CHALMERS

Bamboo and Wheat Straw as a Green Building Composite Material

Master of Science Thesis in the Master's Programme Design for Sustainable Development

KATARINA BÄCKLUND

Department of Architecture & Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

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Examensarbete 2011:50
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Abstract

One important issue that contributes to several negative impacts on our world is the global deforestation. The global deforestation is a threat to our planet. It destroys ecosystems, forces habitats to find new places to live in and contributes to landslides. The mitigation of these effects creates a need for research about how forests can be preserved. There are millions of solutions at different levels which should be adjusted for each and every specific site and living situation. One possible solution could be exploring solutions for more environmentally friendly alternatives to replace conventional wood materials.

This master thesis is an experimental study with a significant amount of trial and error. The scope of this master thesis work is to study a sandwich panel fully made of natural raw materials of bamboo, wheat straw (agricultural waste) and soy protein as a resin. The main purpose of this thesis work is to investigate the potential for the bamboo sandwich panel as an alternative for conventional panel, through testing its bending, compressive and shear strength. Proposals of potential applications of the panel were also made. The panel was manufactured and tested in the civil engineering laboratory at California State University Long Beach, Long Beach, USA.

One of the main conclusions is that the sandwich panel did not achieve as good strength results as expected. This is probably due to weak soy protein resin. Two main types of early failures were occurring. Either the bamboo mat separated from its core – probably due to the fact that the soy protein resin was too weak to hold the bamboo mats together with the wheat straw core. The other failure was that the wheat straw core cracked in an early stage. If a stronger resin was to be used, the wheat straw core would probably resist more loads.

Key words: Bamboo, wheat straw, bending, compressive and shear strength, sandwich panel

Bambu och Vetehalm Komponerat till ett Grönt Kompositmaterial

Tvärvetenskapligt Examensarbete inom Arkitektur samt Väg och Vattenbyggnad
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Sammanfattning

En viktig fråga som bidrar till flertalet globala konsekvenser på vår miljö är skördningen av skog och regnskog. Den globala skogsskövlingen är ett hot mot vår planet. Den förstör ekosystem, tvingar habitat att finna nya områden att leva i och den bidrar även till förödande jordskred. För att mildra dessa effekter krävs det mera forskning om hur våra skogar kan bevaras. Det finns miljoner av lösningar på olika nivåer, anpassade för var särskild plats och dess lokala situation. En möjlig lösning är att utforska alternativ till miljövänligare material som har potential att ersätta konventionella byggnadsmaterial av trä.

Detta examensarbete är en experimentell studie med en signifikant del av försök och misslyckanden. Tillämpningsområdet är att studera en sandwichpanel gjord av bambu och vetehalm med ett bindemedel, bestående av proteinet från sojabönor. Studien syftar till att undersöka potentialen för sandwichpanelens möjligheter till att användas som ett alternativ till konventionella träpaneler. Detta är utfört genom att testa sandwichpanelen i dess böjdraghållfasthet, tryckhållfasthet och skjuvhållfasthet. Förslag till lämpliga användarområden för sandwichpanelen var även gjorda. Panelen var tillverkad och testad i civilingenjörslaboratoriet på California State University Long Beach, Long Beach, USA.

En av de viktigaste slutsatserna är att sandwichpanelen inte uppnådde så goda resultat som önskat. Orsaken är förmodligen det svaga bindemedlet som inte innehåller några kemiska substanser. Två huvudsakliga typer av tidiga brott uppvisades; Separation av bambuskivan från dess mellanskikt av pressad vetehalm, samt krackelering av mellanskiktet. Sandwichpanelen hade antagligen uppvisat bättre test resultat om ett bindemedel med kemiska tillsatser hade använts.

Nyckelord: Bambu, vetehalm, böjdraghållfasthet, tryckhållfasthet, skjuvhållfasthet, sandwichpanel

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Preface

As an interdisciplinary thesis between the departments of Civil engineering and Architecture and the masters programme Design for Sustainable Development, this work is signified by a technical and sustainable approach. My aim has been to carry out a thesis that promotes environmentally friendly building and construction materials. If locally available and natural materials can be developed as alternatives for wooden building materials, the massive use of wood can be reduced. This could lead to a decrease of deforestation- one of the treats to our planet. The aim and goal for this thesis was supported and encouraged by Professor Tang-Hung Nguyen at California State University Long Beach, Long Beach, USA.

I would like to thank my supervisor Professor Tang-Hung Nguyen, Department of Civil Engineering & Construction Engineering Management, for assisting me in the first phase of defining this master thesis subject, providing the materials and assisting me during this process. Also, I would like to thank Mr. Vahe Kludjian for his enormous work and good will, assisting me while manufacturing and testing 73 specimens during summer 2010. Furthermore, I would like to thank mechanical engineering student Mr. Evan Nishimura for assisting me in the preparation of the materials. (California State University Long Beach, Long Beach, USA)

I would like to thank my supervisor Professor Tang Luping, Department of Civil and Environmental Engineering, for his assistance during this master thesis work. Also, I would like to thank Professor Inger Lise Syversen, Department of Arcitecture, in her assistance during the progress of the thesis. Furthermore, I would like to thank Architect Bengt J.O. Johansson and Heidi Norrström, PhD student, Department of Architecture, for their constructive criticism and helpful advices during my final seminar. Finally, I would like to thank Pernilla Hagbert and Fredrik Metso (master students in the programme Design for Sustainable Development) and Simon Pallin, PhD student in the Department of Civil and Environmental Engineering, for their helpful advices along this process. (Chalmers University of Technology, Gothenburg, Sweden).

Göteborg May 2011

Katarina Bäcklund

Nomenclature/Equations

ASTM	American Society for Testing and Standards
BASTA	A Swedish system that aims at hurrying up the phasing out of toxic substances in construction products
FAO	United Nations Food and Agriculture Organization
GDP	Gross Domestic Product
MDF	Medium Density Fiber
MOE	Modulus of Elasticity. MOE describes the relationship between the stress applied to a material and its corresponding strain.
MOR	Modulus of Rupture. MOR in bending is the maximum fiber stress at failure.
NGO	Non Governmental Organization
UNEP	United Nations Environment Programme

$$\rho = m / V$$

ρ = density, kg/m^3

m = total mass of the specimen, kg

V = volume of the specimen, m^3

$$MOR = 3PL / 2bd^2$$

MOR = modulus of rupture, MPa

P_{max} = maximum load at the fracture point, N

L = length of loading span, mm

$$\sigma = P/A$$

P = maximum load at the fracture point, N

A = Area of the specimen, m^2

1. Introduction

1.1 Problem statement

One of the main global issues today is the climate changes and all the issues behind how to improve the environmental conditions for all living organisms; human beings, animals, vegetation, air, water and soil. Businesses and industries are trying to mitigate to their impact on the environment. This is due to an increased awareness about the environment and at the same time also due to an increased awareness amongst the consumers.

For example, Apple that is one of the world leading multinational corporations in consumer electronics, computer software and personal computers, is using an advanced Life Cycle Assessment, LCA, for a cradle-to-grave life cycle assessment. The components of the electrical devices are evaluated from the extraction out of earth as raw material to the transformation into products to the user stage and finally the recycling is evaluated. This is an advanced way of manufacturing a product where every detail in the process is important. (Apple and the Environment, 2011)

Both consumers and producers are becoming more aware about our environment and demands higher quality on their services and products. Large scale businesses and industries are investing a lot in developing strategies how to perform their work and products with as small impact on the environment as possible. This is done in order to fulfill the increasing demand from consumers and to lower the negative effects on nature.

Millions of people are displaced due to catastrophes such as natural disasters or human conflicts. Many of these people live in temporary camps that become transformed into permanent living areas. The climate changes affect us all and poor people are affected worst. The climate changes bring a lot of negative effects, for example melting polar ices, rising sea levels and drought. Each of these negative factors contributes with many side effects and sets a huge stress on people’s living situations all over the world.

Natural disasters such as flooding, hurricanes, earthquakes and tsunamis have destroyed millions of people's homes during recent years. Mentioning a few disasters of the early 21th century: the tsunami in the Indian Ocean 2004, taking the life of 220 000 – 300 000 people in fourteen countries and making approximately 5 million people homeless. Other recent large earthquakes are the ones in Pakistan 2007 and Haiti 2010, both of them, making millions of people homeless.

Natural disasters will in the future continue to make large numbers of people homeless and as Figure 1.1 shows, natural disasters trends to increase. Therefore, it is of greatest importance to invest more resources into various research projects that is aiming towards mitigating damages after a disaster. Whether natural disasters are increasing or occurring more often are not proven. There are also several theories that natural disasters comes as an effect of global warming and climate changes. Since the beginning of Earth, the climate has always been changing and there have always occurred extreme weather events.

Trends in natural disasters

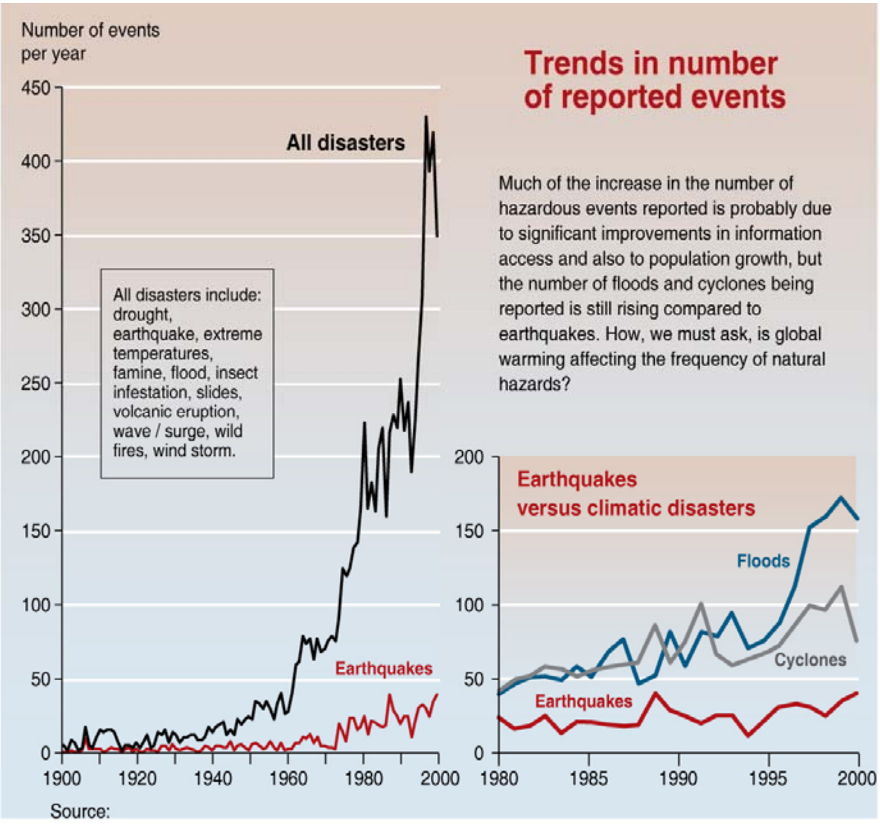

Figure 1.1 Trends in number of reported events, (Bournay, 2005)

Drought, hurricanes and tsunamis are disasters that we as human beings can not affect significantly, or prevent from happening. We can only try to be prepared for these disasters and learn to deal with them.

In order to enforce industries and other responsible sectors to lower their contribution to global warming, The European Union set up in 2007 a commission that decided a 2°C goal to be fulfilled by 2020. The purpose is to limit global warming by maximum 2°C above the temperature in pre-industrial times. This means that by 2020, developed countries shall have decreased their emissions of CO_2 and other greenhouse gases, to an average of 30 percent below 1990 levels. The commission is striving to meet a global agreement. (European Union @ United Nations, 2007)

One important issue that contributes to several negative impacts in our world is the global deforestation. The global deforestation is an enormous threat to our planet. It destroys ecosystems, forces habitats to move and contributes to landslides. The livelihood of over 1.6 billion people depends on forests and forests are home of 80 percent of our terrestrial biodiversity. (United Nations, 2010)

UNEP states that about 1900 million hectares of the total land area is affected by land degradation. UNEP interprets land degradation as the decline in the potential of the land resources to meet human's economic, social and environmental function needs. (United Nations, 2000) Deforestation is one important factor that contributes to land degradation.

