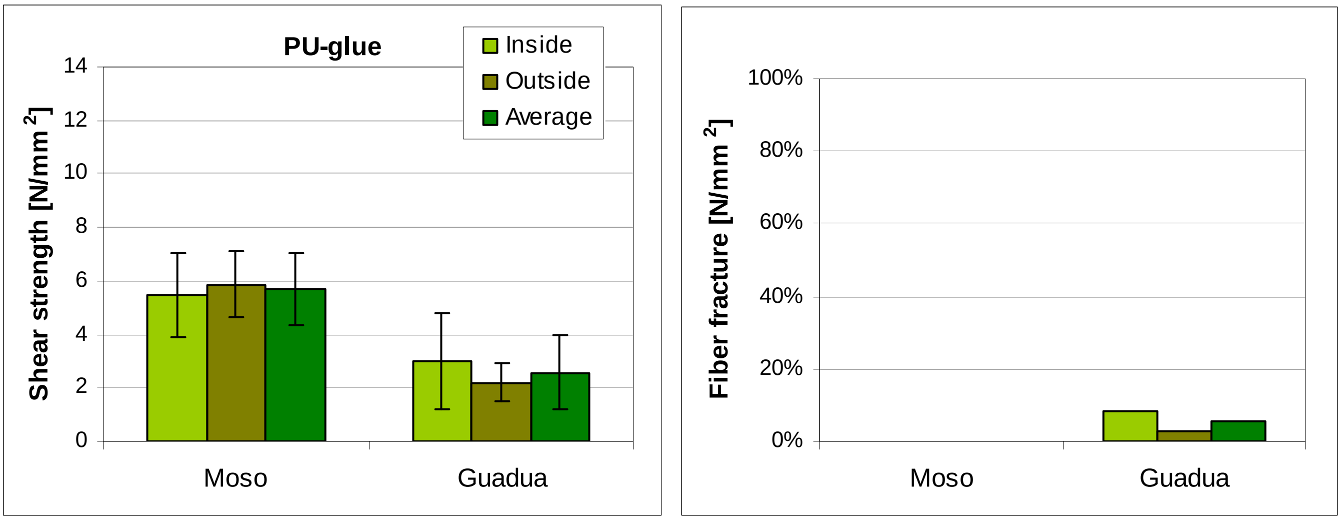


Figure 42 PU-glue, tensile shear strength and fiber fracture

The PU-glue bond did not perform as expected. It is known to have tensile shear strength of at least 10 N/mm^2 on wood (Hunnik, 2010). Instead, the glue bond fully fractured at relatively low values, without significant fiber fracture. Interestingly, the tensile shear strength is higher for Moso than for Guadua, indicating the glue was able to form a better bond with the surface of Moso.

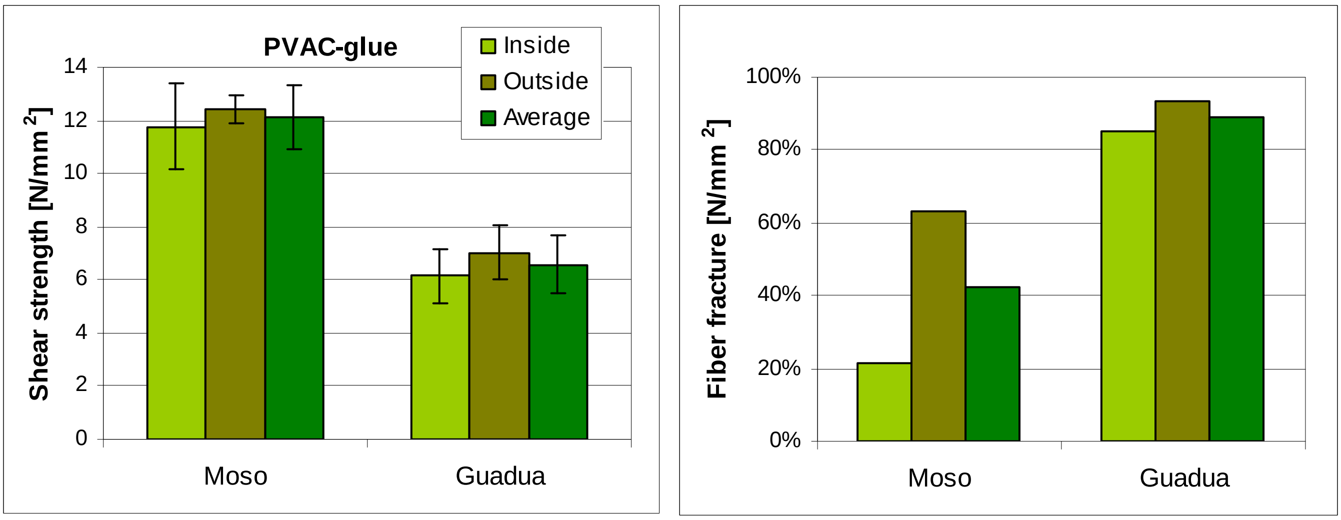


Figure 43 PVAC glue, tensile shear strength and fiber fracture

The PVAC-glue bond was able to withstand over 12 N/mm^2 for Moso, with only 38% fiber fracture. Yet, the PVAC-glue bond with Guadua only reached a little over 6 N/mm^2, with 85% fiber fracture.

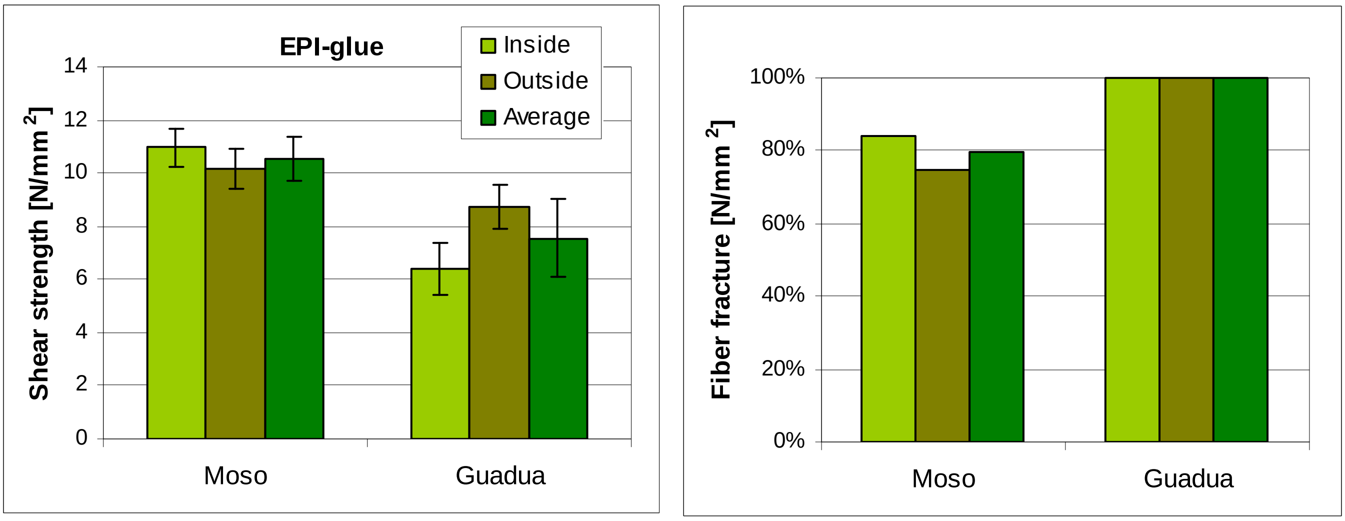


Figure 44 EPI-glue, tensile shear strength and fiber fracture

The EPI-glue bond withstood over 10 N/mm^2 for Moso, with 78% fiber fracture. The same glue bond with Guadua only reached a little over 7 N/mm^2, with 100% fiber fracture.

Conclusion

The used PU-glue was not suitable for gluing either bamboo, what most likely is caused by its chemical composition. Moso can be glued well with a PVAC and EPI-glue, considering they both were able to withstand a tensile shear strength of more than 10 N/mm^2 (required performance for a glue to get certified). Guadua on the other hand, can be glued well with both glues, indicated by the high percentages fiber fracture at the moment of breaking. However, the maximum tensile shear strength between the glue bond and the bamboo surface, was less than for Moso. This is most likely caused by a different micro-structural organization of cell types, for it appeared to be mostly the soft parenchyma tissue which fractured (both for the inside and out side of the culm wall). Nonetheless, this is not a bottleneck for producing laminated bamboo for use in a load bearing application because the glue bond has a more than sufficient strength (Jorissen, 2010).

§3.3.12 Paintability
Two coating systems were tested for their dry and wet adhesion, an alkyd-emulsion based paint and an acrylate-dispersion based paint. Adhesion on nodes was tested twice for each different paint/surface combinations, and three times for internodes. The adhesion is classified in 6 classes, class 0 = 100% adhesion, class 5 = less than 35% adhesion). Only the results for the wet-adhesion are presented below (Table 7), because both coating systems performed very well (class 0) in dry conditions. The alkyd-emulsion (covering primary coating) performed equally well under wet conditions. The acrylate-dispersion (transparent coating system) performed less well under wet conditions, varying from class 0 to class 3.

Table 7 Wet adhesion classes

			Alkyd-emulsion	Acrylate-dispersion
Moso	Node	Inside	0-0	0-1
		Outside	0-0	0-2
	Internode	Inside	0-0-0	0-1-2
		Outside	0-0-0	0-1-2
Guadua	Node	Inside	0-0	0-0
		Outside	0-0	0-2
	Internode	Inside	0-0-0	1-1-2
		Outside	0-0-0	0-0-0

It seemed there is no difference in adhesion for the in- and outside of the culm-wall, as well as for nodes and internodes (in both dry and wet conditions) for both bamboo species.

Conclusion
Both bamboo species have a good bond with the alkyd-emulsion (covering primary coating) in dry and wet conditions. The acrylate-dispersion (transparent coating) performed well in dry conditions, but not well in wet conditions. This could mean that an acrylate-dispersion paint is less suitable for painting bamboo in outdoor applications.

§3.3.13 Machinibility
According to the BGS, certain test concerning the machinablity of a timber species have to be performed, which requires the production of a window frame by a joinery factory. This in order to test if the material can be normally processed with the standard machinery. The machinibility was not tested according to these requirements, however indicative information on the machinibility was obtained while transforming the bamboo culms into strips in SHR’s workshop. The experience with the machinibility of the two bamboos is described below.

Moso
Both longitudinal and transverse cutting went normally. Planing in the thickness planning machine resulted in a very smooth surface; sanding achieved a smooth surface too.
Screwing without pre-drilling caused splitting, what in addition to the material properties, is caused by the limited width of the strips.

Guadua
Both longitudinal and transverse cutting went normally. Planing in the thickness planing machine resulted in a smooth surface for internodes, but a moderately rough surface around nodes. This is caused by the arrangement and thickness of the vascular bundles, which cease to run straight in a node, resulting in a splintery surface when cut. Screwing without drilling caused splitting, but less than for Moso.

Conclusion
Although the machiniblity could not be broadly tested, no major difficulties are expected when machining bamboo with the same machines that are used in the timber industry.

§3.4 Results - Treatability

Bamboo in exterior applications has to withstand the influences of weathering, which requires a suitable durability. At the start of this project it was known that bamboo's natural durability is rather low. To research the possibilities for improving the durability, and to obtain knowledge on the materials behavior, bamboo was tested for the possibility of impregnation (treating). This was done by means of pressure treatment (the 'full cell process') with a copper solution in water.

In order to research the pathways through which the solution would be impregnated into the material, the ends (cross cut) of the specimens were sealed with an epoxy resin in various ways; the first two tests were performed with one closed end and one open, with the difference that one series had a node just behind the open end. The third test was performed on specimens with both ends sealed.
Before the treatment, the specimens were conditioned in a climate of 65% RH and 20 °C. This means the material was relatively dry, where in practice bamboo is often impregnated when the culm is still fresh (Bouchery process; sap replacement). Literature mentions the increased difficulty of impregnation once bamboo is dry, due to the blockage of certain pathways (Liese 2003).
The amount of copper solution which was able to ingress into the material is shown in Figure 45, see Annex 8 for the data (simplified version).

