Seismic proof laminated bamboo structures

an architectural and socio-economical restart in the Groningen area

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Preface

This paper closes the first part of the graduation studio of *Architectural Engineering*. It allows to develop a better knowledge in a specific field of technological innovation in architecture and it will be the basis for the preparation of the final graduation design.

I would like to thank Martijn Stellingweff, for his valuable advices and for steering this research and Job Schroën for his guidance.

I am also grateful to experts out of different fields: Stephane Schröder, Angelo Vallozzi, Francesco Sanna, Cecilia Patrizi, Leen Spruit, Neri Salvatori, Peter Eigenraam, Gaia Salvatori, Olav Bruin, Jorge Mejia Hernandez for taking the time to discuss their view on the subject with me.

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Content

Abstract

It has become a common place that the effects of the scientific and industrial revolutions are threating our environments. This paper analyzes a specific case of the reckless exploitation of resources and the socio-economical consequences: (1) the extraction and use of fossil fuels in Groningen and the impact on Dutch economy; (2) ecological and socio-economical effects of the induced earthquakes and possibile solutions.

The Groningen gas field has been a Dutch goldmine underground for over 50 years but if no measures will be taken this will result in an impoverished area on the surface. Therefore a broader approach versus a mere building reinforcement system is required.

Applications and benefits of bamboo as a sustainable biomass material and earthquake resistant material will be discussed and analysed in order to establish whether it is possible to use laminated bamboo as a sustainable building material in the Netherlands for earthquake proof buildings and for a positive socio- economic development of the Groningen area.

Introduction

Since Francis Bacon (1561-1626) the role of science has been defined in terms of dominating and manipulating nature for the pursuit of man's well being. It is well known, however, that the effects of the scientific and industrial revolutions are threating our environments. Indeed, climate change, loss of biodiversity and dysfunctional ecosystem services are central issues in the actual world views and value systems. And yet, paradoxically, they offer great opportunities, because they may mark a turning point and make it possible to open up a thriving, if different, future. At the basis of this paper is, as a matter of fact, the concern about the reckless exploitation of resources and the increasing socio-economical consequences for the built environment in general, focusing on the specific case of the gas field with induced earthquakes in the Groningen area.

Groningen has one of the largest gas fields in Europe. From December 1963 this field provided gas for decades without creating serious problems. Since December 1991 earthquakes have become an increasingly frequent phenomenon in this area, but only in 1993 the relation between earthquakes and gas production was officially admitted by the local Dutch gas company NAM (NAM Platform 2015).
While in general earthquakes are a natural geological phenomenon, the earthquakes in Groningen, by contrast, are induced by man, because they are due to the extraction of natural gas, causing a gradual subsidence of the ground level (NAM Platform 2015). Dutch economy and government finances rely to a large extent on natural gas winning. Since the 1960s it has generated a profit of more than 265 billion of euros and it still contains ca. 1000 billion m^3 of gas (NAM Platform 2015). However, these economical interests are causing serious and worrying damages to the buildings of the area which are not built to withstand earthquakes. Researchers state that earthquakes will keep going on in the years to come (NAM Platform 2015) and so will the damages to buildings, people, liveability, and environment.

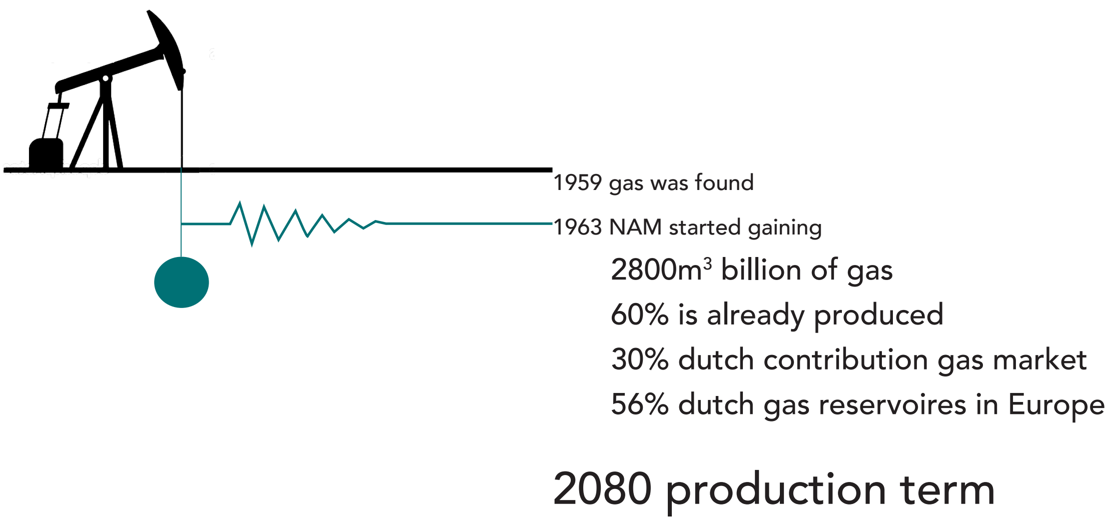

Figure 1. Earthquakes in Groningen (by the author).

What actually is a Dutch ‘goldmine’ underground may result eventually in an impoverished area on the surface. This complex issue has several aspects: (1) the extraction and use of fossil fuels and the impact on Dutch economy; (2) ecological and socio-economical effects of the induced earthquakes and possibile solutions. To be sure, these issues are interrelated, but for present purposes I focus on the latter. The transition to a low carbon urban future will probably not depend upon only one or a restricted number of technological innovations; rather it will arise from a combination of mutually interactive systems of innovations (Zari-Jenkin 2010, p. 21). Indeed, technological innovations should not be viewed as source of merely ingenious solutions that may fit all systems (Hes-du Plessis 2015, p. 34). If we see architecture as a possible binding element within this costellation of active systems, it may become the tool to achieve a systemic change in the area. The aim is in fact to come up with a new, and locally implemented, solution for a relatively recent and unexplored problem in the Netherlands, seeing this as an opportunity rather than a threat for the sustainable energy production market and for the new anti-seismic building industry.

To achieve this, a broader approach is required, because a mere technical innovation or, in this case, a building reinforcement system is surely insufficient to tackle the broader problematics I referred to above.
Thus, I am proposing a positive development strategy (Birkenland 2008, p. 76), where multiple layers of the system are involved. A study and an analysis of earthquake proof structures (see Appendix 1) have led me to the choice of a lightweight material, that is, bamboo, to start a pilot study for a new way of designing earthquake proof buildings for the Groningen area using this material as laminated construction material, considering in addition also possible biomass energy applications.

Therefore I attempt to establish whether it is possible to use laminated bamboo as a sustainable building material in the Netherlands for earthquake proof buildings and for a positive socio-economic development of the area of Groningen.

The choice of the material will be discussed (in section 1) from an ecological, economical and architectural-structural point of view. The production of bamboo, known to be a tropical species, will be analysed (in section 2) considering both options of (worldwide) import and local production, taking in account possible benefits and negative impacts of both. Subsequently, the use of bamboo (in section 3) as both biomass product (sect. 3. 1) and as anti-seismic building material (sect. 3. 2) will be analyzed. By way of conclusion (in section 4) the structural benefits and possible applications for laminated bamboo in anti-seismic constructions are pointed out and resolved in practical design examples, with the aid of mechanical data and seismic configurations.

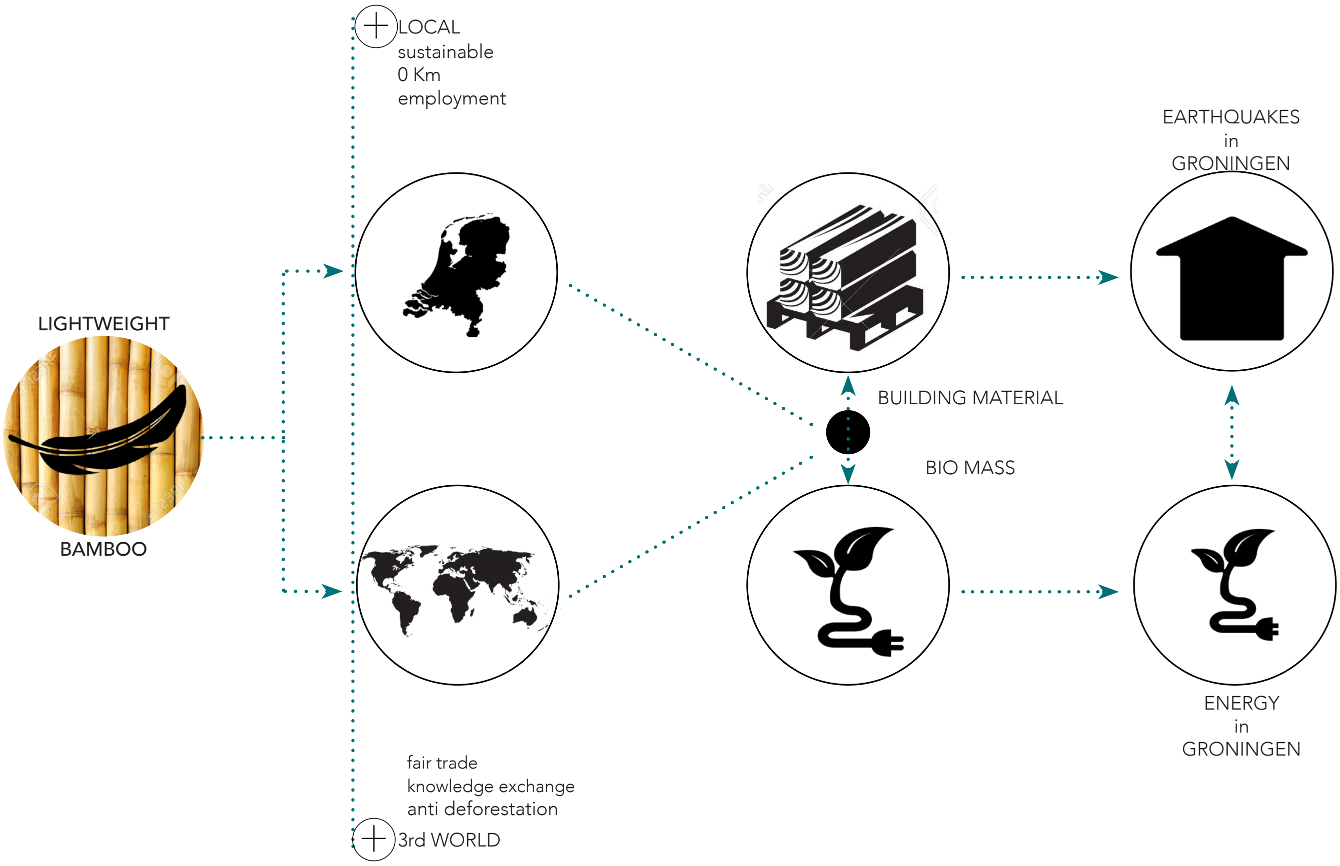

Figure 2. Anti Seismic Bamboo (by the author).

Methods and limits

Before starting the technical research, a site visit has been done in the seismic area of Groningen in order to get an overview of the architecture of the area, the damages, and the local environment and landscape (see Appendix 2).

Two parallel research paths have been followed for the research of the use of bamboo as biomass production and as building material, focusing then more on the latter.

As to the research into the use of bamboo as biomass research, there are several papers that prove the theoretical good performance of this material, but there is only one field study regarding an environment which from a climatic and soil type point of view is similar to the Netherlands. This research has been carried out by Oprins Plants©, a company from Belgium which has runned filed tests over 5 years to test the feasability of such a possibility for Europe. However, different pilot plantations should be set up in different parts of Europe over longer periods of time (over 5 years) to check whether the assumptions and results are correct.

Then, in order to achieve more knowledge about the subject of raw and laminated bamboo, mainly literature study has been done. The application of bamboo in general and laminated bamboo in particular is a relatively recent issue that has attracted much attention. Thus, quite a lot of papers, books and studies are available in the academic world of engineering and architecture. All these scientific studies offer useful overviews of structural data and physical properties, but unfortunately application examples are fairly scarce. The data and information show in fact that an earthquake proof application of laminated bamboo is theoretically possible but not yet applied in construction practices, at least not in the Netherlands, and detailed examples of foreign applications have not been found. Examples of anti-seismic applications of raw bamboo culms structures are available but not considered relevant as case study for this research, because of the different structural design and connection used.

To get a better view on how this 'new' European material is seen by the building industry, an interview has been conducted with the Technical Director and structural bamboo expert of the Bamboo Import Europe© company, which is the main bamboo import company in the Netherlands. Several informations about import benefits, material characteristics and opportunity of the Dutch market in relation with the anti-seismic phenomenon were gained. At Bamboo Import Europe© they are experts of the material itself, but they have no experience in seismic design or structural applications of laminated bamboo, since in the Netherlands it is mostly used for furniture or interior applications. However, they were convinced of the huge structural, economical and sustainable potential of the material related to the seismic phenomena in Groningen.

Good laboratories tests and data are available to determine the properties and the strengths of the material. But there are no rules of thumb to determine the dimensions of laminated bamboo structures. These rules have been calculated by myself (with static and mechanical formulas of statical and material sciences) and it should be underlined that my calculations have not (yet) been tested in a Civil Engineering lab. For the structural part of the research and for the static calculations, I had the benefit of the aid of Ir. A. Vallozzi, former MSc in Civil Engineering at TU Delft and now Senior Structural Engineer at Seaway Heavy Lifting NL. However, although Vallozzi is a structure expert, he has no experience in anti-seismic use of laminated bamboo; indeed, his support was just theoretical.

For the seismic design part basic (lightweight-wood) earhquake structures have been analyzed and combined with the laminated bamboo application methods. For the material connections laminated bamboo can be treated like laminated wood; the difference is in the dimensions of the elements and the seismic structures design that have to be applied. Research by design have been done for the connections between those elements trying to keep the structures as much lightweight possible, adapting the laminated wood connections to the laminated bamboo elements. The outcomes are the basis for further design.

Concluding, the overall limit of those methods is that bamboo has never been used as an anti-seismic structural material in the Netherlands nor for biomass production. Mine is, therefore, an experimental study and plan, and possible costs are not a restriction factor.

OPRINS

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1. Why bamboo

Each intervention or innovation, technological or architectural, will affect the whole and it should cross over multiple system boundaries in order to have a balanced impact on the system itself. In a neutral kind of practice the whole system should be in balance. In ancient Greek the terms of the main elements of the system itself had the same linguistic root: *οίκος* (for house, home, family), *οίκο-λογία* (for ecology) and *οικο-νομία* (for economy). In effect, they belong to a common linguistic and conceptual realm. In my view, they do not only share a common root but they also share a common goal and significance.
In this section the possibilities of bamboo (in the fields of *οίκος* - *οίκο-λογία* - *οικο-νομία*) to solve the interconnected problems of the Groningen area are analysed to see if this material can be the solving and binding element. In other words, is bamboo, as the famous bamboo architect Oscar Hidalgo Lopez stated, "the gift of the gods"? (Lopez 2003).

Figure 3. Bamboo (by the author).

1. 1 Ecology

Considering that the world population in 2050 will reach 8,9 billion (compareed to the 6 billion of 2000) we certainly will need "a gift of the gods". Predictions state that the consumer rate will be doubled in 2050 and annually 13 million of hectares are being deforested (Vos 2014, p. 1). More in detail, in 2003 (Vogtlander-van der Lugt-Brezet 2010, p. 1261) the ecological footprint was 14,1 billion hectares whereas the global productive area was 11,2 billion hectares. This means that man is currently consuming more than 1,25 times the amount of resources the earth can produce. A similar situation will lead, *inter alia*, to deforestation, resulting in carbon emissions caused by less carbon sequestration (Lugt-Vogtländer-Vegte-Brezet 2014, p. 77). Building materials are commonly selected through functional, technical and financial requirements. However with sustainability as a key issue in the last decades, also the environmental load of building materials has become a more important criterion. In 1990 the relationship with the world population, average welfare rate and environmental impact of welfare commodities was introduced demonstrating the need of achieving a factor 20 environmental improvement by the year 2040. Approximately 60% of the environmental load of building materials in Dutch governamental offices is caused by the supporting structure of buildings. Bamboo as a fast growing and renewable material is expected to be a sustainable alternative for more traditional structural materials, such as concrete, steel and timber (Lugt-Dobbelsteen-Janssen 2005, p. 648). Moreover the results of LCA analysis show that bamboo can achieve a factor "20" environmental impact, which means that it has 20 times less load on the environment than currenlty used alternatives (Mahdavi-Clouston-Arwade 2011, p. 1036).
The state of the art is that in Western Europe and in the United Stated laminated bamboo is not officially recognized as a structural building material. This prevents it from being accepted freely by the construction industry. It is in fact mainly used for non-structural applications. In Europe or USA in fact it is not an indigenous product and lack of knowledge prevents a broader use and intensive application.

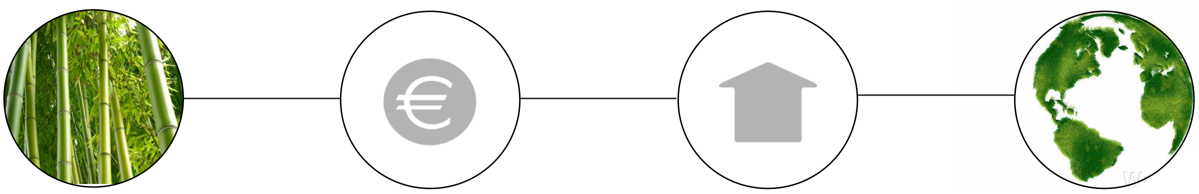


Figure 4.a Why bamboo (by the author).

1.2 Economy

Bamboo could obviously have advantages for our building industry. It has extraordinarry mechanical properties, it can grow in areas which are non productive at the moment, it has a very high yield and its roots stay intact after harvesting. Bamboo could be an even better solution if we combine and integrate the opportunities of the new Dutch seismic market and the problems of Groningen (socio-economic shrink). Since the value of laminated bamboo is added locally, this industrial bamboo material could make a good contribution in terms of local employment (Vogtländer-van der Lugt-Brezet 2010, p. 1261). Production, manufacture and application can generate a positive intervention in the area (Poppens-Dam-Elbersen 2012) for structural applications. And if we consider to use this material for bioenergy production as a possible alternative after the extinction of the natural gas field, this will generate 3 to 4 times more employment than natural gas and petroleum production. A possible bioenergy powerplant would have a socio-economic impact with the creation of sustainable jobs (Gielis 2001, p. 9).

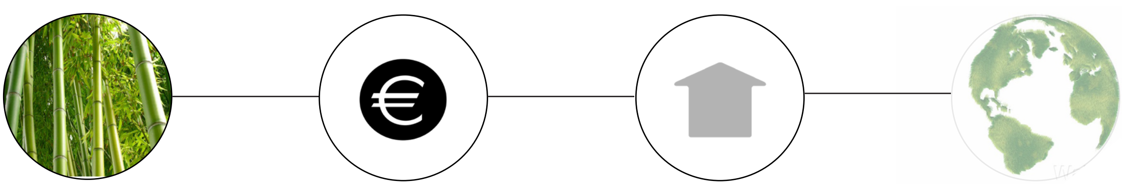


Figure 4.b Why bamboo (by the author).

1.3 Built environment

It should be stressed that for present purposes the benefits listed above are merely additional advantages with respect to those generated by employing laminated bamboo for structural applications in antiseismic solutions. Test results show that the strength and stiffness (the most important proprieties when looking for a material for antiseismic proposals) of bamboo are comparable to those of wood, making bamboo capable of replacing wood in structural applications from a load carrying standpoint. Also the strength to weight ration of bamboo is far better that those of structural steel, aluminium alloy, cast iron, timber and concrete, showing that it has a very efficient load bearing capability and thus efficient anti-seismic potentials (Mahdavi-Clouston-Arwade 2011, p. 1041).

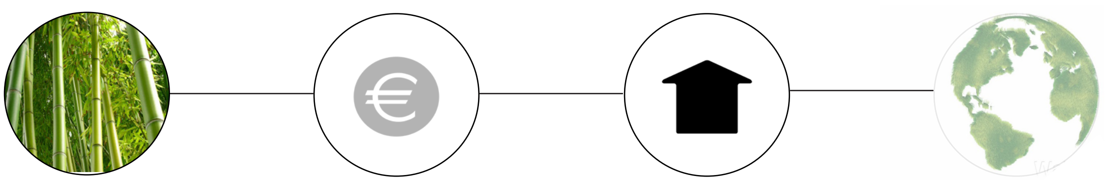


Figure 4.c Why bamboo (by the author).

2. Production

In order to let bamboo be a binding element and a solution for the problems mentioned in the previous chapter this material has to meet the criteria of the European market and building industry.

If bamboo is to become a global product and fulfil a significant role in the use of natural resources in building and constructions, it needs to become easy to use, standardised and competitive (Flander-Rovers 2008, p. 210). Bamboo needs to be accepted as an alternative for concrete, bricks, plastic and wood, by using it in modern innovative constructions products such as laminated structural elements (figure 6). But, to let it be an advantageous alternative and a competitive material, also from an eco-cost prospective, it is recommended to use it only in Europe in applications in which the specific competitive advantages of it are utilized, like its elasticity and capacity to absorb energy. Those properties make this species in fact ideal for seismic resistant constructions (Vogtländer-van der Lugt-Brezet 2010, p. 1268).

De Flander and Rovers (Flander-Rovers 2008, p. 212) state that bamboo can contribute to a real shift in resource management if we can prove that bamboo has potential as a modern construction material. To do so the challenge is to adapt bamboo to Europe, or in this case to the Netherlands, and not vice versa (Gielis 2001, p. 1).

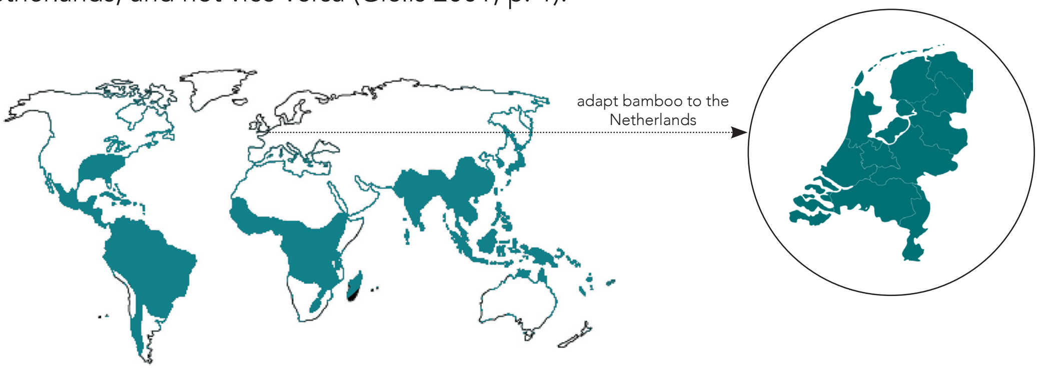


Figure 5. Adapt bamboo to the Netherlands (by the author)

Figure 6. Laminated beams (BambooImport 2015)

2.1 Species and use

In this section two options will be considered for the bamboo use and production. Structural bamboo (*Guadua Angustifolia*) is a tropical species typical of South America, in particular Colombia. This species could be imported and shipped to the Netherlands or it could be, from an experimental point of view, be produced locally in greenhouses for the fabrication of laminated structural elements. Some other species (for non-structural use) can grow in the Northern European environment. For example, species like the *Phyllostachys Aurea* can grow on the fields but only with biomass energy proposals (or for B quality products similar to wooden MDF panels).
Those two production options give two potential solutions for two interconnected problems in Groningen (figure 7). On the one hand laminated structural elements (from *Guadua Angustifolia Bamboo*) for antiseismic constructions in Groningen, on the other biomass energy production (from *Phyllostachys Aurea Bamboo*) that can be a valid alternative after the extinction of the natural gas field that caused the earthquakes in the first place.

Figure 7. Species and use(by the author)

2.2 Import and yield

At the moment, bamboo is usually imported through the Rotterdam harbour. This remains a feasible option, but since we are focusing on the earthquake area in Groningen, one should take into account the option of the use of the Eemshaven (harbour) near Groningen. It is in fact the main commercial harbour in the northern territory of the Netherlands. From a commercial point of view and looking at price breakdown (figure 8) after the shipment of the raw material, the import, processing and retail value is added locally and is 55% of the total value of bamboo (*CBI Product Factsheet* 2014, p. 10). From a marketing perspective this relatively new earthquake phenomenon in the Netherlands can be seen also as a new market opportunity for a new product development.

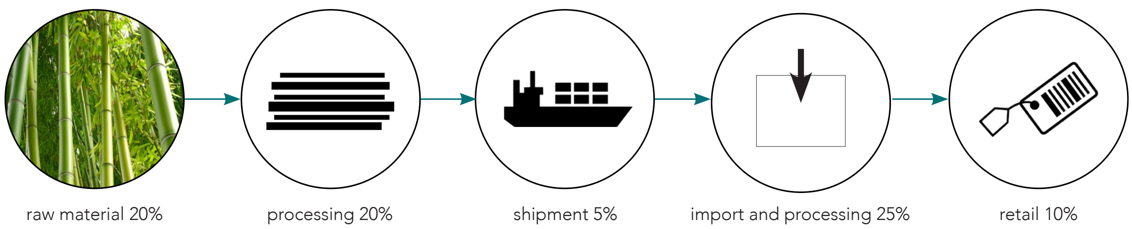


Figure 8. Price breakdown (by the author)

Because of its high growing speed, bamboo has a lot of potential for this application. Guadua is based on a yield of almost 4 times the one of the European Oak. While Radiata Pine performes quite well compared to bamboo. A general benefit of bamboo as a reforesting crop compared to wood is the short establishment time of the bamboo plantation. Bamboo plantations will be able to deliver the annual yield of a mature plantation faster than any wood species (figure 9) (Vogtländer-van der Lugt-Brezet 2010, p. 1267). Since the demand for tropical hardwood is more than the supply from plantations (only 35-40% of FSC-wood is from plantations) trying to shift our resource management is worth a try.

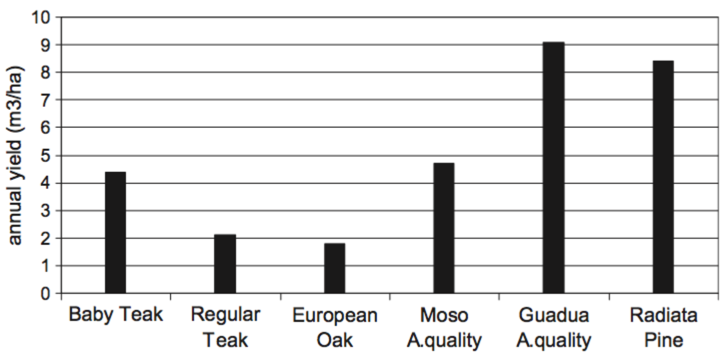


Figure 9. Bamboo yield (Vogtländer-van der Lugt-Brezet 2010)

This leads to two manufacturing-production options (figure 10): an import option where the manufactured material is shipped to the Netherlands with benefits for the local economies of the importing countries; another where the raw material is imported to the Netherlands and the added value is added locally with the manufacturing in situ.
Both are feasible options but since we are looking for a positive development of the area of Groningen a combination of import *plus* local manufacturing with local production *plus* local manufacturing must be considered.

Figure 10. Import and use (by the author)

2.3 Make it local

According to Vogtländer-van der Lugt-Brezet (Vogtländer-van der Lugt-Brezet 2010, p. 1268) if the stems of bamboo are industrially processed into engineered bamboo and transported to Western Europe the environmental edge of this material compared to the European grown wood species is lost mainly because of the extra transport costs. Known as a tropical material, adapting it to Europe, making it local, is the challenge and the opportunity that the earthquake phenomenon in Groningen offer us for a positive economic revitalization of the area with benefits for the building industry. We are in fact considering here local production in the industrial Delftzijl area of Groningen of *Guadua Bamboo* for laminated structural elements and Phyllostachis Aurea Bamboo for biomass energy proposals (figure 11).