United Nations Environment Program, UNEP, has defined factors that contribute to the world's deforestation. The growing need for land to meet the increasing demands for agricultural land to grow crops and breed cattle, accounts for 60-80 percent of the total deforestation, growing cities and infrastructural needs. Forests are cut down in favour of meeting the needs of urbanization and for agricultural purposes, such as beef, soybeans, tropical fruits and tropical vegetables. (UNEP, 2010)

The United Nations General Assembly declared the year of 2011 as the International Year of Forests. The initiative to this forum was developed to raise awareness on sustainable management, conservation and sustainable development of all types of forests. The Initiative coordinates events and conferences all over the world based on managing and preserving our forests. (United Nations, 2010)

The mitigation of all these effects creates a need for research about how forests can be preserved. There are millions of solutions at different levels which should be adjusted for each and every specific site and living situation. One possible solution could be changes in regulations on cutting down forests in favour of agricultural purposes or improved controls for illegal logging. Another important factor is research about exploring possibilities for environmentally friendly alternatives to replace conventional wood materials.

1.2 Scope

The scope of this master thesis is to study a sandwich panel fully made of natural raw materials of bamboo, wheat straw and soy protein as a resin. The panel was manufactured and tested in the civil engineering laboratory at California State University Long Beach. The main purpose of this thesis is to investigate the potential for the bamboo sandwich panel as an alternative for conventional panels, through testing its shear, bending and compressive strength. Proposals of potential applications of the panel will also be made.

1.3 Objective

The main objective is to explore the potential of using bamboo and agricultural waste (wheat straw) as raw materials for wall panels in constructions of one story or small (residential) buildings. This thesis is an experimental study with a significant amount of trial and error. This project strives to serve as a source of inspiration to combine the two natural materials -bamboo and wheat straw, into a sandwich panel, making a sustainable building composite panel.

1.4 Subject limitation

The results from testing a sandwich panel made of bamboo and wheat straw in bending, shear and compression is presented and discussed in this thesis. Based on the test results, an analysis over suitable application areas of the panel is made. No definite conclusions about what the panel could be used for are presented, only suggestions are made. Suggestions for future research are also presented.

1.5 How this study will contribute to the field of knowledge

This work will contribute to the field of knowledge through serving as an inspiration source for discovering existing possibilities to use green materials as a substitute for conventional materials. This research thesis strives to encourage research in the field of environmentally friendly building materials.

This master thesis is an experimental study that combines wheat straw and bamboo into a sandwich panel and explores the bending, compression and shear strength of the panel. There has probably never been any laboratory testing of the mechanical properties of a sandwich panel of wheat straw and bamboo of this type. Through presenting and discussing the results in this report, students, researchers and scientists can further develop their research studies with this thesis as a relevant source for their work.

This master thesis project has contributed to the field of sustainable built environment with information of the green building materials; bamboo and wheat straw and the possibilities how to combine them into a sandwich panel. The project presents a number of test results. Even if the test results are not as good as expected, they still indicate that it is possible to use bamboo and wheat straw, together as a building material. However, these test results will contribute with statistical valued results to add to the ongoing research about green building materials like wheat straw and bamboo. The thesis also points out what the sandwich panel is doable to be used as in a building.

1.6 Structure of the thesis

This thesis is divided into five chapters, which are further divided.

Chapter one is the introduction chapter, which strives to give an overall view of the background issues of this research project. The problem statement and the scope are defined. Further, the objectives are described and the limitations are also clarified in the first chapter.

Chapter two is a significant part of the thesis, since it provides a background to this experimental study. Green building materials are discussed and a background to bamboo and wheat straw as green building components are presented. The laboratory testing procedure and the equipment for the sandwich panel are explained.

In chapter three, the research method is presented. The research method will give an overview for how the sandwich panel was manufactured and tested. The materials used in this research are described. The procedure of manufacturing the materials is explained and the appliances used in manufacturing the panel are presented. Testing equipment is also described and the three different test methods are explained.

In chapter four, the results from bending, compression and shear tests are analyzed. The validity limits of the results and possible sources of error are also analyzed. Furthermore, a life cycle analysis of the panel is presented. Finally, how this research work will extend to the field of already existing knowledge is discussed.

In chapter five, the results from the laboratory tests are concluded. Possibilities for future research of green composite sandwich panels made of bamboo and wheat straw are discussed. Lessons learnt are also concluded in this chapter.

2. Background

Global environmental phenomena like rising sea levels, polar ices disappearing, rising global average temperature and rapidly decreasing of natural resources, bring high pressure on our society and every single industry. Especially the building and construction sector has a great responsibility to develop new technologies, new methods of carrying out production and new products in order to mitigate climate change, to save energy and to decrease the use of ending resources. The building and construction sector includes infrastructure, public and private housing, non-residential public property (e.g. hospitals and schools) and industrial (e.g. factories and processing plant) and commercial construction.

In May 2011, the world population was estimated to 6,9 billion people and (US Census Bureau, 2011:1) by 2044, the population is expected to rise towards approximately 9 billion people (US Census Bureau, 2011:2). This implies that the population probably will have increased with 30 percent by 2050. This fact requires preparation and planning for the building and construction sector. How to cope with providing people with homes and also restoration of old homes is an issue that needs to be solved.

At the same time as polar ices are melting, the land area is diminishing due to rising sea levels, which means that people is forced to build their habitat on less land. In the future, building on the height will be required in order to meet the demands of a growing population. Building on the height will require strong and stabile materials. It will be important to use materials which are durable and materials that can withstand different strains. Durable materials should manage extreme weather and meet the basic needs from people living in the building.

Factors as global deforestation, decreasing supply of wood and rising lumber prices are relevant reasons to find alternatives to conventional wood materials. World population is growing at a rapid speed and more wood is demanded to supply human beings. Straw and bamboo are both alternative sources to replace conventional wood panels. The use of conventional wooden building materials could decrease, which means less demand for wood and thereby less demand for harvesting forest.

2.1 Deforestation

Timber is one of the most common and durable vernacular building materials. This can be reflected in the widespread distribution of forests. Forests cover today about 30 percent or 4 billion hectares of the total land area. There are ten countries that provides two thirds of the total forest area; Australia, Brazil, Canada, China, The Democratic Republic of Congo, India, Indonesia, Peru, The Russian Federation and United States of America. (Kourous, 2008)

The over logging of forests causes problems for many areas and affects the whole world. In some regions, forests are being cut down in a greater pace than nature can cope with. This is due to the high demand for wood, an increasing demand for agricultural land and the usage of wood as a source of fuel. The highest rate of deforestation occurs in tropical areas and relies mostly on the fact that there is a great demand for agricultural land to grow crops and feed animals. On average, 13 million hectares of forest are logged down every year (Kourous, 2008).

Although replanting and natural expansion of existing forests indicates that the deforestation has slowed down. Also, according to the United Nations Food and Agriculture Organization, FAO, deforestation has been declining during the past 10 years, but the rate of deforestation is still extremely high. Every year an area large as Costa Rica (51 100 km^2) is harvested. (Un News Centre, 2010)

Other important resources, for example oil and gas, are expected to run out before the second half of the twenty-first century. Although timber can be acknowledged as a renewable resource, it is threatened due to increasing demands of wooden products. Therefore, it is important to implement a good management of cutting down forests, in order to guarantee healthy and living forests (Vellinga et al. 2007). However, in Sweden, deforestation is not a problem. During recent years Sweden has managed to double its forested area through preserving management programs. Forests store a lot of carbon dioxide. In order to capture carbon dioxide, after cutting down forest, replanting of forests is very important.

Deforestation causes many different impacts on our planet. A lot of species are depending on the forest and there is a great loss of bio diversity when ecosystems are threatened. Also erosion of soils is a big problem, which brings floods, landslides and avalanches. Deforestation threatens the cultural survival of indigenous people who are depending on the exploitation of forest resources. (Kourous, 2008)

For example, the third largest island in the world, Borneo, is one of the regions in the world that is suffering from deforestation of its rainforests. Half of the lowland forests have been cut down due to illegal logging, large scale agriculture, oil palm plantations and due to fires. If deforestation continues in the same pace, the rainforests in Borneo will be gone in a decade. (WWF, 2010)

Figure 2.1 illustrates world changes in deforestation. The red spots indicates regions that are experiencing a net loss of forests, the dark green regions shows a net gain of forests and the green regions illustrates the current forest regions. As shown in the map; areas threatened of deforestation are Southeast Asia, Central America, Brazil, Central Africa and Northwestern Russia.

World map changes in deforestation

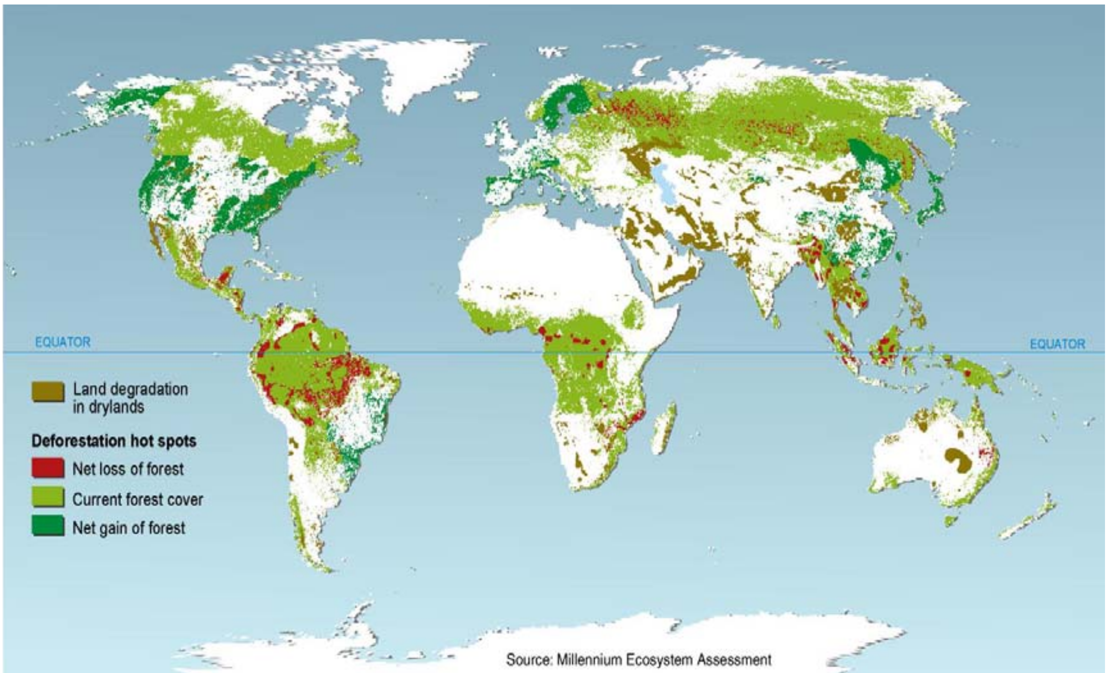

Figure 2.1 World map changes in deforestation. (Climatelab, 2010)

2.2 Green building and environmentally friendly materials

During the last decades the terms green building material and environmentally friendly materials has become an important aspect for our built environment. The purpose of green building materials is to save energy, to minor its impact on climate change and to decrease the rate at which we are consuming natural resources. A green building material has little or no impact on the environment. There are several definitions for the term green building material. But what they all signify is a focus on energy, material, water, waste and habitat. There are a numerous different building materials today that are acknowledged as green building material. Examples of green building materials are clay, mud, native stone, different types of grass, hemp, bamboo and turf.

The term environmentally friendly is a widely used concept that could be describing more or less as any material, building or technique. In this master thesis the term environmentally friendly aims at a concept where a responsible object or action are used in a long term perspective with minor or none negative impact and where consequences for the environment are prioritized.

A green building material is a material that is manufactured of mainly or (in best cases) 100 percent renewable materials. A green building material should be biodegradable and locally available, in order to help natural processes to break down the material and reduce worldwide transportations and. A green material should contribute to a good indoor quality, it should provide a long life span and be recyclable. One of the most important qualities of a green building material is that it should help to reduce the energy consumption in the building. Green materials should also be manufactured in order to be environmentally responsible and their impact on the environment should be considered over the total life span of the material. (Calrecycle, 2010)

However, today there is almost no 100 percent green and renewable structural component in buildings. In conventional building today, concrete, steel, aluminum and wood are still the most common structural building members. There is a need for research in green building materials that also can be used as a structural member and not only as visible interior design or non-structural members of the building.

Green building materials are used all over the world and they are mostly used in vernacular building art. One example of building with green building materials is straw bale houses (Figure 2.2), which are built in various parts of the world. Architects and other designers are creating straw bale houses and there are numerous web pages that describe the procedure of building your own straw bale house. Straw bales are used as infill between structural members (wooden beams) or framing. Straw bales can also be used as a structural member. Wooden beams are in those cases unnecessary. The roof is straw-thatched and clay is often used as a finish for the walls. Straw bale houses often possess very good insulation qualities, due to the thick walls. Very good acoustics are also obtained, due to these thick walls. However, very good ventilation is required when building with straw bales and thick walls in countries with high humidity.