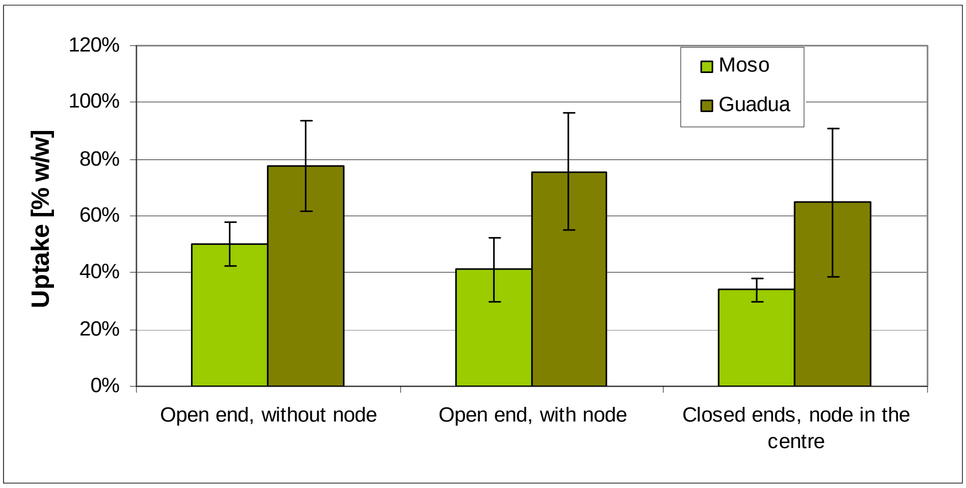


Figure 45 Uptake of copper solution, as a percentage of the dry weight

On the whole, the amount of copper solution which was able to ingress into the material is significantly less for Moso than for Guadua. A statistical probability test (Students T-test) indicated that there is no significant difference in treatability between the specimens with an open end, and with a node just behind the open end. In other words, a node seems not to effect treatability significantly. Specimens with an open end were impregnated with a reasonable amount of solution, this was not the case for specimens with both ends sealed. For Moso, the amount of solution which was able to ingress into the material, is significantly less in the case of two ends sealed compared to only one end sealed. This difference is also noticeable for Guadua, however it is not significant.

Compared to Norway spruce and Scots pine, the amount of solution which is able to ingress into the material seems to be at least equal, see Table 8.

Table 8 Water retention of spruce and pine [kg water/m^3 wood]

	SHR Project nr	AVG	Min	Max
Scots pine	6482	107	14.2	222
Norway spruce	7115	79	21	445
Norway spruce	6373	98	57	227
Scots pine	6483	122	24	213
Norway spruce	6374	168	106	272
	AVG	**115**		

The average water retention is 116.75 kg/m^3 wood. Calculating with an average density of 500 kg/m^3 for both spruce and pine, the percentage water retention is 23.35%.

Source: Zee (2010) - out of SHR internal record on impregnation tests. Size of timber specimens 45 x 145 x 1000 mm. Scots pine heart and sapwood mixed; Norway spruce mostly heart wood.

After impregnation, sections were cut to indentify the different pathways through which the solution was impregnated into the material. These sections were colored with a copper-reagent. Pictures of the most characteristic behavior were taken, which indicated the following (see Figure 46 and 47)

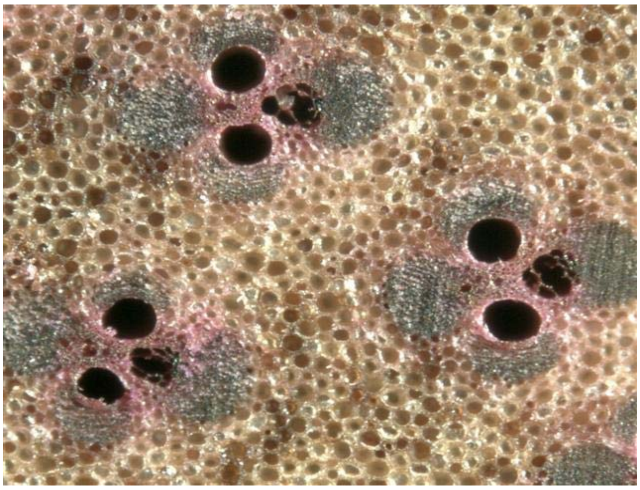


Figure 46 Moso, transvere surface, node behind the open end (violet indacates copper) 40x

Figure 47 Moso, transverse surface, both ends sealed (violet indicates copper) 40x

Explanation Figure 46: One end sealed, one open (with and without node behind the open end)
The copper-solution chooses the vascular bundles as primary pathway into the material in case one end was not sealed for both bamboo species. The violet color (indicating copper) is concentrated around and inside the vascular bundles, the surrounding parenchyma cells have not been impregnated.

Explanation Figure 47: Both cross-section ends sealed
For Moso, the copper-solution was not impregnated into the vascular bundles (note the whitish color) when the specimens were treated with both ends sealed (see Figure 47). Instead of choosing the vascular bundles as primary pathway for impregnation, the copper-solution was impregnated into the parenchyma cells. For Guadua, the copper-solution was impregnated into both vascular bundles and parenchyma cells (no picture).

Conclusion
The sub-question was:
Is it possible to treat bamboo by means of impregnation?

Both Moso and Guadua are treatable with a copper-solution by impregnating it, even when the material is dry. Guadua retained more solution than Moso, making it a more favourable material for impregnation. Compared to the average treatability (water retention) of Norway spruce (which is not a favorable wood species for impregnation) and Scots pine, both bamboo species seem at least equally well treatable. However, the copper-solution chooses the vascular bundles as primary pathway if the cross-section sides are open (what will be the case in practice), hereby leaving a part of the parenchyma tissue untreated. This causes the copper (or other protective agent) not to be dispersed evenly throughout the material, leaving certain parts (parenchyma cells) susceptible to attack of degrading organisms. Therefore, treating bamboo by means of impregnation might not be the best choice for the highest protection against degrading organisms.

§3.5 Conclusion and recommendations
The conclusions and recommendations for the first part of this project follow below. Two bamboo species, Moso and Guadua, were tested according to the requirements in the BGS. This standard is most commonly used for exterior joinery applications in The Netherlands (KOMO).
The following conclusions are shorter versions of the sub-conclusions for every test that was performed. They are described into greater depth in the paragraphs on the results (§3.3 & §3.4).

Conclusions
The density of both bamboos is of a similar order of magnitude as timber species commonly used for exterior joinery applications.

The EMC of both bamboo species is of a similar order as wood. In a climate of 65% RH and 20 °C, Moso leveled out at an EMC of 10.3%, Guadua at 12.6%.

The tangential swelling between 50% and 95% RH for both bamboo species is less than 4%. For both bamboos, the tangential and radial swelling are of a similar order. The longitudinal swelling is, just like for timber, very low

The hardness of Moso (comparable to European Oak) makes it a suitable material for applications which need to be resistant against indentions (door frames for example). Guauda seems not to be a first choice material for these type of applications.

Both bamboos have a high bending strength, superior to many timbers. Moso has a low stiffness, which does not make it a very suitable material for load bearing applications (strength class C16). Guauda is stiffer, even more stiff than dark red meranti and Norway spruce, which makes it a suitable material for load bearing applications (strength class C35)

The water uptake and loss of both bamboos is of a similar order as wood; both bamboos have a higher uptake than dark red meranti, but lower than Norway spruce. Guadua has the highest water uptake, and also a large variation between the individual samples. The amount of water uptake of both bamboos is not as low to allow for a wider range of applications than what is possible on the basis of their (low) natural durability, which necessitates a well protective coating system. Both bamboos lose water quite swiftly, similar to most timbers species.

Although the gluability has not been tested according to the BGS (T-joints and accelerated weathering), it can be concluded that the bamboos can be glued very well with commonly used glues, namely and EPI-glue and an PVAC-glue. However, the PU-glue was not able to form a strong bond with the material. Therefore, bamboo is not suitable for all glues.

Both bamboos can be coated very well with an alkyd-emulsion. The wet-adhesion of an acrylate-dispersion did not perform as is required. This could mean that the bamboos are not suitable for all coatings (an acrylate-dispersion based coating for example).

Both bamboos seem to be suitable for machining with tools that are normally used for wood. Pre-drilling is advised to avoid splitting.

In addition to the requirements in the BGS, the bamboos have also been tested for their treatability. This seemed to be at least equally well possible as for pine and spruce, even in its dry-state which worsens the treatability by blocking certain pathways. However, the solution did not ingress totally even into the material, leaving some parts of it (mostly parenchyma tissue) susceptible to degrading organisms. Because vascular bundles are responsible for the strength of the material, this seems no major bottleneck. However, parenchyma cells which are untreated might be affected by degrading organisms sooner, and speed up the process of decay. Therefore, treating bamboo by means of impregnation might not be the best choice for the highest protection against degrading organisms.

The first research question was:
'Is bamboo suitable for exterior joinery applications on the basis of its material characteristics, and are there differences between the common species used in industrial bamboo manufacturing'

On the basis of the test results above, this question can be answered positively, bamboo seems suitable for exterior joinery applications on the basis of its material characteristics. However, because certain important aspects like the durability were not tested, it is not possible to answer this question with a great deal of certainty. See chapter 5 for a discussion on these aspects.

There are some differences between the species which are commonly used in industrial manufacturing. The main differences are:

- Guadua is stiffer than Moso, making it a more suitable species for load bearing applications
- Because of the higher uptake of solution under pressure treatment, Guadua is more suitable for impregnation than Moso
- Guauda has in most tests a larger variation between the individual samples than Moso, indicating the material has less homogenous properties than Moso
- Guadua has a much lower hardness than Moso
- Guauda has a larger water uptake than Moso

Although there are differences, both bamboos still meet the requirements in the BGS. Considering the often more favorable material properties of Moso, this bamboo species is the first choice for exterior joinery applications.

Recommendations
Certain recommendations with regard to the executed tests follow below. For general recommendations, see chapter 6.
- To exclude the influences of the treatments (fumigation and sap-replacement with a boron solution) of the culms prior to testing, it is advisable to test culms in a totally untreated state to exclude a possible influence on the material properties.
- In order to characterize the material properties of the tested bamboo species better, it is advisable to test bamboo from different batches and origins, and to use more specimens in order to obtain more statistically representative results.
- Certain requirements in the BGS could not be tested, in order to complete the overview on material properties it is advised to perform the following tests. Since the durability is such an important factor with regard to exterior joinery, the natural durability of bamboo (single, planed strips) will need to be tested to assign an official durability class. More time will also allow certain requirements in the BGS to be tested, which are: a calibration curve for the moisture content, several tests concerning the adhesion (angle joints, finger joints and resistance against delamination), coating properties (especially concerning tranparant coatings), processing properties (like cutting slots and drilling dowel holes) and fire retardation.
- Since bamboo in practice will be laminated, it is advisable to acquire more know-how on its properties as a laminated material. Because several material properties are expected to remain similar to the properties of a single strip (paintability, hardness, strength, water uptake), especially the resistance against delamination is of interest.
- To obtain more accurate test results with regard to the dimensional stability, it seems advisable to test split pats of the culms which are not planed. This in order to obtain specimens with larger dimensions, which most likely will demonstrate the actual swelling behavior. Note that the outer and inner cortex will be present for unplaned strips, which could cause a different swelling than a planed strip.
- To obtain more accurate test results with regard to the EMC, it seems advisable to test planned specimens with larger dimensions, which most likely will demonstrate the actual moisture content better (as in § 3.3.5).
- Because part of the parenchyma tissue was not impregnated after treatment, further research into the pathways through which the solution ingresses into the material (air dry) is advisable. Also, further research into the influence of untreated parenchyma tissue on the durability of the material as a whole is advisable too. This in order see if impregnation of dry bamboo strips is and adequate treatment.

PART 2

Market perspectives

Modern bamboo housing in China. The cladding is made from woven bamboo mats, which are pressed into sheets. Source: Lou Yiping, INBAR (China)

The second part of this report (chapter 4) is on the market perspectives of bamboo in exterior joinery applications in The Netherlands.

Reading guide

In addition to the description of the general methods of research in chapter 1, the specific method concerning the second part of the project is described in §4.1. The bamboo products that can be found in The Netherlands are listed in §4.2, and a quick overview of the global bamboo trade is presented in §4.3. Paragraphs 4.4 and 4.5 are on the properties of the two main materials made from bamboo: laminated bamboo and bamboo composite. A characterization of the Dutch bamboo-sector and a description of the main companies and experts is given in §4.6. The applications in exterior joinery which are possible on the basis of the material characteristics are clarified in §4.7. The strengths and weaknesses and opportunities and threats for laminated bamboo, as well as bamboo composite were captured in the SWOT-analysis in §4.8. Finally, the answer to the second research question is given in §4.9.

Chapter 4 MARKET PERSPECTIVES

§4.1 Method
The methods of research for the second part of this project are partly described in the general method of research in chapter 1, and will be explained in more detail below.

The primary method for the market research was a series of interviews. A standardized, semi-open interview was used. This because open questions leave room for a wider range of individual opinions and obtaining additional information, which allowed a qualitative image of the current state of affairs to be drawn up. It was chosen to (officially) interview five key-parties in the Dutch bamboo sector: three trading companies, one joinery factory and one expert. There are only a limited number of companies and experts involved in the Dutch bamboo sector. Therefore it was possible to obtain representative information. See Annex 9 for the questions which were posed. A different set of questions was used for the joinery factory, this to obtain specific information on their relationship with bamboo. See Annex 10 for a description of the respondents most important answers.

In order to identify the perspectives of bamboo for exterior joinery, the *opportunities* and *threats*, as the *strengths* and *weaknesses*, were captured in a classical SWOT-analysis.
The key information that was obtained worked out during the first part of this project, together with the results from the interviews and additional surveys (literature/internet), were used as input.