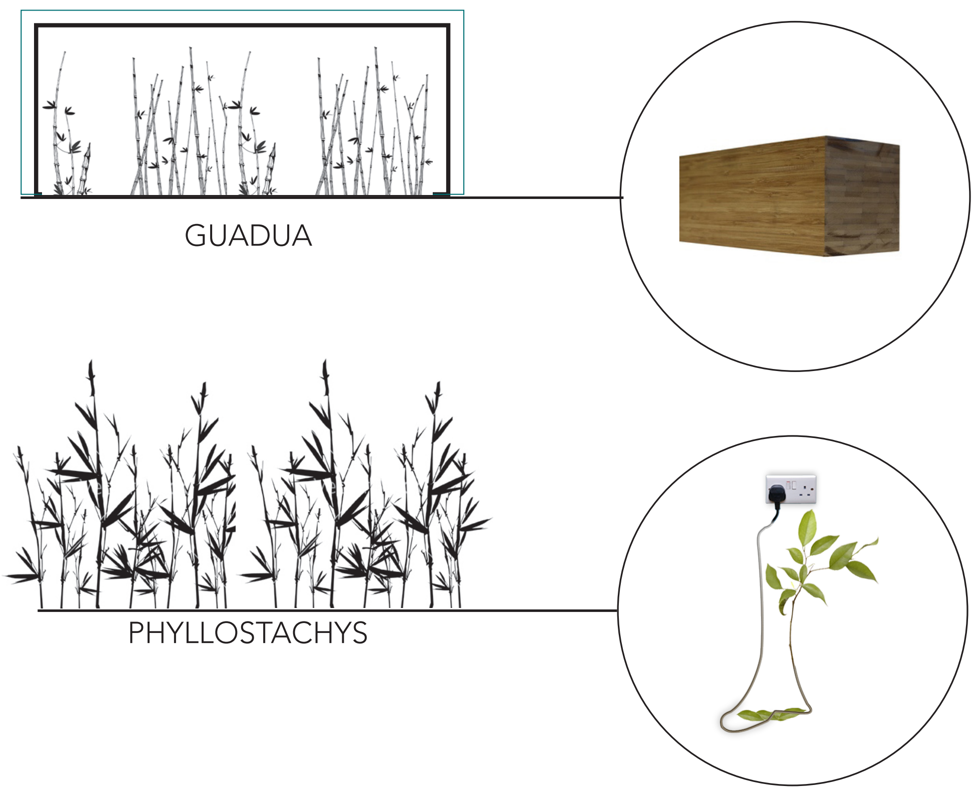


Figure 11. Make it local (by the author)

2.4 Guadua Angustifolia Production

Guadua Angustifolia can reach the full height (which is between the 15 and 25 m) within a period of 2-4 months by diurnal growth rates of about 20 cm up to 100 cm (Xiao-Yang-Shan 2013, p. 766). Guadua bamboo can be harvested 3 to 5 years after the sprouts pops up (figure 13). This is because it needs 3 to 4 years to lignify and reaches its stiffness (Vongsingha-Vos-Moya 2014, p. 4). It should be planted in conditions as similar as possible to its original habitat, which might raise a problem. But this should not be an obstacle because one may seek the assistance of a professional agriculturist for the correction of unfavorable chemical soil conditions in order to provide better fertility and chemical conditions for the cultivation of this species. The soil (figure 12) of the north-east part of the Netherlands is between loam and sandy loam which could be a good basis for the production and growth of Guadua bamboo (Schroder 2012, p. 6). But the Netherlands has an oceanic climate heavily influenced by the Gulf stream, the temperature amplitude does not exceed 8-9° Celsius and most of the precipitations are in the winter period. The average yearly precipitation is around 812 mm while Guadua needs 2200 mm, but the ph of the soil (6,3-6,5ph) is on average. From a research conducted at the TU Delft (Vongsingha-Vos-Moya 2014) two possible options come out to let Guadua Bamboo grow in the Netherlands; both options include extra water supply from a local creek or river. An Energy-Greenhouse or a Earth Heating Greenhouse are both feasible (but challenging and never tried before) possible solutions. Both greenhouses types should have an average heigh between the 15-20 m to let Guadua grow up to a height where it can be used for structural purposes.

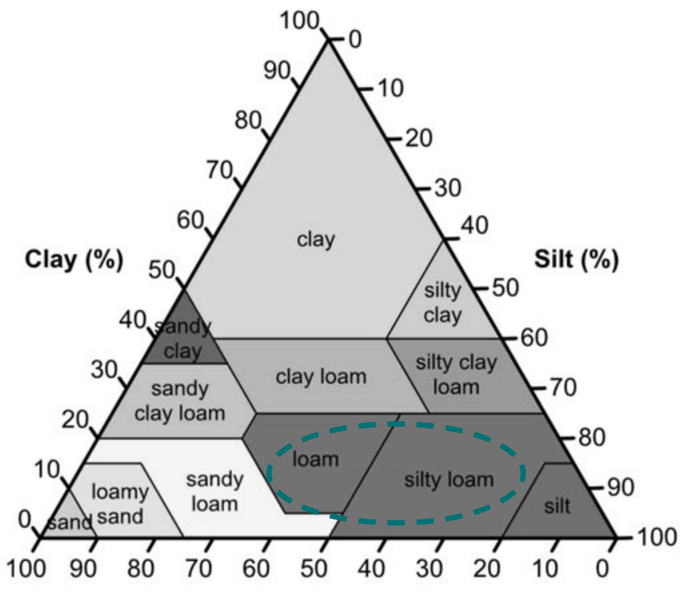


figure 8

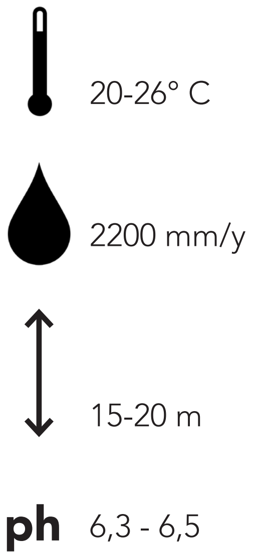


Figure 12. Growth conditions (Schroder 2012)

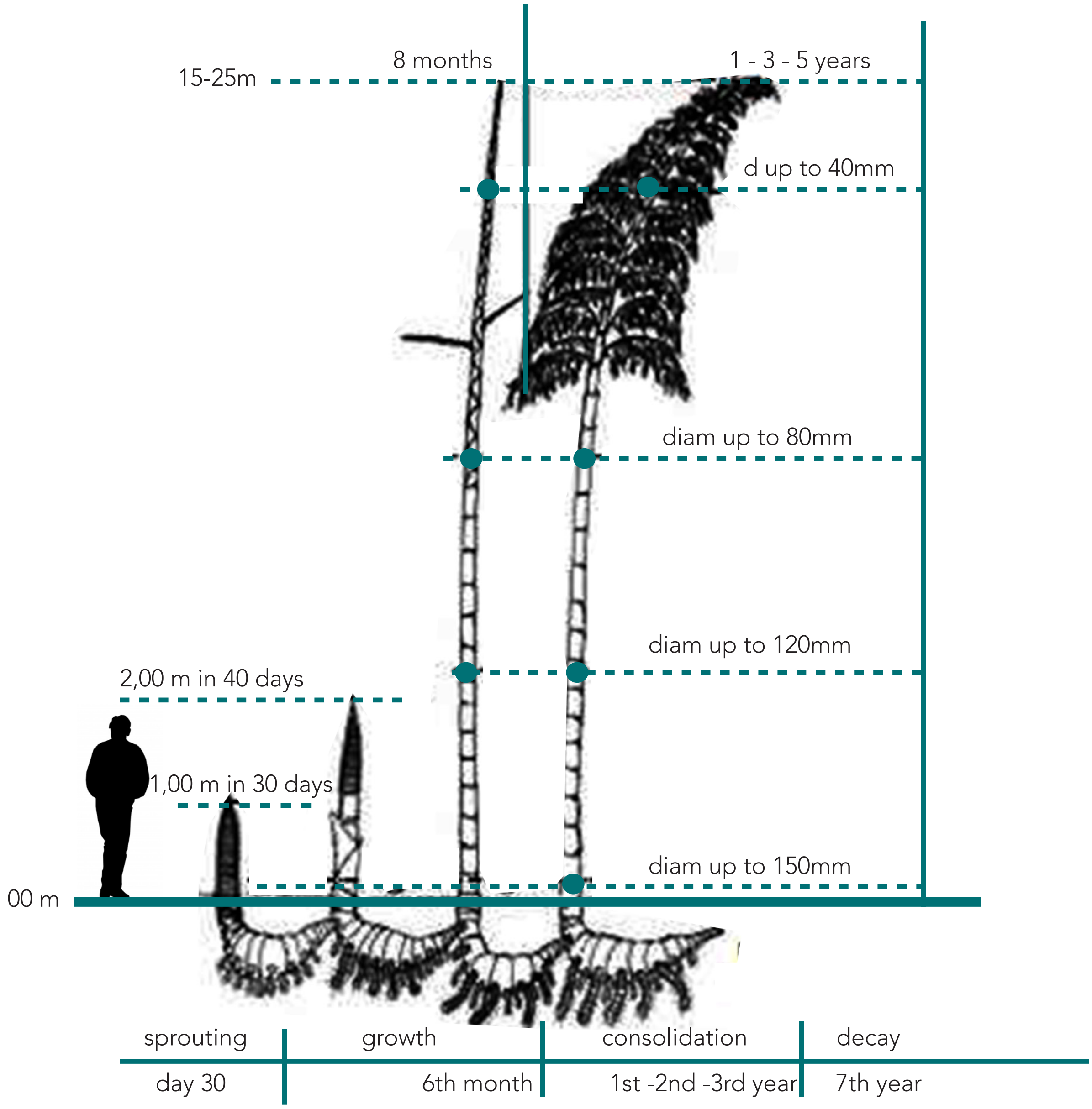


Figure 13. Guadua growth (by the author)

2.4.1 Guadua Angustifolia Production - Energy Greenhouse

The Energy Greenhouse is an energy efficient system that can produce electricity from roof wind turbines placed at a height of minimum 30 m. Roof photovoltaic panels pv generate electricity using sunlight, a heat exchanger works as ventilator in the winter keeping the temperature at a suitable level and should be switched off during summer. Radiators inside the greenhouse keep the temperature at a suitable level during winter, while adjustable facade openings during summer provide the optimal interior climate (figure 14).

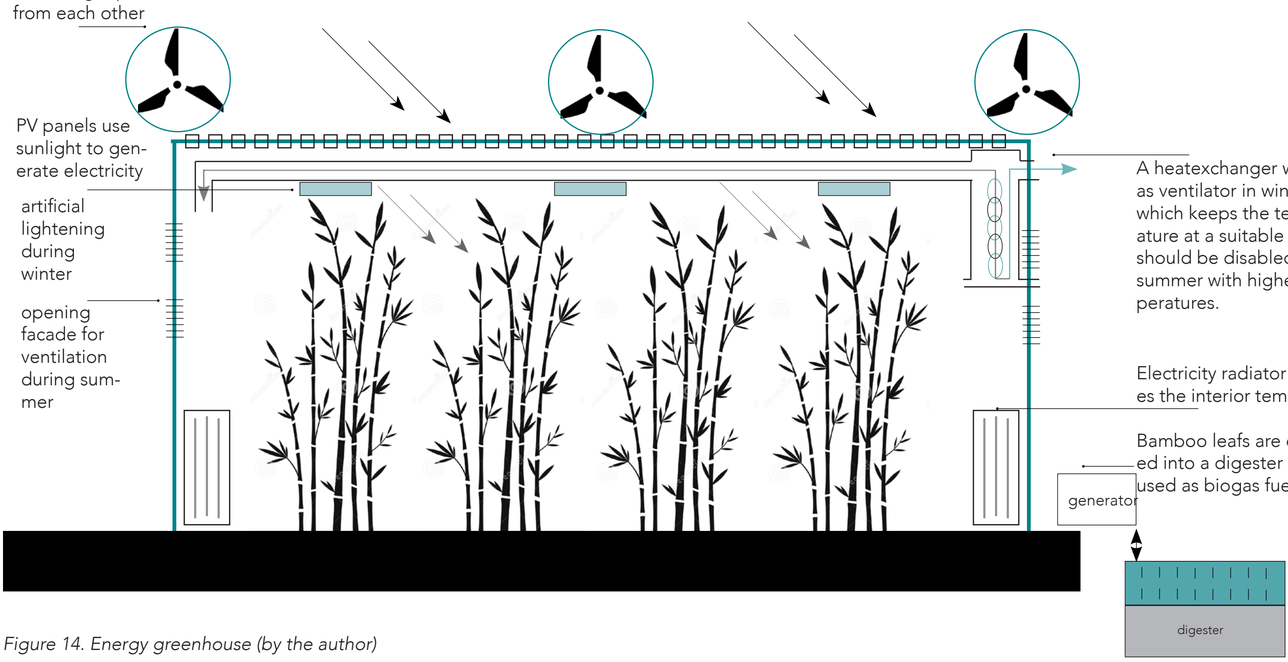


Figure 14. Energy greenhouse (by the author)

2.4.2 Guadua Angustifolia Production - Earth heating Greenhouse

The Earth heating Greenhouse is a system that uses the heat from the underground water (aquifer) to warm the greenhouse during the winter using a thermal seasonal storage. Also here a heat exchanger works as ventilator during winter and adjustable facade openings during summer provide a suitable ventilation (figures 15a-b).

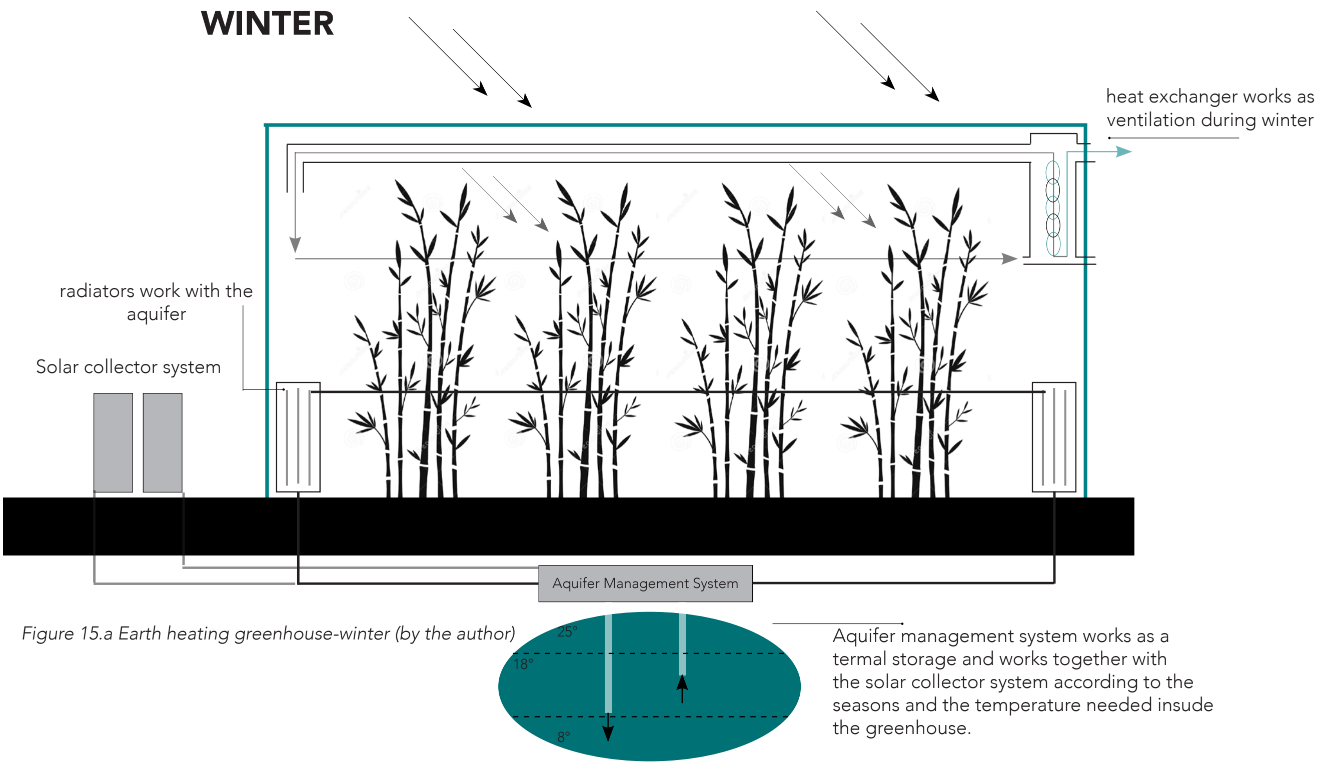


Figure 15.a Earth heating greenhouse-winter (by the author)

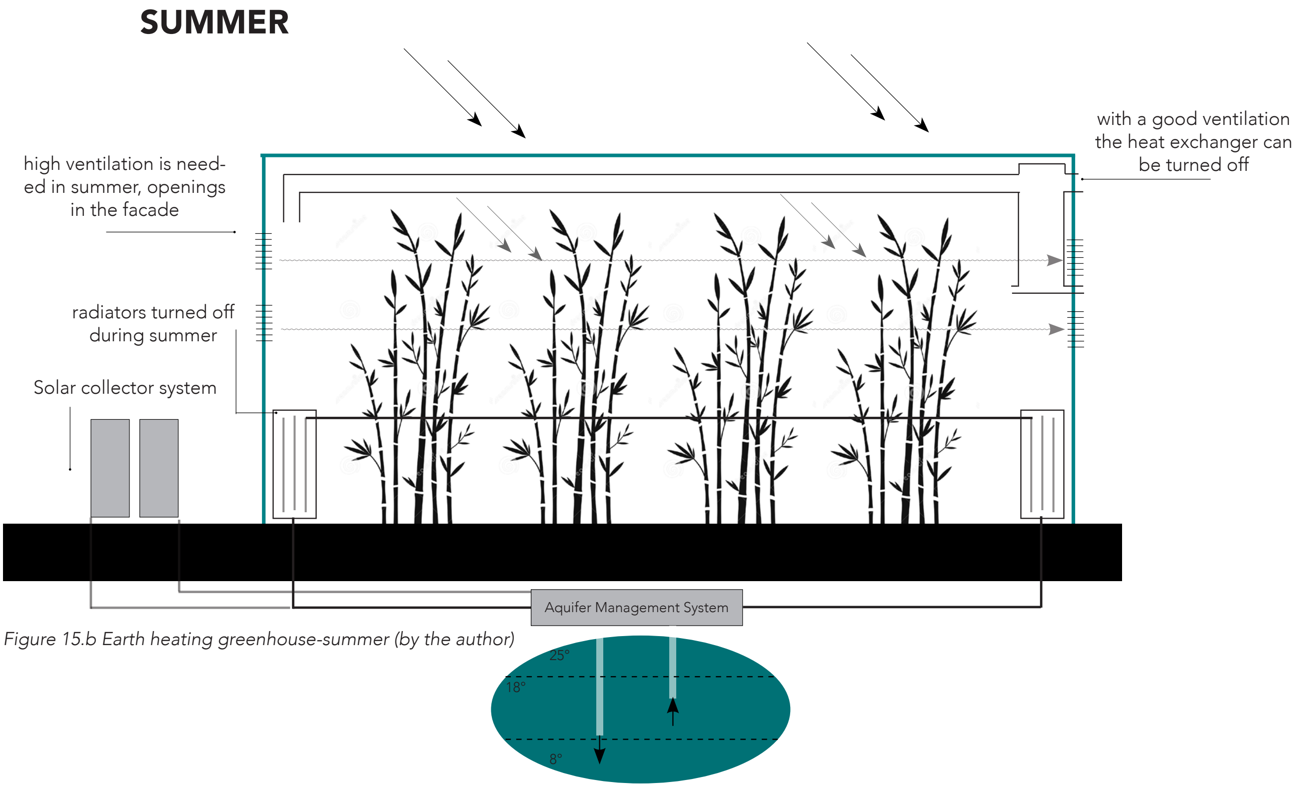


Figure 15.b Earth heating greenhouse-summer (by the author)

2.4.3 Greenhouses comparison

This last system is more suitable for large scale greenhouses and geology survey should be done beforehand to check if an aquifer solution is possible, while the energy greenhouse mentioned before has the difficulty of the turbines on the roof; here a special structure that can carry horizontal loads should be designed.
It is thus possible, from a design and theoretical point of view, to let Guadua Bamboo grow in the Netherlands. It goes without saying that field tests should be runned to see if the Greenhouse industry in the Netherlands could be expanded from food and flower production to building material production, i. e. with Guadua Bamboo. The greenhouse's dimensions would be bigger and there is no real experience with those larger typologies.
Since we are considering a local production near Delftzijl where plenty of industrial activity takes place we should consider recycling the CO_2 produced by those using it in the bamboo greenhouse(s). Purification systems have been developed to use the CO_2 produced by combustion gases in the food and greenhouse industry (TNO 2008).

2.5 Phyllostachys Aurea Production

While the results of greenhouses field tests are expected in the near future, tests for the production of bamboo for biomass proposals (on fields in Belgium) were done with positive results (Gielis 2001, pp. 1-10). The best species tested was indeed the *Phyllostachys Aurea*. In the laboratories of Oprins Plant in Belgium a very efficient technology has been developed for the mass scale propagation of this temperate kind of bamboo. This makes it possible to keep the prices of the plants down and let it be a competitive product on the European market. In fact it was necessary to develop a suitable propagation method that is commercially viable and that can give added value to plant producers, foresters and those who transform the biomass harvested. The uniformity of the culm's width and height (up to 2,5-4 m) provides in fact a major advantage for mechanical harvesting comparable to the European corn or sugarcane (Gielis 2001, p. 7).

Figure 16. Phyllostachys production (by the author)

2.6 Outcomes

While all the bamboo is nowadays imported through container shipment, research shows that both Guadua and Phyllostachys could be locally produced.
But before we analyse the uses of this production as a possible and sustainable solution for earthquake structures and energy production in Groningen, here are some outcomes.
A quantitative analysis conducted by De Flander and Rovers (Flander-Rovers 2008, p. 216) shows that laminated bamboo frame buildings could be a direct alternative for wood frame buildings. According to their calculations an average timber frame house of 175m^2 needs 13,3m^3 of wood. Since a stable Guadua plantations gives 15m^3 of laminated product (which is only 30% of the total production of a plantation) each year for one hectare, we can conclude that a hectare of Guadua bamboo produces one laminated bamboo frame house each year (figure 17). Thinking big, if we compare this potential with the construction market of the Netherlands where 3000 houses a year (out of 60. 000) are made of timber frame constructions, the bamboo production could take over part of the other non biobased mainstream construction materials such as concrete and bricks.
Concerning the Phyllostachys the production (in Belgium) is of 60 tonnes per hectares (figure 17) for biomass use (Gielis 2001, p. 4).

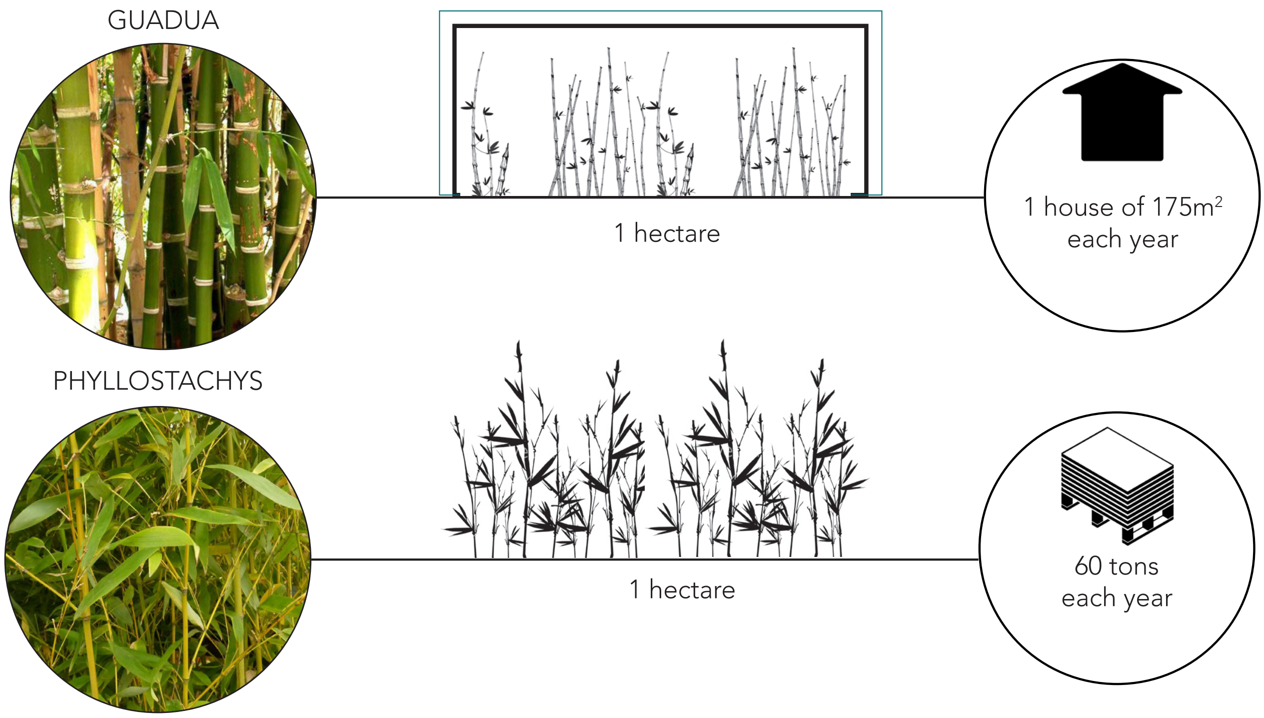


Figure 17. Production outcomes (by the author)

So in terms of annual yield it was found that bamboo is the best performing resource if used as "A quality" finished material (in housing and structures) while for "B quality" semi-finished materials (like mdf boards etc) fast growing softwood species (like Eucalyptus) are competitive compared to Guadua (figure 18) (Vogtländer-van der Lugt-Brezet 2010, p. 1268). Carbon dioxide emissions and production energy consumptions are showed in the figures 19a-b-c (Xiao-Yang-Shan 2013, p. 770).

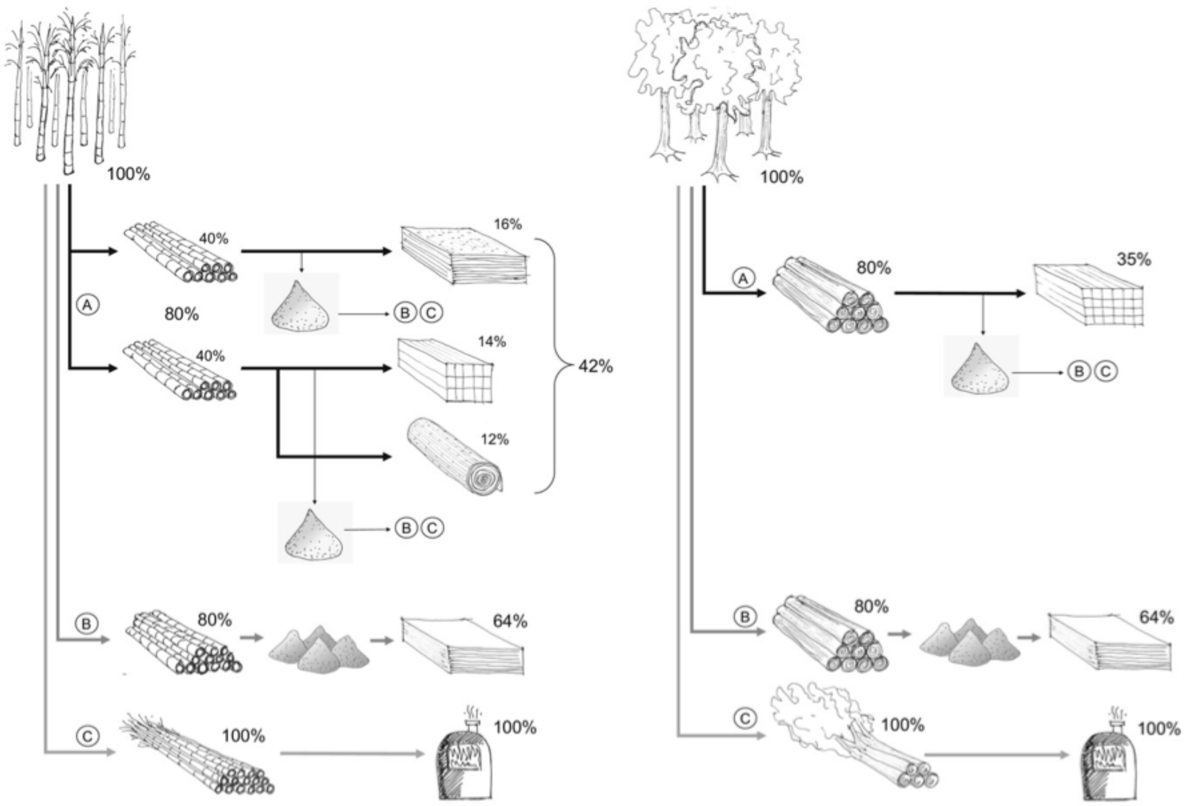


Figure 18. A vs B quality (Vogtländer-van der Lugt-Brezet 2010)

Surfaced dry lumber recovery per ha per year compared with Guadua-Bamboo

Lumber British Columbia (lumber recovery/year) surfaced dry lumber (m^3)	1 year rotation (m^3)	40 years rotation (m^3)	125 years rotation (m^3)	400 years rotation (m^3)
66.7 (=71% × 94 m^3/ha)	NA	1.67	0.53	0.17
142 (=71% × 200 m^3/ha)	NA	3.55	1.14	0.36
284.7 (=71% × 401 m^3/ha)	NA	7.12	2.28	0.71
Guadua (net recovery products/year)				
15	15 m^3	NA	NA	NA

NA: not applicable.