Figure 2.2 Straw bale house in Bohuslän, Sweden. Photo by Lena Falkheden

Environmentally friendly building materials can be used more or less as any building component in a building. These materials have had a perception about being “poor”, but it is becoming more acceptable to build with green materials. Today, there are mostly inspirational projects that demonstrate 100 percent green building. Such projects can be found in worldwide exhibitions, for example *Green Architecture for the Future*, Louisiana, Denmark (2009).

2.3 The impact of the building and construction sector

In several studies the relationship has been proven between the built environment and public health. The building and construction sector has a negative impact. Energy use, use of natural resources, waste generation, and consumption of hazardous materials are examples of prominent environmental impact from this sector. Toxic releases from land-fill waste can get into our food chain when the air, soil and groundwater become contaminated. (Barbut, 2006)

The building and construction sector uses more energy than any other sector and is responsible for about 40 percent of total global energy use, according to The World Business Council for Sustainable Development. Thereby the sector is contributing extensively to CO_2 emissions. If including energy consumed in preparing and transporting building and construction materials like steel, concrete, aluminum and glass, the proportion grows from 40 to 50 percent. The proportion is expected to increase, due to countries like for example China and India that are going through rapid development and an increase of population. The building and construction sector has great responsibilities to improve all their activities towards a more sustainable future. The sector needs to reduce its energy use with 60 percent by 2050, in order to meet global climate change targets. (World Business Council for Sustainable Development, 2010)

The building and construction sector is the sector that has the greatest potential to lower its energy consumption at a lower societal cost and a higher return, compared to other sectors. Several declarations have been signed between many well-known businesses. One declaration is the Manifesto for Energy Efficiency in Buildings by The World Business Council for Sustainable Development. For example ABB, Skanska, Philips, and Toyota have signed this declaration. All the companies that have signed the declaration agree to strive towards meeting energy saving goals. The companies agree also to encourage employees, stakeholders and the market to save energy.

In order to be able to achieve these goals, it is very important that relevant strategies are developed to steer the work in a direction towards meeting the goals. The building and construction sector has developed strategies at different levels and the work with improving and developing new strategies is continuously in process. Strategies like green building rating systems (for example LEED –Leadership in Energy and Environmental Design and BREEAM –BRE Environmental Assessment Method) are already been developed in a large scale and are applicable in every part of the world. These systems give credit to environmentally friendly design and construction. The systems are produced while taking environmental aspects for choice of material, energy, waste, water, recycling and transportation into consideration.

UNEP has also started an initiative called SBCI –Sustainable Buildings and Climate Initiative that strives to provide a common platform for stakeholders within the building and construction sector. The initiative develops tools and strategies, establishes baselines and demonstrations of developed plans through pilot projects.

The building and construction sector possesses an important role of shaping our future society. According to a report from UNEP, the building and construction sector is responsible for about 30 to 40 percent of landfilled waste and more than 20 percent of fresh water resources. Continuously growing cities and population requires new buildings, which will grow old and will be in need of restorations. Growing cities contributes to the landfill waste and overuse of fresh water resources. Researchers predict that resource consumption and waste will increase about 30 percent over the next 20 years. (Barbut, 2006)

In Sweden, the building and construction sector uses BASTA, which is a system that assesses products according to their chemical substances. Only products approved with regards to the environment and to the health of people are to be found in the BASTA database. The BASTA database makes it easier to choose non-harmful products. BASTA was developed by a consortium of The Swedish Construction Federation and representatives from several building companies.

One area that could be improved within the building and construction sector is transportations. Reducing transportations could be done through using locally produced goods and services and ordering materials from locations in the vicinity. Other important factors to consider when planning for sustainable building are minimizing the use of energy and water through installing water and energy saving appliances. The use of renewable building materials with minimum or none negative impact on the environment is also important.

Despite the contribution to large impacts on our environment, the building and construction sector provides the society with many essential functions such as housing, hospitals, schools, offices, water and sanitary infrastructure and thereby provides important keystones for economic and social development. Between five and ten percent of the employment belongs to this sector and at national level, the sector contributes to 5-15 percent of the Gross Domestic Product, GDP. (Climate Neutral Network, 2010)

100 percent green building materials as wheat straw, turf and clay are not used in the professional building and construction sector. The focus in the building and construction sector lies on research and developing new technologies in order to save energy and also in order to use new technology together with conventional building materials. The environmental consequences of building create a need to find alternatives. Building with vernacular materials used in a combination with new technologies would be a good alternative for the building and construction sector to adapt and mitigate to the climate changes.

2.4 Bamboo

Bamboo belongs within the kingdom of *Plantae*, the division of *Magnoliophyta* and the family of *Gramineae* (*Poaceae)* (American Bamboo Society, 2011). Approximately 1200-1500 species have been found and the greatest varieties of species are to be found in South- and Southeast Asia. Other parts of the world where bamboo has great varieties are Polynesia, South America, Southeast USA and Africa. In these parts of the world bamboo is an important part in the vernacular building culture.

In Europe, bamboo is mostly used as an interior material, for example floor and furniture's. The purposes and techniques how bamboo is used vary a lot and depend on geographical location and application purpose. The different application aspects – depending on locations, seem to connect with the type of bamboo used, and available local resources. Also the mechanical properties of bamboo vary a lot, depending on its location and the type. (Vellinga et al. 2007)

In several parts of the world, different types of grass have been used for thousands of years and are still used as a traditional building material. It is a natural and practical choice to build with grasses, such as bamboo. It is accessible in the nature and it possesses many qualities. Bamboo has been used as a vernacular building material mainly in China, South East Asia, Central and South America. Except for the use as building material, bamboo serves also as a food resource and a versatile raw product.

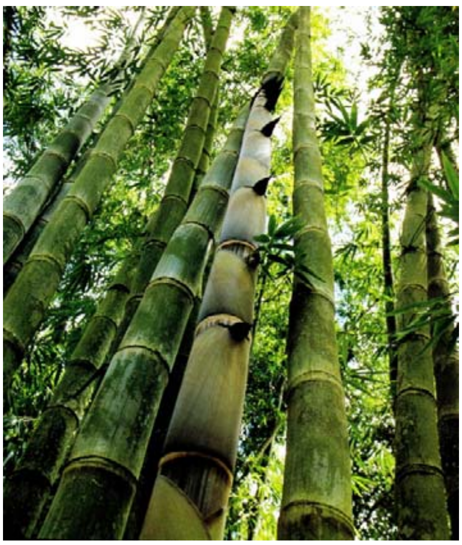

Figure 2.3 Bamboo forest. (Vellinga et al. 2007)

Bamboo may grow in every part of the world, but the most species flourishes at equatorial latitudes. Bamboo is found between latitudes 46'N and 47'S. Bamboo also grows in a wide range of heights, from sea level to a level of 4000 m. The grass grows in a wide range of climate zones; in tropical, subtropical and temperate climate (Figure 2.4). Certain types of bamboo can grow in very cold temperate climates, up to -29 °C (Bamboo Grove, 2008). Some species are known to also grow well indoor in less temperate climates. However, there is a geographical limitation of bamboo, since it does not grow as extensively in Europe, Northern America, Northern Africa and Russia (i.e. the Northern Hemisphere).

World map bamboo

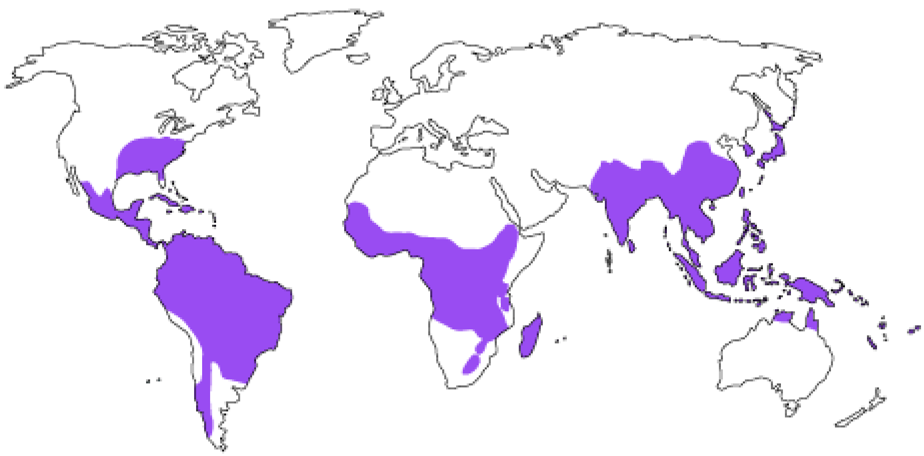

Figure 2.4 Distribution of all woody bamboos, *Bambuseae*. (Dr. Clark L., 2005)

Since bamboo grows extensively in many parts of the world and also in those parts of the world where the population is very high, bamboo is an important component for "*the future provision of ecologically, sustainable and culturally appropriate housing*". Bamboo brings many economical and ecological benefits addressing the issues of climate change, rapidly growing populations, ending resources, and pollution. Bamboo as a building material has a great availability and its user friendly qualities among its mechanical properties makes it a material that can meet the growing demand for housing. (Vellinga et al. 2007)

Francisco “Bobby” Mañosa is a Filipino architect who is working with promoting bamboo as an alternative to conventional wooden materials. Mañosa strives to find alternatives to wooden building materials made from local wood since the Filipino rainforest is suffering from severe deforestation and local wood should be preserved. Mañosa tries to enhance the status of natural materials like bamboo. According to Mañosa:

> *“Bamboo is the only plant, that can grow fast enough to cope with the growing demand for present and future housing. But unless we apply new found technology and encourage willingness and acceptance by the people, it cannot prove its worth.”* (Pearson, 2005)

Figure 2.5

The natural length of bamboo is divided into several hollow segments, which are separated by nodes. These nodes reinforce the resistance of the cane against splitting and buckling, and give the bamboo a high strength-to-weight ratio. Bamboo is strong and flexible, fast growing and easy harvested and is easy to handle with simple tools. Bamboo is also a material that is easy to use together with other building materials, such as timber, grass or mud. Bamboo is often used to fulfill purposes like beams, floors, walls and roofs (Figure 2.5). This is probably why bamboo is used as a building material, by many cultures in every part of the world where bamboo grows (Vellinga et al. 2007).

The advantages of bamboo are many. Bamboo is easily cultivated and harvested. It doesn’t require any harmful effects on other plants, animals and the environment as a whole. Bamboo is a renewable resource, it is one of the fastest growing grasses in the world. Compared to oak that takes 120 years to grow to maturity, bamboo can be harvested in only three years. Depending on soil and climate, bamboo can grow 60 cm per day, due to its unique rhizomedependent system (American Bamboo Society, 2011). Bamboo also has a very high tensile strength and can be compared to mild steel, since it can withstand great forces as 231 kN (Environmental Bamboo Foundation, 2011). This can be compared to untreated wheat straw which tensile strength is only 0,04 kN. (Han et al. 2008)

There is no need for advanced or complex tools in order to work with bamboo. The only tool that is needed is a knife. When harvesting bamboo, it is important to cut the grass in a proper way. Bamboo needs to be cut at its nodes, in order to prevent the bamboo from splitting and cracking. This can be a bit complicated, since the nodes are placed at different distances. At the node, there is an inner disc called the septum. The septum connects the outside walls, strengthens the stalk and separates it in into compartments. Bamboo should be cut at a mature age. A bamboo culm matures in three years. Young bamboo also gives nurture to the plant, therefore it is important to be aware about cutting the culm when it is mature. The moisture content of bamboo is also important for cultivating, bamboo should be cultivated when the moisture content is low.

The authors of the book *Atlas Vernacular Architecture of the world*; Marcel Vellinga, Paul Oliver and Alexander Bridge, states in the book that there is a need for more research about the use of bamboo as a sustainable building material for the future. Bamboo has great potentials to be implemented as a green material and to replace many of the conventional wooden building components. Bamboo was chosen in this experimental study because it is a natural material that possesses great potential. Even though the test results did not turn out to be desirable, this experimental study still aims at raising the awareness about bamboo as a suitable material to be used as a composite, together with other materials. Bamboo has great opportunities to meet the demands of tomorrow, according to the Bruntdland commission definition of sustainable development: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". (IISD, 2011)

There are numerous international and national networks that are working with promoting bamboo as a sustainable building material. International Network for Bamboo and Rattan, American Bamboo Society and Green Home Building are some of the organizations. The International Network of Bamboo and Rattan are striving to meet the Millennium Development Goals, through assisting and teaching people to improve their livelihoods through building with bamboo.