§4.2 Bamboo applications in The Netherlands

The Dutch bamboo-sector is typified by its own parties as a small sector, but one which has a large potential for growth (see Annex 10 for a summary of the interviews).
Of the many timber-like products which can be produced from bamboo, the following are to be found in The Netherlands. The two types of bamboo material which are used for the mentioned applications are either laminated bamboo (the majority), or bamboo composite; see §4.4 and §4.5 for more information on these materials.

- Engineered flooring for indoor (mainly laminated, also composite)
- Decking for outdoor (composite)
- Sheet-material (laminated)
- Veneer (laminated)
- Furniture (laminated, parts of the whole culm)
- Utensils (laminated, single strips, part of the whole culm)
- Culms commonly used in agriculture for supporting plants, and larger culms for small garden chalets)

Other products of mainly bamboo composite (window frames, heavy duty decking, garden furniture) are available in The Netherlands, but are not widely known.

Figure 48 Engeneered bamboo flooring

Although especially bamboo utensils and culms have been used in The Netherland for quite some time, the material attracted more interest with the introduction of engineered flooring (Figure 48), which is by far the most commonly used engineered bamboo product. Nowadays, bamboo products often have a trendy and green image.

Engineered* bamboo products in The Netherlands are almost exclusively used for interior purposes at this moment, there are some changes to be noticed however (see §4.6.1).

*All bamboo products which are industrially produced from strips; not of parts from the whole culm.

§4.3 Global trade

The EU and USA represent the largest western markets for bamboo, accounting for 80% of the global bamboo trade. The Netherlands and Germany pioneered industrial bamboo products in the west, of which flooring is the most important. The consumption of bamboo flooring in the EU was estimated at 0,67 million m^2 in 2003, and growing rapidly (possibly already 0,9 million m^2 in 2005). Of this volume, 95% originates from China, while the rest comes from Australia, Vietnam and the Philippines. Compared to the consumption of timber, the global consumption of bamboo pales; the estimated 0,67 million m^2 flooring in 2003 accounted only for 0,7% of the wooden flooring market in the EU. The potential market for bamboo however, is very large, since the current market for wood products can be considered as a vey suitable analogues substitute market. Due to the high demand for wood (which is expected to double itself by the middle of this century), and increasing interest in sustainably produced timber, the potential market for industrial bamboo products is expected to grow (Lugt & Lobovikov, 2008).

The amount of bamboo exported* by each producing continent is shown for the year 2007 in Table 9.

Table 9 Bamboo exports per continent in 2007

Continent	**Quantity** (metric ton)
Asia	695.244
North & Central America	73.478
South America	69.135
Africa	6.825
Oceania	4.647

Source: INBAR 2010, based on COMTRADE data of UN)

*Only the large product groups were taken into account when retrieving the data, this because the table only serves an indicative function. The selected product groups were:

-Bamboos for plaiting
-Basketwork etc., of bamboo
-Furniture of bamboo & rattan
-Mats, & screens, of bamboo
-Plaits, Plaited Prods, of bamboo
-Seats of cane, bamboo
-Plywood, Bamboo
-Roundwood, Charcoal, Bamboo

It remains clear that Asia is the major bamboo exporter in the world, of which the majority is produced in China.

§4.4 Laminated bamboo

Laminated bamboo is roughly produced in two ways, the most common type is composed of small, edged strips which are glued together (see Figure 49 - A). The other type is composed of flattened parts of the culm that are glued together (see Figure 49 - B). See also Figures 50 and 51.

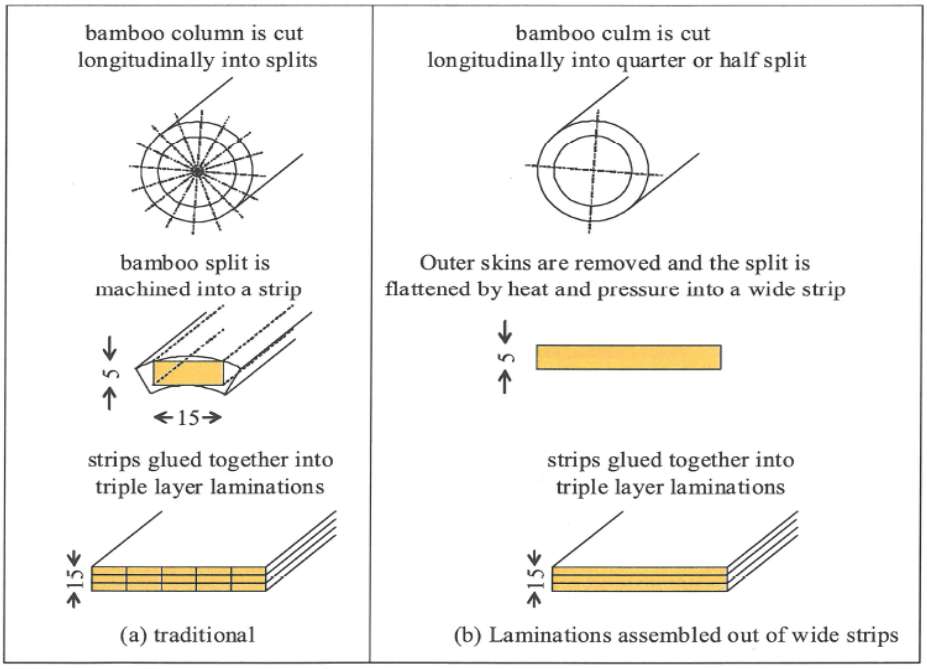


Figure 49 Two main types of laminated bamboo (Wan Tarmeze 2005, in Jorissen & Voermans 2009)

Laminated bamboo is produced from strips which are either plain-pressed (tangential surface faces upwards- see Figure 51), or side-pressed (radial surface faces upwards).

The mechanical properties of laminated bamboo that constists out of small strips, are described below for the Moso-species (Jorissen & Voermans 2009).

Bending strength (MOR): 72 N/mm^2
Modules of elasticity (MOE): 8357 N/mm^2
(Density 613 kg/m^3, moisture content 8,32%)

For an indication of other material properties of laminated bamboo, see the results in the first part of this report. Although these results were obtained by using single (non-laminated) bamboo strips, they provide a good indication of the properties once they are glued together.

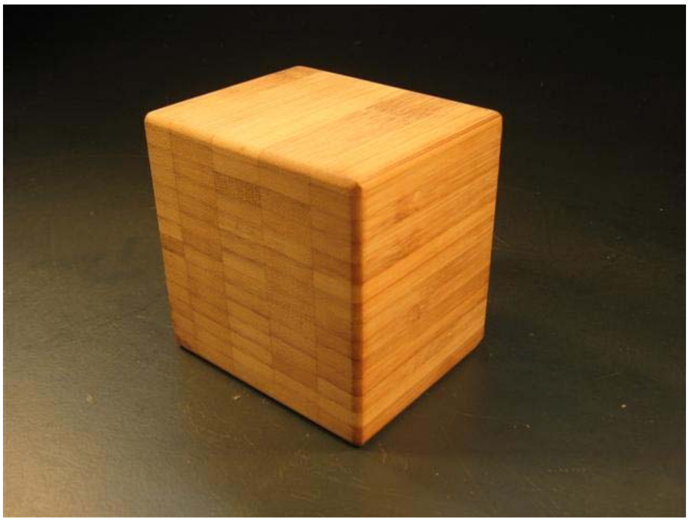


Figure 50 Part of a bamboo beam of laminated strips (produced by GreenBoo)

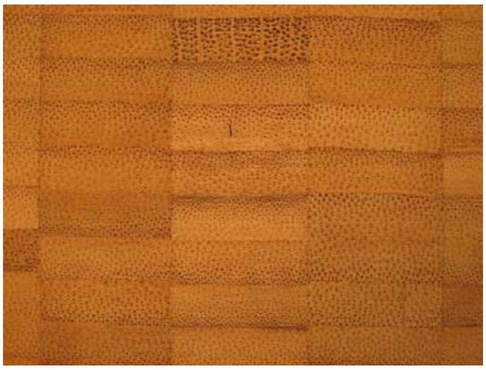


Figure 51 Transversal surface of laminated strips of ±2 cm wide, plain-pressed (product from GreenBoo)

§4.5 Bamboo composite
In addition to laminated bamboo to obtain material with larger dimensions, it is also possible to crush the strips and to press them together with glue. This results in a composite, which in essence is a new, man-made material. The common name for 'bamboo composite' which is used in this report, is 'strand woven bamboo'. Because the term 'strand woven bamboo' indicates a different material and causes confusion (Younge, Zaal, Janssen, Vos 2010), it is decided to use bamboo composite instead. Be aware that there are also other types of bamboo composites, like MDF or fiber board.

Bamboo composite originated from China, where it was developed into a stable material with interesting material properties. This has not always been so, its development knew difficulties like swelling and delaminating caused by water.The material characteristics of bamboo composites can vary, because they depend on the type of production process and its specific parameters. For example, a different pressure causes a different density. See Annex 11 for pictures of the bamboo composites which are available on the Dutch market today, note the differences. To provide a better understanding of this relatively new material, the production process of bamboo composite is described, see also Figures 52 and 53.

Start as a whole culm, freshly cut (still green)
1) Splitting of the culm, then edging the strips on four sides into straight strips
2) The strips are turned into loosely attached strands, the finer these strands the higher the density in the end
3) Strands are boiled in water against fungi/bacteria (± 4 hours)
4) Strands are kiln dried (± 6 hours)
5) Strands receive heat treatment (steam and pressure) in an autoclave, which causes destruction of the sugars and darkening of the color due to the 'caramelization process'
6) Strands are submerged into glue (phenol-resin mixture), they maximally contain about 20% glue
7) Strands are dried in a ±50 m long conveyer kiln
8) Strands are placed inside a mould, (up to 1 meter high) and cold-pressed at 1800 tons until a beam of 14 cm high (the high pressure inflicts a high temperature which causes the outside of the beams to char)
9) Further sawing, profiling and finishing into the desired final product
Source: BIC/Plyboo 2010 - production process of 'Advanced Bamboo Composites®' (online)

To provide a good idea of the material properties of bamboo composite, the properties of Moso International's 'Density'(used for Bamboo X-treme®' decking), is described below.

- Durability class (EN113 / EN350-1):	class 1
- Surface fungus resistane (EN152):	class 0
- Dimensional stability:	(24 hours submergion in water of 20 °C) Length +0,1% / width +0,9% / thickness 2,4%
- Density:	appr. 1200 kg/m^3
- Hardness (EN1534):	9,5 kg/mm^2 (Brinell)
- Modulus of elasticity (EN408):	10737 N/mm^2
- Bending strength (EN408):	50 N/mm^2
- Strength class (EN338):	D50

Source: Moso International 2010 - Information brochure 'Bamboo X-treme' (tested by SHR)

Figure 52 Bamboo composite of BambooXL (dark)

Figure 53 Transverse surface (bamboo composite of BambooXL - dark)

§4.6 The Dutch bamboo-sector
As mentioned, there are only few Dutch companies engaged in trading bamboo products. Besides companies, there are also other people involved in bamboo (in this report commonly referred to as 'bamboo experts'). An overview of these parties is given below, see Annex 10 for a summary of the interviews.

Bamboo Information Centre - BIC / Plyboo (Schellinkhout)
The bamboo information centre was one of the driving forces behind the introduction of bamboo products in The Netherlands, for many years this 'company' promoted the use of bamboo, and gathered a lot of expertise. The trading part of the BIC operates under the trademark 'Plyboo'. Their assortment encompasses various products like flooring, sheet material, veneer and culms, and are mostly geared towards larger projects.

Moso International (Zwaag)
Moso International is the best known bamboo trader in The Netherlands, and has the largest share of the market. Especially due to thorough marketing, this company raised awareness for bamboo products among the general public. Moso trades many products, but especially its flooring can be found at different resellers throughout the country.

BambooXL (Amsterdam)
This is a relatively young company, which focuses entirely on bamboo composites. They supply finished products like flooring and cladding, but also raw material for exterior and interior joinery like window frames. They market bamboo composites as a sustainable alternative for tropical hardwoods, and aim to develop a completely bio-based bamboo composite.

Bamboo Solutions (Maastricht)
This company is focused on the market for interior products. Its assortment comprises mainly flooring and sheet material.

Jules Janssen, (pensioned) professor at Technical University of Eindhoven
Jules Janssen was a professor at the TU-Eindhoven. He was among the first in the world to start laboratory testing on the mechanical properties of bamboo culms, and developed suitable construction methods for especially joints between culms. He contributed to many aspects of a better understanding of bamboo, and is without doubt one of the few Dutch bamboo experts. During his career (and even afterwards) he kept track of the bamboo related developments world wide, and was active for INBAR (International Network for Bamboo and Rattan).