Figure 19.a Lumber vs Bamboo

(Xiao-Yang-Shan 2013)

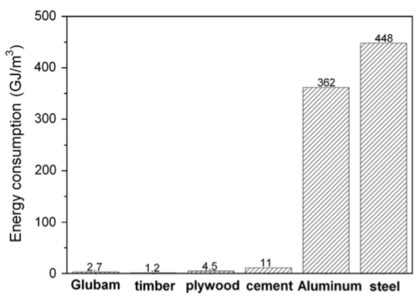


Figure 19.b Energy consumption

(Xiao-Yang-Shan 2013)

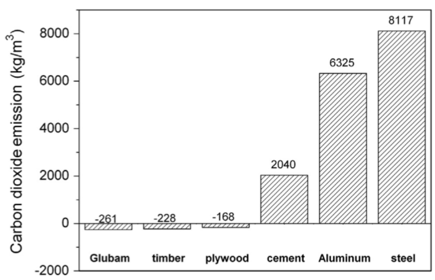


Figure 19.c Carbon dioxide emission

(Xiao-Yang-Shan 2013)

3. Use and application

It is thus possible to use laminated bamboo from Guadua as a structural building material (if imported or locally grown in greenhouses) and it is possible to use Phyllostachys for biomass use and energy production if we manage to propagate and harvest this specific species in the fields around Groningen. But, in order to achieve a real socio-economical change in the area and in order to come up with feasible structural solutions for antiseismic constructions we have to focus on the applications of those species of bamboo both as biomass use and as antiseismic building material.

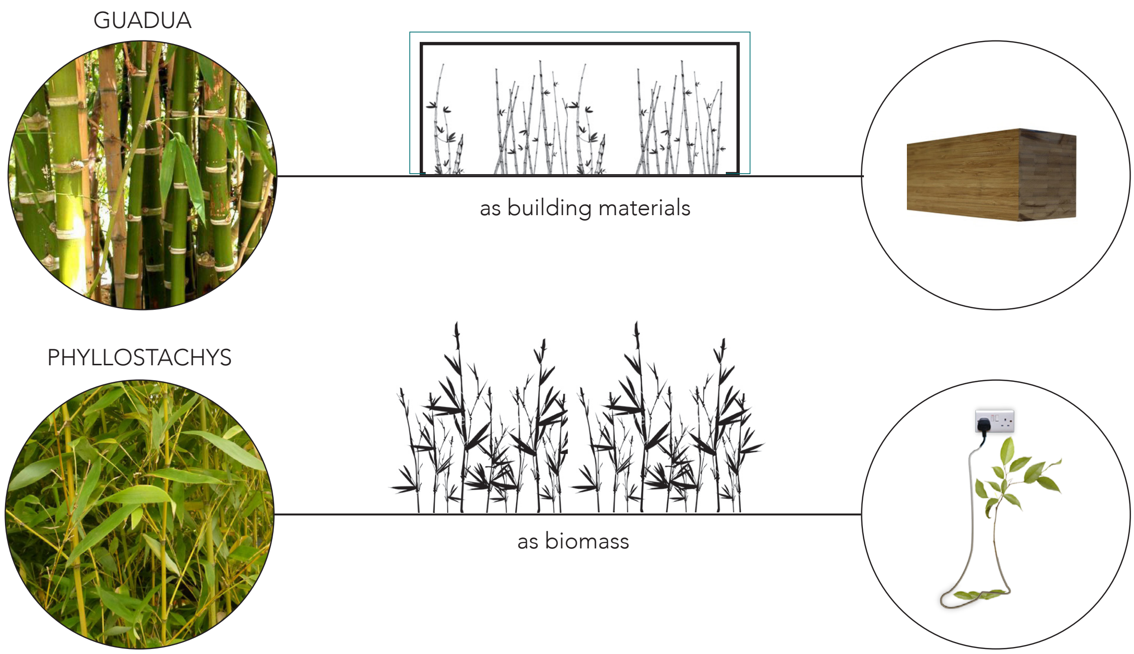


Figure 20. Use and application (by the author)

3.1 Biomass

In Europe the Renewable Energy Directive on the promotion of the use of energy from renewable sources sets targets for GHG (GreenHouse Gas) reduction. The Directive includes sustainability requirements for bio fuels and bio liquids (electricity, heating and cooling). In February 2010, the European Commission adopted a report on requirements for a sustainability scheme for solid and gaseous biomass used for generating electricity, heating and cooling (ECN 2013, p. 13).

In the past century most of our fuel demands have been met with fossil fuels, including petroleum and natural gas. However those present a great threat to health and environment. The costs of fuels do not include the ecological cost and health costs. Increase of CO_2 and carcinogenic effects are just two examples. Renewable biomass can contribute to a solution of those effects (Gielis 2001, p. 3).

Figure 21. Bamboo as biomass (by the author)

3.1.1 Yield

According to a research conducted at the University of Wageningen (Poppens-Dam-Elbersen 2012) it seems quite probably that bamboo will play an important role in the near future in the Biobased Economy. Some bamboo species, like the Phyllostachys we have seen in the previous chapter, have the best fast growing characteristics for biofuel applications. Bamboo has a low alkali index and a low ash content which make it a good biofuel material (Vogtländer-van der Lugt-Brezet 2010, p. 1269). Of course we can obtain biomass material from both species analysed before: Guadua and Phyllostachys. But since the main function of Guadua will be the use for laminated structures and since the annual biomass yield (in optimum circumstances in south America) are of 19 tons per hectare (Lugt-Dobbelsteen-Abrahams 2003, p. 213) we will focus on the Phyllostachys which can grow on the fields (according to Oprins's research) with an annual yield of 60 tons per hectares.
Moreover the Phyllostachys Aurea can be harvested over a period of 6 months and the bundles can be kept for another 3 months after harvesting, this means that bamboo can be supplied as raw material to the industry for about 8-9 months a year. Another advantage is that the roots stay intact after chopping, with no need to be replanted (Poppens-Dam-Elbersen 2012) and when grown as an agricoltural crop the biomass produced by bamboo can be considered as a renewable energy source (Gielis 2001, p. 3). Specific technical assessment for the use of bamboo as biomass are still on trial but "torrefaction" seems to be one of the most feasible processes to transform bamboo into pallets. This process assures to the finished product the 90% of the original energy content (ECN 2013, p. 8).

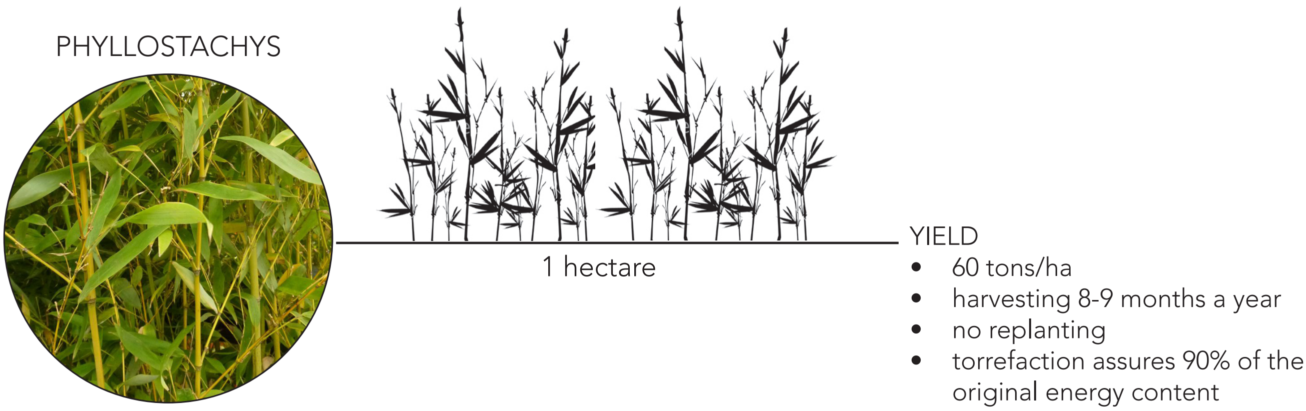


Figure 22. Phyllostachys yield (by the author)

3.1.2 Biomassa - energy

The net calorific value of bamboo is comparable or higher than other wood species like beech, spruce, eucalyptus and poplars, and stays in a range of 18,3-19,7 MJ/kg. But the annual production of plantations is 3 times as great with respect to an average timber forest (figure 24) (Lugt-Dobbelsteen-Janssen 2005). Its heating value, however, is 5-10 % lower than softwood (Lugt-Dobbelsteen-Janssen 2005, p. 652) and its calorific value is 25-30 % of natural gas (Gielis 2001, p. 8). The reference GHG emissions value for coal and gas based electricity is 198 kg of CO_2/MJ. The resulting GHG emissions of the bamboo chain are calculated as 26 kg of CO_2/MJ. When calculated along the complete supply chain, GHG emissions reductions are above 70% when compared to coal based electricity in the Netherlands. However, as bamboo is not yet included in the list of the default biomass chains considered by the European Commission, it still needs to be proved that the GHG emissions reduction is of at least 50-70% of the fossil based route. As there are no default values for bamboo plantations, the GHG emissions reductions data needs to be demonstrated, therefore monitoring activities are required (ECN 2013, p. 18).

ENERGY

- 10% lower energy than softwood
- 70% lower energy than gas
- -->70% less CO_2 emissions

Figure 23. Phyllostachys energy (by the author)

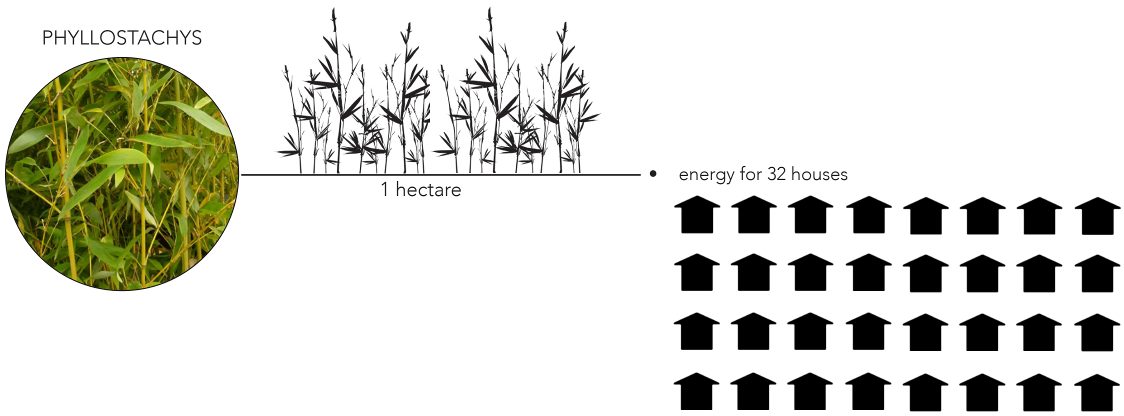
Annual production of plantations for producing wood and bamboo [17,19]

	Green (total)	Dry (total)	Green (culm only)	Dry (culm only)
Annual production (tons/ha)				
Bamboo	78.3	47.4	55.7	36.0
Wood	17.5	13.5	14.0	10.8
Ratio bamboo/wood	4.5	3.5	4.0	3.3

Figure 24. Phyllostachys yield (Lugt-Dobbelsteen-Janssen 2005)

3.1.3 Biomass - application

According to my calculations, as shown below (figure 25), the assumed field production of Phyllostachys Aurea of just one hectare in the seismic area around Groningen will produce energy for 32 households each year. While the Guadua rests from manufacturing could produce bio energy for 9.
Those numbers explain why the interest in bamboo as an alternative feedstock is increasing rapidly. However, the end use of the feedstock and the supply chain development requires the direct involvement of the private sector as well as the support of public institutions. The development of the supply chain requires an active role of all actors involved in the market (ECN 2013, p. 17). But when introduced into the market all the data suggest that it will have a positive socio-economic impact (Gielis 2001, p. 10).
A plant that we know as ornamental in our gardens can thus have such an impact and perhaps shift our energy management resources towards a more sustainable one being an alternative or an implementing factor for energy production in the seismic area of the Netherlands during the extinction of the natural gas fields managed by the local NAM industry.



LaminatedBamboo_BioMass_Calculations

Phyllostachys aurea, field production.

60.000 kg per ha à 19,7 MJ/Kg

19,7 MJ/Kg . 60.000 kg = 1.176.000 MJ = 326.666 kW

1 house = 10000kWh a year (6 pp unit) ((yearly energy consume/house))

326.666 kW : 10000kWh/y = 32,6 houses/y energy production

Guadua angustafolia, greenhouse (rests) production.

19000 kg per ha à 18 MJ/Kg

18 MJ/Kg . 19000kg = 342000MJ = 95000 kW

1 house = 10000kWh a year (6 pp unit) ((yearly energy consume/house))

95000 kW : 10000kWh/y = 9,5 houses/y energy production

Figure 25. Biomass application (by the author)

3.2 Building material

Engineered bamboo has the potential to be a competitive product in the marketplace. Bamboo has several advantages over other materials and offers not only strength but aesthetic value too. The use of bamboo in construction is still an emerging field, as is the use of engineered bamboo pruducts (figure 26). These products have properties that in some cases exceed those of structural timber, yet they are used inefficiently in solely ornamental applications. Several factors need to be addressed for engineered bamboo products to be used to in construction. While studies demonstrate the increasing interest, there is also a need for further testing (figure 27 a-b) based on standardised methods, such as existing timber methods (Sharma et al. 2014, p. 8).

Here is offered an attempt to develop this knowledge further hoping that soon also the codification necessary will be developed to use this material in the market as a competitive and sustainable alternative to conventional structural materials.

Figure 26. Engineerd bamboo (BambooImport 2015)

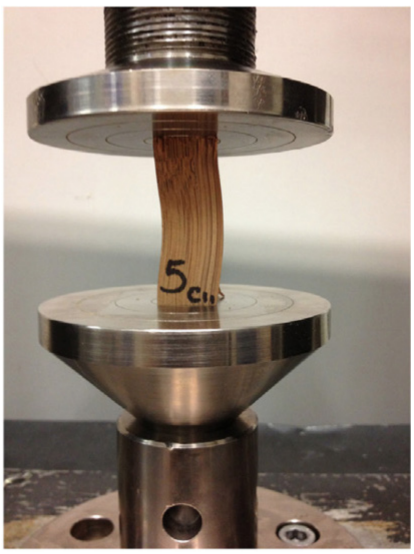


Figure 27.a Bamboo testing (Sharma et al. 2014)

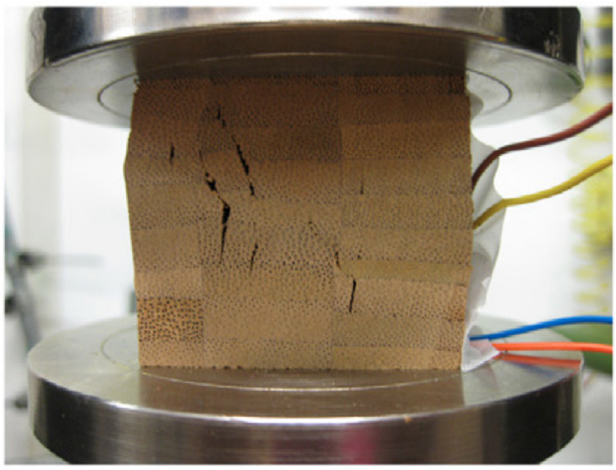


Figure 27.b Bamboo testing (Sharma et al. 2014)

3.2.1 Building material - lamination

Laminated bamboo is manufactured with culms that are split in half, then the bamboo is planed into thin strips that are glued then heated and pressed to form the laminated elements (figure 28) (Sharma et al. 2014, p. 5). Although it is more efficient to apply just a thin layer of adhesive and since the outer surfaces do not bond well with one another the stacks can be arranged so that the inner surfaces of the middle layers form the centermost interfaces and the inners surfaces of the outer layers contact the outer surfaces of the inner layer (figure 29). An example of such processing is the trademarked material GluBam© imitating the well known GluLam or glue laminated timber, which is started to be used for housing in China. This process, however, creates a high strength composite that reduces the influence of the fibre gradation, which can affect the mechanical performance.

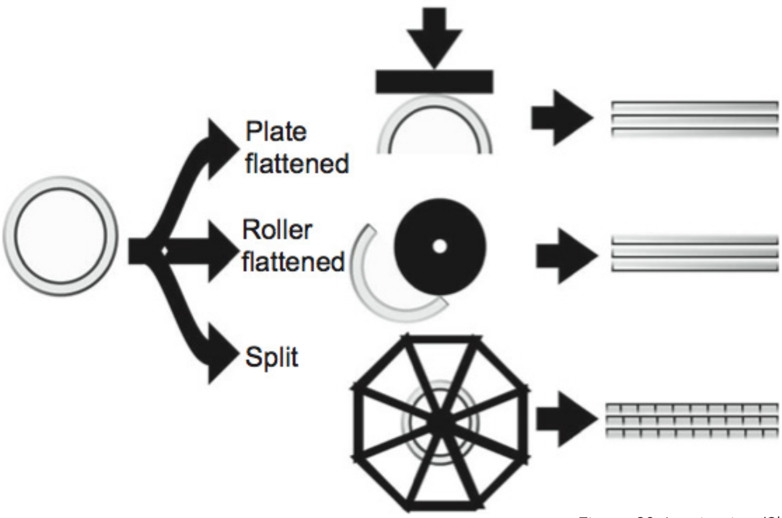


Figure 28. Lamination (Sharma et al. 2014)

outer surface
inner surface
outer surface
inner surface
inner surface
outer surface
inner surface
outer surface

Figure 29. Layers (by the author)

3.2.2 Building material - strength

Bamboo is in its natural form a highly efficient material. But with lamination processes it becomes a potential material for structural use in Western countries. As shown in the scheme below (figure 30) the mechanical data of laminated bamboo from Guadua Bamboo is interesting compared to timber (Sharma-Gatòo-Bock-Ramage 2015, p. 69).

According to this study of 2015 the Modul of Elasticity is between the 11-13 GPa and the Modul of Rupture around 77–83 Mpa. However another current study demonstrates that the Elastic Modul can go up to 19-21 Gpa (Becker 2013, p. 197) instead of only 11-13 GPa, while according to Sharma (Sharma et al. 2014, p. 8) the Module of Rupture is between 39-145 Mpa and the Module of Elasticity between 7–14 GPa.
On the basis of the available data it is impossible to establish which of those is most close to reality. More knowledge has to be gained and more tests have to be run to come up with clearer results. It is likely that those different data are the result of slightly different test procedures or manufacturing processes.
For this study the Module of Rupture (MoR) has been considered between 77-102 MPa and the Module of Elasticity (MoE) between the 13-19 GPa, which correspond to the data reported on most of the academic studies taken into account for this research.

Material properties for structural bamboo and comparable natural bamboo and timber products.

		Density	Compression		Tension		Shear	Flexural		$\frac{E_b}{\rho}$
		ρ kg/m^3	$f_{c\parallel}$ MPa	$f_{c\perp}$ MPa	$f_{t\parallel}$ MPa	$f_{t\perp}$ MPa	$\tau_{\parallel}$ MPa	f_b MPa	E_b GPa	10^6 (m^2 s^{-2})
Laminated bamboo[a]	$\bar{x}$	686	77	22	90	2	16	77–83	11–13	16–19
	COV	0.05	0.05	0.07	0.26	0.13	0.05	0.06–0.08	0.05–0.06	
Bamboo scrimber[a]	$\bar{x}$	1163	86	37	120	3	15	119	13	11
	COV	0.02	0.02	0.05	0.14	0.13	0.11	0.08	0.04	
Raw Bamboo *Phyllostachys pubescens* [b,c]	$\bar{x}$	666	53	–	153	–	16	135	9	14
Sitka spruce [d,e]	$\bar{x}$	383	36	–	59	–	9	67	8	21
Douglas-fir LVL[f,g]	$\bar{x}$	520	57	–	49	–	11	68	13	25

Figure 30. Mechanical data laminated bamboo (Sharma et al. 2015)

3.2.3 Building material - bamboo vs timber

It is easier to understand the significance of those numbers comparing bamboo with timber. The ratio of strength over density of the bamboo pole, indicating material efficiency, is 2,5 times higher than wood and 3 times higher than steel. The efficiency of bamboo is mainly because of the lightness associated with its high strength, the modulus of elasticity or the stiffness is almost one tenth of structural steel. Laminated bamboo has 1,5 times more stiffness than wood lumber by comparing their Module of Elasticity. If laminated bamboo is used, for instance, in the same way as wood, it will provide extra protection of earthquake movement (Rittironk-Elnieiri 2008, p. 91). Similar to timber, the strength perpendicular to grain is significantly lower than the strength parallel to grain (Sharma-Gatòo-Bock-Ramage 2015, p. 72).

3.2.4 Building material - earthquake resistant

But the interesting application of this new biobased engineered material is in the anti-seismic field. According to an MIT research (MIT 2014) the earthquake and hurricane resistance of (raw) bamboo is due to the fact that its strength in combination with its low mass make bamboo a favourable material in disaster prone regions. For example 30 homes located near the epicenter of a 7.6 magnitude rector scale earthquake in Costa Rica survived the disaster without any major damage. Bamboo also does not have rays, radiating curves in wood, which are mechanically weak and therefore bamboo is better in resisting shear than timber elements. The ration strength / mass per volume is shown in the table below (figure 31). This is the main property that makes it an excellent building material for earthquake prone regions. Laminated bamboo has been successfully used, for example, for the design of temporary buildings in the area of Sichuan, devastated by the earthquake in May, 2008 (Xiao-Yang-Shan 2013, p. 772).

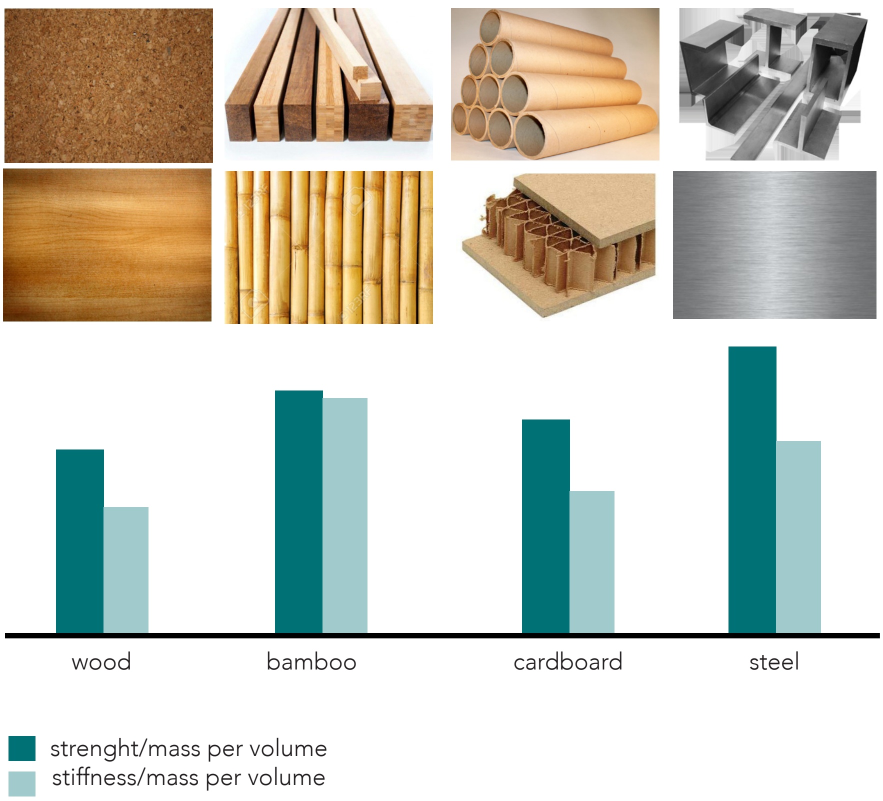


Figure 31. Bamboo strenght and stiffness (by the author)

3.2.5 Building material - shaking table test

A laboratory test (figure 32) has been run and commented by Aicher, Reinhardt and Garrecht in 2014 (Aicher-Reinhardt-Garrecht 2014, p. 599). Here a full scale lightweight frame laminated bamboo room model was tested on a shaking table, with peak input accelleration up to 0,5g. The result showed excellent seismic resistance. Only some minor damages, such as pulling out or penetrating of nails from or through shating board, were observed when seismic accelleration was 0,5g. This is especially interesting considering that in Groningen damages to houses and risk for people occur from a peak ground accelleration of just 0,1g (NAM Platform 2015). The full scale room model used in the shake table test was reconstructed with finishing of the inside surfaces by gypsum boards and voids filled with rock wool. In addition, fire resistance was tested placing a wood crib at the centre of the room. This was then ignited and allowed to burn for an hour to test the integrity of the lightweight frame laminated bamboo building. After one hour of exposure to fire inside the room, the structures of the walls and the ceilings were essentially intact. Like timber structures, the existence of carbonization layer under fire can delay further penetrating of fire into the structure.