2.4.1 Some known advantages

When bamboo fails, it splits. Split bamboo can easily be temporarily repaired with lashes. The building can be kept together without falling apart until the split bamboo can be replaced. This is a main reason why a bamboo structure can survive an earthquake or storm. A wooden material is not as easy to repair. When a wooden material fails, it is useless and needs to be replaced.

Bamboo possesses also advantages due to its high tensile strength. Applying load to bamboo, the material bends, and adjusts to the stress. When load is removed, bamboo recovers back to its original shape. This behavior implies that bamboo also possesses better elastic properties than wood. (Hanssen, 1995)

2.4.2 Some known disadvantages

Despite the good qualities of bamboo, it also possesses some bad qualities. Bamboo can bring insect problems and it can be attacked by fungi and rot. The bamboo mite is a small pest, which feeds on bamboo. Insects can be controlled with pesticides. Awareness about recognizing the mite and its feeding patterns is very important and action should immediately be taken. It is important to discover the pests at an early stage, in order to prevent them from spreading. Insects are much harder to get rid of if they are allowed to settle and start feeding on the bamboo. It is therefore important to keep away harmful insects. It can be difficult to treat bamboo, due to its thick layer of cells on both the inside and the outside of the cane. (Bamboo Sourcery, 2011) There should not be any problem with mites, if bamboo is taken care of in a proper way, for example if bamboo poles are used, the openings should always be covered, so that no mites are able to get into the hole.

Bamboo does not interact well with soil, therefore bamboo cannot be built directly on the ground. If the soil is dry and no termite’s starts feeding the bamboo, there will be no problem. However, problems arise when the soil gets wet and moisture spreads to the bamboo.

Bamboo does not possess any good fire resistance. Once bamboo has been exposed to flames, the fire spreads rapidly along the material and it will be destroyed in a short amount of time. Plastering the walls in order to protect them from fire is a good intervention, keeping a fire disaster away. Avoid building houses close together is also a good advice, preventing a fire spreading to neighbor's houses. Regarding simple structures in rural areas, all cooking should be done outside the house and any stove or cooking place inside the house should be properly attached. Many fires are started due to an earthquake or due to a stove or other cooking equipment are overturned. (Hanssen, 1995)

2.4.3 Building with bamboo

Figure 2.6 shows a traditional house in Northwestern Thailand, Asia. The walls are made of thin mats of bamboo. The thin mats provide good ventilation to the house. Due to very humid climate, the building requires a lot of ventilation and should not be built directly on the ground. Therefore, the house is built on poles to heighten the building from the ground. It is also built on poles to avoid problems with flooding and animals intruding the house. The space under the building is often used as storage and animals are also kept there. The walls will be replaced after a few years, often due to rain exhaustion. Since bamboo is available in nature, there is usually no problem in replacing the bamboo components.

The roof of bamboo houses in rural areas often consists of grass. Grass burns quickly, therefore the roof should be protected. Covering the roof with a non-combustible material such as a galvanized iron sheet, fiber cement roof sheet, plaster or tiles is not a cheaper alternative, but from a fire resistant perspective, it is a better alternative. (Hanssen, 1995)

Bamboo is also used as water pipes on rural areas in China, due to its outer waterproof film. Also the inner part of the pipe is water proof. Bamboo is a natural composite, the walls are composed of five types of "vascular bundles". The outer layer of the wall is dense and it contains about 5 percent silica. Due to this slick waterproof coating, bamboo cannot be painted.

Figure 2.6 Traditional bamboo house in Thailand. Photo by Fredrik Metso

Bamboo structures are very suitable for areas in risk of being affected by earthquakes and storms, since the grass is a very light-weight material (It will cause less damage, if a bamboo structure will collapse during an earthquake, compared to structures made from brick, steel or concrete). If a bamboo structure is broken, it is also easy to repair compared to conventional building materials (Hanssen, 1995). The favorable elastic properties of bamboo and its high tensile strength make it also a suitable material to use as earthquake resistant building. In Costa Rica, 30 houses made of bamboo structures, placed in the epicenter of a 7.6 magnitude earthquake, all survived without any damage. (INBAR, 2011)

2.4.4 Bamboo versus wood

Bamboo is a vernacular wooden building material and it can be compared to conventional building materials. There are several important differences between bamboo and wood. Bamboo has for example a different structure of chemical extracts. The outer skin of bamboo cannot be glued, due to the many silica particles inside the outer layer.

From economical aspects, the return of capital is quicker for bamboo than for wood, since bamboo can be grown and harvested in only a very short period of time compared to wood. (Hanssen, 1995)

Bamboo requires treatment in order to maintain its qualities and compared to wood, the natural durability of bamboo is not as lasting. When bamboo interacts with soil or atmosphere, the durability is 1-3 years. If bamboo is covered, the durability is a bit longer, 4-6 years. If bamboo is covered and not used in a humid climate, the durability is 10-15 years. (Hanssen, 1995)

When cutting down forest, trees needs to be replanted in order for the forest to grow back. But bamboo does not need to be replanted, since it grows back by itself due to its belonging to the grass family with a root system that produces new shoots every season.

An advantage of bamboo over timber is that it does not have rays, which are mechanically weak. Therefore bamboo material is better in shear strength, compared to timber material (INBAR 2, 2011).

2.5 Wheat straw

Wheat straw is an agricultural byproduct that possesses many good qualities to serve as a building material. Straw is a vernacular building material that is used by many cultures and it is used all over the world for many different purposes. In rural areas, straw is often used as roofing material.

Straw, as an agricultural straw-waste product is a suitable source for producing environmentally friendly sandwich panels. The use of panels made from green materials can help slow down the rate of global deforestation. A green composite board made from straw binds the CO_2 longer, compared to converting the straw directly to bio energy or using straw fiber as a component in recyclable paper, which only can be recycled a few times. Straw panels can also be recycled or converted to energy after its service life as building material.

There are several organizations that are promoting the advantages of building with straw, for example, The Straw Bale Building in the United Kingdom.

Even if straw has many potential application areas, it is a byproduct that is not taken care of. Often, straw is burnt in order to get rid of it. Therefore, straw should be taken care of, in order to avoid open field burning. Panels made from straw can be recycled or converted to energy after utilization. (Halvarsson et al. 2010)

It would be useful, not only for the environment, but also for farmers if the market for straw would grow. Also, through manufacturing products from straw, economical incentives for making a use of straw would probably emerge. The economical incentive of using straw is that farmers will have an opportunity to generate an income supplying straw to panel producers.

Straw is cheap, renewable, environmentally friendly and possesses many good building qualities, therefore people in the building industry considers straw as an excellent alternative to conventional wood materials. Only in North America, about 150 million tons of straw each year is produced due to the massive cereal grain harvest. There is a sufficient quantity of straw raw material available, the issue is how to make a market of it. The technical performance of products produced from straw, for example strawboard or other panels consisting of straw, will be of essence for the market and the demand. (Fouts, 2011)

2.5.1 Some known advantages

Wheat straw has good thermal and acoustic insulation qualities. Therefore, wheat straw is a very good component to be used in structural building panels. Straw is also a good building material since it is durable and if it is used in a proper way, it resists moisture and rot.

Straw is a light weight material that burns easily, when allowed space in between the straws. Straw can be compared with paper; one thin sheet will burn easily, but a thick pile of paper, will not burn that easily (i.e straw should be compressed). Straw should be covered by protective substances (render), in order to improve its fire resistance.

2.5.2 Some known disadvantages

Straw does not possess any good moisture resistance. Straw will rotten if moisture content is above 20 percent. It is difficult to protect straw against rain and moisture. Mold can arise, if humid air is allowed to standstill. A good method of preventing moisture is to make sure enough ventilation is allowed to circle. (The Strawbale Building Co, 2009)

2.5.3 Building with wheat straw

Straw is commonly used as a vernacular building material in rural areas all over the world. It is mostly used as roof and insulation material. In countries with a colder climate, straw was used as insulation before modern and conventional insulation materials such as glass wool came to use. In modern green building practices, straw is still popular to use as insulation.

Mixing straw together with clay creates a green building material, called cob. Cob is used as a plaster in green building technology and it has very good insulation properties. It keeps the building cool in the summer and warm in the winter. Plaster is very useful in climates with warm summers and cold winters and thereby it is suitable for Scandinavian climate.

Except from roof material and insulation, straw is also used as strawboards. Strawboards are a type of environmentally friendly particleboards that can be used as floor underlay, doors, cabinets, furniture and structural insulated panels. The board is manufactured under intense heat and pressure. When straw is exposed to both heat and pressure, the natural resin mixed in the straw bonds the straw into a hard wood-like material. Before straw is exposed to heat and pressure, the straw is fine grained into very small particles. It is sorted, dried and bond together with a formaldehyde-free resin. The formaldehyde-free resin contains no harmful substances and therefore, it emits no toxic emissions during production and neither in the application stage.

Manufacturing fiberboards made from renewable agricultural resources, saves energy and makes a use of straw that otherwise would have contributed to open field burning. Wheat straw and soy beans are considered to be suitable as fiber components and binder for panel products. Building a house from structural fiberboard panels demands 85 percent less timber, compared to a conventional wood frame construction. If the straw building industry would use only 25 percent of the available straw in Northern America (37,5 million tons), this would provide structural panels (exterior wall, roof, floors, interior partitions) for one million two-story houses every year. (Fouts, 2011)

2.6 Soy protein resin

The construction and building sector are today using solely conventional building materials and chemically based adhesives. Theses adhesives are approved by health organizations to be non-hazardous to the people living in the building. However there are no further exact criteria's about how the chemicals should be taken care of after its application stage as a building component.

Chemical binders that are used as an adhesive in building materials are not supposed to be harmful for the people living inside the building. Most countries have their own regulations and restrictions about which chemicals not to use. If not forbidden, it is often very strict regulations for the use of toxic binders in building materials. Chemical binders can also be dangerous during production, if they are not handled in a correct way. A chemically based binder can emit hazardous gases if it would catch fire. One of the main problems with chemicals is that it takes a very long time for nature to take care of them and to break them down. Some toxic chemicals cannot be broken down at all. Binders based on minerals and organic materials are more suitable for the environment, since nature can take care of them after their time of practical use.

To develop a building material requires knowledge about the whole life cycle of the material and its impact on the environment. Using a non-toxic, environmentally friendly binder in a sandwich panel would create a panel that is user friendly both for the nature and for human beings living in the building. The plywood industry needs to come up with environmentally friendly adhesives, made from renewable resources that can replace old adhesives made from limited and finite petroleum resources.

Soy beans grow in Central, Southeast and South Asia, Central America and South America, Canada, Africa, Australia, New Zeeland and Oceania, Caribbean and West Indies. Soy protein resin is produced through extracting the soy proteins from the soy bean plant. This can be done through both chemical and mechanical processes. The soy protein can be combined with other chemicals depending on which characteristics that are desired, for example, improving properties such as water resistance, tensile strength and elastic modulus. Based on the results of Wool et al., soy protein adhesives can likely provide adequate bonding for straw medium density fiber boards.

Soy beans are a crop cultivated for mostly oil and protein. Soybeans are the world's biggest single source of edible oil and accounts for about 52 percent of the total oil seed production. The U.S. and Brazil accounts for the largest soy bean production. (Kumar et al. 2002)

Using soybeans as an adhesive is not a new invention. There has been some earlier research done that implies that soy based adhesives can be used in oriented strand board and straw composite panels (Zhiyong et al. 2005). Utilization of soy beans as biodegradable adhesives and resins will help to overcome environmental problems and add value to agricultural by-products. (Kumar et al. 2002)

2.7 Why bamboo and wheat straw together

Both bamboo and wheat straw is used as vernacular building materials for thousands of years, in many parts of the world where bamboo and straw is accessible. Bamboo and wheat straw have been combined together before, mostly in rural areas. There is some earlier research in construction of sandwich panels of bamboo and rice straw, but probably no earlier research similar to the type of sandwich panel constructed in this project. When constructing a building material from wheat straw and bamboo, qualities of both materials are desired to be combined in the very best way. Combining bamboo and wheat straw in a sandwich panel, could be one alternative.

Bamboo and wheat straw possess each beneficial advantages to be used as a building material. Bamboo possesses very good tensile strength and is a material that is easy to work with and it also has favorable tactile properties. Wheat straw possesses good thermal and acoustic insulation.