Pablo van der Lugt
As a student at the Delft-University he became fascinated by bamboo during an internship in Costa Rica. He researched among other the feasibility of bamboo as a construction material in Europe, and organized a series of workshops for Dutch designers to get acquainted with bamboo during his PhD project. He has published the book 'Dutch design meets bamboo'(2007), as well as articles of his several research projects on bamboo. While he currently is not actively engaged in bamboo, he is next to Jules Janssen one of the few commonly known bamboo experts in The Netherlands.

Other…
In addition to these main companies and experts, there are of course many other people in The Netherlands involved in 'bamboo'. ATC Houthandel (Almelo) for example, produces cages for horses from bamboo composite, which they source themselves in China. And there are several small traders and agents who occasionally import a container of bamboo products (mostly for projects), and larger traders who next to wood also sell some bamboo. A large supplier of bamboo culms for the agricultural sector is Amevo in Dronten.

§4.6.1 Current developments

Several developments with regard to bamboo products for exterior use are to be noticed on the Dutch market. These developments primarily concern bamboo composite. Its material characteristics make it suitable for applications in exterior circumstances (see § 4.5).

BambooXL, Plyboo, Moso International and ATC-Houthandel all import this material from China. Although it seems to originate from the same source, there are several Chinese factories that are able to produce a good quality bamboo composite, and this is why the bamboo composites on the Dutch market can look quite different from one another (Younge, 2010), see also Annex 11 for pictures on the differences. Despite its suitability for exterior applications, it is not (yet) allowed to be used under KOMO-certification.

The current developments concerning bamboo in exterior circumstances are shortly listed below.

- Joinery factory Helwig is the first joinery factory in The Netherlands which aims to use bamboo composite (supplied by BambooXL) for KOMO-certified exterior joinery applications. So far, they successfully trailed the first indoor en exterior window frames, and received much interest for their products.
- Two other joinery factories (names not to be mentioned publically), are interested in producing window frames from bamboo composite for indoor use.
- BambooXL markets its bamboo composite as a sustainable alternative for tropical hardwoods, and is seeking possibilities to get the material KOMO-certified.
- Plyboo is involved in several projects with its bamboo composite, of which one is a bridge in Heemskerk (Haasnoot), another is road side poles in their own municipality and maybe even furniture for public spaces (Delta street furniture).
- Moso International recently also targets the exterior market by introducing terrace decking of bamboo composite, which has received heat-treatment (very dark color) and are claimed to be resistant against blue stain fungi. They are currently not interested in supplying its bamboo composite for exterior joinery applications.
- While the Dutch companies have chosen bamboo composite as their material for exterior applications, the Chinese company ‘GreenBoo’ aims to market their products from laminated bamboo (treated) for exterior applications in The Netherlands.

§4.7 Possible applications in exterior joinery
Although there is certain information lacking, the material properties of both bamboos studied in this project indicate they meet the requirements in the BGS, thereby making them in principal suitable for certain (KOMO-certified) applications in exterior joinery (see conclusion of part 1 in § 3.5). As explained in § 2.5, the BGS functions as a threshold for timber species in exterior joinery applications in general. It comprises the requirements in the different National Assessment Directives for specific exterior joinery applications like window frames and cladding. If a wood species meets the requirements in the BGS, it is then allowed to be used for the applications in exterior joinery which are described in the following National Assessment Directives:

- BRL 0801 'Wooden façade elements' (window frames)
- BRL 0803 'Wooden exterior doors'
- BRL 0812 'Wooden glazing beads'
- BRL 4103 'Wooden and wood-based façade covering systems' (cladding)

Conclusion
Both bamboos, given the results in first part of this project, seem in principal suited for the above applications, on the basis of its material characteristics. Whether it will be a good choice in practice remains to be seen, see §4.8.1 and chapter 5 for a discussion in the possible applications.

§4.7.1 Possible applications based on opinions from the market
The previous paragraph was on the possibilities for bamboo in KOMO-certified exterior joinery applications. To identify for which exterior (joinery) applications the Dutch bamboo sector regards bamboo as a viable option, a market research was conducted among present traders and experts. For a full description of the interviews, please see appendix 10.

The following question box was used to obtain the participant's opinions on the use of bamboo (laminated or composite) for different applications in exterior conditions. The respondents were asked to express their opinion in terms of promising, neutral or not promising.

Exterior applications of bamboo	Laminated	Composite
1. Exterior joinery (frames for windows/doors, and doors)		
2. Cladding (sheet material)		
3. Garden applications (decking, fences, poles)		
4. Exterior furniture (private, public space)		
5. Ground and waterworks (sheet piling, guard rail)		

The main results are described below, see Annex 10 for more details on the answers of the individuals.

All of the respondents* did not see bamboo laminated bamboo, even treated for enhanced durability, as a viable option for any application in exterior circumstances. On the other hand, all respondents regarded bamboo composites as very promising, and in principle suitable for all applications in exterior circumstances - most of them reasoning from its interchangeability with tropical hardwoods.

*Except for the Chinese company GreenBoo, but they were not interviewed officially.

Conclusion
According to the opinions among the present traders and experts in the Dutch bamboo-sector, laminated bamboo is not a suitable choice for exterior applications; they believe bamboo composite is better suitable and market this material for exterior applications.

§4.8 SWOT-analysis

The main strengths and weaknesses, as well as opportunities and threats, were drawn from the test results and the market survey among present participants in the Dutch bamboo-sector. They are described for the two most common engineered materials of bamboo; laminated bamboo and bamboo composite. Although this project focuses on bamboo strips in their natural condition, a SWOT-analysis for bamboo composite was performed too, in order to provide additional perspectives for bamboo in general in the Dutch market.

SWOT analysis for laminated bamboo	
Strengths	**Weaknesses**
- Decorative material, with real 'bamboo' feel to it - Green and trendy image	- Bamboo in its natural (untreated) state is not durable - Contains many glue-bond which could delaminate - Susceptible to surface moulds
Opportunities	**Threats**
- The market is always open for trendy and decorative materials - Increasing interest in renewable resources - Dutch government's sustainable sourcing policy	- Dutch companies do not market this material for exterior applications - Not (KOMO) certified - Bamboo's image of low durability, and the market's unfamiliarity with regard to bamboo for exterior applications

SWOT analysis for bamboo composite	
Strengths	**Weaknesses**
- Similar look and feel as tropical hardwoods - Durable - High hardness	- Susceptible to (blue stain) moulds, although depending on the specific production process (can be resistant) - Material properties can easily vary according to different production parameters - No long term experience
Opportunities	**Threats**
- Negative perception of tropical hardwoods - One-to-one replacement for tropical hardwoods - Increasing interest in renewable resources - Dutch government's sustainable sourcing policy	- Not (KOMO) certified - Market is conservative towards new materials

Conclusion

Both materials share a similar set of opportunities, which are mainly forthcoming from bamboo's sustainable image compared to tropical hardwoods. That the materials are not (KOMO) certified is the main threat, this because it is almost a necessity in order for the materials to compete on the Dutch market for exterior joinery applications. Both materials (especially laminated bamboo) remain susceptible to moulds due to bamboo's high starch content, which seems of rather marginal influence, but nonetheless could cause the loss of its decorative value. The main difference between the materials is their durability, as well that Dutch bamboo traders only market bamboo composites for exterior applications.

§4.9 Conclusion

The conclusions and recommendations for the second part of this project are listed below.
The second part focused on the applications for exterior joinery which are possible on the basis of the material characteristics, the perspectives for bamboo in The Netherlands, and a characterization of the Dutch bamboo sector along with the current developments.

The Dutch bamboo sector is very small, and is mostly geared towards products for indoor use. These products are almost all made from laminated bamboo, which was the main material type in The Netherlands since the introduction of industrial manufactured bamboo products. There are some changes to be noticed however, which primarily concern bamboo composite. Nowadays, this is a stable product, with material properties similar to tropical hardwoods. Dutch companies market this material for both indoor and outdoor applications, and is their primary choice for exterior applications; not laminated bamboo. Some Dutch companies even aimed to use this material for KOMO-certified exterior joinery applications.

The second research question was:
'Which applications in exterior joinery are possible on the basis of the material characteristics, and what are the perspectives for bamboo on the Dutch market for exterior joinery?

Concerning the first part of this question, the following answer can be formulated.
The tested material properties of both bamboo species seem to meet the requirements in the BGS (conclusion part 1). In principle, this makes it possible to use them as a certified material for the following applications:

- Frames for doors and windows
- Doors
- Glazing beads
- Cladding

However, as mentioned in the conclusion of the first part of this report, the durability was not tested. This most likely renders bamboo (in its natural condition) unsuitable for the applications above, see chapter 5 for a discussion on this issue.

Concerning the second half of the research question, the general perspectives for bamboo (laminated) are the following (based on the interviews).

A main opportunity for laminated bamboo is the market's demand for products with a distinctive decorative value, as well as the increasing interest in renewable resources.
A major threat is that the material is not KOMO-certified, which causes it not to be competitive on the Dutch market. Furthermore, the fact that Dutch companies do not market this material for exterior applications, as well as the market's unfamiliarity with this product in exterior applications, are both additional threats. The main strength of laminated bamboo is its decorative look, and green and trendy image. The major weaknesses are its low natural durability, the susceptibility for moulds and necessity of many glue bonds. Therefore, the general perspective for laminated bamboo in exterior joinery applications in The Netherlands, is limited. This general perspective is considered to apply for the different applications above.

Chapter 5 DISCUSSION

The discussion is divided into two parts, the first focuses on the material properties (part 1 of report). Certain aspects which could have influenced the test results are discussed, as well as the most important material property which was not tested: the durability. The second on part of the discussion focuses on the market perspectives (part 2 or report), in which certain aspects with regard the suitability of laminated bamboo in practice are discussed.

Discussion part 1 - Material properties

With regard to the executed tests, the following matters are subject to discussion.

The test strips of Moso were sawn from culms which had been fumigated (smoked). This was done by placing them upright in a long chamber with a smoldering fire underneath it (usually fueled by bamboo branches and foliage), in order to create a material which is inedible to insects (culms are usually smoked between a temperature range of 50/60 – 120/150 °C). The goal is to prevent the tar from condensation, so that it can ingress into the material in a gaseous condition (Conbam 2010, Liesse 2003). This treatment could have influenced certain material properties, especially the hygroscopicity. The material had a caramelized scent, indicating sugars were burned. This could have resuted in reduced water uptake and a lower EMC for Moso. According to Ohmae et al. (2009), the water adsorbtion capacity of *Phyllostachys pubescens* decreases after up to 2 hours heating in 200 °C. This is attributed to a decrease in the number of hydroxyl groups.

The Guauda culms were treated with boron by means of the Bouchery-process (sap replacement treatment). Furthermore, Guadua was for a large part infected by blue stain fungi, although certain distinct parts were not infected. This indicated the boron-solution did not ingress into the material evenly. The latter was also indicated by the selective growth of surface moulds on Guauda during the water uptake test, while Moso was totally covered with several moulds. The large variation between the individual specimens for Guauda (especially with regard to hygroscopic related tests), could have been caused by the factors above. They might have influenced the structure of the tissue, for pressure had been applied, and the hyphae of the blue stain fungi had produced additional pathways between cell walls. Other causes for the large variation could be that the two culms-parts which were used for producing the specimens (both from the middle-upper region of a culm - branches were present), originated from a different location, or were harvested under different conditions. As described in §3.3.4, differences in starch (sugar) content depend on the time of harvest, age and position in the culm. The starch content could have influenced the hygroscopicity, which demonstrated a large variation especially during the water uptake test.

Another point of discussion is the size of the specimens. Certain test were performed on specimens with sizes that deviated (much) from the standard. The size of the specimens for the dimensional stability (swelling) and EMC tests, were very small (5 x 20 x 5 mm) compared to standard sizes for wood (minimum of 20 x 20 x 5-10 mm). This was clearly demonstrated by the difference in EMC for a climate of 65% RH and 20 °C. For specimens with large dimensions, the EMC was 10.3% for Moso and 12.6% for Guadua (§3.3.5). For specimens with small dimensions, the EMC was 13.4% for Moso and 16.6% for Guadua (§ 3.3.6). No other factor which was influential enough to cause this difference could be identified, except for the small dimensions of the specimens. Because the same specimens were used for measuring the dimensional stability (swelling), the swelling was larger due to higher moisture content. Therefore, the actual swelling of the material will be less, although the results in this report indicate that both bamboos already meet the requirements in the BGS.

As already mentioned in §3.2.6, the value of the depth (thickness) of the specimens has to be modified with a certain modification factor before calculating the MOR for a depth which is less than 200mm but larger then 75mm (NEN 5498). The depth of the bamboo specimens was much less (5 mm). Therefore no modification factor could be applied without losing the indicative value of the results. Therefore, the MOR values will be lower in practice. However, the values obtained for the single strips, do not deviate much from values obtained for laminated beams. Jorissen & Voermans (2009) found that laminated beams of Moso had a MOE of 8357 N/mm^2, and a MOR of 72 N/mm^2. This means the obtained values on the strength provide a good indication of the properties of a laminated product.