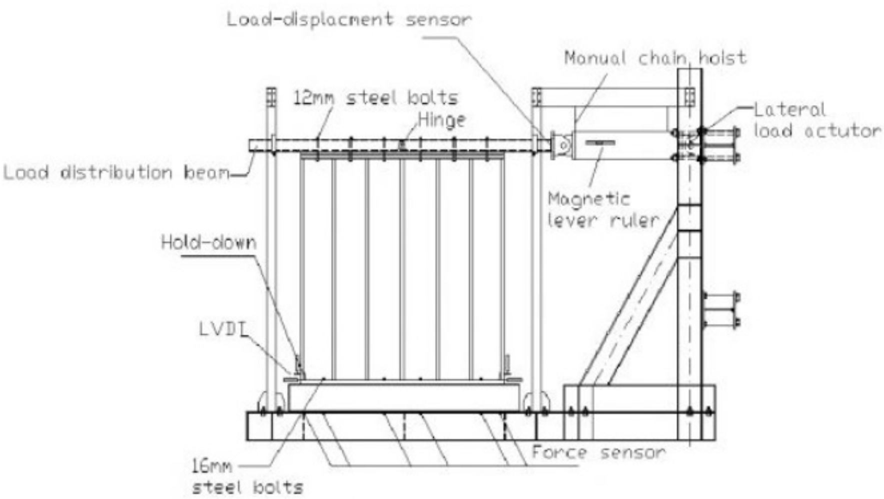


Figure 32. Shaking table test (Aicher-Reinhardt-Garrecht 2014)

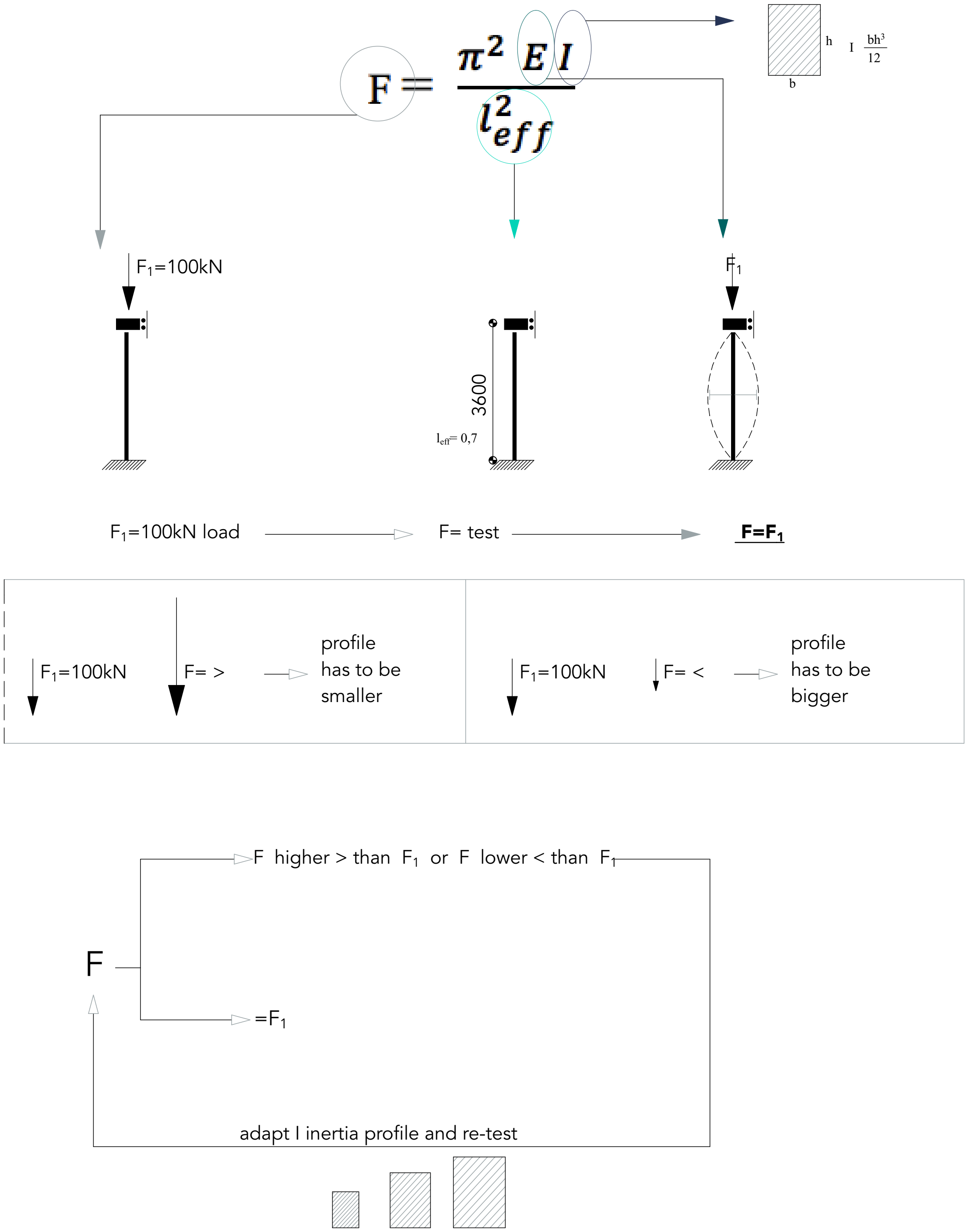
3.2.6 Building material - calculations

In Section 2 a quantitive analysis shows that one hectare of structural bamboo can produce a laminated bamboo frame house a year even in the Netherlands.
But in order to use it as a competitive antiseismic material for the area of Groningen a preliminary static study has to be done in order to define some "rules of thumb" to set the dimensions of the elements that we are going to use in a laminated bamboo structure.
To achieve that I have calculated "new rules of thumb" with static and mechanical formulas of statics and material sciences (Raven 2003). For the extended version of those calculations I refer to the Appendix 3.
However it should be stressed that if we calculate the dimensions of the laminated bamboo beam with the real MoR (Module of Rupture) and MoE (Module of Elasticity) the result is an oversizing. This is due to the fact that bamboo is not only very strong but also very flexible. This means that with the same applied force a wooden beam will collapse (having a lower MoE) while a bamboo beam will keep bending.
Therefore we could consider the bamboo beam working on a lower tension-value taking, for example, the wood MoR which is 4 times lower.
In case of any seismic forces the bamboo beam will have 4 times more potential capacity to resist those forces assuring the safety of the construction.

Overall beam and column dimensions are almost the 0,5 times the dimensions used for timber structures and those can be summed up in the following schemes. Moreover the material efficiency can be used to its maximum when using lightweight profiles, like I profiles or Box profiles (figure 33).

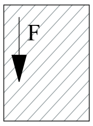
Figure 33. Bamboo profiles (by the author)

Laminated bamboo column calculations

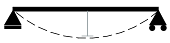


Laminated bamboo beam calculations

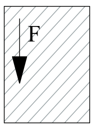
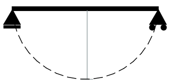
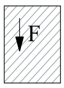
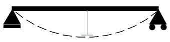
$$\frac{h}{L} = \frac{2 \,.\, 5 \,.\, 8fm}{384 \,.\, 0{,}004\, E} = \frac{52fm}{E}$$

f_m= MoR= 

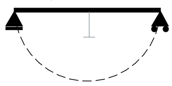
when does the strength of the material itself not bear the applied load anymore and collapse?

E= MoE = 

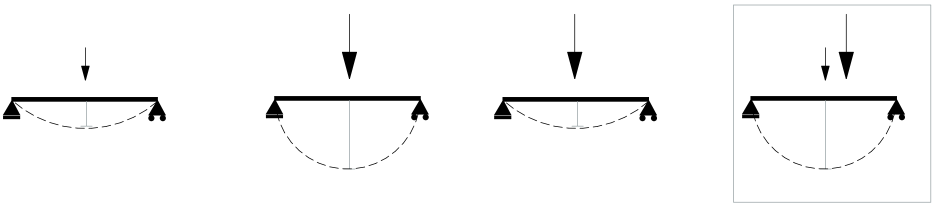
to what extend can the material be elastic?

bamboo 	f_m= MoR= 80N/mm² 	E= MoE =19000N/mm² 
wood 	f_m= MoR= 15N/mm² 	E= MoE = 8000N/mm² 

→ f_m= MoR= 15N/mm² 

→ E= MoE =19000N/mm² 

letting the bamboo beam work on a lower tension value will give us 4 times the capacity to bear extra-seismic forces



3.2.7 Building material - finance

On the basis of those dimensioning "rules" some financial consideration can be made:

- Laminated bamboo is 4 times more expensive than wood lumber and 1,6 more expensive than Laminated Lumber (Rittironk-Elnieiri 2008, p. 91).
- But considering that we could use between 2 and 4 times less material we could keep those costs lower than if we would use the dimensioning rules used for wooden constructions.

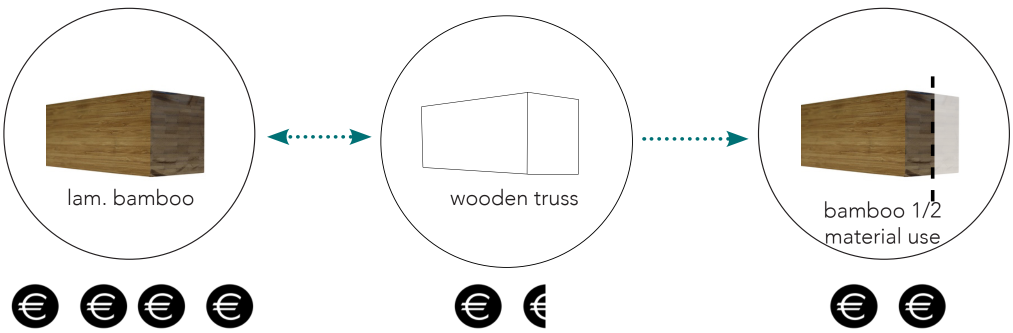


Figure 34. Bamboo-Finance (by the author)

3.2.8 Building material - seismic constructions

Before deepening the seismic construction methods, lets sum up the advantages of using bamboo for those kind of structures:

- Dimensioning the bamboo beam with a MoR which is 4 times lower assures 4 times more potential capacity to resist extra forces like seismic ones, assuring the safety of the construction.
- Bamboo's higher MoE assures that under a certian load the construction will keep bending while a wooden construction would have collapsed.
- Bamboo overall is 1,5 times stiffer than timber, this means that the ratio strength/weight is higher and therefore it is a good seismic performing material.
- The rules of thumb that resulted from those calculations will be used to dimension the main anti-seismic structures like moment frames and shear walls. (To design those properly I refer to section 4. 2).
- Even with bamboo constructions at least one joint between the columns and the beams and between the shear walls and the floors has to be rigid. In case of seismic forces there will be tremblings and vibrations in the single elements without propagating further.

4. Seismic design and laminated bamboo

During earthquakes we have to deal not only with vertical forces, but with horizontal ones too. Most designers have acquired a sense of vertical static forces, but a sense of dynamic forces is harder to acquire. One way of attempting to transfer a general idea for the way in which lateral forces work is to imagine them as vertical forces, rotated 90°. The following sketch represents an elementary course in this approach. However seismic forces are more complex than gravitational forces and must always be visualized as dynamic and multidirectional rather than operating in a single direction (Arnold-Reitherman 1982, p. 38).

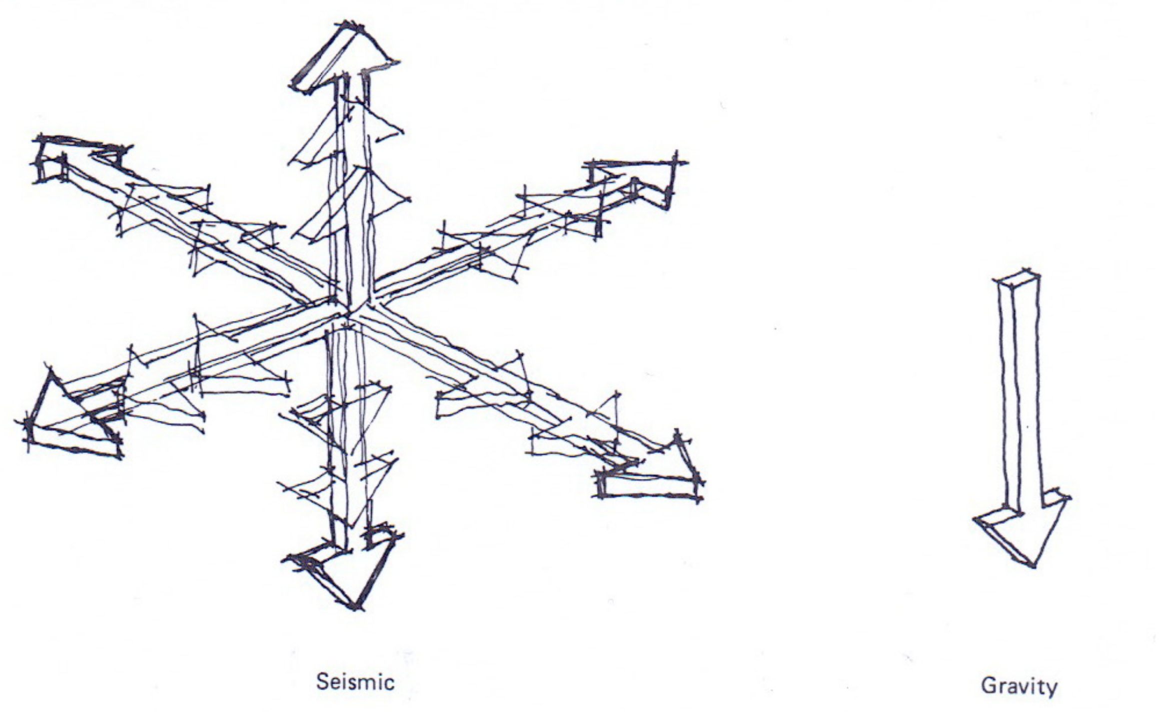


Figure 35. Seismic forces (Arnold-Reitherman 1982)

The challenge pointed out by Mahdavi (Mahdavi-Clouston-Arwade 2011, p. 1038) is that construction and engineering professionals around the world are not yet adequately familiar with modern bamboo structure design and there are no generally accepted formal codes yet. As we have seen from the previous chapter laminated bamboo properties are better than those of wood. According to Hollee Becker's (Becker 2013, p. 198) calculations (from the Catholic University of America), structures in laminated bamboo are capable of resisting simultaneous 320km/h winds and earthquakes of 9,0 and tests with the shaking table prove that too (Aicher-Reinhardt-Garrecht 2014, p. 599).

My calculations (see Appendix 3) could prove in this sense the assumption made by Hollee Becker who stated stat a laminated bamboo beam can carry 1,93 times the load of a laminated timber beam because of the peculiar MoE and MoR of the material itself (figure 36). We should be more careful in the design of columns. According to my calculations they have the same dimension advantages of the laminated beam for columns, but we should use more prudence here dealing with the slenderness issue (figure 37). However the calculations have been made starting with the MoE and the MoR of the material and have certainly a margin of safety. Those properties of the mechanical behaviour are fundamental to the discussion of structural analysis and design reccommandations for antiseismic design (United Nations 1975, p. 42).

Beams wood vs bamboo

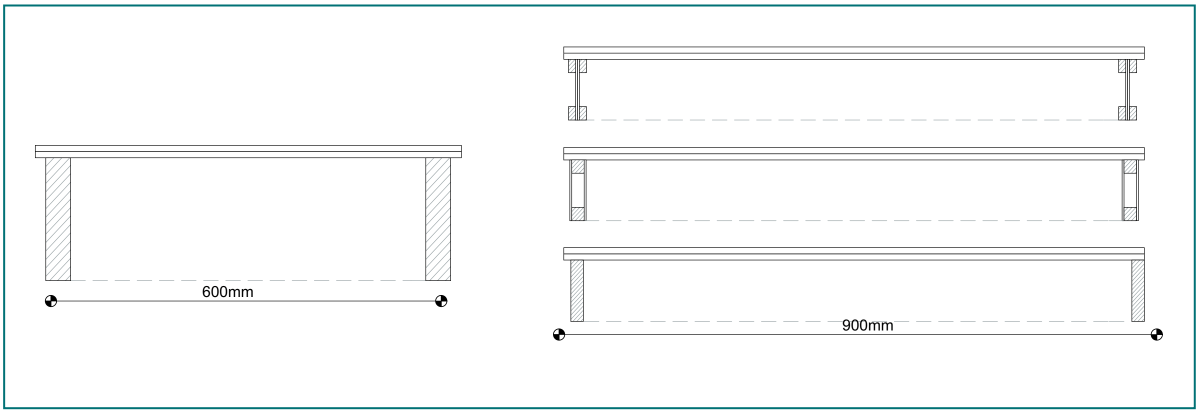


Figure 36. Beams wood vs bamboo (by the author)

Columns wood vs bamboo

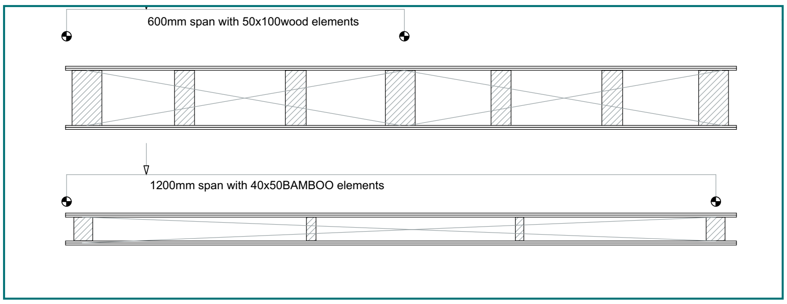


Figure 37. Beams wood vs bamboo (by the author)

Bamboo has in fact a high strength and stiffness. Those two are the most important characteristics of any structure dealing with seismic design. One measure of stiffness is deflection, and for vertical gravity loads it is in most cases the only relevant aspect of stiffness. But with horizontal forces the issue is how to prevent the structure from moving out of alignment more than a given amount. In general damages occur because of internally generated inertial forces caused by vibration of the building's mass according to F = m . a (Arnold-Reitherman 1982, p. 26). Acceleration (a) is the change of velocity over time, and it is a function of the nature of the earthquake. Mass (m) is an attribute of the building itself. If we can keep down the mass of the building using a material like laminated bamboo, which we can use as lightweight profiles and with a high strength to mass ratio, we can partially have control on this Second Law of Newton. It should be clear that the building's mass, size, and shape partially determine both the nature of those inertia forces and how well they will be resisted.
Therefore some general considerations about anti seismic configurations and design strategies need to be pointed out.

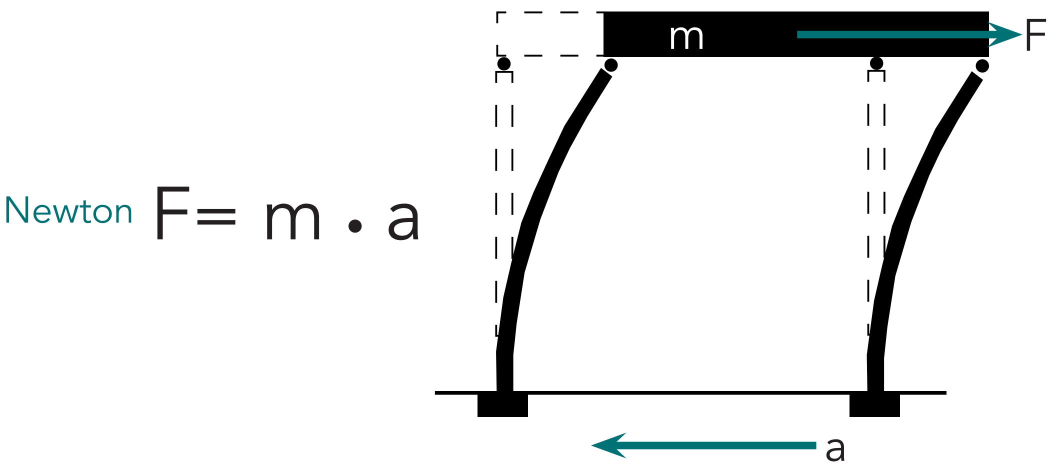


Figure 38. Newton's formula (by the author)

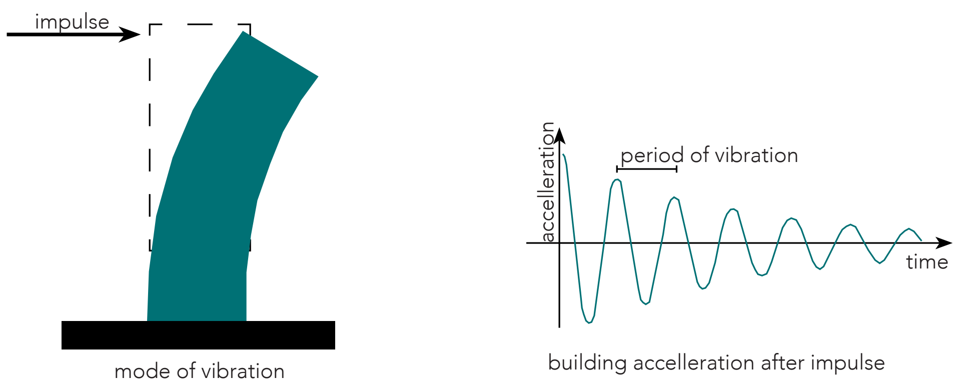


Figure 39. Earthquake's vibration (by the author)

4.1 Configuration

The magnitude of the seismic stresses to which the various members in a structure are subjected depends both on the characteristics of the earthquake and on the design of the structure itself. Eccentricity, symmetry, story rigidity, expansions and basement design all play a role in the resistance of a building (figure 40).

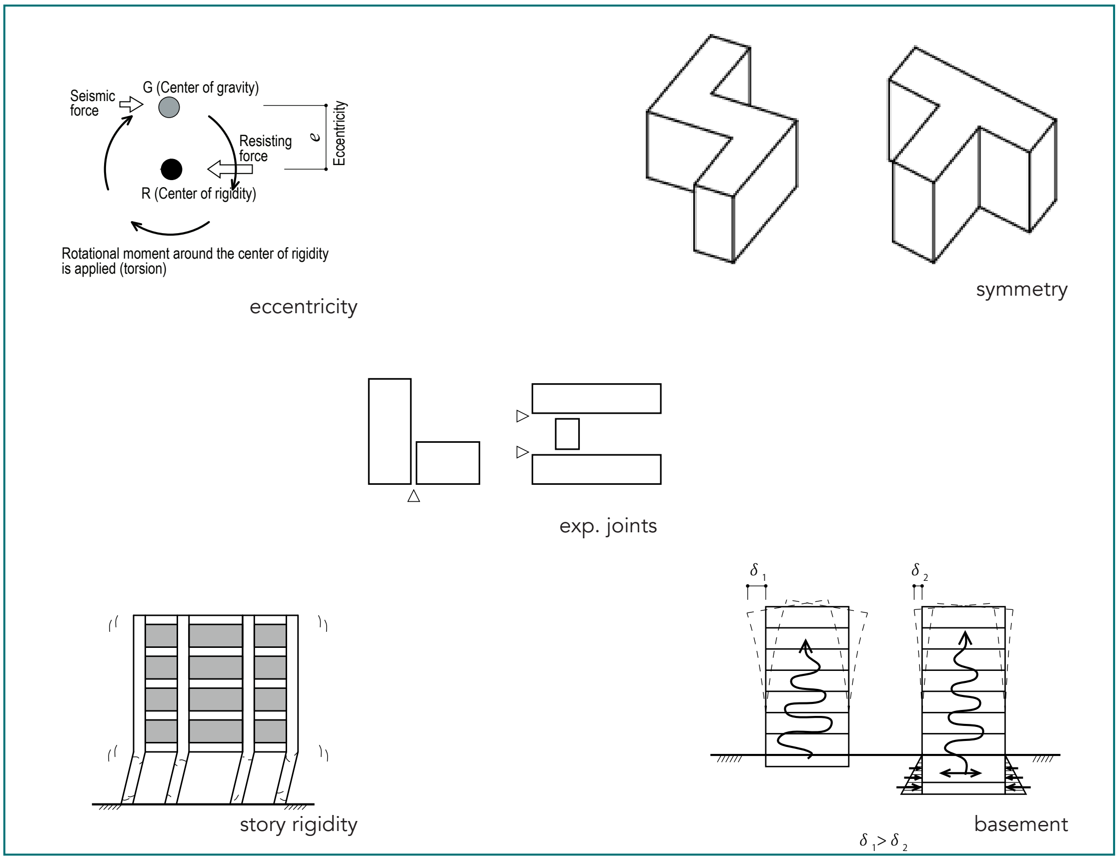


Figure 40. Anti seismic configuration (Yano 2015)

4.1.1 Eccentricity

The modulus of eccentricity is defined as a ratio of the distance between the center of gravity and the center of rigidity: the smaller the value the better the building is balanced (Yano 2015, p. 94). The centre of rigidity is the centre of gravity of the rigidities of the structural members in the ground plan of the building. The centre of mass is the centre of gravity of the masses of the various structural members and non structural elements making up the building (United Nations 1975, p. 56).

While complex engineering calculations must always be done, we as designers could design our structure keeping these principles in mind to come as close as possible to positive outcomes from those calculations. Here I set up a simplified method (see p. 45) to determine whether our structure is balanced or not.

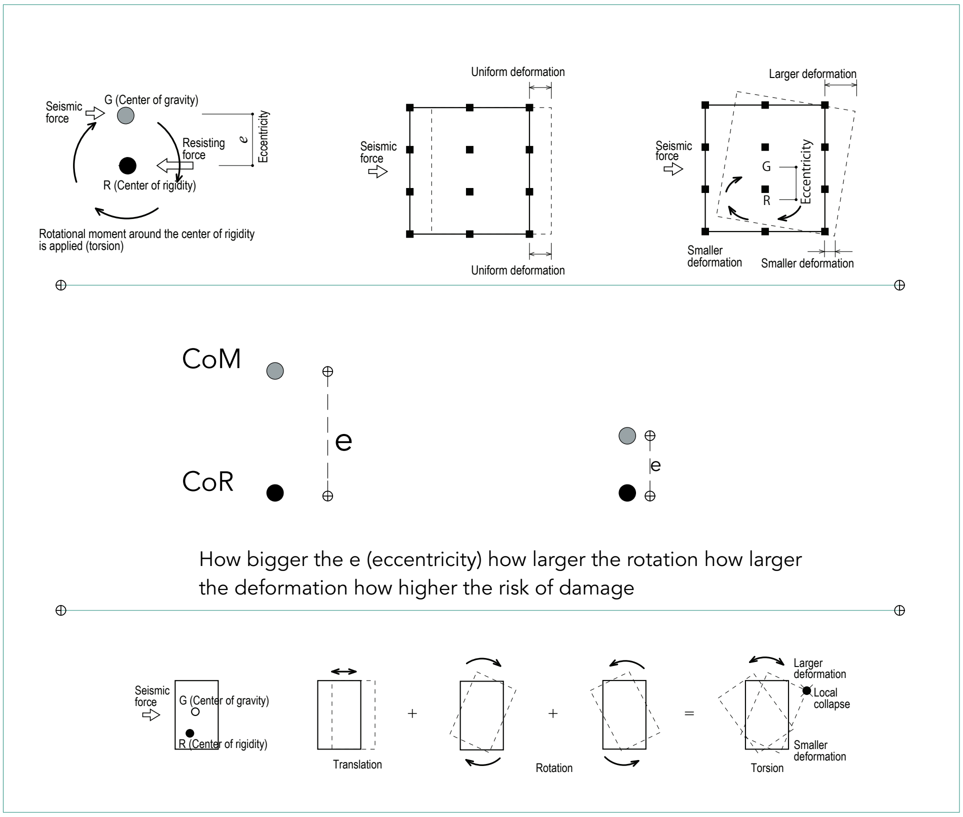


Figure 41. Eccentricity (Yano 2015)

Calculations:

CoM is where the vertical forces act through

CoR is where the lateral (seismic) forces act through

CoM -CoR gives the e (eccentricity)

CoM (x,y)

x,y= sum of all (b . h/2 . load) / sum of all (b . h . load)

CoR(x,y)

x,y= sum of lateral stiffness . distance in x,y direction / sum of stiffness

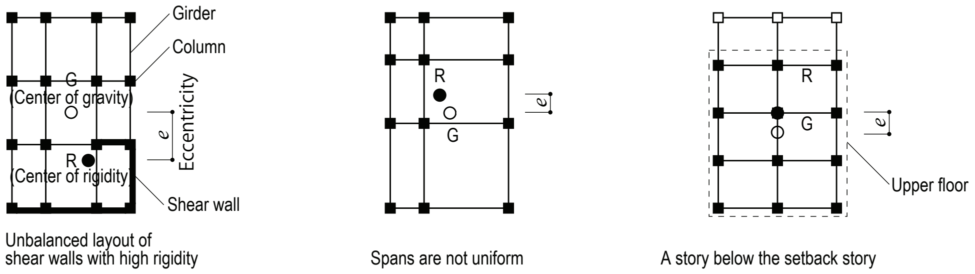
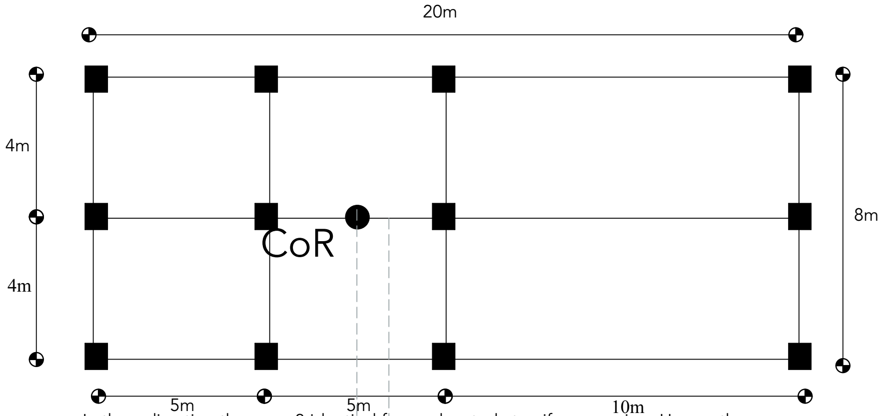
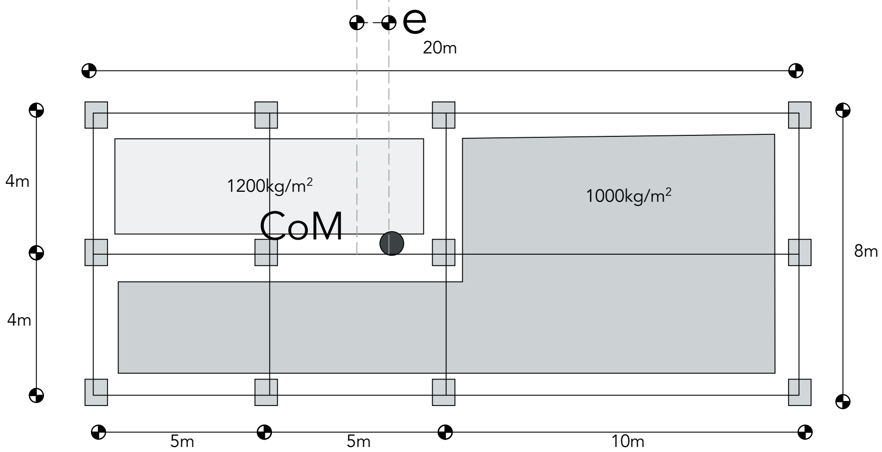


Figure 42. CoR and CoM (by the author)



In the x direction there are 3 identical frames located at uniform spacing. Hence, the y coordinate of the CoR is located symmetrically ie at 5m from the left bottom corner.
In the y direction there are 4 identical frames having equal lateral stiffness. The spacing is here not uniform.
K=lateral stiffness of each transverse frame=1



CoR

$$X = \frac{k \cdot 0 + k \cdot 5 + k \cdot 10 + k \cdot 20}{k + k + k + k} = 8{,}75\text{m}$$

$$Y = \frac{k \cdot 0 + k \cdot 4 + k \cdot 8}{k + k + k} = 4\text{m}$$

CoM

$$X = \frac{(10.4.1200)5+(10.4.1000)15+(20.4.1000)10}{(10.4.1200+10.4.1000+20.4.1000)} = 9{,}76\text{m}$$

$$Y = \frac{(10.4.1200)6+(10.4.1000)6+(20.4.1000)2}{(10.4.1200+10.4.1000+20.4.1000)} = 4{,}1\text{m}$$

4.1.2 Plan symmetry

In anti-seismic design we should strive for structural symmetry in plan to reduce torsion in a building (figure 43) (Charleston 2008, p. 65). These are floor plans in which the members resistant to horizontal forces are arranged symmetrically. As the mass of a building is generally distributed more or less uniformly in the floor plan, a symmetrical floor plan ensures that the centre of mass and the centre of rigidity, discussed in the paragraph above, will coincide.