2.8 Laboratory testing of the sandwich panel

In order to investigate the mechanical properties of the sandwich panel, the panel was tested in bending, compression and shear strength. All the testing's were conducted in the civil engineering laboratory at California State University Long Beach, during summer 2010.

This project is an exploratory study upon how the sandwich panel behaves when tested under load. There is no earlier published literature reference regarding the strength of the panel and no earlier research was to be found about this type of configuration of materials in a sandwich panel.

2.9 Relevant previous work

At California State University Long Beach, there have been some earlier research studies in the field of green composite materials. Professor Tang-Hung Nguyen at the Department of Civil Engineering & Construction Engineering Management has conducted research about using bamboo as an alternative to conventional building materials. One of Professors Nguyen's papers, *Using Bamboo and Agricultural Wastes to Fabricate Construction Materials*, discourses a sandwich panel of two bamboo laminates used as skin panels and a core of sugar cane bagasse. The bamboo laminates consists of five woven bamboo mats compressed together, using hot steam and adhesive bonding. The specimens were tested in bending, compression and shear strength (Nguyen, 2009).

There has also been some previous research by university students, making panels consisting of wheat straw and soy protein resin. Mechanical and aerospace engineering student, Evan Nishimura, performed during spring term 2010 a research thesis, *Manufacture and Properties of Soy Protein Resin Wheat Straw Boards*. The objective was to characterize the mechanical properties of a MDF (Medium Density Fiber) board made from wheat straw and soy protein. Mr. Nishimura was recommended the soy protein, Pro-Cote® 5000, after some consulting with technical representatives at the soy polymer distributor DuPont/Solae. The same soy protein was used for this project.

This student project involved manufacturing MDF board's and testing them after exposure of two curing temperatures; 150 °C and 170 °C. The testing panels were also exposed to various bonding pressures, 0.138 MPa, 0.286 MPa and 0.552 MPa.

The conclusions from Mr. Nishimura's master thesis are a summary of how the board behaved during exposure for load. Suggestions how the board can be improved and also some suggestions for future research was done. One suggestion for future research is to add chemicals to the resin, which will probably result in better mechanical properties.

One conclusion is that increasing the curing temperature, probably makes the board stronger and the ability to resist more load increases. The Modulus of Elasticity, MOE, (describes the relationship between the stress applied to a material and its corresponding strain) was greater when testing a board prepared under a higher curing temperature. Another conclusion was that increasing bonding pressure also resulted in a stronger board. The two higher bonding pressures resulted in a higher Modulus of Elasticity, which means that a board exposed to higher pressure while curing, will resist more load. It was also stated that, the higher the density of the board, the better the mechanical properties. (Nishimura, 2010)

There is an ongoing research for green composites in order to try and develop environmentally friendly alternatives to conventional fiber boards and other wooden building materials. For example, the mechanical properties of a bamboo-starch resin composite have been examined in a research by Takagi et al., The objective of the study was to improve bending strength properties of a three-layer board, composed of wood-porcelain stone composite. One of the main conclusions was that using bamboo fiber as reinforcement increased the Modulus of Rupture, i.e. the maximum fiber stress at failure. (Takagi et al. 2004)

The use of natural fibers, such as hemp, wheat straw, jute, flax, bamboo, ramie and bagasse in composite materials has been studied and discussed by several researchers. Fiberboards made of rice straw have been manufactured by Halvarsson et al. In their project, rice straw was used as a raw material in the manufacturing of medium- and high- dense fiberboards. The purpose was to develop an economical, sustainable and environmentally friendly medium density fiberboard. One of the most important conclusions is that medium density fiber boards, consisting of straw, could be made of different kinds of straw species and adhesives.

3. Research Method

3.1 Selection of material testing standard and equipment

In order to obtain correct directions about how to carry out the actual testing in a suitable way, a standard testing method was chosen. The method is in accordance to ASTM International (the American Society for Testing and Standards). The standard test method provides guidelines for dimensions of the specimen, which testing apparatus to choose, the setting of the testing, proper climate conditions for the laboratory and what kind of information to record. All of these requirements are set up in order to reach the best comparable testing results.

ASTM International is one of the world's leading development organizations that provide testing standards for materials, products, systems and services. The testing method chosen for this project is *Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure*. This test method was conducted only for the static bending test. The static compression and the static shear tests did not follow any acknowledged testing method. SI units (Newton, Celsius degrees, meter and kilogram) was used.

3.2 The Apparatus

The preparation of bamboo and especially wheat straw required several types of apparatus. Mostly kitchen apparatus were used and all the apparatus were available in the civil engineering laboratory at California State University Long Beach. The wheat straw was, step by step, grinded to fiber length with the use of a hand scissor and kitchen machines. Two kitchen machines were used in order to process the wheat straw from hand cut length to fiber length; a food processor: Cuisinart EV11PC9 (Figure 3.1) and a kitchen blender: Blendtec Total Blender Model ES3 (Figure 3.2).

Figure 3.1 Blender Model ES3 (Food Processor)

Figure 3.2 Blendtec Total Blender Model ES3

3.3 Testing equipment

The testing equipment that was used for all the testing’s was a universal compression testing machine, Tinius Olsen, hydraulic testing machine (Figure 3.3). This machine was used both for compressing the material and for performing the tests. The amount of load applied was controlled manually through using a steering wheel when adding load. Maximum load that could be applied to the testing specimen was 53,4 kN. An electronic device which measures the deflection in millimeter was attached to the testing machine in direct link to the specimen, in order for the deflection to be recorded. The humidity and the indoor temperature were recorded by a digital thermometer.

Figure 3.3 Tinius Olsen hydraulic testing machine

3.4 The materials

The materials used in this project:

- Wheat Straw
- Bamboo
- Soy Protein powder
- Distilled water
- Ammonia, NH_4OH (5 percent)
- Clorox regular bleach blanqueador

The two essential components in this research project were bamboo and wheat straw. Soy protein resin (as a powder structure) was used as a binder. Distilled water was used, in order to use 100 percent clean water. Tap water contains particles that might contaminate the mixture. Clorox regular bleach blanqueador was used to bleach the wheat straw. Ammonia was used in the resin mixing process of water and soy protein. Ammonia is added to the resin as an alkaline that will increase the solubility of the dry soy adhesive powder. Soy protein contains of long molecules. Ammonia is used to stretch out the chain and it also dissolves the micro particles of the soy protein resin. (DuPont Pro-Cote Soy Polymers, 2004)

3.5 The worksheet

An excel worksheet was prepared in order to collect all the specimen information and data from the testing. The worksheet includes information about the measurements of the specimens; the actual width, length and thickness. Other information included in the worksheet is specimen number, date specimen made, date specimen tested, the temperature and relative humidity during the preparation of the specimen and also during the testing of the specimen. The curing temperature of the laboratory oven and the curing duration were also recorded. The specimen volume, the mass, the density, cross-sectional area, failure load, time to failure and compressive strengths are other important factors that were recorded in the worksheet.

3.6 Preparing materials

All the materials were prepared in the laboratory at California State University Long Beach during the summer 2010.

3.6.1 Bamboo

The bamboo material consisted of a woven bamboo mat (Figure 3.4). These woven bamboo mats was supplied to California State University Long Beach by a wood manufacturer *NAVIFICO Inc.* in Vietnam. This bamboo originates from local areas in Vietnam. In order to manufacture the woven bamboo mats, the bamboo poles was first cut into thin and long stripes (about 1 mm thick, 20 mm wide and 1-2 m long). The long stripes were afterwards inter-woven by hands into the mats. Woven bamboo mats are usually used as household items, for example baskets and rice containers. (Nguyen, 2009)

Figure 3.4 Woven bamboo mat

The bamboo mat was cut with a fine blade band saw into 7.62 x 20.32 cm and 5.08 x 5.08 cm pieces, to fit the wheat straw cores. The woven bamboo mat was 3 mm thick.

3.6.2 Wheat straw

The wheat straw was delivered in a binding bale format to California State University Long Beach by a local farmer. The first step in handling the wheat straw was to hand cut it with a kitchen scissor into pieces about 7-10 cm long (Figure 3.6). The initial length of the wheat straw was on average 23 cm. After hand cutting the wheat straw, it was further chopped down with a food processor (Figure 3.1). The first step of hand cutting the straw was essential in order to fit the wheat straw into the food processor. After this step, the size of the straw was in a range of 0,6-1,8 cm.

3.6.3 Wheat straw moisture content

The wheat straw moisture content was not measured in this project, since it was already measured in the project made by mechanical engineering student Evan Nishimura at California State University Long Beach. The exact same materials were used and therefore there was no need to measure the moisture content one more time. The moisture content was measured to approximately three percent and was determined by method *B Oven Drying* (ASTM D4442-07) by *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood Base Materials*. The moisture content was measured after the grinding process and it was the last step in preparing the wheat straw. (Nishimura, 2010)

3.6.4 The bleaching process

The main objective for bleaching the wheat straw is to improve the mechanical properties. Wheat straw has a natural waxy surface, which limits the straw to react with other materials. If the waxy surface is removed, the soy protein can better easily react and bond with the wheat straw. Except from the waxy surface, the bleaching process will also remove dirt from the wheat straw. Clean straw without ash and soil and other particles also contributes to a better bonding between the straw and the soy adhesive. (Boquillon et al. 2004)

The wheat straw was bleached with Clorox regular bleach blanqueador, which contains six percent of the active ingredient Sodium Hypochlorite (Other ingredients 94 percent). The bleaching process was conducted, with some modifications, following the guidelines in (Mo, X. et al.). Only three percent of the active ingredient is required. Therefore, the bleach was diluted with the same amount room tempered tap water as bleaching.

The bleach was mixed with the straw in a big plastic barrel and reacted for about 30 minutes (Figure 3.5). During the reaction, the straw and the bleaching were mixed every tenth minute, in order to ensure that all the straw fibers were properly soaked in bleach. Already after reacting a few minutes, the reaction process was clearly evolving. When the reaction process releases energy, the wheat straw became warm. The wheat straw also lost its color and faded into a whiter shade. After the reaction process, the wheat straw was rinsed three times with lukewarm tap water and dried in the barrel. The drying process took three-four days, due to the thick layers of straw in the barrel. An electric fan was used on top of the barrel, in order to speed up the process. A few times every day the wheat straw was stirred by hand in order to speed up the drying process. The bleaching was the most time consuming process, due to the long period of drying.

Figure 3.5 The bleaching process

The last step in preparing the wheat straw was to ground it into very fine particles. To blend the straw into fiber particles, a kitchen blender: Blendtec Total Blender Model ES3, was used (Figure 3.2). A 50 second manual rotation was used with 10 seconds maximum speed. The bleached, fine grounded wheat straw was stored in plastic bags at room temperature in the laboratory, until it was prepared together with the soy adhesive.

Figure 3.6-3.8 illustrates the three steps, chopping down the wheat straw from its initial length to fiber length.

Figure 3.6 Hand cut with scissor

Figure 3.7 Chopped in Cuisinart food processor

Figure 3.8 Ground in Blendtec Total Blender

3.6.5 The soy protein resin

The resin used in this project is water soluble soy protein resin (DuPont Pro-Cote® 5000) and it is manufactured and supplied by DuPont Soy Polymers in St Louis, Missouri, USA). The company DuPont Soy Polymers is a world leading supplier of soy polymer products and is committed to supply high quality environmentally friendly chemicals. (DuPont Soy Polymers, 2010)

The resin is an environmentally friendly resin, based on soy beans, which are a renewable resource. Mechanical Engineering student Evan Nishimura used this soy protein resin in his project and it was recommended to Mr. Nishimura by technical representatives at DuPont/Solae. The resin is in powder form (Figure 3.9) and has a moisture content of 7,6 percent. (Nishimura, 2010)

Figure 3.9 The soy protein resin

The resin powder was mixed with approximately 60-70°C distilled water. The distilled water was heated in a microwave oven. Ammonia was also added to the mix of distilled water and resin. The soy powder was mixed with distilled water and ammonia for about 20 minutes, until the soy powder and the water were mixed into a homogenous mass.

The recipe and the procedures for how to prepare the soy resin together with water and ammonia was supplied by the manufacturer of the soy resin. The preparation was, with some small modifications, in accordance with the manufacturer's specifications. The procedure how to prepare the resin is specified in *Dupont Pro-Cote Soy Polymer Guidelines: Properties, Use, Storage, Handling* (Nishimura, 2010).

The resin was mixed in a stand mixer: Kitchenaid KG25H3X (Figure 3.10). After mixing the soy resin for about 20 minutes, the wheat straw fibers were added to the mixture. The wheat straw was mixed with the soy adhesive for about ten minutes, until it became a homogenous mass. The proportions of the components making the wheat straw core are the same as used in (Nishimura, 2010).