With regard to the suitability of bamboo for exterior joinery applications on other grounds than the tested material properties, the following matters are subject to discussion.

One of the most important material properties with regard to the suitability of a timber species for exterior joinery, is the durability. This was not tested in this project. Literature survey indicated that the natural durability of bamboo has not been tested according to European or Dutch standards (NEN-EN 113, 807 or 252). Furthermore, hardly any other reliable tests (graveyard tests with planed, single strips) according to other commonly trusted standards were found. According to Liesse (1998), untreated bamboo culms may have an average life of less than 1-3 years when exposed to atmosphere and soil. Under cover, it may be expected to last 4-7 years or more. Under favorable circumstances, bamboo was in service as support for frames for more than 15-20 years. Results from 'graveyard tests' with a number of bamboo species in Dehra Dun, India, showed generally a low durability (class 3) with only slight differences (Liese, 1998). It was shown that split culms are more rapidly destroyed than un-split bamboo, and although there are differences in durability between different species, they are all more or less equally vulnerable to wood degrading organisms. Therefore, it is expected that bamboo in its natural state, and planed (without protective cortex), belongs in durability class 5 (the lowest durability: less then five years service life in soil contact). This would be a major bottleneck for bamboo's suitableness for exterior joinery applications in the Netherlands. The following application-classes for wood in exterior joinery are to be distinguished (BGS):

Usage class	Temp. [C]	RH [%]	Water contact	Solar-UV	Clarification	Risk	Durability class
3.1	-10 - 30	30-90	Limited	Limited	(Partly) sheltered exterior	+/-	1-4
3.2	-10 - 30	30-95	Frequent	Frequent	Standard exterior application	+	1-4*
3.3	-10 - 30	30-95	Permanent	Permanent	Exterior application with high risk in e.g. design, detailing etc.	++	1-2

Risk: risk of damage (attack by wood degrading organisms) in case of a calamity (+/- = limited risk; + = risk; ++ = high risk)

*for durability classes 3 and 4, appropriate measures should be taken, to ensure a high resistance against attack by wood degrading organisms, or to prevent the wood from becoming wet for longer periods

From this table one can conclude that timber species with a durability class of 5 are not allowed to be used for KOMO-certified exterior joinery, and only timber species with a high natural durability (class 1 and 2) are suitable for applications with high risk. This is further elaborated with regard to the possible applications in exterior joinery in the second part of this chapter.

Discussion part 2 - Market perspectives

Although not all tests could be entirely executed according to the standards, and the durability was not tested at all, both bamboos exhibit material properties which are able to meet most of the requirements in the BGS. There are however, certain side notes concerning its suitability in practice.

As discussed in the first part of this chapter, bamboo most likely has a durability class 5, which is a major bottleneck for applications in exterior joinery, especially for applications with high risk of getting wet. If the natural durability is increased up to class 1 or 2, this problem would be solved. There are several options for increasing the natural durability of bamboo (Liese, 2003). However, these treatments will always require a more sophisticated and more expensive productions process. As Rene Zaal (director of Moso International) mentioned during the interview, this makes treated bamboo less attractive. Nonetheless, the Chinese company GreenBoo treats its strips before lamination them, and is able to market it against competitive prices (Wang, 2010).

Although all companies in the Dutch bamboo sector are only marketing bamboo composite as a suitable material for both interior and exterior applications, treated laminated bamboo is not unsuitable. Especially in applications with a high need for a distinctive decorative value, laminated bamboo has the edge over bamboo composite, because the bamboo looks are still present. Bamboo composite (solid) is regarded to not be very suitable for cladding (Vos 2010), especially due to its heavy weight, which makes bamboo sheet material a better option.

With regard to the introduction of KOMO-certified laminated bamboo on the Dutch market, the following issue arises.

In order to obtain material dimensions which are suitable in practice, bamboo strips need to be laminated. With regard to the requirements for exterior joinery applications in The Netherlands, laminated bamboo faces several difficulties. Because it is a manufactured product, differences between producers will always exist. Therefore, production needs to be continuously controlled for the same material characteristics. Producers will have to operate according to a certain quality standard. When this happens, it will be possible to test laminated bamboo according to the BGS. The BGS is not written for testing a laminated product, therefore there are (in theory) several ways of going about.

- If laminated bamboo were to be added to the list of ‘Approved timber species for exterior joinery’ (SKH publication 99-05), certain parts of the BGS would have to be modified. In addition to altering specific standards on testing, a matter of discussion is that bamboo botanically is a grass, not a wood species.
- However, it is possible when laminated bamboo was tested according to the BGS and meets the requirements, to publish a conformity declaration which says it meets the requirements, without adding the material to SKH publication 99-05. Laminated bamboo, provided the production is controlled, will then also be allowed for KOMO-certified exterior joinery applications.

Chapter 6 Epilogue

In addition to the conclusions for the first and second research question in part 1 & 2 of this report, a general conclusion and recommendations of this project follow below.

The bamboo species Moso and Guadua were tested according to the most common set of requirements on exterior joinery applications in The Netherlands: the ‘Evaluation standard for wood species for application in timberwork’ (BGS in Dutch). In doing so, the most important material properties were tested, except the durability. The tested material properties indicated that both bamboos meet the requirements in the BGS. Therefore they are most likely suitable for (KOMO-certified) exterior joinery applications in The Netherlands. However, as discussed in chapter 5, the natural durability class of bamboo is low, most likely class 5. This excludes bamboo on the basis of its natural durability from exterior joinery applications. This would imply the need for <u>always</u> having to improve the durability of bamboo by treating it, even before it can be applied in the usage class with the lowest risk of getting wet. There are however, many ways of improving the natural durability of bamboo up to a suitable level. Therefore, if the natural durability of bamboo is improved, the material is suitable for exterior joinery applications.

The relentless pressure on the world’s forests, which is partly caused by the increasingly high demand for timber, makes bamboo a favorable renewable resource compared to timber. It can be used for reaforresting bare lands, and has a high production in terms of dry material per year per hectare. Currently the material is hardly used for exterior joinery applications. It will most likely gain market share as a composite material, since its similarity to tropical hardwoods, and not as a laminated material. Nonetheless, there are opportunities for laminated bamboo for exterior joinery applications.

General recommendations
With regard to a successful use of bamboo, either laminated or as composite, the following recommendations can be made.

- In order to publish a list of material properties for a certain bamboo species, there needs to be consensus on how to demarcate the factors which influence these properties, for especially age and position in the culm are of a large influence.
- Bamboo will, unlike sawn timber, always need to be glued to obtain a material with sufficient size. There are many production parameters which can differ in doing so, which raises the need for the development of certain production standards (quality system) and their control. Otherwise, bamboo can not be marketed as a material for which the material properties are generally known.

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- BRL 0801 'Wooden façade elements' SKH, version 07-12-2005
- BRL 0803 'Wooden exterior doors' SKH, version 15-03-2006
- BRL 0812 'Wooden glazing beads' SKH, version 06-02-2004
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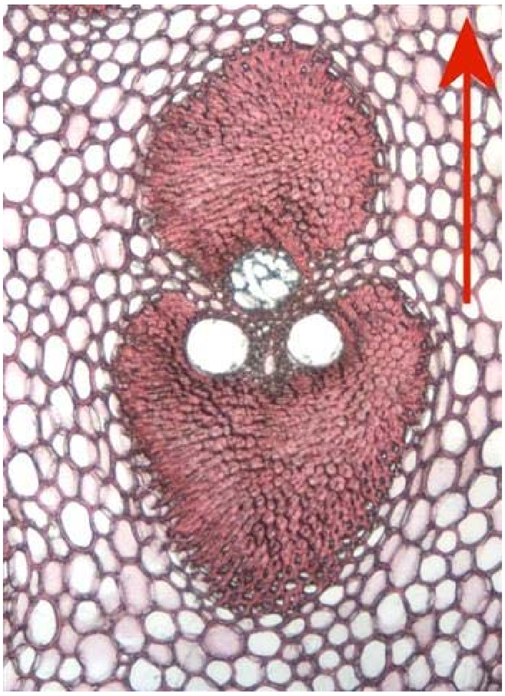
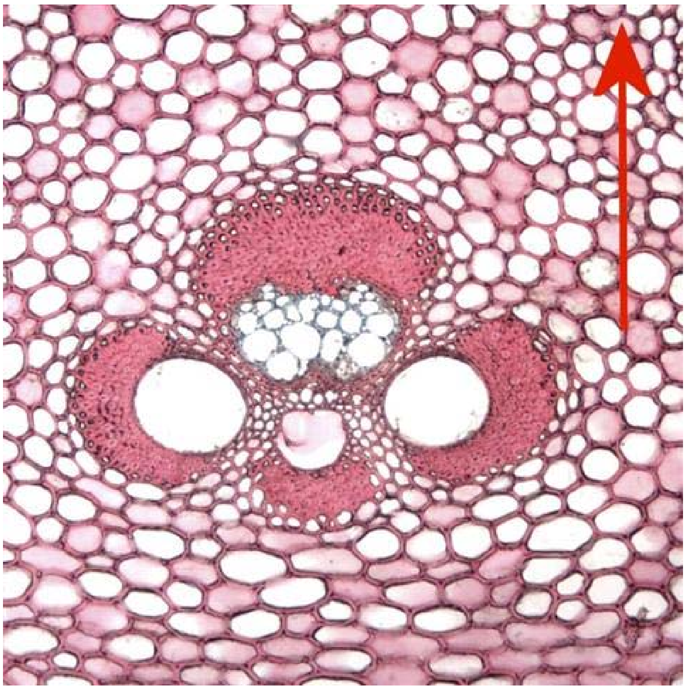
Annexes

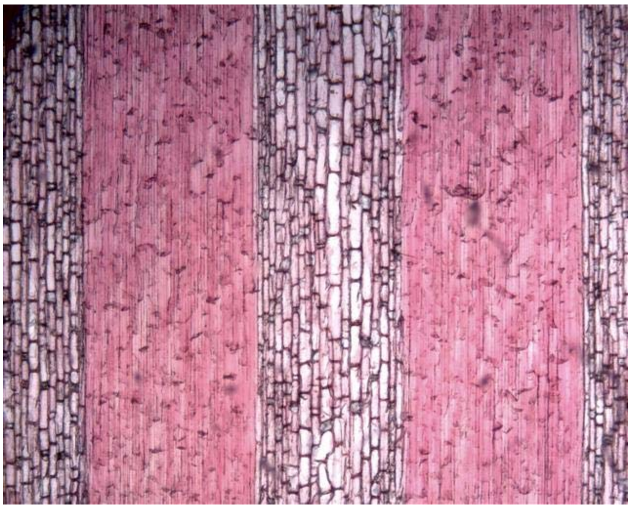
Annex 1 Different shapes of vascular bundles



Vascular bundle near outside of culm wall - Guadua (40x)



Vacular bundle near inside of culm wall - Moso (40x)



Radial surface - Guadua (40x)

Tangential surface - Moso (40x)

Annex 2 Data density

Code	Density [kg/m3]	MC [%]
MI-1	595	10,3%
MI-2	567	10,0%
MI-3	610	10,2%
MI-4	696	10,3%
MI-5	591	10,3%
MO-1	554	10,1%
MO-2	621	10,3%
MO-3	566	10,2%
MO-4	568	10,1%
MO-5	567	10,5%
AVG	593	10,2%
Stdev	42	0,001228
V%	7%	1%

Code	Density	MC
MOK-1	665	10,5%
MOK-2	591	10,6%
MOK-3	688	10,4%
MOK-4	674	10,6%
MOK-5	674	10,5%
MIK-1	574	10,2%
MIK-2	552	10,2%
MIK-3	585	10,4%
MIK-4	578	10,4%
MIK-5	615	10,2%
AVG	620	10,4%
Stdev	51	0,001508
V%	8%	1%

	Density	MC
GI-1	652	12,7%
GI-2	663	12,5%
GI-3	681	12,6%
GI-4	620	12,5%
GI-5	622	12,5%
GO-1	661	12,5%
GO-2	667	12,8%
GO-3	630	12,4%
GO-4	707	12,7%
GO-5	609	12,4%
AVG	651	12,6%
Stdev	31	0,001294
V%	5%	1%

	Density	MC
GOK-1	660	12,7%
GOK-2	612	12,4%
GOK-3	698	12,8%
GOK-4	627	12,6%
GOK-5	735	12,8%
GIK-1	626	12,9%
GIK-2	654	12,7%
GIK-3	588	12,7%
GIK-4	659	12,7%
GIK-5	669	12,7%
AVG	653	12,7%
Stdev	43	0,00124
V%	7%	1%