Structural symmetry should not be understood in absolute terms. In the case of low rise buildings it is sufficient to produce a design with the centres of mass and rigidity as close to each other as possible, and this can generally be achieved by balancing the rigidities of the horizontal resistant members and selecting appropriate dimensions, structural type or materials for them (United Nations 1975, p. 57). Even here bamboo is an answer to this requirement.

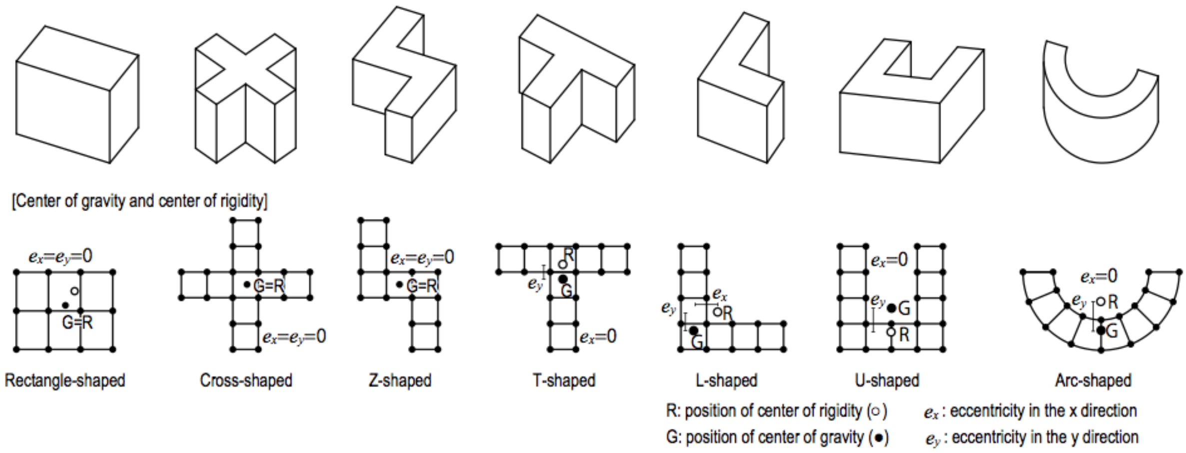
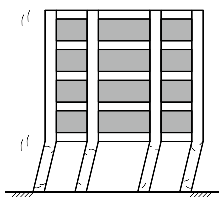


Figure 43. Plan symmetry (Yano 2015)

4.1.3 Story rigidity

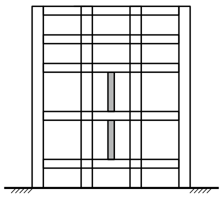
A difference in story rigidity and strenght or different type of structures in stories can cause damage at intermediate stories in a building (Yano 2015, p. 96).

When owing, for example to shear walls the upper stories have greater rigidity and strength, than a lower story, a lower story suffers great damage even when the upper stories suffer minimal damage, because seismic energy centers on the lower story. An appropriate countermeasure, in terms of earthquake resistant construction, is to plan a good balance of rigidity between stories, so that the building as a whole can absorb seismic energy. Specifically, one method is to increase the rigidity and strength of the building as a whole by placing earthquake resistant elements (refer to sec. 4. 2) on stories in a balanced way (Yano 2015, p. 97).

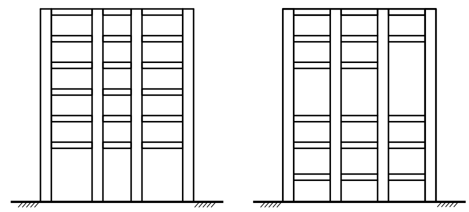


Story collapse of a pilotis-style building

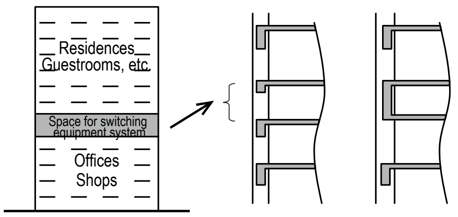
Examples of frame style



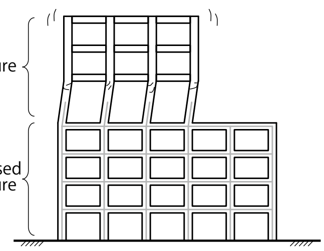
Installation of studs



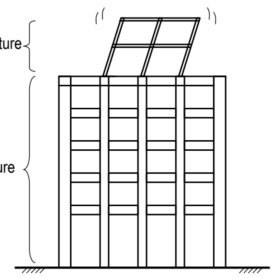
Buildings to which attention should be paid



An example of switching building use



An example of jointing in a building with different structure types



An example of damage to a penthouse

Figure 44. Story rigidity (Yano 2015)

4.1.4 Expansions joints

Expansion joints are used to control harmful behaviours in terms of structure caused by fluctuating factors like winds or earthquakes. The following eight building's elements need expansions joints and attention should be paid to each behaviour (Yano 2015, p. 98):

a. Connecting parts between buildings with different vibration characteristics.
b. Connecting parts between buildings of different structure types or formes.
c. Connecting parts between buildings built on different geological ground conditions.
d. Connecting parts between the constituent buildings of an irregular shaped building.
e. Very long buildings for which deformation due to temperature change or drying of concrete is of concern.
f. Connecting parts between an existing building and extensions.
g. Atrium roof and any corridor connecting separate buildings
h. Periphery of a base isolated building and its connecting part to an adjacent building.

Those cases are shown in the image below.

The dimensions of the expansion joint are determined by the building height. In most cases those are dimensioned as 1/50 of the height. For a building of 20m height for example we need a clearance of at least 40cm.

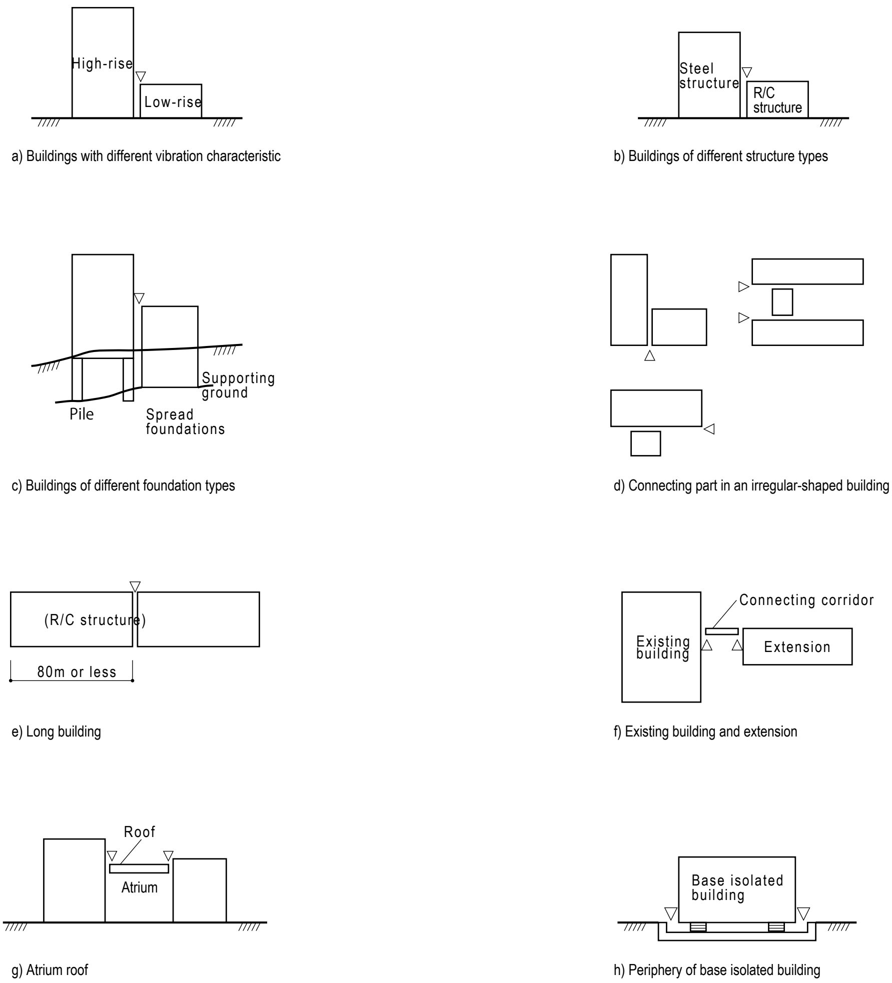


Figure 45. Expansion joints (Yano 2015)

4.1.5 Basement

It has been demonstrated by the records of past earthquakes that the existence of a basement is effective for increasing the earthquake resistant performance of a building. Inertia forces which act on the foundation are reduced by underground earth pressure resistance and frictional resistance. When a building is buried deep in the ground with a basement, input of seismic motions to the superstructure can be further reduced (Yano 2015, p. 100).

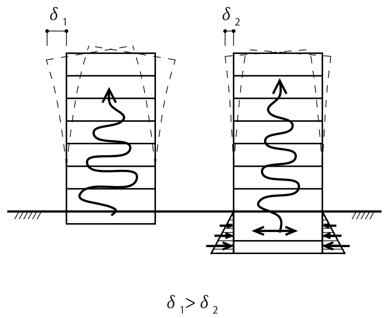


Figure 1. Reducing effect on the input of seismic motion

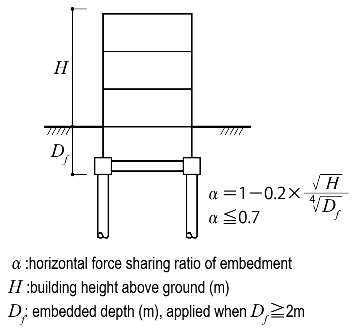


Figure 2. Horizontal force sharing ratio of embedment

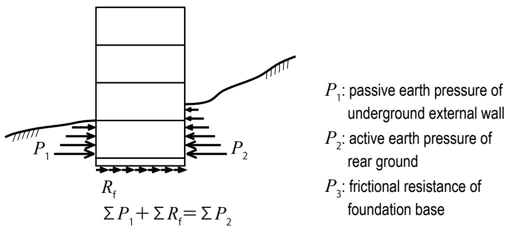


Figure 3. Basement which is effective as a countermeasure against sliding

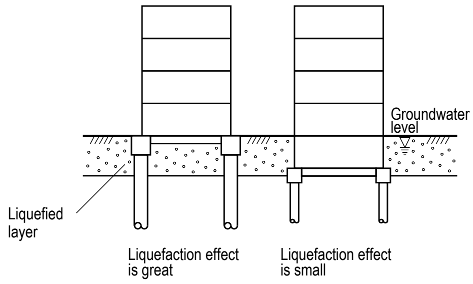


Figure 4. Liquefaction effect on piles

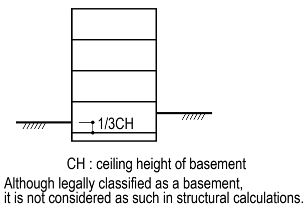


Figure 5. An example of a structurally ineffective basement

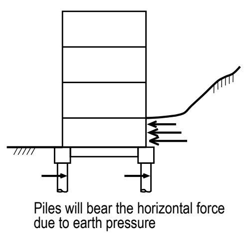


Figure 6. A building subject to earth pressure on one side

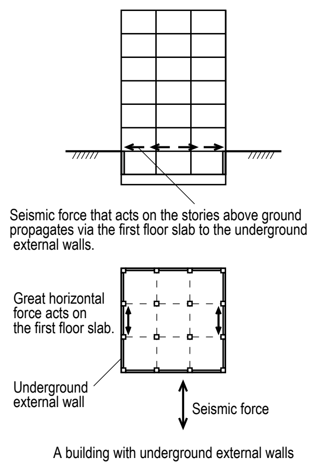


Figure 46. Basement (Yano 2015)

4.2 Structures

Here the design of horizontal and vertical structures in general and in laminated bamboo in particular for anti-seismic constructions will be discussed. Systems as base insulation or dampings will not be discussed in this chapter. Since they are not common for timber structures (the main comparison of laminated bamboo) and mostly used for mansory, concrete buildings or retrofit projects we assume that they are not relevant for our laminated bamboo constructions. Furthermore a seismically isolated building still requires structures like moment frames or shear walls. Not mentioning that when designing a seismically isolated building, an architect must collaborate with the structural engineer over a number of unique design decisions (Charleston 2008, p. 202).

The main anti seismic structures used for timber frame design will be discussed: Diaphragms, Shear Walls and Moment Frames.

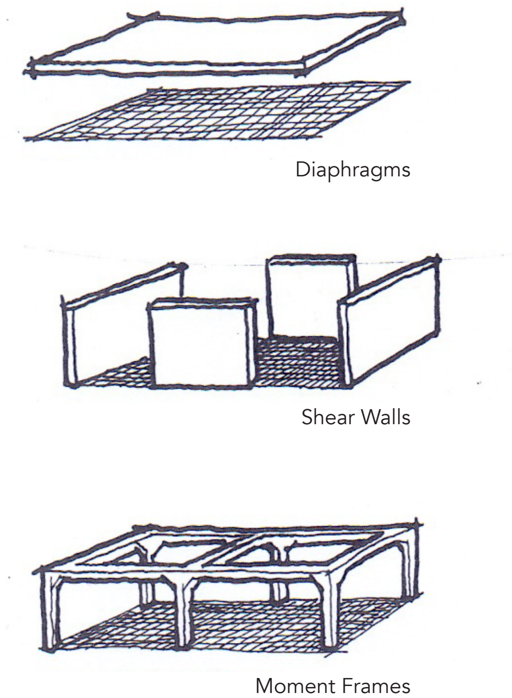


Figure 47. Structures (Arnold-Reitherman 1982)

4.2.1 Diaphragms

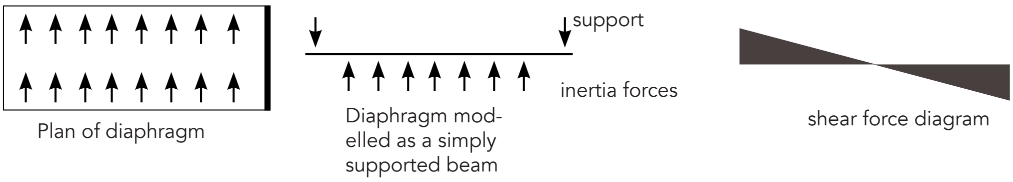


Figure 48. Diaphragms (by the author)

The structural members of a buildings, appropriately distributed and oriented in a building (to assure a low eccentricity as shown in sec. 4. 1) may be joined to one another at the level of each floor by highly rigid diaphragms that makes it possible to distribute the horizontal forces appropriately among the resistant members. If they are not jointed the result is a deformable floor as shown in the figure below (United Nations 1975, p. 58).

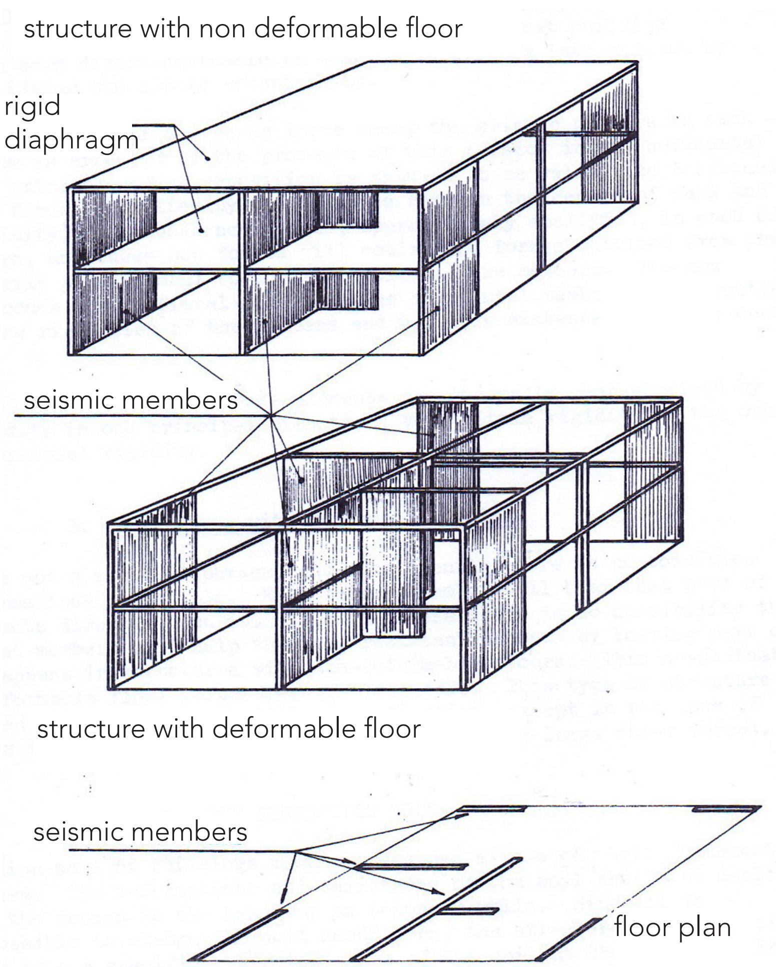


Figure 49. (non) Deformable floors (united Nations 1975)

Diaphragms are horizontal resistant elements (generally floors) that act to transfer lateral forces between vertical resistance elements (shear walls or moment frames). They act like a beam as shown in the sketch below, figure 50 (Arnold-Reitherman 1982, p. 38).

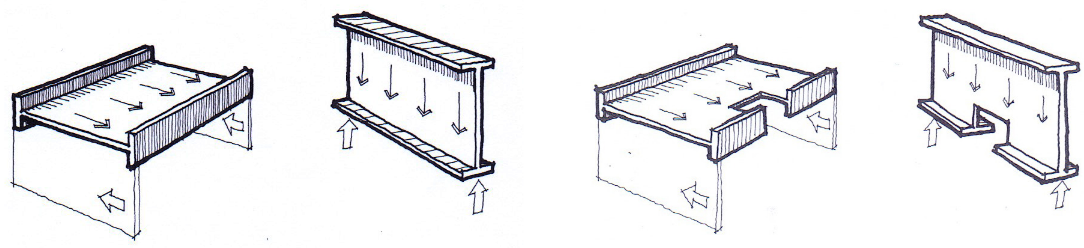


Figure 50. Diaphragms like beams (Arnold-Reitherman 1982)

When made from timber, diaphragms are called “flexible” because the material behaves flexibly, and not rigidly like concrete. The connections between the horizontal structures and the vertical structures are of crucial importance (figure 51). As soon as a diaphragm is tied to vertical resisting elements it will force those elements to deflect to the same amount

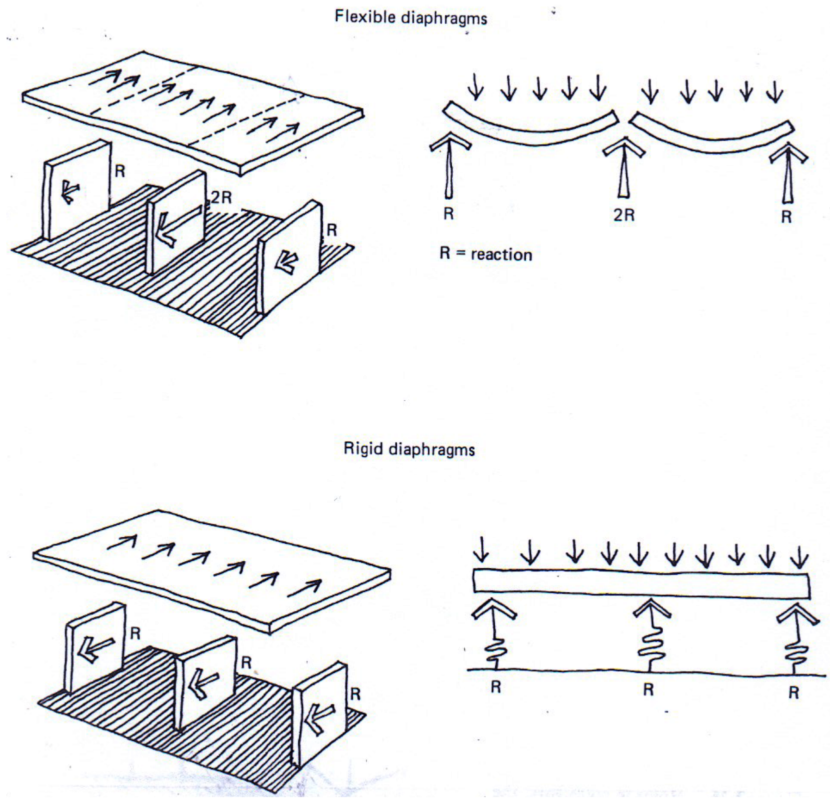


Figure 51. Flexible and rigid diaphragms (Arnold-Reitherman 1982)

This structure is designed by nailing plywood or plybamboo plates to the laminated bamboo floor structure (figure 52). The nailing of the plates must be done (as shown in the figure 53) each 300 mm for the nailings around the boundary of the floor and each 150 mm for the single plates.

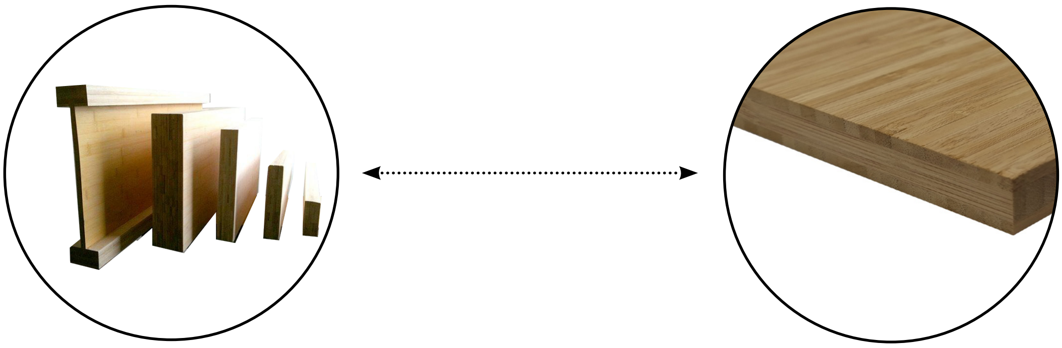


Figure 52. Laminated and Plybamboo (by the author)

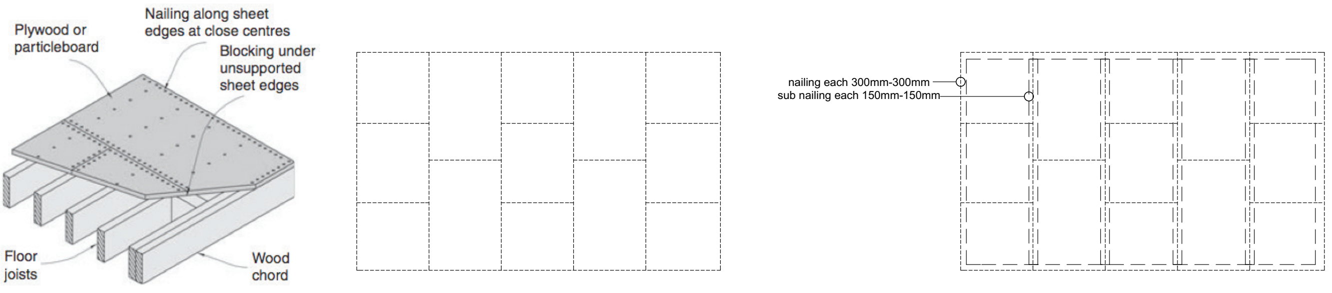


figure 30

Figure 53. Nailing (by the author)

Openings in the floor should not destroy the continuity of the perimetral chords as shown in figure 54.

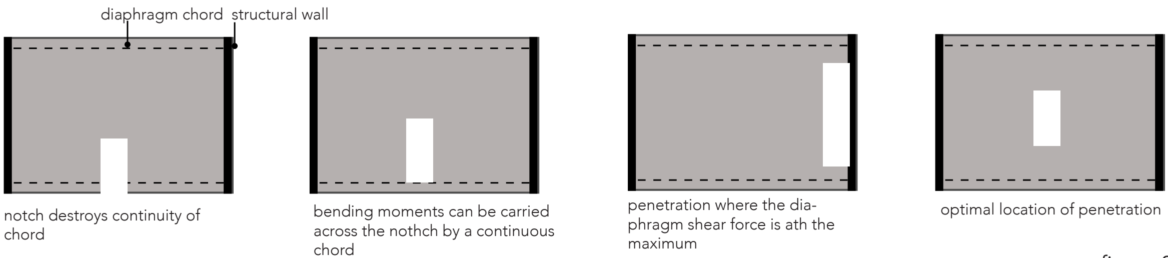


figure 31

Figure 54. Openings in diaphragms (by the author)

And last but not least lightweight wooden or bamboo diaphragms can be unblocked or blocked (figure 55), the last providing greater shear capacity. The difference is that the nailing along the perimeter of the sheathing panel is combined with extra floor joists perpendicular to the main floor joists to block lateral forces (Cobeen et al. 2014, p. 6).