Figure 3.10 Kitchenaid KG25H3X

Table 3.1 The recipe for one specimen

Size of the specimen (l x b x d)	20,32 x 7,62 x 2,10 cm	5,08 x 5,08 x 2,10 cm
Wheat Straw	145,20 g	24,20 g
Soy Protein Resin	36,30 g	18,15 g
Distilled Water	71,50 ml	11,92 ml
Ammonia	21,50 ml	10,75 ml

3.7 The molds

Aluminum molds was used for the larger specimens 20,32 x 7,62 x 2,10 cm, (Figure 3.11). Steel lids to cover the specimens were specially made for this testing. Two thin sheets of Kapton® (Figure 3.12) were placed in the molds, under and on top of the wheat straw core. The reason for using the Kapton® sheets was in order to easily be able to remove the wheat straw core from the mold. Regarding the smaller specimens, 5,08 x 5,08 x 2,10 cm, a brass mold with belonging lids was used (Figure 3.13). Also for the smaller specimens, a Kapton® sheet was used under the specimen and on top of the specimen.

A Kapton® sheet is a thin sheet of polyimide film, developed and produced by DuPont Soy Polymers, the same company that manufactures the soy protein resin used in this research. The sheet is developed to be used for flexible electronics and thermal micrometeoroid garments. The Kapton® sheet is also stable in very cold and very high temperatures, it can function in temperatures between -273 and +400 °C.

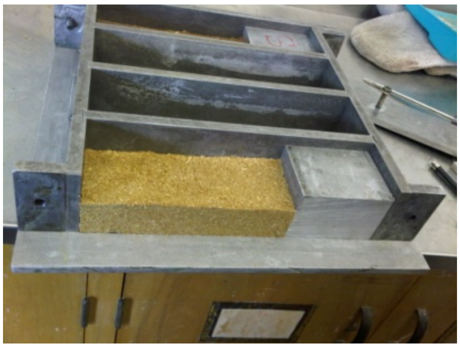

Figure 3.11 Aluminium mold

Figure 3.12 Kapton® sheet

Figure 3.13 Brass mold

The material was weight by a laboratory scale before it was put into the aluminum molds (Figure 3.14). The mass of the prepared material was 250 gram for the larger (20,32 x 7,62 x 2,10 cm) specimen and 42 gram for the smaller (5,08 x 5,08 x 2,10 cm) specimen.

Figure 3.14 laboratory scale

3.8 Fabrication of Specimen

This specific type of panel, is a sandwich panel consisting of three layers. Two layers of bamboo on each side and a core of wheat straw. Placing the bamboo as a skin, protects the wheat straw core. The panel is constructed in this way to get the most stabile panel as possible. Adding layers to a panel makes it more stable and resilient.

3.8.1 The Compressing moment

The wheat straw material was manually packed down into the molds by a spatula. The thickness before compressing it down was approximately 67 mm. The desired thickness of the wheat straw core was 15 mm. Therefore, the specimens were compressed down 52 mm. (67-15=52). The specimens were compressed by a universal compression testing machine, Tinius Olsen hydraulic testing machine (Figure 3.15). The material was compressed with a constant load of maximum 53,38 kN. After removing the load the specimens automatically strived to adjust back to its original thickness. Therefore, clamps were used to keep the specimens compact.

Figure 3.15 Compressing

3.8.2 Curing

The wheat straw core was cured in a laboratory oven (Figure 3.16). The curing temperature was set to rise from room temperature (which varied between 22-26°C) to 130°C for the compression and shear samples and 120°C for the bending specimens. An average initial temperature in the laboratory, before placing the specimens in the oven, was 24,8°C and average temperature inside the oven, after three hours, reached approximately 128,3°C. Depending on initial room temperature the oven temperature rose to its set temperature with an inconsistent rate.

The laboratory oven could fit two aluminum molds or three brass molds to be cured together. The molds were put in the oven directly after compressing at room temperature. The suitable duration of three hours was decided based on earlier research work and laboratory testing of wheat straw panels. (Nishimura, 2010)

Figure 3.16 the laboratory oven

3.8.3 Adding the bamboo

The last step in the process of manufacturing the sandwich panel was to add the bamboo to the wheat straw core. Prior to adding the bamboo, the cores were stored in the laboratory for a few days, in order to give the material some time to harden.

Bamboo mats was glued together with the wheat straw core. One mat was attached on each side of the core. The glue was composed of the same recipe that was used as binder for the wheat straw core (soy protein, water and ammonia). A generous amount of soy protein resin was added with a spatula to the wheat straw core. The sandwich panel was cured in the oven a second time. The same molds were used for the second curing and the curing time and curing temperature was also this time three hours and 130°C.

3.9 Specimen dimensions

Two different sizes of specimens were manufactured. The specimens for the bending tests was 20,32 x 7,62 x 2,10 cm, which followed the ASTM recommendation regarding size appropriate to bending test. After some discussions, it was decided that compression and shear tests also should be made. These tests will serve as a complement to the bending tests. Smaller specimens was made for compression (5,08 x 5,08 x 2,10 cm) and shear tests (5,08 x 2,54 x 2,10 cm). Compression and shear tests do not follow any specific ASTM guideline, regarding size or specific testing procedure. 12 specimens were made for each test (shear and compression), in order to get statistical valued results.

Figure 3.17 Cross section sandwich panel

Every specimen was numbered in order to distinguish them. The mass of each specimen was recorded by a laboratory scale before testing. The width (b), thickness (t) and length (l) were measured with a digital caliper. The density, ρ, was calculated for each specimen.

$$\rho = m / V$$

Where;

ρ = density, kg/m^3

m = total mass of the specimen, kg

V = volume of the specimen, m^3

3.10 Testing method

Except from some small modifications the testing method was in accordance with the *ASTM Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure*.

For each specimen flexural strength, (MOR, Modulus of Rupture) was calculated. MOR describes the materials ability to resist a given amount of load over a certain area.

$$\mathrm{MOR} = 3\mathrm{PL} / 2\mathrm{bd}^2$$

Where;

MOR	= modulus of rupture, MPa
P_{max}	= maximum load at the fracture point, N
L	= length of loading span, mm
b	= width of specimen measured in dry condition, m
d	= thickness (depth) of specimen measured in dry condition, m

To get a valid statistically result, 30 specimens were tested in bending. In compression and shear, 12 specimens were tested for each and every test. All together 73 specimens were tested (Figure 3.18).

Figure 3.18 73 tested specimens

There are several different stresses that a building is forced to withstand, therefore it is important to test building materials to ensure that they are able to withstand these loads. Bending, compression, and shear are three of those stresses a building must withstand. Compression is a force that squeezes something together. Bending is a force that makes the material bend when it is squeezed on one side, while being stretched on the other side. Shear is a force that makes two parts of the material slide past each other in a parallel direction. Other loads that a building can be exposed to are tension and torsion, however these were not tested in this study. Tension is a force pulling the material apart, for example during an earthquake. Torsion or twisting is a load that can occur when a force approaches the material from an angel, for example a tornado. (Snell et al. 2005)

3.11 Bending tests

Static bending was the first test to be conducted and 30 specimens (20,32 x 7,62 x 2,10 cm) were tested. Bending tests were performed in order to get statistical valued results for how much load the material can resist in bending. The static bending tests were conducted in accordance to *ASTM Designation C 393/C 393M -06*. This ASTM testing method is applied when testing sandwich construction beams under a bending moment normal to the plane of the sandwich. The testing method determines the shear properties of flat sandwich constructions subjected to flexure (bending) in such a manner that the applied moments produce curvature of the sandwich facing planes. The only acceptable failure modes are core shear or core-to-facing bond. Force versus deflection is recorded.

A three point load setting was arranged, in accordance to the guidelines in the ASTM testing method. A span of six inches (15,20 cm) was set up and the specimens were tested with a single-point loading perpendicular to the plane.

Figure 3.19 Bending test

For this testing, two persons were required. One person recording the deflection and the other person controlling the universal testing machine, the load applied and the time to failure. The deflection was recorded every 250 Newton. As for the rate of loading the specimens, the Tinius Olsen testing machine that was used controlled strain and, therefore, rate of increase in strain. The deflection increase rates used when loading the specimens were within 0.08 mm/s and 0.11 mm/s.

3.12 Compression tests

The compression tests were carried out with the same testing machine, although with the whole surface of the specimen leaning against the testing surface. This testing was not performed in accordance to any ASTM. The compression tests were performed both perpendicular and parallel to the testing surface. The setting for compression testing was constructed in the same way as for both perpendicular and parallel testing. The specimens were placed on a cylinder in order to provide a stabile testing surface (Figure 3.20-3.21). The size of the compression specimens were 5,08 x 5,08 x 2,10 cm.

Compression strength testing provides values over how much load the specimen can handle before it fails. Each and every specimen was weight and the cross-sectional area was calculated before testing.

3.12.1 Static compression tests perpendicular to the plane

One specimen was tested with the load applied perpendicular to the testing surface, which means that the load was applied directly on the bamboo mat with the core constituting the height. (The explanation for why solely one specimen was tested perpendicular to the plane is explained in 4.2.1).

3.12.2 Static compression tests parallel to the plane

12 specimens were tested in compression parallel to the plane. The load is applied on top of the specimen, with the wheat straw core facing the testing surface. Load was applied to the specimens with a constant strain. A digital measuring device was applied to the testing machine in order to record the deflection.

The compressive strength, σ, was calculated in order to produce information about how much load the specimens can resist.

$$\sigma = P/A$$

Where;

σ	=compressive strength, MPa
P	= maximum load at the fracture point, N
A	= Area of the specimen, m^2

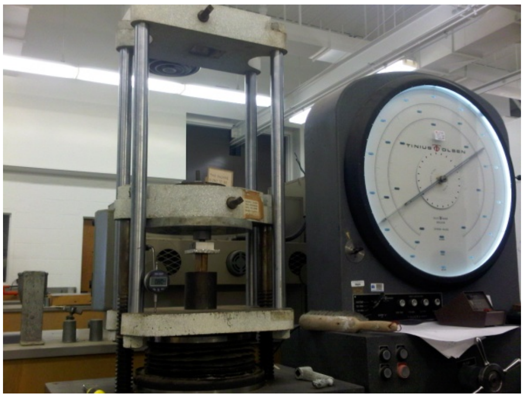

Figure 3.20 Compression test

Figure 3.21 Compression test

3.13 Shear tests

It is well known that bamboo possesses good tension and compression properties. However, there is less information about how bamboo behaves under shear compression. Regarding a bamboo and wheat straw composite, no information was found about shear properties. Therefore, a shear compression test was conducted in order to produce data for comparison with the results from the bending and compression tests. The more tests conducted, the better interpretation for how the panel behaves under different types of stress.

The setting of the shear tests consisted of a Tinius Olsen testing device that is designed to perform shear tests, Figure 3.21. The device shears the specimen between two vertically offset, horizontally parallel faces. This system uses a self adjusting blade to shear the specimen against the supporting surface. (Tinius Olsen, 2007)

The shear specimens were cut into half (5,08 x 2,54 x 2,10 cm), compared to the compression specimens (5,08 x 5,08 x 2,10 cm). The shear tests were also performed both parallel and perpendicular to the plane.

The shear strength, σ, was also calculated from the shear tests to get an assumption about how much strain the panel can resist when exhausted under shear stress and also to be able to compare the strength between the different tests.

$$\sigma = P/A$$

Where;

σ	=compressive strength, MPa
P	= maximum load at the fracture point, N
A	= Area of the specimen, m^2

3.13.1 Static shear tests perpendicular to the plane

12 specimens were tested perpendicular to the plane with the bamboo facing the blade (Figure 3.22).

Figure 3.22 shear perpendicular-to-the-plane

Except from the way of placing the specimen in the testing device, the procedure was the same for both testing parallel and perpendicular to the plane. The load was applied with a constant pressure and recorded every 250 N added. This was done in order to have a constant procedure of manually recording the deflection. For shear testing no deflection was recorded. Only time to failure was recorded.

Also for the shear tests it required two persons, one person managing the load applied and another registering the amount of time to failure. The person managing the load was also responsible for observing at what load the specimens failed.

3.13.2 Static shear tests parallel to the plane

12 specimens were tested parallel to the testing surface. The wheat straw core was facing the testing surface (Figure 3.23).