Moso - total				**Guadua - total**			
	Density	MC			Density	MC	
1	595	10,3%		1	652	12,7%	
2	567	10,0%		2	663	12,5%	
3	610	10,2%		3	681	12,6%	
4	696	10,3%		4	620	12,5%	
5	591	10,3%		5	622	12,5%	
6	554	10,1%		6	661	12,5%	
7	621	10,3%		7	667	12,8%	
8	566	10,2%		8	630	12,4%	
9	568	10,1%		9	707	12,7%	
10	567	10,5%		10	609	12,4%	
11	665	10,5%		11	660	12,7%	
12	591	10,6%		12	612	12,4%	
13	688	10,4%		13	698	12,8%	
14	674	10,6%		14	627	12,6%	
15	674	10,5%		15	735	12,8%	
16	574	10,2%		16	626	12,9%	
17	552	10,2%		17	654	12,7%	
18	585	10,4%		18	588	12,7%	
19	578	10,4%		19	659	12,7%	
20	615	10,2%		20	669	12,7%	
AVG	607	10,3%		AVG	652	12,6%	
STDEV	47			STDEV	36		
V%	8%			V%	6%		
5%-perc.	525			5%-perc.	589		
Min	552	Deviation of AVG	-9%	Min	588	Deviation of AVG	-10%
Max	696	Deviation of AVG	15%	Max	735	Deviation of AVG	13%

Code	
M =	Moso
G =	Guadua
I =	Inside culm wall
O =	Outside culm wall
K =	Node

Annex 3 Data dimensional stability & EMC

RH [%]		Length [%]	Radial [%]	Tangential [%]	EMC [%]	RH [%]		Length [%]	Radial [%]	angential [%]	EMC [%]
25%	M1	-0,18%	1,29%	1,30%	9,16%	25%	G1	-0,28%	1,33%	1,38%	13,03%
25%	M2	-0,39%	0,59%	1,68%	9,00%	25%	G2	-0,52%	-0,41%	1,62%	11,26%
25%	M3	-0,31%	0,42%	1,49%	8,49%	25%	G3	-0,23%	0,30%	0,54%	12,78%
25%	M4	-0,42%	0,06%	1,55%	8,26%	25%	G4	-1,34%	-0,96%	0,77%	9,73%
25%	M5	-0,14%	0,59%	1,16%	8,17%	25%	G5	-1,08%	-0,79%	1,80%	9,55%
25%	M6	-0,19%	1,97%	1,70%	9,97%	25%	G6	-0,23%	1,78%	1,47%	12,57%
25%	M7	0,04%	1,35%	1,40%	9,10%	25%	G7	-0,29%	0,93%	1,30%	12,52%
25%	M8	-0,23%	1,32%	1,40%	8,86%	25%	G8	-0,47%	0,72%	0,99%	9,49%
25%	M9	0,12%	1,17%	1,78%	8,85%	25%	G9	-0,35%	1,45%	1,71%	10,97%
25%	M10	-0,06%	0,85%	1,79%	9,09%	25%	G10	-0,70%	0,86%	1,02%	12,19%
	AVG	-0,18%	0,96%	1,53%	8,89%		AVG	-0,55%	0,52%	1,26%	11,41%
	stdev	0,17%	0,56%	0,21%	0,52%		stdev	0,38%	0,96%	0,42%	1,41%
	V%	-99%	59%	14%	6%		V%	-70%	184%	33%	12%
50%	M1	-0,18%	1,73%	1,80%	11,66%	50%	G1	-0,07%	2,34%	2,30%	15,95%
50%	M2	-0,27%	1,44%	2,27%	11,54%	50%	G2	-0,33%	0,45%	2,48%	14,20%
50%	M3	-0,19%	0,83%	2,10%	11,15%	50%	G3	-0,29%	0,85%	1,51%	15,76%
50%	M4	-0,23%	0,52%	2,29%	10,83%	50%	G4	-1,15%	0,00%	1,57%	12,52%
50%	M5	-0,06%	1,00%	1,71%	10,73%	50%	G5	-0,95%	0,00%	2,50%	12,29%
50%	M6	-0,14%	2,10%	2,25%	12,63%	50%	G6	-0,26%	2,48%	2,40%	15,54%
50%	M7	-0,06%	1,71%	1,97%	11,76%	50%	G7	-0,27%	1,99%	2,18%	15,59%
50%	M8	-0,10%	1,78%	1,95%	11,43%	50%	G8	-0,50%	1,39%	1,84%	12,48%
50%	M9	0,14%	1,74%	2,22%	11,53%	50%	G9	-0,37%	2,23%	2,47%	13,84%
50%	M10	-0,02%	1,26%	2,29%	11,77%	50%	G10	-0,61%	1,64%	1,71%	15,19%
	AVG	-0,11%	1,41%	2,09%	11,50%		AVG	-0,48%	1,34%	2,10%	14,34%
	stdev	0,12%	0,50%	0,22%	0,54%		stdev	0,34%	0,96%	0,40%	1,47%
	V%	-107%	35%	10%	5%		V%	-70%	72%	19%	10%
65%	M1	-0,09%	1,80%	2,20%	13,59%	65%	G1	-0,10%	3,27%	2,99%	18,40%
65%	M2	-0,19%	1,56%	2,62%	13,44%	65%	G2	-0,24%	1,00%	3,03%	16,51%
65%	M3	-0,12%	1,16%	2,58%	13,02%	65%	G3	0,02%	1,67%	2,14%	18,08%
65%	M4	-0,21%	0,89%	2,61%	12,75%	65%	G4	-1,06%	0,61%	2,01%	14,66%
65%	M5	-0,05%	1,78%	2,15%	12,49%	65%	G5	-0,89%	1,45%	2,94%	14,46%
65%	M6	-0,05%	2,43%	2,68%	14,64%	65%	G6	-0,23%	3,32%	3,15%	17,96%
65%	M7	0,06%	2,12%	2,49%	13,78%	65%	G7	-0,18%	2,83%	2,95%	18,05%
65%	M8	-0,01%	2,02%	2,39%	13,26%	65%	G8	-0,43%	1,90%	2,43%	14,66%
65%	M9	0,10%	1,61%	2,70%	13,46%	65%	G9	-0,31%	3,03%	3,15%	16,12%
65%	M10	-0,15%	1,82%	2,76%	13,66%	65%	G10	-0,67%	2,31%	2,25%	17,50%
	AVG	-0,07%	1,72%	2,52%	13,41%		AVG	-0,41%	2,14%	2,70%	16,64%
	stdev	0,10%	0,45%	0,21%	0,60%		stdev	0,35%	0,96%	0,44%	1,58%
	V%	-143%	26%	8%	4%		V%	-87%	45%	16%	9%
80%	M1	0,06%	2,77%	3,02%	17,13%	80%	G1	0,06%	4,89%	4,62%	23,46%
80%	M2	-0,01%	2,31%	3,46%	17,14%	80%	G2	-0,08%	2,59%	4,25%	21,36%
80%	M3	-0,01%	1,97%	3,39%	16,62%	80%	G3	-0,05%	3,64%	3,75%	23,23%
80%	M4	-0,13%	1,82%	3,50%	16,28%	80%	G4	-0,75%	2,42%	3,16%	19,27%
80%	M5	-0,21%	2,06%	2,96%	15,73%	80%	G5	-0,64%	2,52%	3,91%	19,02%
80%	M6	0,32%	3,30%	3,52%	18,47%	80%	G6	-0,04%	4,67%	4,87%	22,91%
80%	M7	0,18%	2,84%	3,13%	17,54%	80%	G7	-0,01%	4,84%	4,54%	23,21%
80%	M8	0,06%	2,69%	3,33%	16,71%	80%	G8	-0,25%	3,03%	3,95%	19,44%
80%	M9	0,16%	2,36%	3,48%	17,04%	80%	G9	-0,12%	4,59%	4,80%	20,97%
80%	M10	0,16%	2,25%	3,45%	17,39%	80%	G10	-0,47%	3,83%	3,72%	22,57%
	AVG	0,06%	2,44%	3,32%	17,00%		AVG	-0,23%	3,70%	4,16%	21,54%
	stdev	0,16%	0,46%	0,21%	0,75%		stdev	0,28%	1,01%	0,55%	1,78%
	V%	270%	19%	6%	4%		V%	-122%	27%	13%	8%
95%	M1	0,43%	3,62%	4,22%	22,66%	95%	G1	0,29%	6,03%	5,57%	31,96%
95%	M2	0,38%	3,28%	4,43%	22,48%	95%	G2	0,16%	4,11%	4,86%	28,46%
95%	M3	0,56%	3,25%	4,63%	22,17%	95%	G3	0,22%	5,26%	5,46%	30,80%
95%	M4	0,11%	2,92%	4,64%	21,43%	95%	G4	-0,19%	5,35%	4,65%	25,81%
95%	M5	0,04%	3,17%	4,03%	20,60%	95%	G5	-0,13%	5,33%	5,24%	25,50%
95%	M6	0,47%	3,63%	3,90%	25,20%	95%	G6	0,04%	5,41%	5,94%	30,39%
95%	M7	0,45%	3,68%	3,52%	24,15%	95%	G7	0,31%	6,16%	5,60%	31,95%
95%	M8	0,31%	3,60%	4,40%	21,93%	95%	G8	0,16%	4,36%	5,52%	25,20%
95%	M9	0,45%	3,80%	4,40%	22,64%	95%	G9	0,21%	5,98%	5,56%	27,50%
95%	M10	0,41%	3,18%	4,38%	23,10%	95%	G10	-0,10%	5,13%	4,79%	30,77%
	AVG	0,36%	3,41%	4,26%	22,64%		AVG	0,10%	5,31%	5,32%	28,83%
	stdev	0,16%	0,29%	0,35%	1,31%		stdev	0,18%	0,67%	0,42%	2,68%
	V%	46%	8%	8%	6%		V%	187%	13%	8%	9%
100%	M1	0,56%	3,93%	4,19%	65,38%	100%	G1	0,38%	7,04%	5,69%	78,90%
100%	M2	0,89%	3,64%	4,73%	73,63%	100%	G2	0,15%	5,09%	5,21%	82,35%
100%	M3	0,88%	4,02%	5,08%	67,31%	100%	G3	0,29%	5,88%	5,31%	86,07%
100%	M4	0,53%	3,44%	4,85%	66,94%	100%	G4	0,11%	7,72%	5,70%	105,61%
100%	M5	0,24%	3,38%	4,38%	69,27%	100%	G5	0,17%	7,06%	5,62%	98,02%
100%	M6	0,63%	3,74%	4,01%	80,18%	100%	G6	0,23%	5,83%	6,33%	71,09%
100%	M7	0,52%	3,91%	3,96%	75,08%	100%	G7	0,38%	6,79%	5,79%	79,06%
100%	M8	0,43%	3,59%	4,64%	68,75%	100%	G8	0,38%	4,80%	5,97%	73,25%
100%	M9	0,63%	3,37%	4,63%	66,32%	100%	G9	0,39%	6,65%	6,16%	69,35%
100%	M10	0,38%	3,43%	4,57%	68,27%	100%	G10	0,32%	5,66%	5,29%	84,93%
	AVG	0,57%	3,64%	4,51%	70,11%		AVG	0,28%	6,25%	5,71%	82,86%
	stdev	0,20%	0,24%	0,37%	4,70%		stdev	0,11%	0,94%	0,37%	11,58%
	V%	36%	7%	8%	7%		V%	39%	15%	7%	14%

Code	
M =	Moso
G =	Guadua

Annex 4 Data janka hardness

Order	Moso - outside up	Order	Moso - outside up (node)
1	5379	1	7190
2	6232	2	8195
3	6358	3	8076
4	6192	4	7842
5	5956	5	6774
6	6106	6	6578
7	5844		
8	5916		
9	5237		
10	5682		
11	5775		
12	5634		
AVG	5859,2	AVG	7442,6
STDEV	341,1	STDEV	690,7
V%	5,8%	V%	9,3%
	Moso - inside up		Moso - inside up (node)
1	5200	1	6701
2	5357	2	5598
3	5255	3	5883
4	5781	4	6772
5	5749	5	6507
6	5779		
7	5434		
8	5059		
9	5513		
10	5600		
AVG	5472,7	AVG	6292,2
STDEV	256,3	STDEV	522,8
V%	4,7%	V%	8,3%
	Guadua - inside up		Guadua - inside up (node)
1	2211	1	2724
2	1932	2	3373
3	2233	3	2619
4	2425	4	2718
5	2382	5	3155
6	2186		
7	1910		
8	2226		
9	2071		
10	2781		
11	2294		
AVG	2241,1	AVG	2917,8
STDEV	242,1	STDEV	327,7
V%	10,8%	V%	11,2%
	Guadua - outside up		Guadua - outside up (node)
1	4227,14	1	3867,49
2	3301,98	2	3559,3
3	3461,75	3	3794
4	3078,35	4	4345,96
5	2835,31	5	2615,06
6	3241,09		
7	2615,48		
8	2647,28		
9	3259,61		
10	2636,47		
AVG	3130,4	AVG	3636,4
STDEV	494,8	STDEV	638,5
V%	15,8%	V%	17,6%