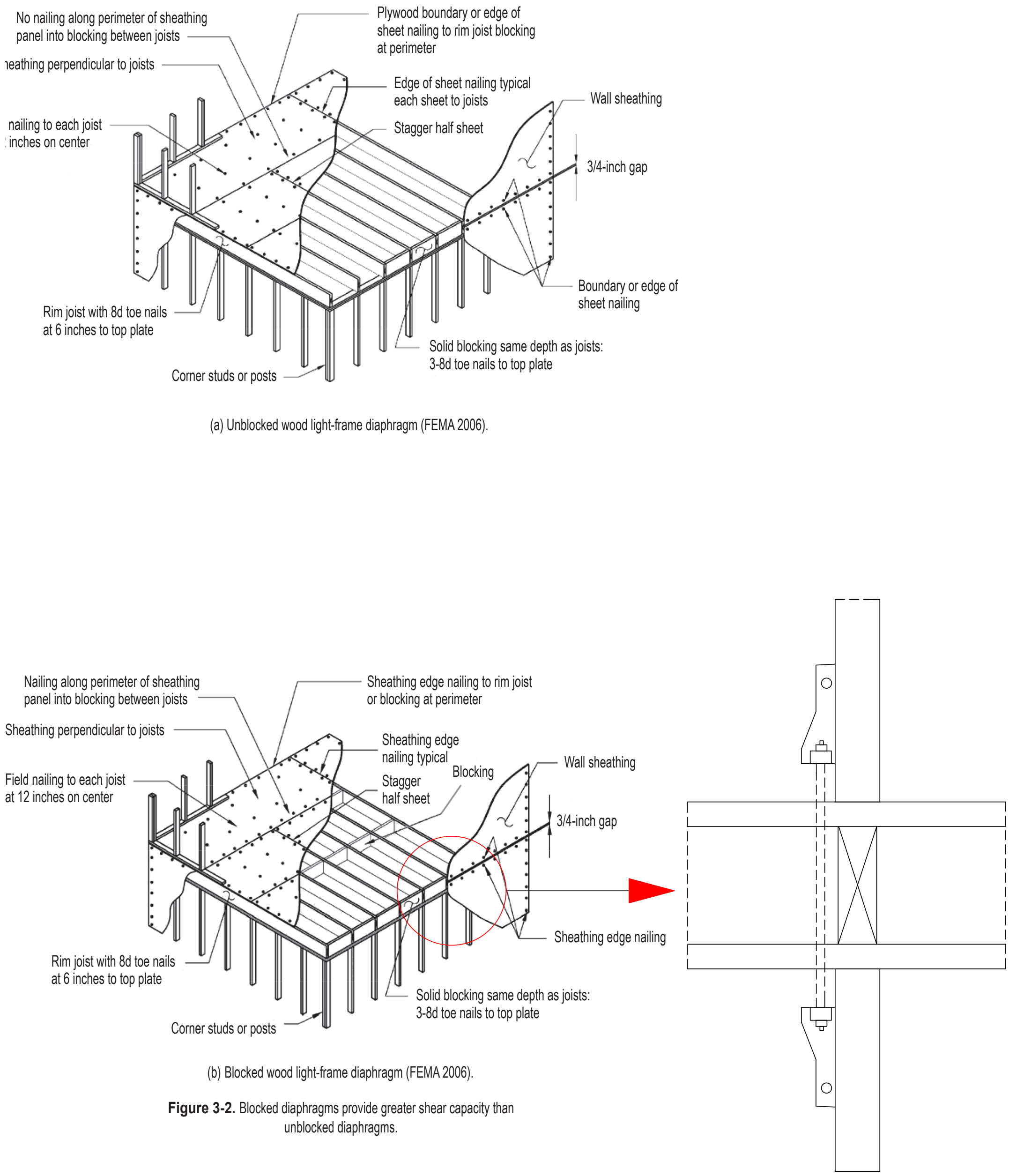


Figure 55. (un) blocked diaphragms (Cobeen et al. 2014)

4.2.2 Shear walls

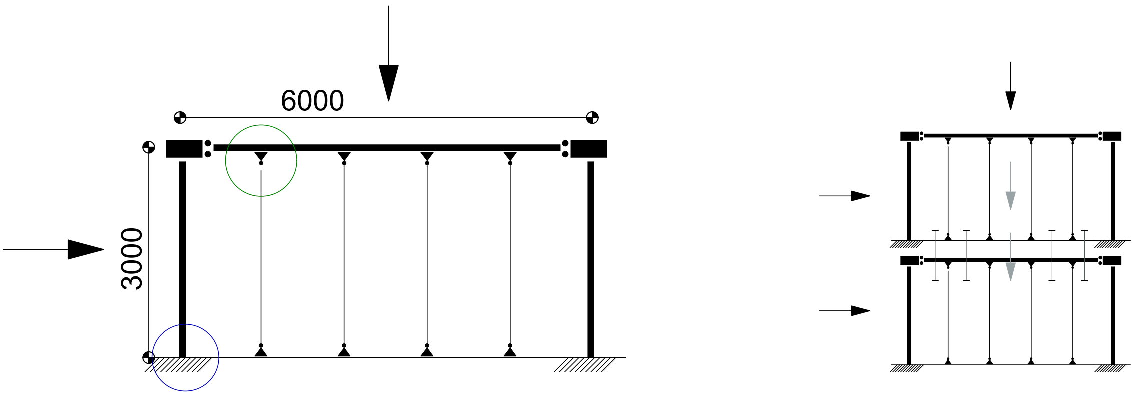


Figure 56. Shear walls (by the author)

Vertical cantilever walls that are designed to receive lateral forces from diaphragrms and transmit them to the ground are commonly termed shear walls. The forces in these walls are predominantly shear forces, though a slender shear wall significant bending will occur. When an earthquake occurs the forces are resisted by the shear walls and transmitted back down to the foundation.

In the figure below are shown ideally located shear walls (figure 57). Those schematic plans can be conceived of as collections of resistant elements with varying orientation (to resist translation) and with varying distances from the center of rigidity to resist torsion. Those are meant to give an idea to us designers for the ideal placing of those vertical elements.

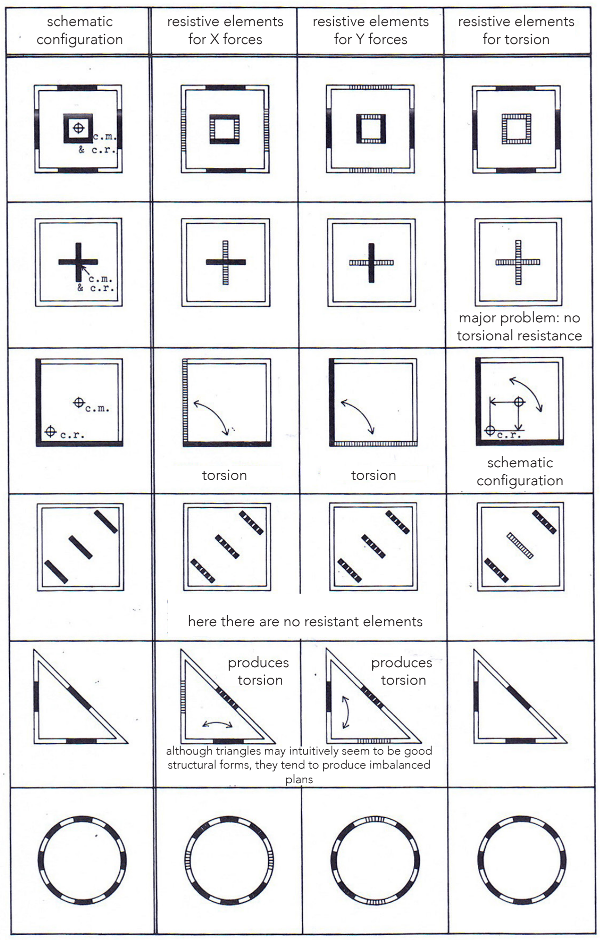


Figure 57. Shear walls location (Arnold-Reitherman 1982)

Furthermore there is a linear relation between the length and the rigidity of shear walls as shown in the figure 58 (Arnold-Reitherman 1982, p. 36). . The length and the rigidity of a wall are directly proportional.

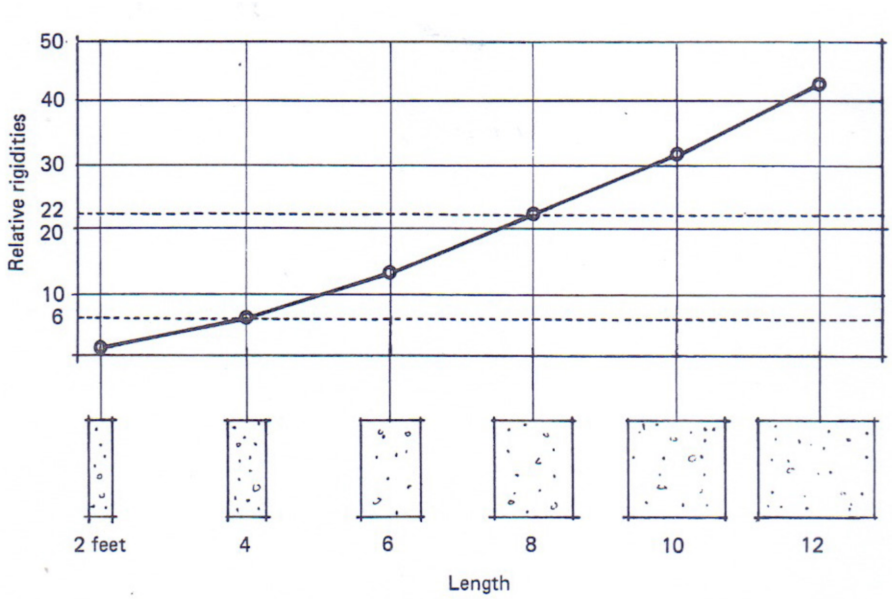
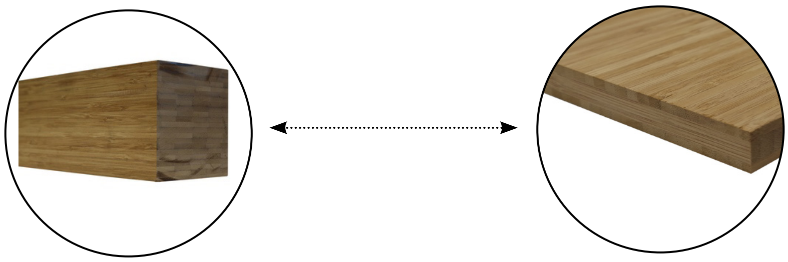


Figure 58. Length - wall rigidity (Arnold-Reitherman 1982)

For the design of this kind of structure in laminated bamboo we refer to the design methods of lightweight wood shear walls (FEAM 2014). To resist lateral forces the same principle used for the design of diaphragms is used. Panels of plywood or plybamboo are nailed to the vertical frame.



For the design of a shear wall the perimetral nailing of the plates to the structure has to be each 75mm and sub nailing of 150mm each as shown in the vertical section in figure 59. Between the main vertical elements sub vertical elements are placed to make the wall stiff. Anchoring is of fundamental importance here because it has to transfer the forces to the foundation. The anchoring at the external part of the wall has to be major than the anchors placed between the sub elements. Usually there are two sub anchorings for each vertical module in the wall. The figures 59 and 60 show also the types of anchoring that can be used to transfer forces and to fix the shear walls to the ground.

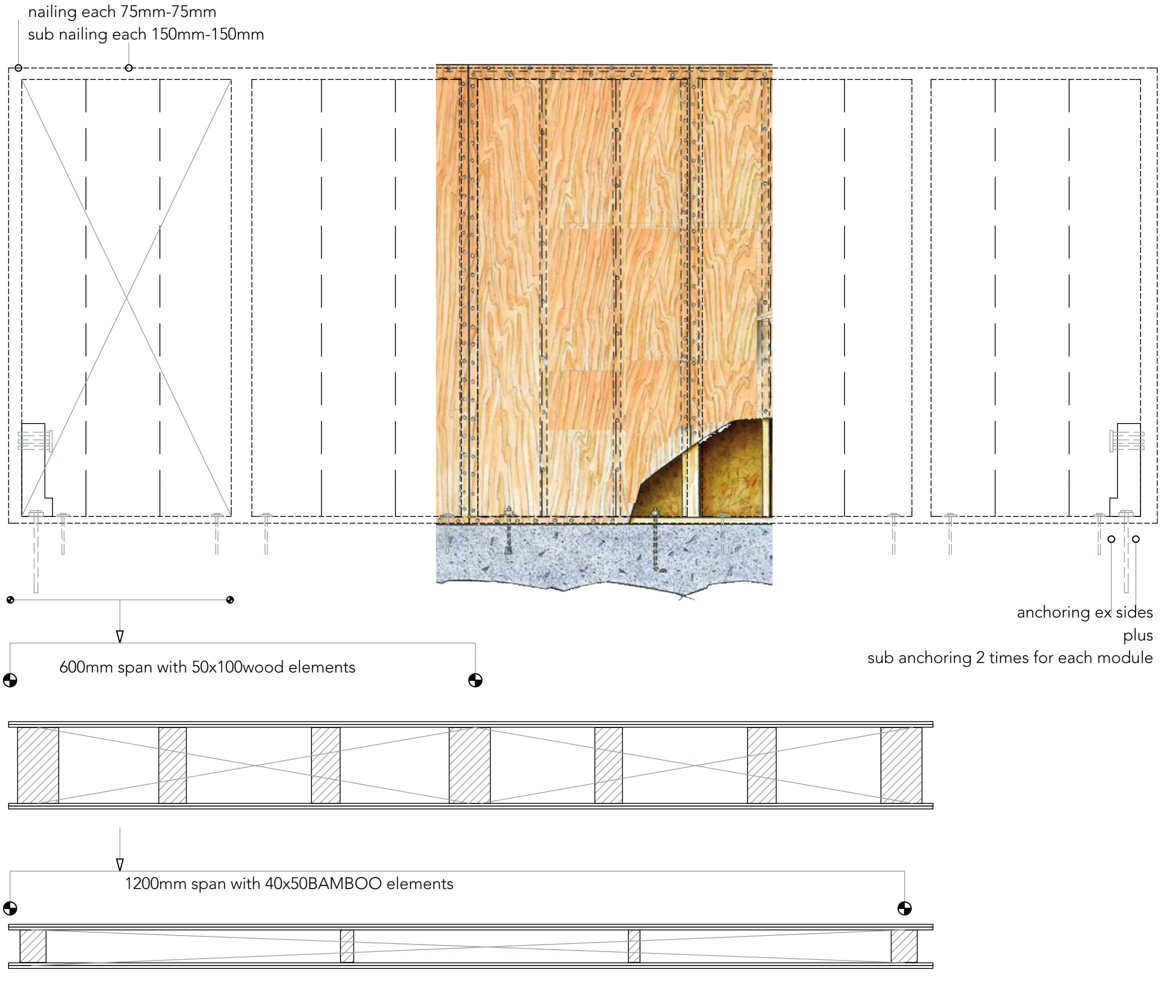


Figure 59. Shear walls design (by the author)

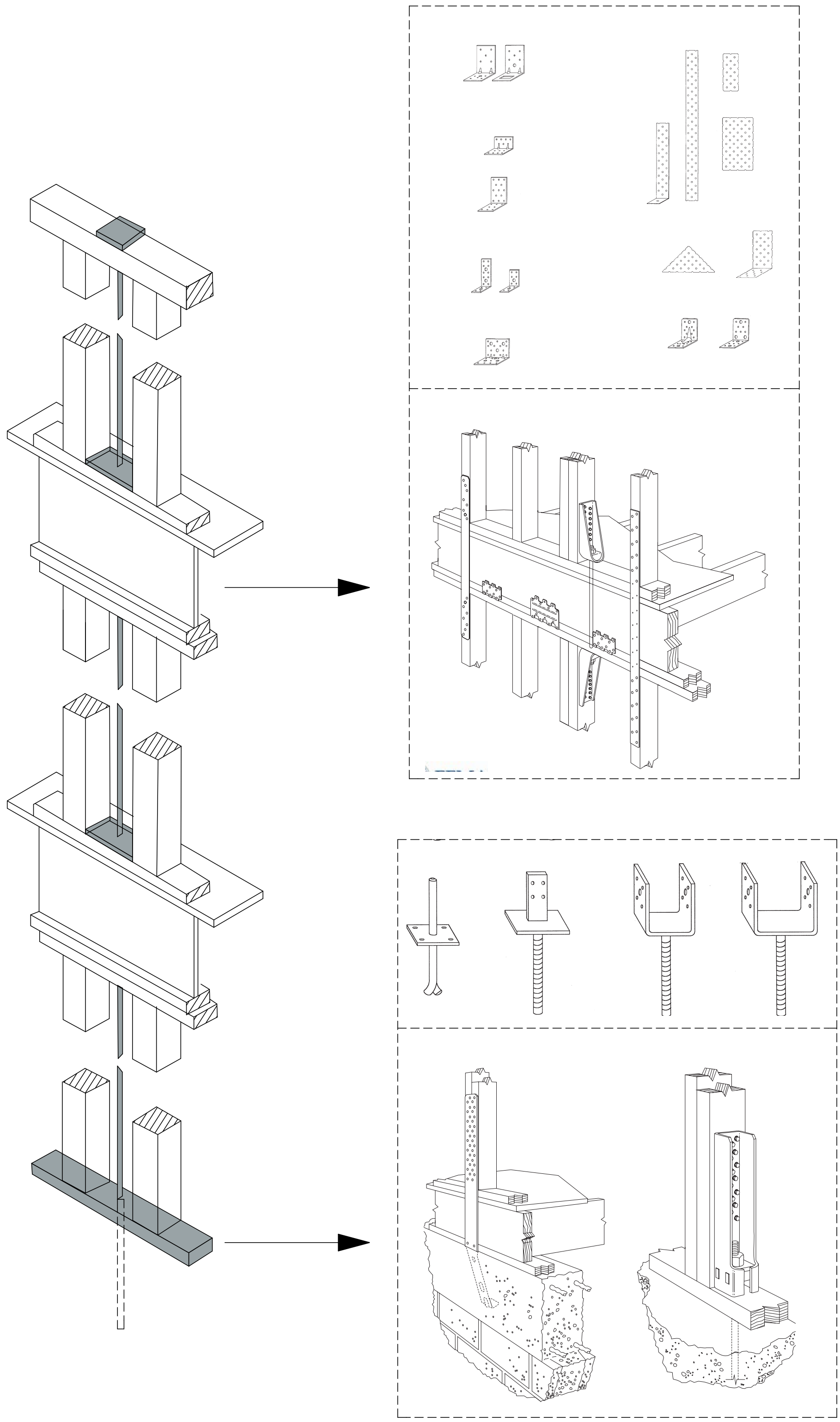


Figure 60. Transfer forces (by the author)

4.2.3 Moment frames

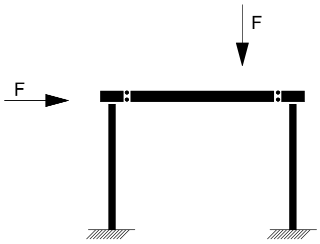


Figure 61. Moment frame (by the author)

When seismic resistance is provided by moment resistant frames, lateral forces are resisted by bending and shearing of columns and beams, which are connected by moment connections (figure 62). Joints become highly stressed and the details of their connection are important. The elastic behaviour (in our case the MoE of laminated bamboo) becomes an important feature in resistant strategy by using the energy absorption obtained by permanent deformation of the structure prior to ultimate failure (refer to the structural considerations in sec. 3. 2).
The use of moment frames is of architectural significance in two ways. Their use often obviates the need for shear walls, eliminating the possible restrictive planning implication. The other is that moment frame structures tend to be much more flexible than shear walls. However, a combination of those in most cases is recommended.

Moment frames have rigid connections that resist rotation, causing the column to resist the lateral forces through shear (Becker 2013, p. 200).

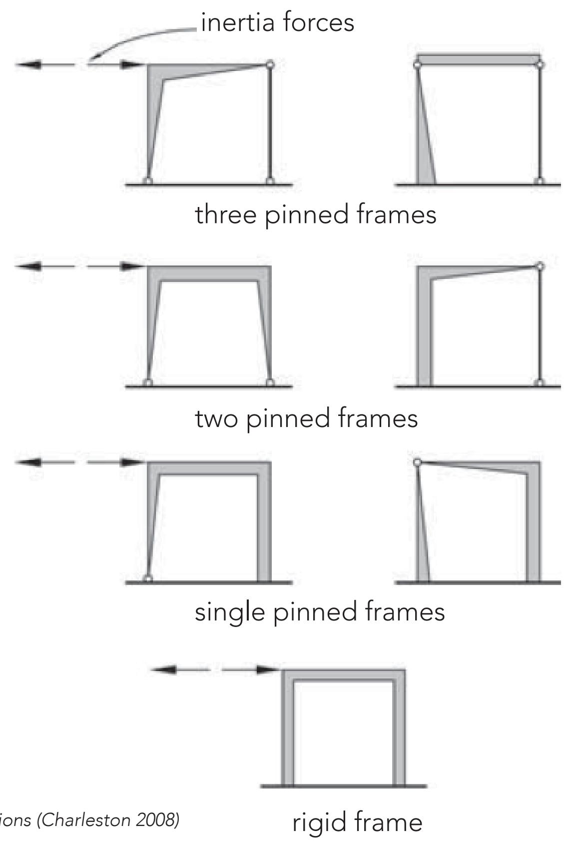


Figure 62. Rigid connections (Charleston 2008)

For the design of this type of structure from the New Zeland Timber Design Journal (Batchelar-McIntosh 2009, p. 13) examples of earthquake resistant connections for laminated lumber have been taken and adapted to laminated bamboo elements dimensioned according to the calculations of ch. 3. 2. Lightweight profiles and moment resistant connections have been taken from the Timber design manual (Hertzog 2008, pp. 157-203) and adapted to the laminated bamboo elements. Lightweight profiles from laminated bamboo seem feasible according to the company Lamboo. us© (Lamboo 2010).

For the design of this structure an inventory of the type of lightweight profiles that can be used has been carried out, first (figure 64a, p.62) with the standards dimensions of laminated wooden elements and then (according to the calculations of sec. 3. 2) with the assumed dimensions of laminaded bamboo elements (figure 64b, p.63). Detailed possibilities for moment connections have been designed as showed in the figures 39a-e (pp. 64-68). Finally the vertical elements and the horizontal one of the frame have to be as much as possible on one line.

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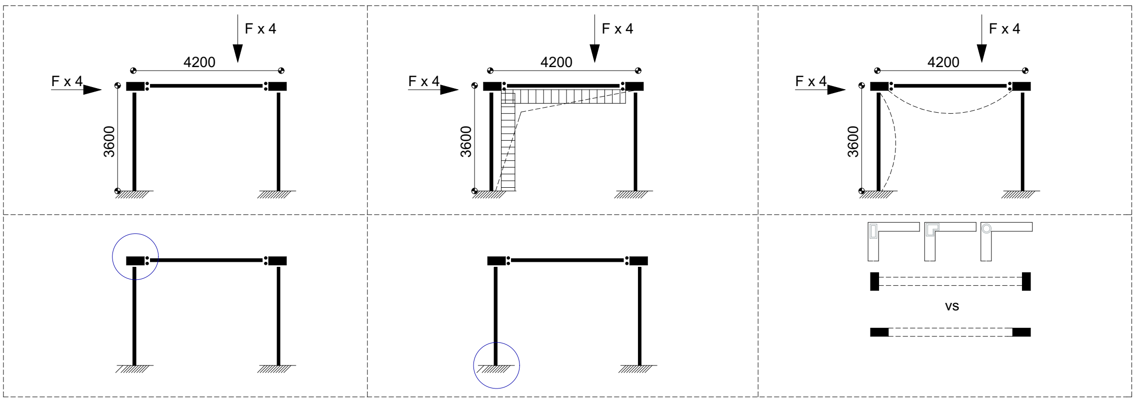


Figure 63. Moment frame design (by the author)

Elements and connections

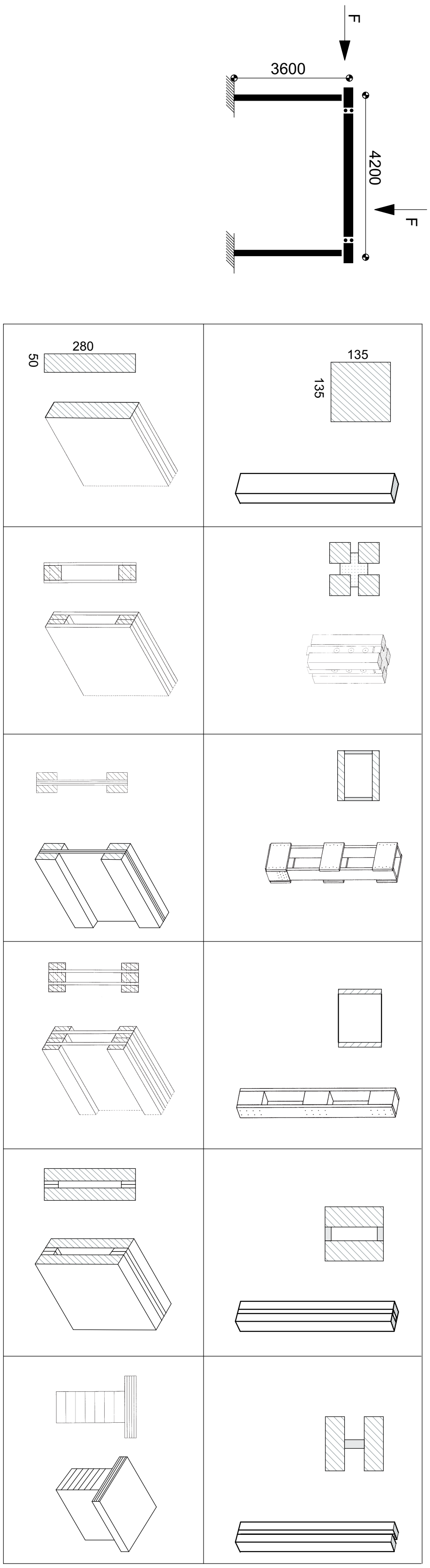


Figure 64.a Moment frame design in wood (by the author)

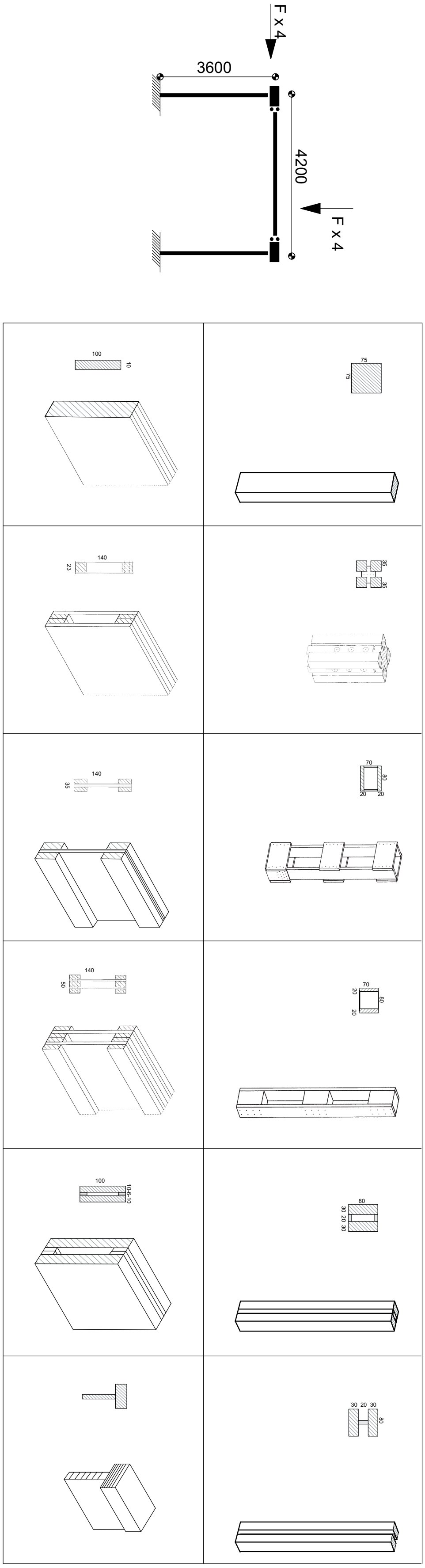


Figure 64.b Moment frame design in bamboo (by the author)

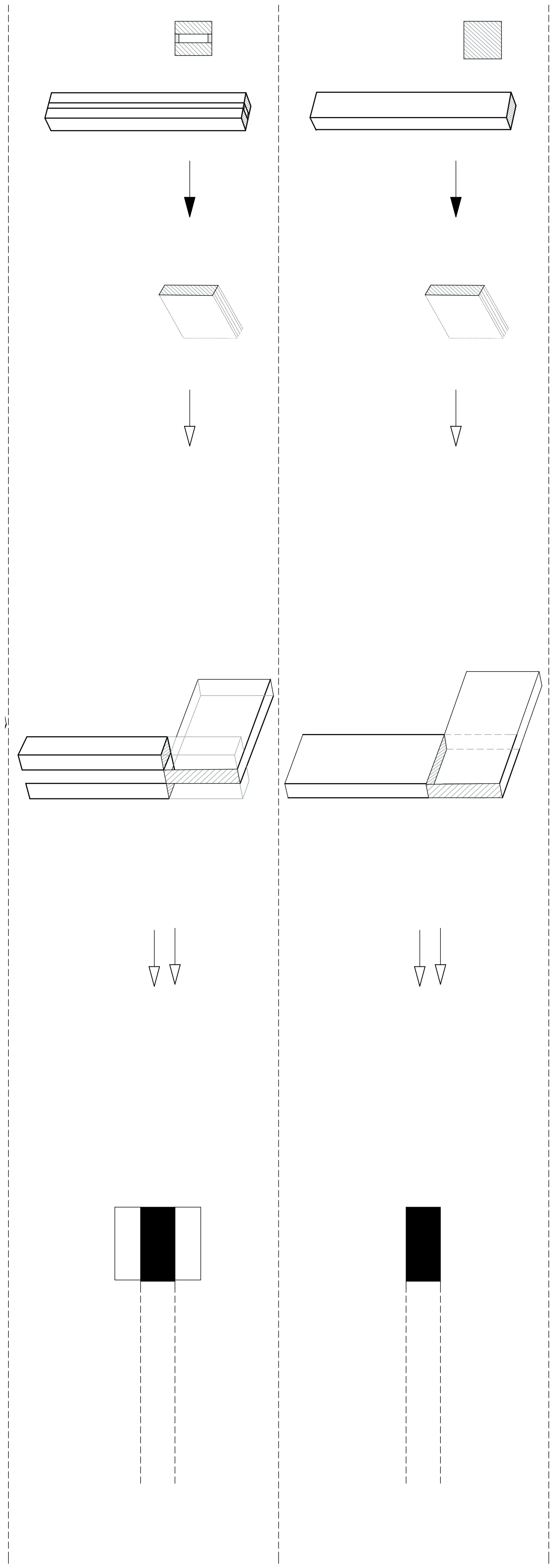


Figure 65.a Connections (by the author)