Figure 3.23 shear parallel-to-the-plane

3.14 Moisture content tests

In order to record how much moisture the sandwich panel stores and absorbs, two different moisture content tests was performed. Before performing the tests, weight and size of each specimen were measured. Volume and density were calculated before and after exposing the specimen to water or heat. The moisture tests was conducted on the larger type of specimens (7,62 x 20,32 x 2,10 cm). The specimens were stored in the laboratory between one and ten days prior to the tests, at an average room temperature of 23,7°C and relative humidity of 53 percent.

3.14.1 Dry test

The moisture content in the specimen was determined in order to get an assumption about how much moisture the specimens contain. A piece of specimen was dried in the oven for 24 hours. When the specimen was put in the oven, the oven increased the temperature from room temperature, 24°C to the preset temperature of 120°C.

3.14.2 Wet test

In order to get information about how much water the material absorbs, a wet test was conducted. The specimen was put in a box, filled with room tempered water, in order to absorb the water for about 30 minutes (Figure 3.24).

Figure 3.24 Wet test

All the specimens was leaved to cure in the laboratory in a relative humidity of between 49-62 percent and between 21,7-24,7°C (temperatures during night in the laboratory was not measured) before tested.

4. Analysis of Results

No complete failure was recorded for any of the tests. When the specimens once started to yield (the universal testing machine indicated when the specimens started to yield and the ability to carry load then decreased), the load applied at that moment was recorded and also the deflection. Load was not continued to be applied to the specimens, since they already had started to indicate failure. The primarily focus was to record at what load the specimens first started to yield. And not when the specimens became completely failed. If complete failure is recorded and used as a reference for how much load the specimens can carry, it would misled information about the material and provide false data concerning the mechanical properties of the sandwich panel.

4.1 Bending tests (20,32 x 7,62 x 2,10 cm)

Static bending test was conducted in order to explore how much load the sandwich panel can resist and to investigate how the panel behaves when exhausted to load under a three point setting.

When applying stress to the sandwich panel, it was often the wheat straw core that failed first. It was difficult to fail the bamboo, presumably due to its very high tensile strength. For some specimens, it appeared signs of the bamboo mat to start splitting. The bamboo did not fail entirely. It should eventually fail, but the load applied in this testing was not enough to make the bamboo fail completely.

The wheat straw core was compressed to a required thickness of 15 mm, before it was put in the oven. The compression was performed before curing the specimen in the oven. If instead compression had been applied with a constant load, during the three hours of curing, the specimens would have had a chance to assimilate the glue better, develop a stronger structure and bonded better. There was also some duration between removing load after compressing and clamping the molds, where the specimens immediately strived to reshape back to its original form and thickness. During this time, loss of qualities of the wheat straw could have arisen. Perhaps the oven should have been set to a higher temperature or the duration in the oven should have been longer than three hours.

When tested in bending, the bamboo mats often separated from its core. This is illustrated in Figure 4.1, where it can clearly be seen that the bottom bamboo mat has separated. One possible explanation could be that the soy protein resin is not strong enough to function as glue. The failure in the interface creates an early failure and provides thereby low test results.

Figure 4.1 failure in bending test

Another reason for an early failure of the specimen could be that the method for applying the soy protein resin was not suitable. The soy protein resin was mixed exactly in the same way as for the wheat straw core and it was applied to the bamboo and the wheat straw core with a spatula at room temperature.

Another explanation for the bamboo separating from its core, could be that the soy protein was not allowed to cure properly and therefore a weak bonding arises between the bamboo mat and the wheat straw core. When testing the specimens, it also seemed as the wheat straw did not bond that well with the soy protein resin.

Figures 4.2-4.4 represent the relation between the amount of load applied (kN) and the deflection (mm) of the specimen. The graphs were constructed to illustrate low, medium and high deflection. The behavior of most curves is typical for many types of materials when failure under load is occurring, showing a linear curve under a certain level of stress, which reaches a maximum point until the specimen yields and eventually fails.

Figure 4.2 illustrates the load-deflection curve for low deformation. Maximum amount of load applied was 1,11 kN and failure deformation was 0,5 mm.

Figure 4.2 Load-deflection curve from static bending test –low deformation. Specimen No 13

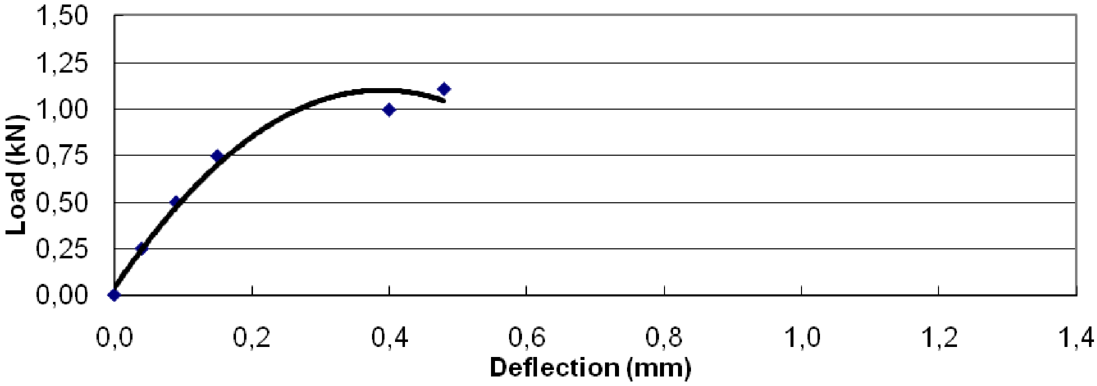

Figure 4.3 illustrates the specimen that represents medium deformation, achieves a maximum load of nearly 1 kN and a failure deformation of 0,4 mm.

Figure 4.3 load deflection curve from static bending test –medium deformation. Specimen No 15.

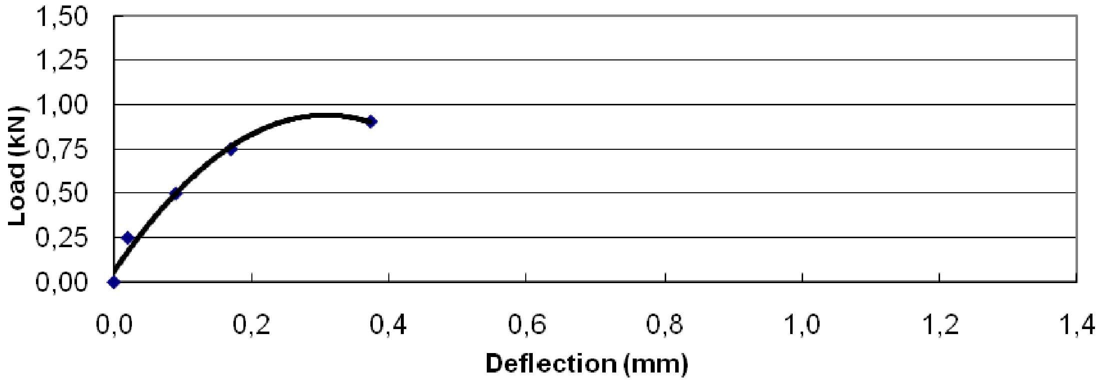

Figure 4.4 illustrates high deformation. The graph composes an almost linear load-deflection curve. Reading from the graph, specimen number 1, is obviously stronger and tends to be more tenacious, compared to specimen number 13 and 15. The highest load achieved was 1,25 kN with the deformation of 1,2 mm. One explanation could be that specimen number one was compressed under a longer time and thereby the wheat straw core could have better possibilities to develop better mechanical properties. Another explanation could be that the bonding between the bamboo mats and the core somehow cured better, compared to the other specimens.

Figure 4.4 Load–deflection curve from static bending test –high deformation. Specimen No 1.

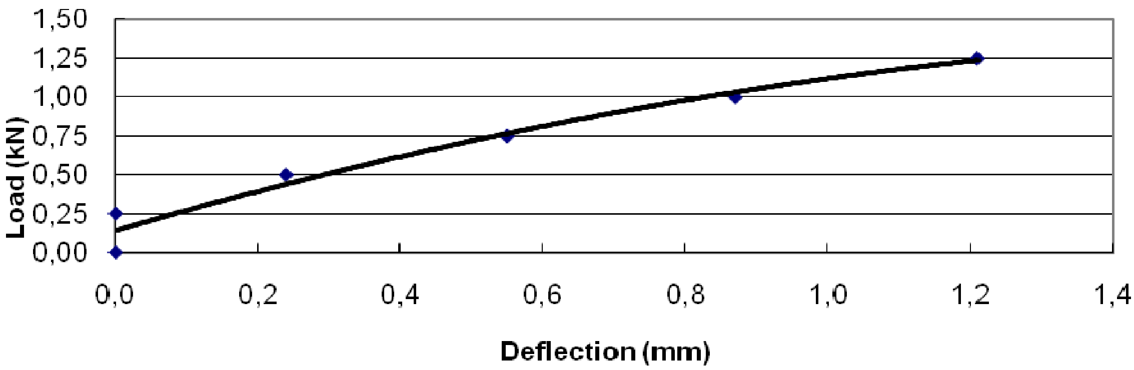

Table 4.1 presents a summary of the results from bending tests. The test results are based on a mean of 27 specimens. The minimum Modulus of Rupture achieved was 1,529 MPa and the maximum bending strength achieved was 10,963 MPa.

Table 4.1 Test result summary bending

	Mean value:	Min (MPa)	Mean (MPa)	Max (MPa)
Modulus of Rupture (MPa)	27(30)	1,529	6,195	10,963

There are several reasons behind the low test results. One reason is the curing process of the specimens. If the specimens had been cured under a higher temperature, an expected higher MOR could be achieved. However, according to (Nishimura, 2010), some of the specimen which had been cured in a lower temperature, 150°C resulted in a higher MOR, compared to the specimen that had been cured at 170°C (Table 4.2). This implies that increased MOR and increased curing temperature does not necessarily correlate.

The strength of the wheat straw core was expected to improve, when adding bamboo and thereby making the core thicker and also taking advantage of the mechanical properties of bamboo. Comparing to (Nishimura, 2010) where the achieved maximum MOR was 10,14 MPa, with the maximum achieved MOR for the sandwich panel tested in this project that was 10,963 MPa. The results in this testing are weaker, compared to the results in (Nishimura, 2010). The conclusions drawn from this are that adding the two bamboo mats to the core, did not add as much strength value to the wheat straw core as first expected.

Table 4.2 Results from Nishimura, 2010

Table 3. Properties of wheat straw MDF bonded at 150°C			
Bonding Pressure (MPa)	Density (kg/m^3)	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)
0.138	504	5.30	923
0.286	634	12.18	2064
0.552	662	10.14	2112

Table 4. Properties of wheat straw MDF bonded at 170°C			
Bonding Pressure (MPa)	Density (kg/m^3)	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)
0.138	514	6.79	1071
0.286	615	11.14	2416
0.552	684	9.99	2183

The density of the specimens tested in this research thesis is 665g kg/m^3 (mean density of the 30 specimens tested in bending), which means that the density of the specimens manufactured in this research thesis almost have the same density, as the specimens tested in (Nishimura, 2010). Therefore the density could not be used an indicator for any conclusions about whether the specimens tested in this testing is behaving different due to its density (Table 4.3).

Table 4.3 presents a comparison between the wheat straw specimens made in (Nishimura, 2010) and the bamboo sandwich panel tested in this master thesis. The wheat straw core solely resisted almost 4 MPa more load, comparing to the sandwich panel.

Table 4.3 Comparison to the results achieved in Nishimura, 2010

	Wheat straw core	Wheat straw + bamboo
Density (kg/m^3)	662	665 (mean value)
Modulus of Rupture (MPa)	10,140	6,195 (mean value)

The specimens tested in bending showed a very small deflection. Nearly all specimens showed minimal permanent deflection owing to limited deflection and due to the elastic behavior of the material in recovering some of the deflection, upon releasing of the bending load.

It is also important to point out that the failure in bending of bamboo is not actually entire failure. Due to its strong fiber structure, it first cracks unlike timber which breaks if bending fails. This behavior of bamboo provides an opportunity to repair or replace parts of the house. The elasticity of bamboo is better than wood for seismic resistant housing and this has also been verified for several small houses (INBAR 2, 2011).

4.2 Compression test

The original purpose for this master thesis was to test the static bending for 30 specimens. During the process of testing the specimens in bending, it was decided also to test the sandwich panel in both compression and shear. This was done in order to obtain more test results to complement the static bending test results.

4.2.1 Static compression tests perpendicular to the plane (5,08 x 5,08 x 2,10 cm)

The compression testing procedure did not follow any standard testing method. The same universal testing machine was used as for testing the specimens in bending. The setting of the testing machine was composed to fit the size of the specimen and to achieve a suitable testing procedure for this type of material.