Annex 5 Data strength

Guadua - inside up

No.	MOE	MOR
1	15320	125
2	14031	113
3	14614	128
4	14203	118
5	13209	117
AVG	14275,4	120,2
STDEV	776,2	6,1
V%	5,4%	5,1%
5%		108

Moso - inside up

No.	MOE	MOR
21	7991	105
22	7876	107
23	7887	113
24	8746	140
25	8042	111
AVG	8108,4	115,2
STDEV	363,2	14,2
V%	4,5%	12,3%
5%		87

Guadua - outside up

No.	MOE	MOR
6	14525	130
7	14680	136
8	13175	118
9	15527	163
10	12611	124
AVG	14103,8	134,3
STDEV	1186,1	17,5
V%	8,4%	13,0%
5%		99

Moso - outside up

No.	MOE	MOR
26	7834	103
27	9782	134
28	8289	109
29	8958	115
30	7212	93
AVG	8414,8	110,7
STDEV	995,7	15,3
V%	11,8%	13,8%
5%		80

Guadua - outside up (node)

No.	MOE	MOR
11	12331	111
12	10383	86
13	13788	120
14	12244	97
15	15320	130
AVG	12813,2	108,5
STDEV	1850,5	17,5
V%	14,4%	16,1%
5%		73

Moso - outside up (node)

No.	MOE	MOR
31	9876	127
32	8312	93
33	9518	115
34	9318	115
35	9232	119
36	9061	93
AVG	9219,3	110,3
STDEV	525,0	14,2
V%	5,7%	12,8%
5%		82

Guadua - inside up (node)

No.	MOE	MOR
16	11763	100
17	12580	111
18	9997	86
19	11852	103
20	12823	109
AVG	11803,0	101,8
STDEV	1107,8	9,9
V%	9,4%	9,7%
5%		82

Moso - inside up (node)

No.	MOE	MOR
37	7884	100
38	8590	110
39	7492	99
40	9344	112
AVG	8327,3	105,1
STDEV	816,0	7,0
V%	10%	7%
5%		91

Guadua - Total

No.	MOE	MOR
1	15320	125
2	14031	113
3	14614	128
4	14203	118
5	13209	117
6	14525	130
7	14680	136
8	13175	118
9	15527	163
10	12611	124
11	12331	111
12	10383	86
13	13788	120
14	12244	97
15	15320	130
16	11763	100
17	12580	111
18	9997	86
19	11852	103
20	12823	109
AVG	13248,8	116,2
STDEV	1572,3	17,8
V%	11,9%	15,3%
5%-perc.		85,3

Moso - Total

No.	MOE	MOR
21	7991	105
22	7876	107
23	7887	113
24	8746	140
25	8042	111
26	7834	103
27	9782	134
28	8289	109
29	8958	115
30	7212	93
31	9876	127
32	8312	93
33	9518	115
34	9318	115
35	9232	119
36	9061	93
37	7884	100
38	8590	110
39	7492	99
40	9344	112
AVG	8562,1	110,6
STDEV	788,7	12,8
V%	9,2%	11,6%
5%-perc.		88,4

Annex 6 Data water uptake & loss

Water uptake Guadua [g]														Water loss Guadua [g]					
Time [days]	0,00	0,29	1,00	4,00	7,00	11,12	13,99	18,00	21,00	26,03	29,10	32,15	34,98	35,04	35,30	36,00	39,00	43,00	47,99
G1 N-h	0,00	0,99	1,76	3,47	4,73	6,23	7,06	8,37	9,17	10,28	10,81	11,40	11,52	10,99	8,46	4,11	-0,73	-1,16	-1,22
G2 N-l	0,00	0,74	1,48	3,07	3,99	5,00	5,51	6,50	7,21	8,35	8,89	9,49	9,52	9,06	6,58	2,21	-1,18	-1,38	-1,42
G3	0,00	0,83	1,37	2,67	3,67	4,85	5,47	6,49	7,17	8,15	8,61	9,10	9,00	8,63	6,64	3,25	-0,69	-0,98	-1,02
G4	0,00	0,97	1,72	3,35	4,59	6,18	7,10	8,55	9,49	10,82	11,38	11,88	11,99	11,57	9,16	4,86	-0,90	-1,18	-1,22
G5	0,00	0,97	1,64	2,99	4,05	5,41	6,16	7,42	8,18	9,30	9,83	10,20	10,52	10,11	7,85	4,45	-0,71	-1,24	-1,32
G6 N-m	0,00	0,77	1,24	2,42	3,31	4,43	4,94	5,63	5,95	6,64	6,90	7,07	7,36	6,98	5,14	2,24	-1,00	-1,17	-1,21
G7 N-m	0,00	0,91	1,56	2,86	3,69	4,81	5,28	6,04	6,34	7,10	7,43	7,68	7,88	7,42	5,31	1,45	-1,19	-1,36	-1,41
G8 N- m	0,00	0,61	1,20	2,77	3,84	4,74	5,18	5,73	6,03	6,51	6,71	6,95	7,08	6,64	4,81	1,87	-0,91	-1,05	-1,09
G9 N-m	0,00	0,79	1,22	2,41	3,14	3,89	4,26	4,61	4,83	5,20	5,35	5,55	5,62	5,24	3,78	1,29	-0,91	-1,05	-1,09
G10 N-m	0,00	0,90	1,59	2,57	3,35	4,28	4,71	5,26	5,54	5,92	6,05	6,24	6,21	5,77	4,15	1,18	-1,02	-1,15	-1,19
avg	0,00	0,85	1,48	2,86	3,84	4,98	5,57	6,46	6,99	7,82	8,20	8,56	8,67	8,24	6,19	2,69	-0,92	-1,17	-1,22
stdev	0,00	0,12	0,21	0,36	0,53	0,76	0,94	1,30	1,55	1,88	2,04	2,19	2,20	2,18	1,85	1,37	0,18	0,13	0,13
min	0,00	0,61	1,20	2,41	3,14	3,89	4,26	4,61	4,83	5,20	5,35	5,55	5,62	5,24	3,78	1,18	-1,19	-1,38	-1,42
max	0,00	0,99	1,76	3,47	4,73	6,23	7,10	8,55	9,49	10,82	11,38	11,88	11,99	11,57	9,16	4,86	-0,69	-0,98	-1,02
Water uptake Moso [g]														Water loss Moso [g]					
Time [days]	0,00	0,28	1,00	3,99	6,99	11,11	13,98	18,00	20,99	26,02	29,09	32,14	34,98	35,03	35,30	36,00	38,99	42,99	47,99
M1 N-h	0,00	1,15	1,66	2,40	3,27	4,11	4,57	5,27	5,63	6,31	6,50	6,78	7,14	6,62	4,51	1,06	-0,72	-0,82	-0,84
M2 N-l	0,00	0,57	1,21	3,11	3,89	4,86	5,43	5,88	6,05	6,40	6,44	6,58	6,86	6,38	4,83	2,42	-0,71	-0,94	-0,97
M3 N-l	0,00	0,83	1,40	2,59	3,65	4,51	4,95	5,43	5,65	6,21	6,38	6,66	6,96	6,43	4,34	1,07	-0,92	-1,02	-1,05
M4 N-m	0,00	0,76	1,46	3,01	3,86	4,74	5,19	5,47	5,44	5,61	5,70	5,93	6,25	5,80	4,27	2,12	-0,75	-1,06	-1,09
M5 N-m	0,00	0,56	1,16	2,52	3,24	3,88	4,18	4,32	4,29	4,79	5,01	5,32	5,78	5,34	3,68	1,35	-0,82	-0,91	-0,93
M6 N-m	0,00	0,74	1,33	2,67	3,23	3,92	4,30	4,66	4,80	5,29	5,59	5,99	6,27	5,84	4,17	1,70	-0,90	-1,02	-1,06
M7	0,00	0,99	1,35	1,96	2,73	3,49	3,90	4,64	5,01	5,83	6,15	6,45	6,66	6,22	4,13	1,01	-0,68	-0,78	-0,82
M8	0,00	0,65	1,19	2,39	3,11	3,87	4,33	5,02	5,44	6,27	6,58	6,79	6,98	6,56	5,00	2,65	-0,42	-0,90	-0,95
M9	0,00	0,86	1,16	1,77	2,48	3,22	3,65	4,32	4,64	5,32	5,55	5,93	6,11	5,59	3,16	0,13	-0,78	-0,85	-0,88
M10	0,00	1,02	1,47	2,19	3,13	4,02	4,49	5,13	5,34	5,89	5,96	6,28	6,46	5,90	3,49	0,45	-0,80	-0,88	-0,91
avg	0,00	0,81	1,34	2,46	3,26	4,06	4,50	5,01	5,23	5,79	5,99	6,27	6,55	6,07	4,16	1,40	-0,75	-0,92	-0,95
stdev	0,00	0,20	0,16	0,42	0,45	0,52	0,56	0,52	0,54	0,53	0,52	0,48	0,44	0,44	0,58	0,83	0,14	0,09	0,09
min	0,00	0,56	1,16	1,77	2,48	3,22	3,65	4,32	4,29	4,79	5,01	5,32	5,78	5,34	3,16	0,13	-0,92	-1,06	-1,09
max	0,00	1,15	1,66	3,11	3,89	4,86	5,43	5,88	6,05	6,40	6,58	6,79	7,14	6,62	5,00	2,65	-0,42	-0,78	-0,82

Code	
G	Guadua
M	Moso
N	node
l	low
m	middle
h	high

Annex 7 Data gluability

Moso PU

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	1590,11	0%	1	1459,22	0%
2	1003,79	0%	2	1034,09	0%
3	1318,29	0%	3	1283,14	0%
4	1087,21	0%	4	1148,98	0%
5	676,2	0%	5	1596,57	0%
			6	908,04	0%
	Min	0%		Min	0%
	AVG	0%		AVG	0%
	Max	0%		Max	0%

Guadua PU

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	633,98	10%	1	615,25	5%
2	228,57	5%	2	524,93	5%
3	529,71	5%	3	503,11	0%
4	427,12	10%	4	244,82	0%
5	1396,86	15%	5	336,18	0%
6	685,75	5%	6	628,14	5%
	Min	5%		Min	0%
	AVG	8%		AVG	3%
	Max	15%		Max	5%

Moso PVAC

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	2514,95	20%	1	2591,29	100%
2	1849,57	5%	2	2823,78	60%
3	2128,89	10%	3	2819,62	50%
4	2662,79	30%	4	2794,89	40%
5	2659,11	25%	5	2593,08	70%
6	2511,1	40%	6	2725,93	60%
	Min	5%		Min	40%
	AVG	22%		AVG	63%
	Max	40%		Max	100%

Guadua PVAC

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	1102,6	80%	1	1644,33	100%
2	1188,04	100%	2	1510,51	90%
3	1158,36	80%	3	1153,86	90%
4	1471,03	70%	4	1576,03	90%
5	1486,25	90%	5	1795,63	90%
6	1635,67	90%	6	1537,62	100%
	Min	70%		Min	90%
	AVG	85%		AVG	93%
	Max	100%		Max	100%

Moso EPI

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	2141,67	70%	1	2574,22	50%
2	2233,33	100%	2	2063,85	40%
3	2366,12	80%	3	2113,08	100%
6	2300,77	85%	4	1844,45	60%
4	2264,49	90%	5	2244,81	100%
5	2234,95	80%	6	2050,14	100%
	Min	70%		Min	40%
	AVG	84%		AVG	75%
	Max	100%		Max	100%

Guadua EPI

Inside			Outside		
Order	Fmax	Fiber fracture	Order	Fmax	Fiber fracture
1	1094,49	100%	1	1871,35	100%
2	1347,01	100%	2	1774,95	100%
3	1745,99	100%	3	1924,23	100%
4	1219,82	100%	4	2072,68	100%
5	1392,74	100%	5	1685,18	100%
6	1428,71	100%	6	2087,56	100%
	Min	100%		Min	100%
	AVG	100%		AVG	100%
	Max	100%		Max	100%

	Total PU fiber fracture		**Total PU tensile strength**	
		Guadua		Guadua
	Moso	10%	Moso	2,89
	0%	5%	7,31	1,05
	0%	5%	5,15	2,50
	0%	10%	6,50	1,93
	0%	15%	5,34	6,33
	0%	5%	3,17	3,15
	0%	5%	7,04	2,83
	0%	5%	4,84	2,41
	0%	0%	6,00	2,31
	0%	0%	5,44	1,12
	0%	0%	7,45	1,52
	0%	5%	4,29	2,89
AVG	0%	5%	5,69	2,58
Stdev	0,00	0,05	1,34	1,37
V%	#DEEL/0!	83%	23%	53%

	Total PVAC fiber fracture		**Total PVAC tensile strength**	
	Moso	Guadua	Moso	Guadua
	20%	80%	12,72	5,04
	5%	100%	8,89	5,35
	10%	80%	11,01	5,29
	30%	70%	12,16	6,69
	25%	90%	13,26	6,88
	40%	90%	12,57	7,57
	100%	100%	12,09	7,25
	60%	90%	12,69	6,90
	50%	90%	12,95	5,25
	40%	90%	12,70	7,34
	70%	90%	12,71	8,40
	60%	100%	11,55	6,95
AVG	43%	89%	12,11	6,58
Stdev	0,27	0,09	1,19	1,09
V%	64%	10%	10%	17%