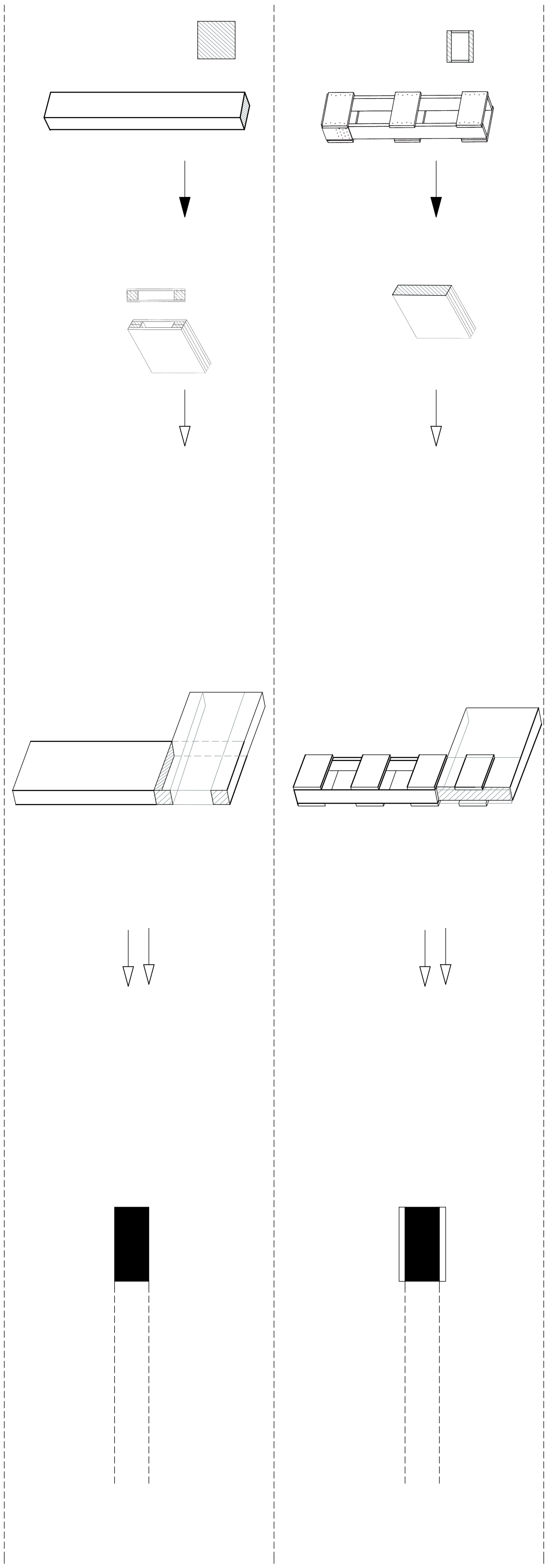


Figure 65.b Connections (by the author)

figure 39b

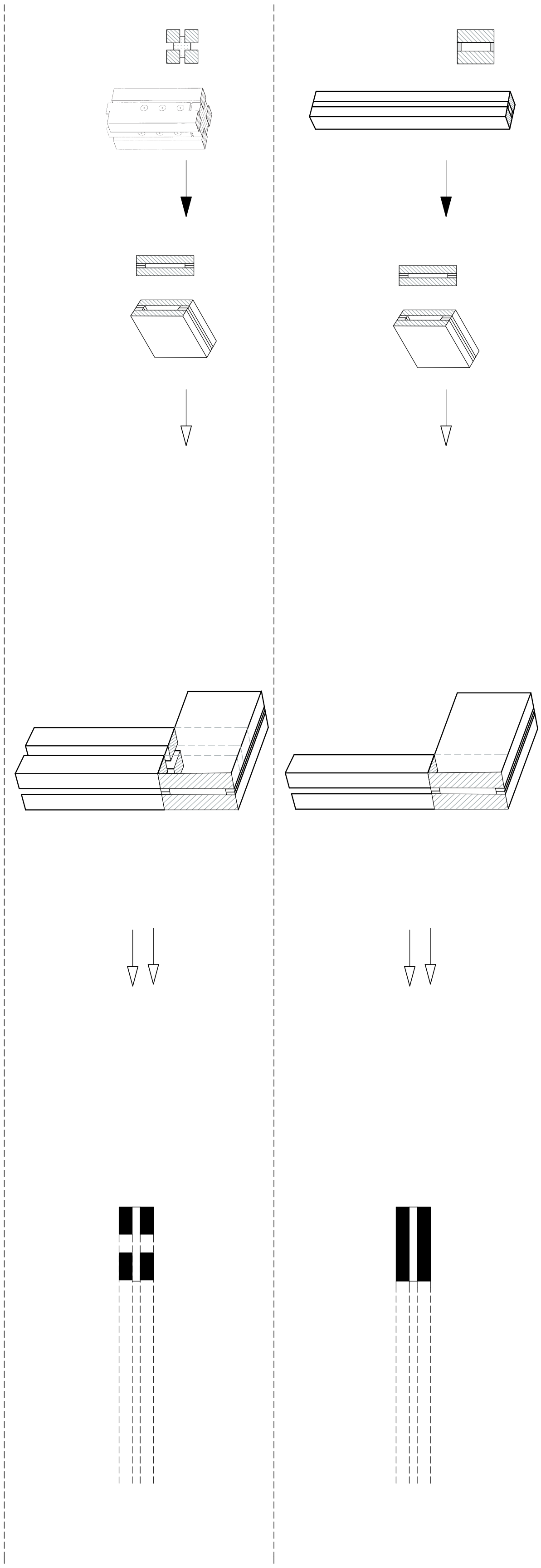


Figure 65.c Connections (by the author)

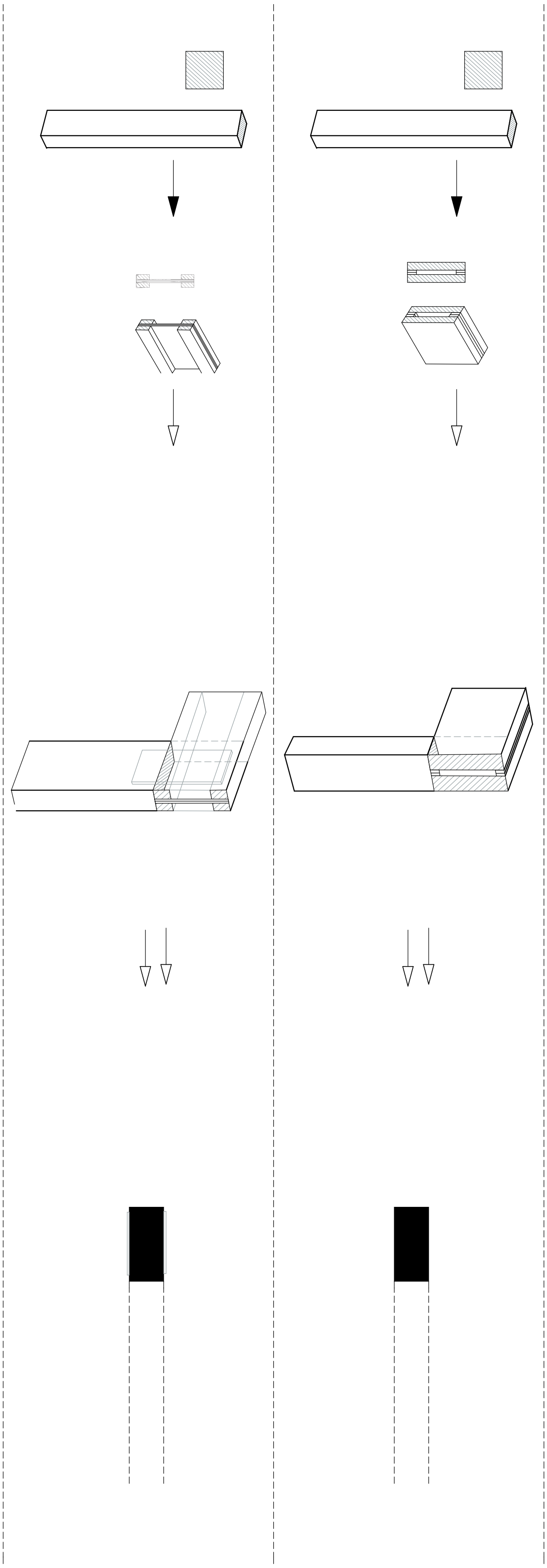


Figure 65.d Connections (by the author)

figure 39d

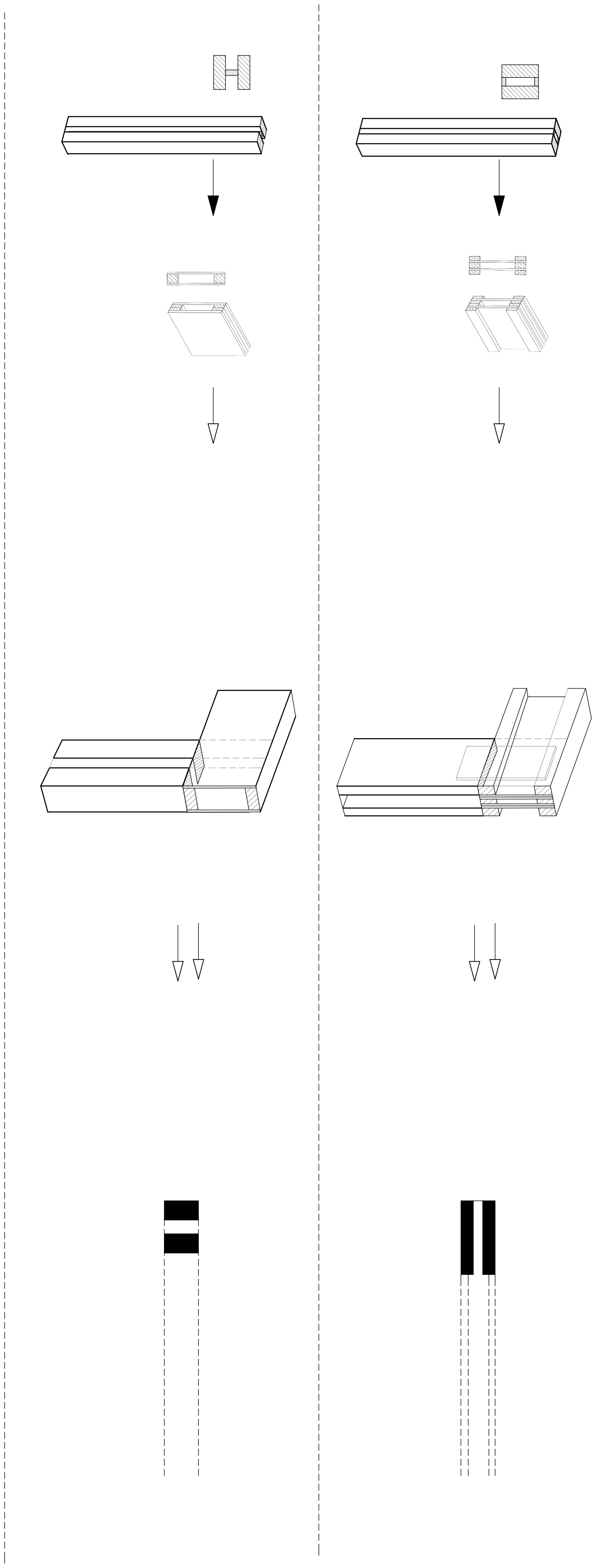
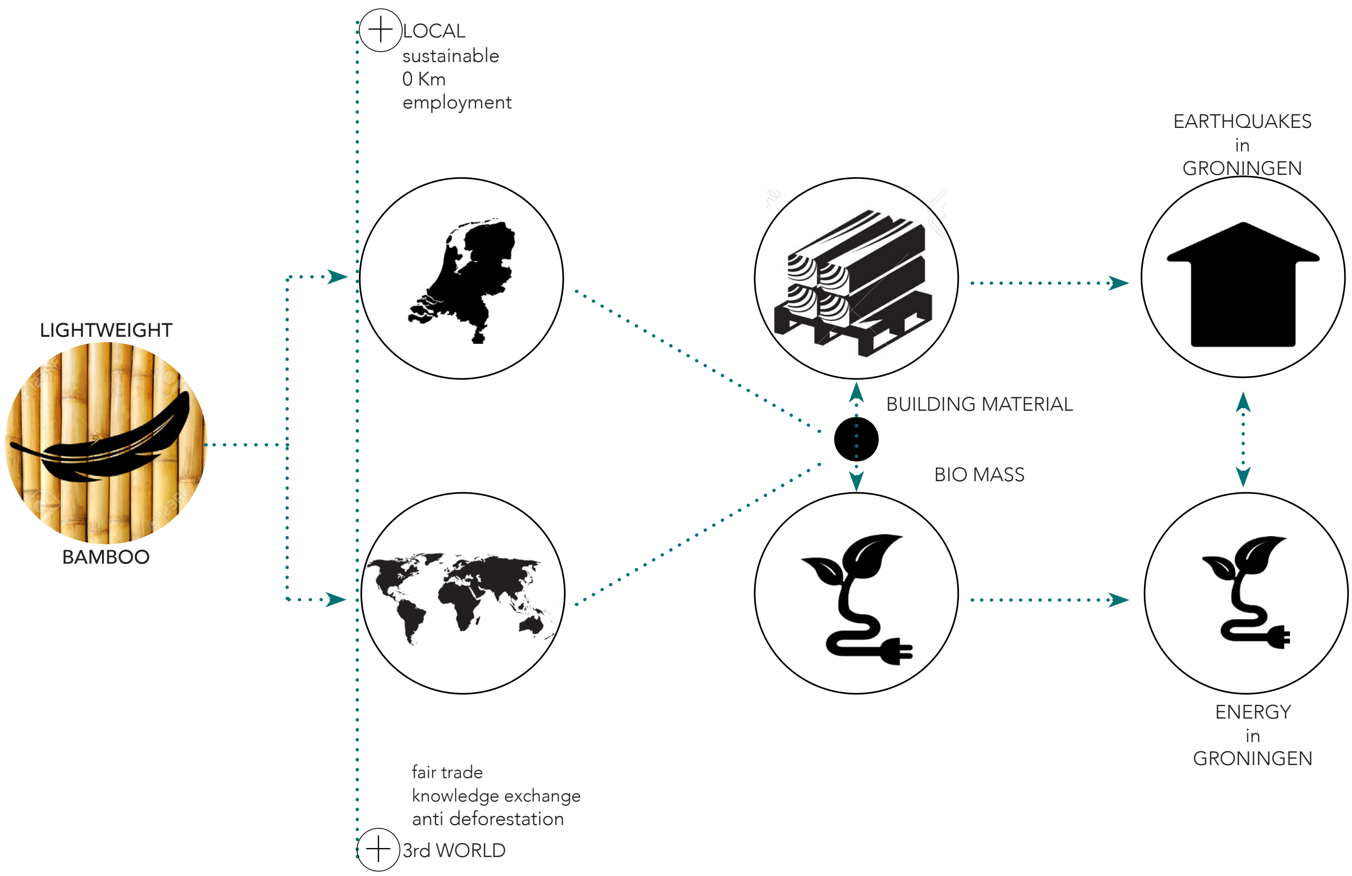


Figure 65.e Connections (by the author)


LOCAL
sustainable
0 Km
employment
EARTHQUAKES
in
GRONINGEN
LIGHTWEIGHT
BAMBOO
BUILDING MATERIAL
BIO MASS
ENERGY
in
GRONINGEN
fair trade
knowledge exchange
anti deforestation
3rd WORLD

Conclusion

Bamboo has extraordinarry mechanical properties, it can grow in (Dutch) areas which are non productive at the moment, it has a very high yield and its roots stay intact after harvesting. Bamboo can even more be a good solution if we combine and integrate the opportunities of the new Dutch seismic market and the socio-economic problems of Groningen like the demographic shrink and the economical depression.

The state of the art is that in Western Europe and in the United Stated laminated bamboo is not officially recognized as a structural building material, or it is considered a local material. However theoretical greenhouse studies and field tests runned by Oprins show that a local production for Europe is feasible.

Production and use analysis have shown that on the one hand laminated structural elements (from *Guadua Angustifolia Bamboo*) can be used for antiseismic constructions in Groningen, and on the other that biomass energy production (from *Phyllostachys Aurea Bamboo*) can be a valid alternative in the period following upon the extinction of the natural gas field that caused the earthquakes.

A quantitative analysis points out that one hectare of *Guadua Bamboo* may generate enough building material for a 175m^2 house of laminated bamboo a year. And calculations show that field production of *Phyllostachys Aurea* of just one hectare in the seismic area around Groningen will produce energy for 32 households each year.

Due to its high strength and stiffness bamboo is an extraordinary anti-seismic material. Dimensioning the bamboo beam with a MoR which is 4 times lower assures 4 times more potential capacity to resist extra forces like seismic ones, assuring the safety of the construction. Bamboo's higher MoE assures that under a certian load the construction will keep bending while a wooden construction would have collapsed. Calculations show that between 2 and 4 times less material is necessary with respect to wooden constructions. This could also keep the costs lower.

Research by design has been done for the connections between those elements trying to keep the seismic resistant structures as much lightweight possible adapting the laminated wood connections to the laminated bamboo elements. The results are the basis for further design.

These outcomes close "the loop" working towards sustainable solutions for the Groningen area where the dominant role of the economy has caused not only social or environmental problems (like the induced earthquakes) but also technical-architectural issues (to the built environment).
Local bamboo production, anti-seismic structural applications, increase of biodiversity, biomass production, local sustainable work opportunities are all part of the costellation of mutually interactive systems of innovation meant to address the complex situation in Groningen.
Bamboo can be the "new golden forest" for the northern part of the Netherlands.

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Figures list

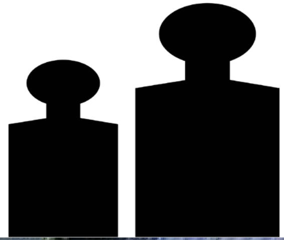
Words count

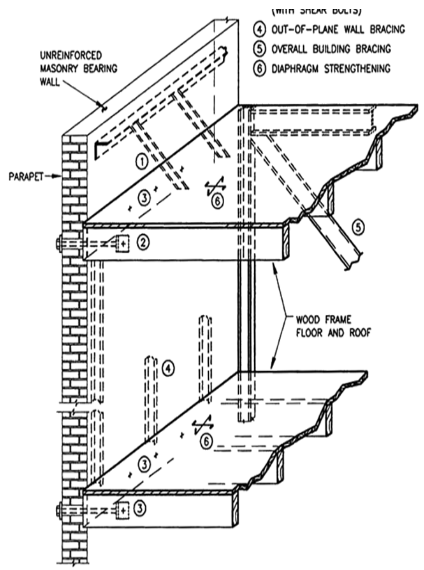
Abstract: 165 words; Paper corp: 9768 words.

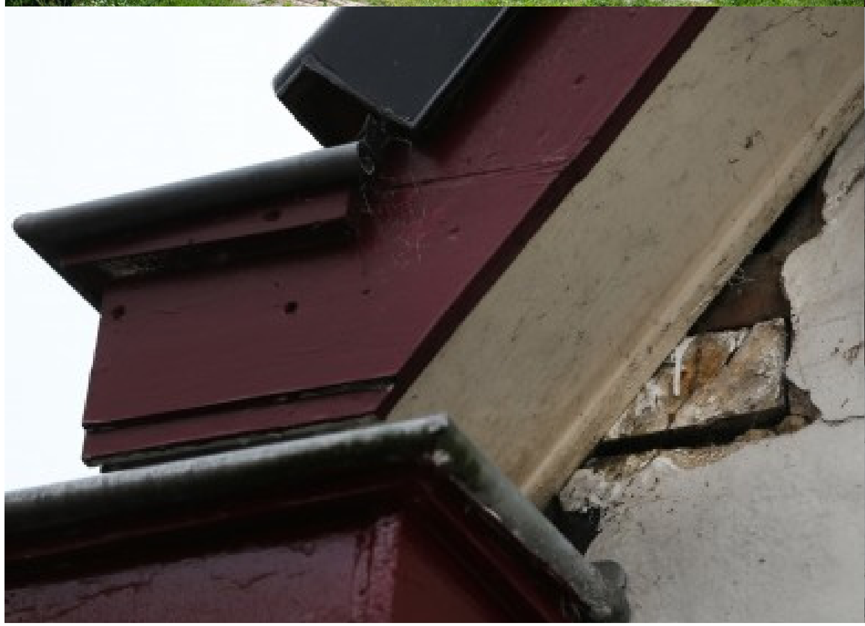
Appendix 1

Lightweight-Seismic

unreinforced masonry







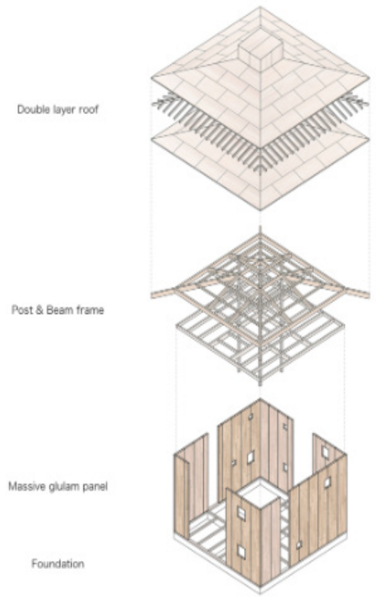
quality
thermal insulation
comfort
wind and snow resistance

aeshetics
landscape
nature
space

earthquakes resistance

new architecture

wood



MASSA 400-500 kg/m3

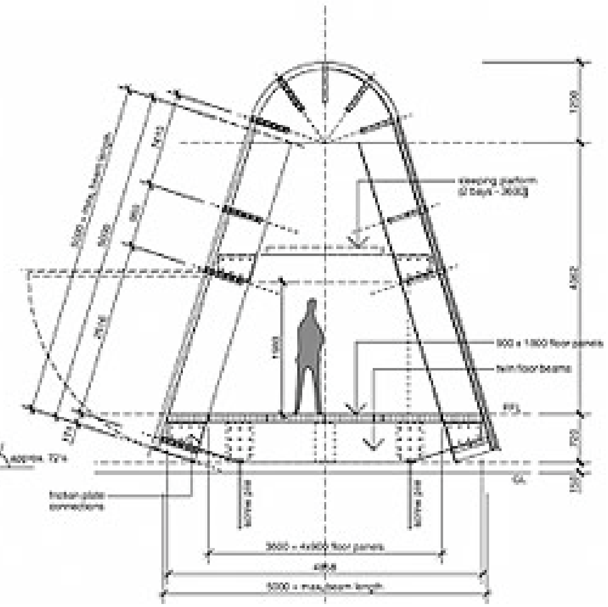
COMPRESSION STRENGHT 24 N/mm^2

BENDING STRENGHT 24 N/mm^2

TENSILE STRENGHT 16 N/mm^2

ELASTIC MODUL 16700 tN/mm^2
8500

cardboard



<u>MASSA</u> 691-1200 kg/m3

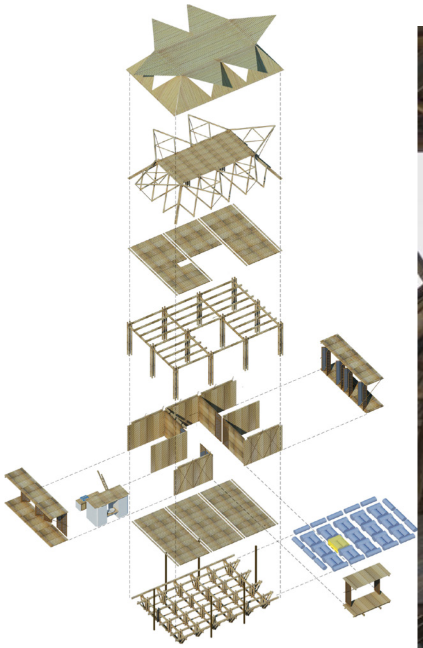
<u>COMPRESSION STRENGHT</u> 8,1 N/mm^2

<u>BENDING STRENGHT</u> 6,9 N/mm^2

<u>TENSILE STRENGHT</u> 8,1 N/mm^2

<u>ELASTIC MODUL</u> 1000N/mm^2
1500

bamboo



MASSA 600 kg/m3, compressed 1050 kg/m^3

COMPRESSION STRENGHT 6,6 N/mm^2

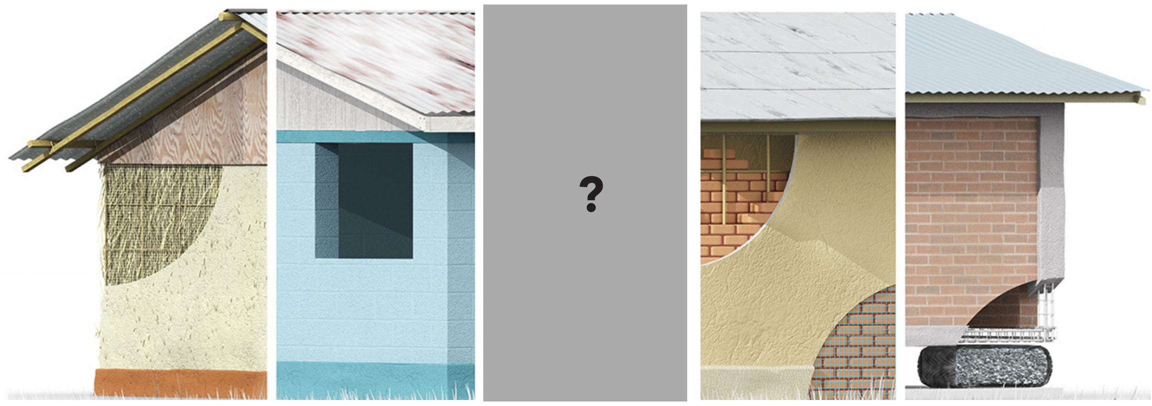
BENDING STRENGHT 8,5 N/mm^2

TENSILE STRENGHT 25 N/mm^2

ELASTIC MODUL 18400 tensile N/mm^2

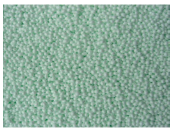
20700compre

How can we develop a methodology for an anti seismic construction approach for NL?