	Total EPI fiber fracture		**Total EPI tensile strength**	
	Moso	Guadua	Moso	Guadua
	70%	100%	9,78	4,97
	100%	100%	10,50	6,46
	80%	100%	11,56	7,94
	85%	100%	11,76	5,73
	90%	100%	11,21	6,63
	80%	100%	10,96	6,68
	50%	100%	11,37	8,55
	40%	100%	10,42	8,07
	100%	100%	10,16	8,75
	60%	100%	9,09	9,42
	100%	100%	10,23	7,66
	100%	100%	9,66	9,85
AVG	80%	100%	10,56	7,56
Stdev	0,21	0,00	0,83	1,49
V%	26%	0%	8%	20%

Annex 8 Data treatability

	Conditioned weight	Weight after treatment	Uptake				Conditioned weight	Weight after treatment	Uptake	
	[g]	[g]	[%]	T-Test			[g]	[g]	[%]	T-Test
Open end, without node										
MA1	18,51	25,45	37,5%			GA1	13,24	23,01	73,8%	
MA2	15,18	22,71	49,7%			GA2	13,15	21,85	66,2%	
MA3	15,82	24,48	54,7%			GA3	13,92	25,07	80,1%	
MA4	11,52	17,56	52,4%			GA4	18,21	29,83	63,8%	
MA5	14,54	22,71	56,2%			GA5	12,81	26,15	104,2%	
		Avg	50,1%	0,30%				Avg	77,6%	38%
		stdev	7,5%					stdev	16,2%	
		V%	14,9%					V%	20,9%	
Open end, with node										
MB1	16,75	21,4	27,7%			GB1	14,10	25,88	83,5%	
MB2	12,90	19,7	52,7%			GB2	13,47	27,73	105,9%	
MB3	16,09	22,12	37,5%			GB3	14,26	24,44	71,4%	
MB4	18,30	24,65	34,7%			GB4	16,28	27,05	66,2%	
MB5	13,56	20,74	52,9%			GB5	20,08	30,25	50,7%	
		Avg	41,1%	23%				Avg	75,5%	49%
		stdev	11,3%					stdev	20,7%	
		V%	27,4%					V%	27,4%	
Closed ends, node in the centre										
MC1	15,81	21,82	38,0%			GC1	27,59	41,31	49,8%	
MC2	16,49	22,67	37,5%			GC2	23,26	36,95	58,9%	
MC3	22,89	29,23	27,7%			GC3	22,03	33,23	50,8%	
MC4	16,74	22,49	34,3%			GC4	15,53	32,81	111,2%	
MC5	18,68	24,82	32,9%			GC5	19,19	29,44	53,4%	
		Avg	34,1%					Avg	64,8%	
		stdev	4,2%					stdev	26,2%	
		V%	12,2%					V%	40,4%	

Code
M= Moso
G = Guadua

Annex 9 Standardized, semi-open interview

Questions in the interviews with BIC/Plyboo, Moso International, BambooXL and Jules Janssen.

1) How would you typify the Dutch bamboo sector (with regard to construction related products such as flooring and sheet material), and which companies are involved?

2) How do you think the demand for bamboo products will develop itself? Which market segments do you distinguish?

3) Bamboo might be an interesting material to not only use indoor, but also in exterior circumstances. How do you see the future of bamboo in exterior applications in The Netherlands?

4) Bamboo needs to be glued together because of its limited size in order to get larger elements. One way is to laminated the bamboo strips, another way is to press it into a composite. For which exterior applications to you believe these materials are suitable for?

In order to research the main differences between the different respondents, the following groups of exterior applications were distinguished. Could you say whether you regard bamboo for the different applications below to be promising, in terms of *promising*, *neutral* or *not-promising*?

Exterior applications of bamboo	Laminated	Composite
1. Exterior joinery (frames for windows/doors, and doors)		
2. Cladding (sheet material)		
3. Garden applications (decking, fences, poles)		
4. Exterior furniture (private, public space)		
5. Ground and waterworks (sheet piling, guard rail)		

5) What do you think makes bamboo a better choice than timber for the exterior applications in the table above – for the laminated and composite material?

6) What do you believe to be the most important bottlenecks where bamboo in exterior applications will be confronted with – both from a ‘market’ and a technical perspective?

7) How continuous is the quality of the material you purchase? Are there any differences between different factories, production batches and the area and cultivation method of the bamboo?

Questions in the interview with joinery factory ‘Helwig’

1) Why did you choose bamboo as a joinery factory in The Netherlands?

2) Have you considered laminated strips in addition to bamboo composites?

3) For which exterior applications do believe bamboo composites to be suitable?

4) At which market do you aim at?

5) What makes the bamboo composite an interesting alternative for timber - both from a ‘market’ and a technical perspective?

6) What are the bottlenecks where you are confronted with for the bamboo composites - both from a ‘market’ and a technical perspective?

Annex 10 Summary of interviews

The most important results from the interviews (standardized, semi-open) are described below.

Bamboo Information Centre (BIC) / Plyboo (Schellinkhout) – Charley Younge
Plyboo trades in both laminated bamboo and bamboo composite.

- Charley Younge typified the Dutch bamboo-sector as small, and almost exclusively focused on interior products.
- He believes the utilization of bamboo in The Netherlands will increase, also because Chinese companies have started marketing their products themselves, without any middlemen. He also thinks the sustainable procurements policy of the Dutch governments is very favorable for the bamboo-sector, especially because bamboo is now more likely to be used in large projects.
- Since he started pioneering with bamboo in The Netherlands, one of his goals was to find an alternative for tropical hardwoods in bamboo. After a long product development stage in China, bamboo composite became a stable and high quality product. Now he sources his bamboo composite from there, and believes he succeeded in reaching his goal of offering an alternative to tropical hardwoods. He believes bamboo composite is the material from bamboo which has a shiny future for exterior applications, and not laminated bamboo (even if treated). He sees all the applications in Annex 9 - question 4, as very promising for bamboo composite, and not promising for laminated bamboo. One of his current projects concerning bamboo composite in exterior use is a bridge in Heemskerk (Haasnoot), road side poles in his own municipality and maybe even furniture for public spaces (Delta street furniture).
- Concerning sustainability, he pictures bamboo as without any counterpart (regarding its Life Cycle Analysis, high production etc.), which he regards as bamboo’s main advantage to timber.
- Although he currently supplies bamboo composites for non-KOMO applications, he sees this as a main bottleneck in order to be able to supply to the Dutch construction business (especially exterior joinery applications)

Moso International (Zaag) Interview with Rene Zaal, general director
Moso is mostly focused on the interior market, but recently also aimed for the exterior market by introducing terrace decking of bamboo composites.

- Rene Zaal pictures bamboo in The Netherlands as a niche market, which is mainly interesting for decorative applications. According to him, the Dutch market for bamboo products is for 98% a market for indoor products, that roughly can be divided into 80% flooring and 20% other products (sheet material, utensils, etc.).
- He thinks the demand for products which serve both a constructive and decorative purpose (interior window frames, stairs) will rise in the future. He pictures bamboo in exterior applications to only be 1-2% of all bamboo traded in The Netherlands, but with a large growth potential (possibly up to 10% of the total market for timber in exterior uses).
- He foresees a good future for bamboo in exterior applications, but it has to be modified due to its low durability and susceptibility for moulds.
- Rene Zaal believes that bamboo composites are far better suitable for exterior applications as laminated bamboo. The durability of laminated bamboo can be improved in order to make it suitable for exterior use, but he believes this has little future due to the extra steps during production and the extra costs.
- He pictured bamboo composite to have favorable perspectives for all the different applications (see question 4 in appendix 9), and laminated bamboo to have a low chance (even sheet material which is not in direct contact with rain).
- The price of bamboo composite is quite favorable compared to many of the common tropical hardwoods (about the same as ipé, below teak and 50% above the price of bankirai).
- Rene Zaal sees the different standards in the countries where they like to market their products as a major bottleneck; they have not yet considered to apply their bamboo composite for KOMO, mainly because they do not target the market for exterior joinery applications.

BambooXL (Amsterdam) – Interview with Michiel Vos, manager projects and development
BambooXL exclusively focuses on bamboo composite, which they supply both as raw-material and finished products. They market bamboo composite as a sustainable alternative for tropical hardwoods, and aim to develop a completely bio-based bamboo composite.

- Michiel Vos pictures the bamboo sector in The Netherlands as small, but with a large potential for growth.
- BambooXL focuses mainly on the market for interior applications (flooring, stairs, guard rails, strips, etc.), and experience a large demand for these products. Michiel Vos believes the demand for bamboo in general will increase, especially due to sustainability related influences like the sustainable procurement policy of the Dutch government.
- Concerning the future for bamboo in exterior applications, he foresees a good future for bamboo composite in exterior applications.
- BambooXL does not direct any effort towards laminated bamboo, because already many company are trading this material, and also because he is not convinced about its material characteristics. He pictures bamboo composites to be suitable for just about any application of a tropical hardwood, and considered it to have favorable perspectives for all the different applications (see question 4 in Annex 9). The market for cladding is of special interest here, because there is a high demand for good quality cladding material.
- He believes the uniform material characteristics, with the possibility to steer the production according to the requirements of the final product (high or low density for example), is the main advantage compared to timber. Furthermore, the easy, fast en sustainable production of bamboo is another main advantage compared to (tropical) timber.
- A bottleneck with regard to technical aspects is the current disability of Chinese factories to produce long lengths of bamboo composite. Their main bottleneck however, is getting the material (KOMO) certified. This is really necessary in order to become a supplier for the Dutch market for exterior joinery applications like window frames.
- There are large differences between the quality of bamboo composite coming from different factories, due to the possibility to adjust the different production parameters.

Jules Janssen, (retired) professor at Technical University of Eindhoven
Jules Janssen was a professor at the TU-Eindhoven. He was the first in the world to start laboratory testing on the mechanical properties of bamboo culms. He contributed to many aspects of a better understanding of bamboo, and is without doubt one of the few Dutch bamboo experts. During his career (and even afterwards) he kept track of the bamboo related developments world wide. During the interview we spoke about many other things besides the interview-questions, from which the information was used in several parts of this report. His main ideas concerning the Dutch bamboo-sector and exterior applications are described below.
Jules Janssen typifies the Dutch bamboo-sector as very small, but nevertheless a sector which has developed itself to a professional level compared to the first introduction of bamboo products (mostly flooring) at the end of the 80's of last century. He does not consider bamboo to be a very suitable material for exterior circumstances, due to it low natural durability. There are of course many possibilities, like enormous light-weight structure of bamboo culms, but the device is always 'keep it dry'. Of the many products which can be made from laminated bamboo, he pictured sheet material (coated and turn-key delivered to the construction site) as the most promising application for exterior use. Concerning bamboo composite, he believes them to be very all-round, but remained skeptical about their viability for ground and waterworks.

Helwig Timmerfabriek B.V. – Loek Reijnardts, manager operations
Because of the difference between trading companies and producing companies in the Dutch bamboo-sector, it was chosen to pose different questions in the half-standardized interview with joinery factory Helwig (see Annex 9).

Helwig is the first joinery factory in The Netherlands which aim to use bamboo composites (supplied by BambooXL) for exterior KOMO-applications.
Their joinery factory produces mainly window and door frames.

- Helwig's main reason for choosing bamboo composite was based on its sustainable image compared to tropical hardwoods, for which they notice more and more negative perception among the consumers. They like to offer an alternative, which looks a lot like a tropical hardwood, and also exhibits similar material characteristics.
- They are only interested in bamboo composite, laminated bamboo has not been considered.
- They are currently producing indoor window and door frames from bamboo composite, and aim to start producing window frames for exterior use when the material is KOMO-certified.
Their main target groups are the government and housing-corporations; contractors are not targeted due to their 'buying at lowest possible price'* behavior.
* The price of the bamboo composite they buy ranges between € 1000-1100/m^3, which is on the high end in the range of timbers they purchase, and can be compared to merbau.
- The negative perception of tropical timbers and the sustainable perception of bamboo is for them the main advantage compared to timber (not price or material characteristics).
- KOMO-certification is their main bottleneck. There are some minor difficulties with regard to the material characteristics, of which mould (blue stain) is the most difficult at the time, but is expected to be solved soon. Another issue for them is their desire for long length material, which (up to now) is not possible to produce in China.

Annex 11 Different bamboo composites on the Dutch market

All pictures where taken from a characteristic section (tangential/radial surface). The surface is planed, and untreated (one stripe on the scale bar is 1 cm).

'Density' of Moso International (Bamboo X-treme® decking for outside)

Advanced Bamboo Composites®' of Bamboo Information Centre/Plyboo

Bamboo composite of BambooXL (dark)

Bamboo composite of BambooXL (light)