Pakistan	Haiti	Groningen	Peru	Indonesia
October 8, 2005 Kashmir 7.6 magnitudo 75000 fatalities	January 12, 2010 Port du Prince 7.0 magnitudo 222500 fatalities	August 8, 2012 Huizingen 3.6 0	May 31, 1970 Chimbote 7.9 magnitudo 70000 fatalities	December 26, 2004 Sumatra 9.1 227900 fatalities
Light walls and gables Straw-Nylon-Netting	Sheet metal roofs Small windows	??? ???	Reinforced walls Bamboo-Plastic meshs	Confined masonry frames bricks-shock absorbers

How lightweight can we go?


biofoam
15-20 kg/m³


vlaswol
25-45 kg/m³


hennepvezel iso
30-42 kg/m³


hennepvezel
35 kg/m³


cellulose iso
40-65 kg/m³


kurk
200 kg/m³

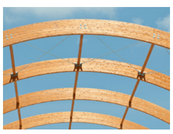

riet
250 kg/m³


vlasspanplaat
350 kg/m³

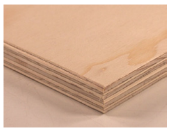

ecoboard
400-700
kg/m³


plexwood
400-800
kg/m³


glulam
450-650
kg/m³


laminated
450-530
kg/m³


bamboo
600 kg/m³


plywood
650 kg/m³


houtenka-
naalplaten
510 kg/m³


accaya massief
510 kg/m³


platowood
497 kg/m³


cardboard
691 kg/m³


bamboo
1050 kg/m³


cardboard
1200 kg/m³


concrete
2400 kg/m³

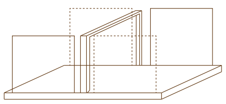

aluminium
2755 kg/m³

Wood_Bamboo_Cardboard_Steel

MASSA 400-800 kg/m3	MASSA 600 kg/m3, compressed 1050 kg/m^3	MASSA 691-1200 kg/m3	MASSA 7800 kg/m3
COMPRESSION STRENGHT 24 N/mm^2	COMPRESSION STRENGHT 6,6 N/mm^2	COMPRESSION STRENGHT 8,1 N/mm^2	COMPRESSION STRENGHT 235 N/mm^2
BENDING STRENGHT 24 N/mm^2	BENDING STRENGHT 8,5 N/mm^2	BENDING STRENGHT 6,9 N/mm^2	BENDING STRENGHT 235 N/mm^2
TENSILE STRENGHT 16 N/mm^2	TENSILE STRENGHT 25 N/mm^2	TENSILE STRENGHT 8,1 N/mm^2	TENSILE STRENGHT 235 N/mm^2
ELASTIC MODUL 16700 tN/mm^2 8500	ELASTIC MODUL 18400 tensile N/mm^2 20700compre	ELASTIC MODUL 1000N/mm^2 1500	ELASTIC MODUL 210 000 N/mm^2

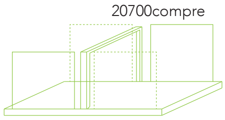
Cardboard_Bamboo_Wood_Steel
earthquake proof

WOOD	BAMBOO	CARDBOARD	STEEL
MASSA 400-500 kg/m3	MASSA 600 kg/m3, compressed 1050 kg/m^3	MASSA 691-1200 kg/m3	MASSA 7800 kg/m3
COMPRESSION STRENGHT 24 N/mm^2	COMPRESSION STRENGHT 6,6 N/mm^2	COMPRESSION STRENGHT 8,1 N/mm^2	COMPRESSION STRENGHT 235 N/mm^2
BENDING STRENGHT 24 N/mm^2	BENDING STRENGHT 8,5 N/mm^2	BENDING STRENGHT 6,9 N/mm^2	BENDING STRENGHT 235 N/mm^2
TENSILE STRENGHT 16 N/mm^2	TENSILE STRENGHT 25 N/mm^2	TENSILE STRENGHT 8,1 N/mm^2	TENSILE STRENGHT 235 N/mm^2
ELASTIC MODUL 16700 tN/mm^2 8500	ELASTIC MODUL 18400 tensile N/mm^2 20700compre	ELASTIC MODUL 1000N/mm^2 1500	ELASTIC MODUL 210 000 N/mm^2



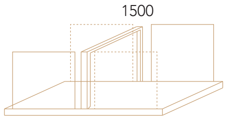
S 0,2m^3 x 600kg/m^3= 120kg
F 0,12m^3 x 600kg/m^3= 72kg
IN 0,1m^3 x 200kg/m^3= 40kg
D 0,2m^3 x 600kg/m^3= 120kg

TOT **352** kg



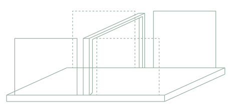
S 0,2m^3 x 1050kg/m^3= 210kg
F 0,12m^3 x 1050kg/m^3= 126kg
IN 0,1m^3 x 600g/m^3= 60kg
D 0,2m^3 x 1050kg/m^3= 210kg

TOT **606** kg



S 0,2m^3 x 1200kg/m^3= 240kg
F 0,12m^3 x 1200kg/m^3= 144kg
IN 0,1m^3 x 690kg/m^3= 69kg
D 0,2m^3 x 1200kg/m^3= 240kg

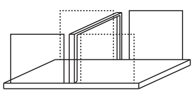
TOT **693** kg



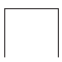
S 0,2m^3 x 7800kg/m^3= 1560kg
F 0,12m^3 x 7800kg/m^3= 936kg
IN 0,1m^3 x 2755kg/m^3= 275kg
D 0,2m^3 x 7800kg/m^3= 1560kg

TOT **4331** kg

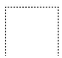
seismic structure	materials
diaphram	WOOD
bound beams	WOOD STEEL
shear walls	WOOD CARDBOARD
braced frames	WOOD CARDBOARD
moment frames	STEEL
	WOOD CARDBOARD
	STEEL



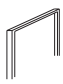
seismic structure



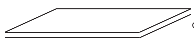
shear wall 0,2 x 0,5 x 2m= 0,2m^3 SW



infill 0,5 x 0,1 x 2m= 0,1m^3 IN



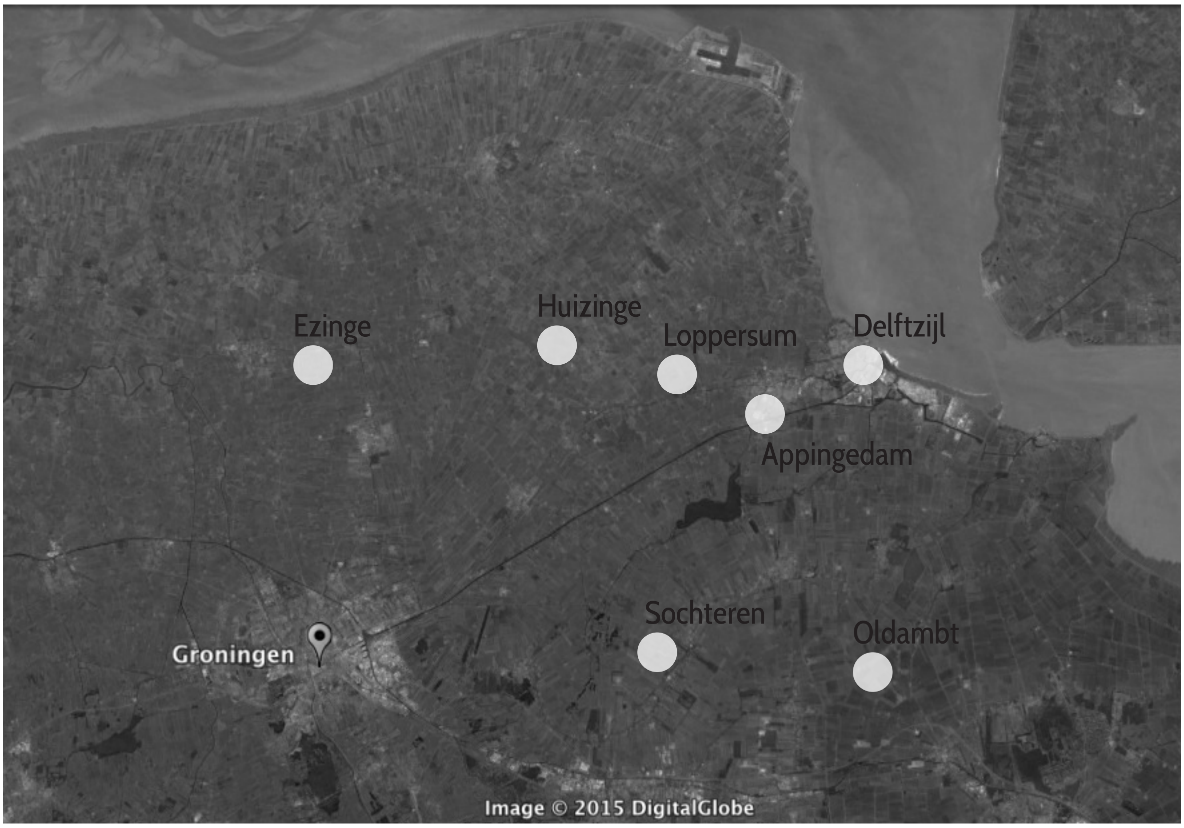
frame (0,2 x 0,2 x 1) x 3m= 0,12m^3 F

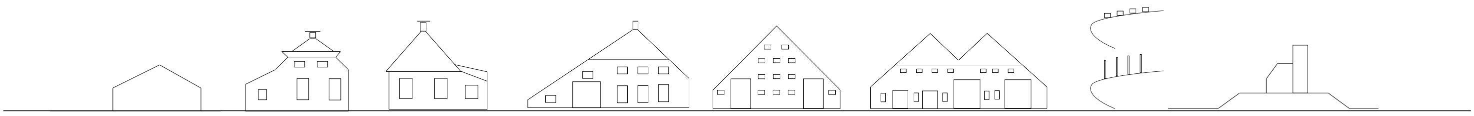


diaphram 1 x 0,2 x 1 = 0,2m^3 D

Appendix 2

Architecture in Groningen





Which elements form the architectural language of the area of Groningen?

Churches_____Houses_____Farms_____Rural_____Landscape_____

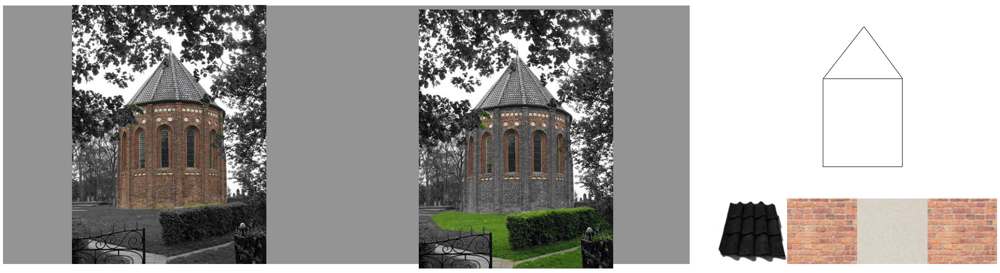
Textures_Materials_Colors

Church_Slochteren _13th century

Church_Appingedam _13th century

Church_Loppersum _13th century

Church_Delftzijl _13th century



Church_Huizinge _13th century

Church_Ezinge _13th century

House_Slochteren _

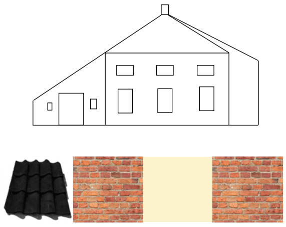
House_Appingedam _1960-70

House_Loppersum _13th century

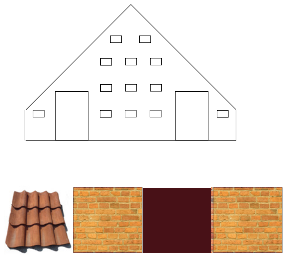
House_Delftzijl _

House_Huizinge_

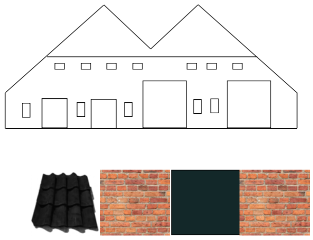
House_Huizinge_

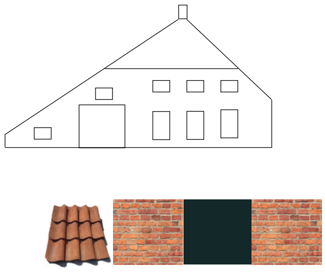
Farm_Appingedam_

Farm_Oldambt_

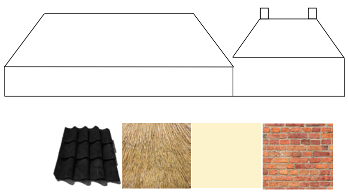



Farm_Loppersum_

Farm_Delftzijl_


Farm_Huizinge_

Farm_Bedum_

Farm_Slochteren_

Farm_Drieborg_

Landscape_Slochteren _Appingedam

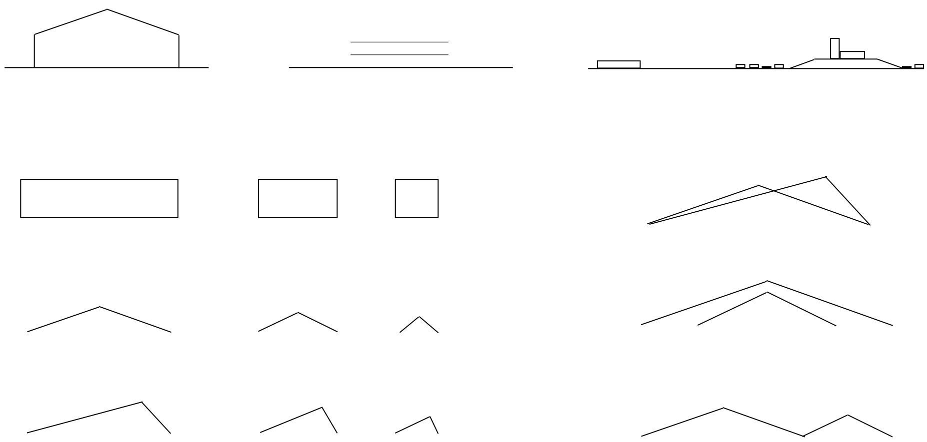
Landscape_Loppersum Delftzijl_

Landscape_Ezinge_Huizinge_Beintum

Landscape_schuur_Slochteren

Landscape_Schuur_Appingedam

Landscape_Schuur_Loppersum



Appendix 3

Calculations

Structural considerations and calculations for building with laminated bamboo

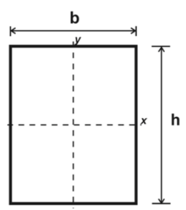
- LaminatedBamboo_Column_Calculations
- LaminatedBamboo_Beam_Calculations
- Rules of thumb
- Material efficiency (how lightweight can we go)

- LaminatedBamboo_BioMass_Calculations
- LaminatedBamboo_Production/year_Calculations

LaminatedBamboo_Column_Calculations

The Euler's formula is used to calculate the critical buckling load for a column and it is given by

F = $\frac{\pi^2\ E\ I}{l_{eff}^2}$



Column 135 . 135 mm
l = 3600mm
load = 100 kN
(NB. Those dimensions satisfy wood constructions with this given load (W.J. Raven p.63))

E bamboo= 19 Gpa = 19000 N/mm^2
Effective length l_{eff}= clamped-hinged= l/ $\sqrt{2}$ =L . 0,7 = 3600 . 0,7 = 2100mm
I (moment of Inertia 135x135mm) = I= $\frac{bh^3}{12}$= 27 . 10^6 N

F = $\frac{\pi^2\ 19000\ .\ 27\ .\ 10^6}{2100^2}$ = 1,14 . 10^6 N = 1140 kN

load = 100 kN

1140 kN / 100 kN = 11x → it can carry 11 times this load. That is why we look for a column which section has a moment of Inertia 11 times smaller.

27 . 10^6 N / 11= 2,4 10^6 N

From the moment of Inertia table for columns with a rectangular section we find that the section with 2,4 10^6 N as intertia moment is 75x75mm.

75 . 75mm ≅ 135 . 135 mm / **2**

So we can conclude:
if wooden columns are dimensioned with d = 1/20 L for bamboo this ratio will be x2
→1/40 L
d = 1/40 L

With the other dimension ratios derived from wood constructions (W.J. Raven p. 76) and compared with the d=1/40L ratio given as:

$h = \frac{L}{40}$

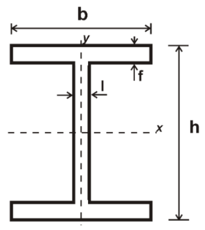
$e = \frac{M}{F} \rightarrow \frac{e}{h}$

$b_1 h = \frac{F}{14}$

$b = b_1 \, . \, (1 + 3 \, . \, \frac{e}{h})$

To maximize the strength potential of bamboo and in order to try to minimize the use of material other column sections have been considered.

I profile



Column 135height . 135width . 8flange . 45 bodywidth mm
l = 3600mm
load = 100 kN

E bamboo= 19 Gpa = 19000 N/mm^2
Effective length= clamped-hinged= l/ $\sqrt{2}$ =L . 0,7 = 3600 . 0,7 = 2100mm
I (moment of Inertia 135x135mm I profile) = I= $\frac{bh^3 - (b-l)\,(h-2f)^3}{12}$= 26 . 10^6 N

F = $\frac{\pi^2 \; 19000 \;.\; 26 \;.\; 10^6}{2100^2}$ = 1,10 . 10^6 N = 1100 kN

load = 100 kN
1100 kN / 100 kN = 11x → it can carry 11 times this load. That is why we look for a column which section has a moment of Inertia 11 times smaller.

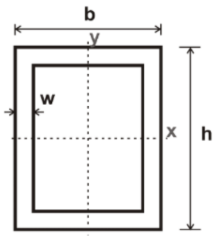
26 . 10^6 N / 11= 2,3 10^6 N

From the moment of Inertia table for columns with a I section we find that the section with 2,4 10^6 N as inertia moment is 72height . 72width . 8flange . 24 bodywidth mm.

72 . 72mm ≅ 135 . 135 mm / **2**

So we can conclude:
if wooden columns are dimensioned 135height . 135width . 8flange . 45 bodywidth mm the bamboo column has to be ≅ 2x times smaller.

Box profile



Column 135height . 135width . 8w mm
l = 3600mm
load = 100 kN

E bamboo= 19 Gpa = 19000 N/mm^2
Effective length= clamped-hinged= l/ $\sqrt{2}$ =L . 0,7 = 3600 . 0,7 = 2100mm
I (moment of Inertia 135x135mm box profile) = I= $\frac{bh^3 - (b-2w)\,(h-2w)^3}{12}$= 10 . 10^6 N

F = $\frac{\pi^2 \; 19000 \;.\; 10 \;.\; 10^6}{2100^2}$ = 0,4. 10^6 N = 400 kN

load = 100 kN
400 kN / 100 kN = 4x → it can carry 4 times this load. That is why we look for a column which section has a moment of Inertia 4 times smaller.

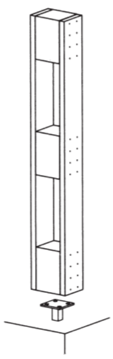
10 . 10^6 N / 4= 2,5 10^6 N

From the moment of Inertia table for columns with a box section we find that the section with 2,5 10^6 N as inertia moment is 80height . 80width . 8w mm.

80 . 80mm ≅ 135 . 135 mm / 1,7

So we can conclude:
if wooden columns are dimensioned 80height . 80width . 8w mm the bamboo column has to be ≅ 1,7x times smaller.

Battened column



here we consider the two vertical elements with structural function and the central part with reinforcement function. Therefore two different tests have to be made. One for the overall section, one for the single vertical element, considering F/2 applied to it.

Global test

Column 135height . 135width . 0flange . 25 bodywidth mm
l = 3600mm
load = 100 kN

E bamboo= 19 Gpa = 19000 N/mm^2
Effective length= clamped-hinged= l/ $\sqrt{2}$ =L . 0,7 = 3600 . 0,7 = 2100mm
I (moment of Inertia 135x135mm I profile) = I= $\frac{bh^3 - (b-l)\,(h-2f)^3}{12}$= 20 . 10^6 N

F = $\frac{\pi^2\ 19000\ .\ 20\ .\ 10^6}{2100^2}$ = 0,84. 10^6 N = 840 kN

load = 100 kN
840 kN / 100 kN = 8x → it can carry 4 times this load. That is why we look for a column which section has a moment of Inertia 4 times smaller.

20 . 10^6 N / 8= 2,5 10^6 N

From the moment of Inertia table for columns with a box section we find that the section with 2,5 10^6 N as inertia moment is 75height . 75width . 0flange . 25 bodywidth mm

75 . 75mm ≅ 135 . 135 mm / 2

So we can conclude:
if wooden columns are dimensioned 135height . 135width . 0flange . 25 bodywidth mm the bamboo column has to be ≅ 2x times smaller.

Local test
Column 75height . 25width mm
l = 3600mm
load = 100 kN →F/2

E bamboo= 19 Gpa = 19000 N/mm^2
Effective length= clamped-hinged= l/ $\sqrt{2}$ =L . 0,7 = 3600 . 0,7 = 2100mm
I (moment of Inertia 135x135mm rectangular profile) = I= = $\frac{bh^3}{12}$ = 0,09 . 10^6 N

F = $\frac{\pi^2\ 19000\ .\ 0{,}09\ .\ 10^6}{2100^2}$ = 3,8 N < F/2 satisfy.

LaminatedBamboo_Beam_Calculations

$\frac{h}{L} = \frac{2\ .\ 5\ .\ 8fm}{384\ .\ 0{,}004\,E} = \frac{52fm}{E}$

MoR= Module of Rupture
MoE=Module of Elasticity
(refer to W.J. Raven p. 36)

E wood = MoE= 8095-9786 N/mm^2
f_m wood =material strength= MoR= 15,4-20 N/mm^2

$\frac{h}{L} = \frac{52f_m}{E}$ = 52 . $\frac{15{,}4\text{N/mm2}}{8095\text{N/mm2}}$ = 0,099 = L= 1/10 h

In structural applications we use 50% of the calculated strength (W.J. Raven). For this reason:

L= 1/20 h (with H section height of the beam)

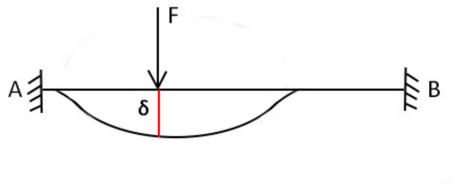
E bamboo =MoE= 9000-19000 N/mm^2
f_m bamboo =MoR=material strength= 77-102 N/mm^2

$\frac{h}{L} = \frac{52f_m}{E}$ = 52 . $\frac{77\text{N/mm2}}{19000\text{N/mm2}}$ = 0,2 = L= 1/5 h

In structural applications we use 50% of the calculated strength (W.J. Raven). For this reason:

L= 1/10 h (with H section height of the beam)

- NB.



F $_{\text{force applied}}$= $f_{m\ (\text{material strength})}$
δ= displacement

When F eguals f_m the δ (displacement) is maximum and the beam will collapse. The formula $\frac{h}{L} = \frac{52 f_m}{E}$ calculates the the dimensions of the beam with the maximum accepted load.
If we calculate the dimensions of the laminated bamboo beam with the real MoR and MoE the result is an oversizing. This is because the bamboo is not only very strong but also very flexible. This means that with the same applied force a wooden beam will collapse (having a lower MoE) while a bamboo beam will keep bending.
Therefore we could consider the bamboo beam working on a lower tension-value taking, for example, the wood MoR which is 4 times lower.
In case of any seismic forces the bamboo beam will have 4 times more potential capacity to resist those forces assuring the safety of the construction.
This (practical) assumption result in the following calculation:

E bamboo = MoE= 9000-19000 N/mm^2
f_m wood = material strength= MoR= 15,4-20 N/mm^2

$\frac{h}{L} = \frac{52 f_m}{E}$ = 52 . $\frac{20\text{N/mm2}}{19000\text{N/mm2}}$ = 0,054 = L= 1/20 h

In structural applications we use 50% of the calculated strength (W.J. Raven). For this reason:

L= 1/40 h (with H section height of the beam)

Calculation for the b/a ratio

b = width beam section and a = hoh distance between the beams
(W.J. Raven pp. 39-40)

$$\frac{b}{a} \geq \frac{20^3}{1000} \cdot \frac{39p}{E} = \frac{312p}{E}$$

with p(load) between 1 kN/m^2 and 3,9 kN/m^2

$$\frac{b}{a} = \frac{312p}{E} = \frac{312\ .\ (1<3{,}9)}{19000} = \frac{1}{16} - \frac{1}{60}$$

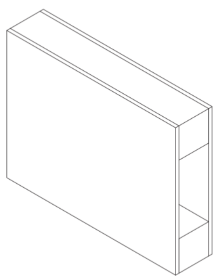
ex.
L = 4200mm
a = 600mm
h = 1/40 L = 1/40 . 4200 = 105mm

$with\ \frac{b}{a} = \frac{1}{16}$

b = 600/16 = 37,5mm

b : 600 =1 : 16 with b=37,5mm
or
b : 800 =1 : 16 with b=50mm….etc etc

To maximize the strength potential of bamboo and in order to try to minimize the use of material another beam sections (box beam) has been considered.



To come up with the rules of thumb for this kind of beam the following comparison has been made:

Wood laminated beam (known) → Wood box beam (known)
Bamboo laminated beam (known) → Bamboo box beam (*unknown*)

Wood laminated beam

L=4200mm

h=1/20L

h=4200/20=210mm

$\frac{b}{h}$= 1/10

b=21mm

refering to $\frac{b}{a} \geq \frac{20^3}{1000} \cdot \frac{39p}{E} = \frac{312p}{E}$

$\frac{b}{a}$= $\frac{1}{6}$ - $\frac{1}{28}$

21 : 600 =1 : 28   with b=21mm

or with a=800mm

b_x : 800 =1 : 28   with b=28mm….etc etc

Wood box beam

L=4200mm

h=1/15L

h=4200/15=280mm

$\frac{b}{h}$= 1/6

b=46mm

refering to $\frac{b}{a} \geq \frac{20^3}{1000} \cdot \frac{39p}{E} = \frac{312p}{E}$

$\frac{b}{a}$= $\frac{1}{14}$

46 : 600 =1 : 14   with b=46mm

or with a=800mm

b_x : 800 =1 : 14   with b=57mm….etc etc

Bamboo laminated beam

L=4200mm

h=1/40L

h=4200/40=105mm

$\frac{b}{h}$= 1/10

b=10,5mm

refering to $\frac{b}{a} \geq \frac{20^3}{1000} \cdot \frac{39p}{E} = \frac{312p}{E}$

$\frac{b}{a}$= $\frac{1}{16}$ - $\frac{1}{60}$

10 : 600 =1 : 60   with b=10mm

or with a=800mm

b_x : 800 =1 : 60   with b=13,3mm….etc etc

Bamboo box beam

Wood laminated beam (known) → Wood box beam (known)

Bamboo laminated beam (known) → Bamboo box beam (*unknown*)

(h=1/20L) : (h=1/15L) = (h=1/40L) : (h=1/30L)

(b/h=1/10) : (b/h=1/6) = (b/h=1/10) : (b/h=1/6)

(b/a=1/28) : (b/a=1/14) = (b/a=1/60) : (b/a=1/30)

<u>Rules of Thumb for laminated bamboo</u>

- Beams (massive)

h=1/40L
b/h=1/10
b/a=1/16-1/60

- Beams (box)

h=1/30L
b/h=1/6
b/a=1/16-1/30

- Column (rectangular section)

d= 1/20L for wood → 2x times smaller for bamboo (1/40)

- Column (I section)

d= 1/20L for wood → 2x times smaller for bamboo (1/40)

- Column (box section)

d= 1/20L for wood → 1,7x times smaller for bamboo (1/30)

- Column (battened section)

d= 1/20L for wood → 2x times smaller for bamboo (1/40)

<u>Material efficiency</u>

- Beams

Keeping L (length) constant
Wooden laminated beam of 210 . 21mm
Area= $4410mm^2$
Wooden box beam of 280 . 46 . 23mm
Area = $2116mm^2$
Bamboo laminated beam of 105 . 10mm
Area= $1050mm^2$
Bamboo box beam 140 . 23 . 15mm
Area= $690mm^2$

$4410mm^2 > 2116mm^2 > 1050mm^2 > 690mm^2$
→$4410mm^2 / 690mm^2$ = **6,4 times** less material use.

- Columns

Keeping L (length) constant
Wooden laminated column 135 . 135mm
Area=$18225mm^2$
Bamboo laminated column 75 . 75mm
Area=$5625mm^2$
Bamboo I column 72height . 72width . 8flange . 24 bodywidth mm
Area= $3648\ mm^2$
Bamboo box column 80height . 80width . 8w
Area= $2304\ mm^2$
Bambo battered column 75height . 75width . 0flange . 25 bodywidth mm
Area= $3750\ mm^2$
→$18225/5625mm^2$=**3,2 times** less material use for full laminated columns wood vs bamboo.

Final check

- Ir. A. Vallozzi, Senior Structural Engineer at Seaway Heavy Lifting NL.

References for the formulas

- PC frame, Constructie berekeningen, 2015. http:/www.mile17.nl (accessed 7 December 2015)

- Matsa wood, slanke stijlen en balken, 2015 http://www.finnjoistschuif.nl/indexK2.html?mat=fji (Accessed 7 December 2015)

- W.J. Raven, *Vuistregels voor het bepalen van afmetingen van vloeren, balken en kolommen*, Delft: TU Delft dictaat, 2003.

LaminatedBamboo_BioMass_Calculations

Phyllostachys aurea, field production.

60.000 kg per ha → 19,7 MJ/Kg

19,7 MJ/Kg . 60.000 kg = 1.176.000 MJ = 326.666 kW

1 house = 10000kWh a year (6 pp unit) ((yearly energy consume/house))

326.666 kW : 10000kWh/y = 32,6 houses/y energy production

Guadua angustafolia, greenhouse (rests) production.

19000 kg per ha → 18 MJ/Kg

18 MJ/Kg . 19000kg = 342000MJ = 95000 kW

1 house = 10000kWh a year (6 pp unit) ((yearly energy consume/house))

95000 kW : 10000kWh/y = 9,5 houses/y energy production

LaminatedBamboo_Production/year_Calculations

One family house of 175m^2 (wood frame construction)
→ 13,m^3 CLS wood and 0,078m^3 /m^2 wood
one ha of bamboo gives 15m^3/ha/year of laminated bamboo

15m^3 ≅ 13,m^3

→one laminated bamboo house (of 175m^2) per ha per year.