These specimens were manufactured in the exact same way as the specimens tested in bending. What distinguishes the compression specimens from the bending specimens is the size. The compression specimens are squarely formed with the length of 5,08 cm, width; 5,08 cm and thickness; 2,10 cm. Square form are the most suitable shape for compression testing.

The compression test perpendicular to the plane resulted in no failure mode. The specimen resisted load up to 44 kN, which was the highest amount of load the testing machine could apply. The reason for the specimen not to fail is probably a result of the dimensions. The specimen was placed on the testing surface with its shortest side representing the height. If there is not enough ratio between height and width, specimens can theoretically be compressed until they become transformed into a thin sheet.

According to Figure 4.5 the relation between height and width ratio needs to be greater than 0,8. In this case the relation is 0,413 (2,10/5,08=0,413). Therefore, dimensions between height and width for these specimens were not applicable to this testing method. Placing the specimen with the bamboo facing the testing surface, causes the width of the specimen to become greater than the height. This resulted in no significantly detectable failure (Figure 4.7).

>0,8 = h/w

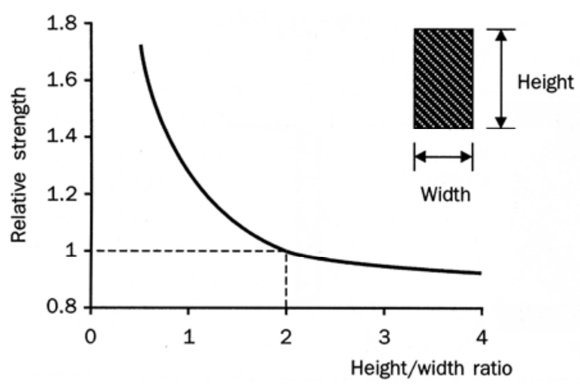

Figure 4.5 Relation between relative strength and height/width ratio. (Domone, 2001**)**

When compressing the specimen perpendicular to the plane, the soy protein was squeezed out from the wheat straw core. Figure 4.6 illustrates the specimen that was tested perpendicular to the plane. It can clearly be seen in Figure 4.7 that the soy protein resin was squeezed out of the wheat straw core, remaining in flakes. This behavior implies that the soy protein resin did not cure properly.

Figure 4.6 compression perpendicular-to-the-plane

Figure 4.7 specimen after testing in compression perpendicular-to-the-plane

The assumption was that every sample most likely would behave in the same way, therefore only one sample was tested in compression perpendicular to the plane. The compression test was henceforth conducted parallel to the testing surface. 12 specimens were tested in compression parallel to the plane with the side of the wheat straw core facing the testing surface.

4.2.2 Static compression tests parallel to the plane (5,08 x 5,08 x 2,60 cm)

The relation between height/width is 5,08/2,60=1,95. Placing the test specimen in parallel to the plane result in a relation between height and width becomes greater than 0,8 (Figure 4.5). Therefore, valid test results are expected when placing the specimen parallel to the plane.

Figure 4.8 illustrates the setting of the testing machine. Two square and thin pieces of metal was used, a cylindrical piece of metal and a bulb, all composed the zone between the specimen and the cylindrical pressure plate that transferred the load on the specimen.

Figure 4.8 compression parallel-to-the-plane

Figure 4.9 illustrates a specimen after testing in compression parallel-to-the-plane. Looking carefully at the picture, it can be noticed that there is a crack between the bamboo mat and the wheat straw core, indicating failure between the bamboo and the core.

Figure 4.9 Failure compression parallel-to-the-plane

Figures 4.10-4.12 illustrates the load-compression relation for the specimens tested in compression parallel to the plane. When tested in compression the test results of the specimens indicates an almost linear curve. Specimen number 1 represents low deformation curve, the highest load applied before failure was 8 kN and the deformation was 1,7 mm.

Figure 4.10 Load-compression curve, static compression parallel-to-the-plane-test –low deformation. Specimen No 1.

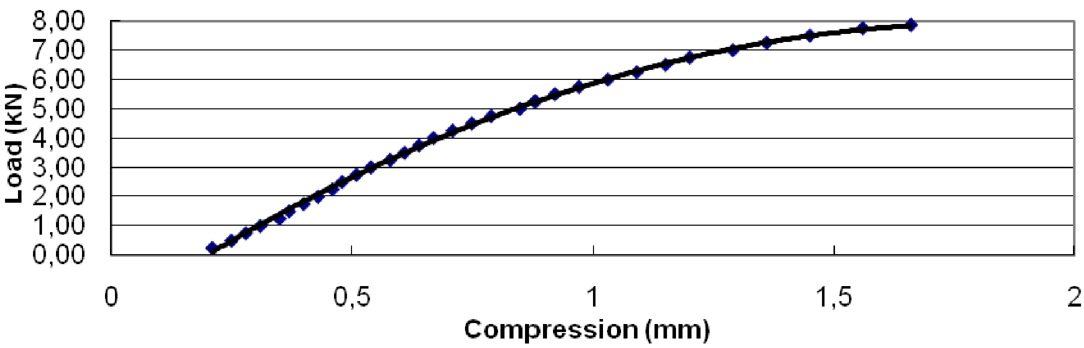

Figure 4.11 illustrates the deformation curve for specimen number 11, representing medium deformation test results. The highest load applied was 7,86 kN and the deformation was 1,7 mm.

Figure 4.11 Load-compression curve, static compression parallel-to-the-plane test –medium deformation. Specimen No 11.

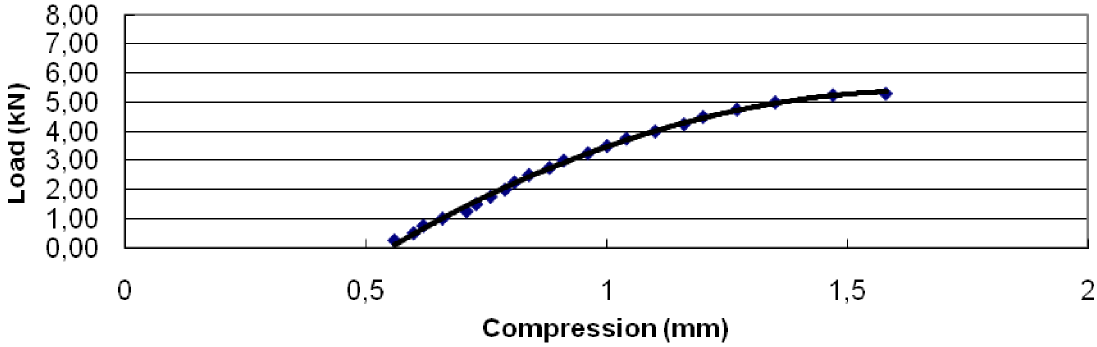

Figure 4.12 illustrates high deformation curve for the specimens tested in compression. Specimen number 4 represents high deformation and it resisted a load of almost 5 kN. The deformation was 1,63 mm.

Figure 4.12 Load-compression curve, static compression parallel-to-the-plane test –high deformation. Specimen No 4.

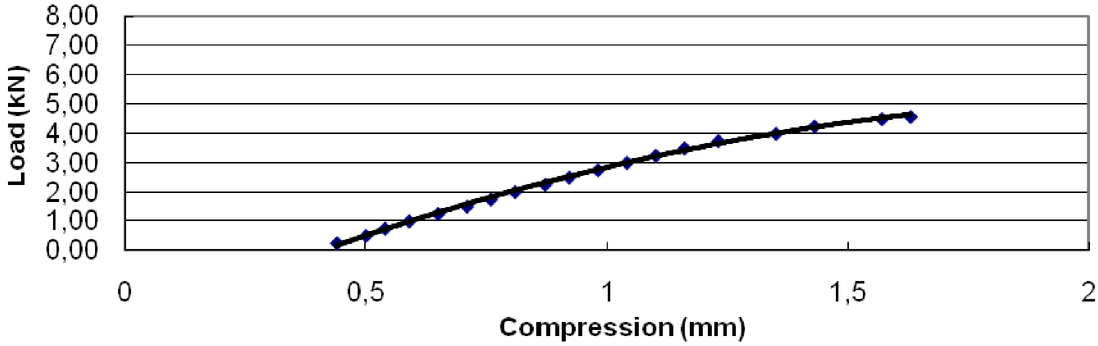

Table 4.4 presents the summarized results from testing the specimens in compression parallel to the plane. These test results are based on a mean value of 9 specimens. The minimum compressive strength achieved was 4,035 MPa and the maximum compressive strength achieved was 9,631 MPa. Comparing to the maximum bending strength, which was 10,963 MPa, implies that the specimens were stronger in bending, compared to compression parallel to the plane.

Table 4.4 Summary of the test result compression parallel-to-the-plane

	Mean of:	Min (MPa)	Mean (MPa)	Max (MPa)
Compressive Strength, σ (MPa)	9(12)	4,035	6,179	9,631

During testing, failure occurred often between the core and the bamboo mats. The same phenomena occurred also when tested in bending. The main reason for the bamboo mat to separate from the wheat straw core is most likely due to weak bonding properties of the soy protein resin. If failure did not occur between the bamboo and the core, the failure occurred as a crack in the wheat straw core. When continuously applying load, although the failure once had occurred either between the two materials or in the core, failure occurred both in the wheat straw core and in the interface between the bamboo mats and the wheat straw core.

4.3 Shear tests

For shear testing no representative load-deflection graphs was constructed, since the deflection was not relevant in this testing.

4.3.1 Static shear tests perpendicular to the plane (5,08 x 2,54 x 2,10 cm)

Table 4.6 presents the summary of the test results from testing the specimens in shear perpendicular to the plane, with the bamboo facing the blade. The test results are based on a mean of 7 specimens. The minimum shear strength achieved was 10,768 MPa and the maximum compressive strength achieved was 18,193 MPa.

Table 4.5 Test result summary shear perpendicular to the plane

	Mean of:	Min (MPa)	Mean (MPa)	Max (MPa)
Compressive Strength, σ (MPa)	7(12)	10,768	14,868	18,193

Figure 4.14 Failure in shear perpendicular-to-the-plane

4.3.2 Static shear tests parallel to the plane (5,08 x 2,54 x 2,10 cm)

When testing in shear parallel to the plane, with the wheat straw core facing the blade, the typical failure mode for the specimens was that the bamboo mat separated from its core (Figure 4.13). This is probably due to the same reasons as for the bending and compression tests.

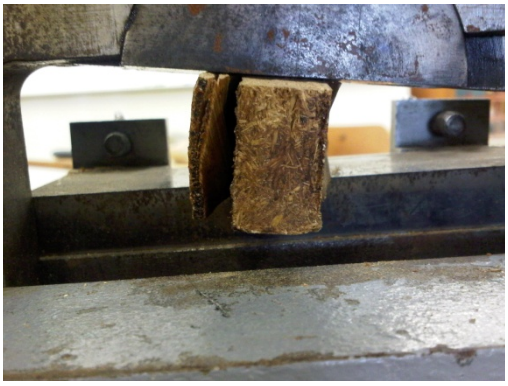

Figure 4.13 failure in shear parallel-to-the-plane

Table 4.6 presents the summary of the results from testing the specimens in shear parallel to the plane, with the wheat straw core facing the blade. The test results are based on a mean of 8 specimens. The minimum compressive strength achieved was 6,118 MPa and the maximum compressive strength achieved was 9,268 MPa.

Table 4.6 Test result summary shear parallel to the plane

	Mean value:	Min (MPa)	Mean (MPa)	Max (MPa)
Compressive Strength, σ (MPa)	8(12)	6,118	7,584	9,268

The shear specimen tested perpendicular to the testing surfaced showed substantially better strength, compared to the specimens tested parallel to the plane. The maximum compressive strength when testing perpendicular was twice as high (18,193 MPa, Table 4.5) as the maximum compressive strength when testing in parallel (9,268 MPa, Table 4.6). An explanation is that when the bamboo faced the testing surface, the shear strength increased, since the testing blade meets resistance from the bamboo (which possesses better mechanical properties than the wheat straw core).

4.4 Moisture content tests

Two different types of moisture content test were performed in order to get an overview of how the moisture content in the sandwich panel changes, when exposed to water or heat. Two specimens were tested, one specimen for the dry test and one specimen for the wet test. The assumption was that the moisture content is similar for all the specimens, therefore only two specimens were tested; one specimen for the dry test and one specimen for the wet test. The results from the moisture content tests are summarized in Table 4.7.

4.4.1 Dry test

The specimen was exposed for desiccation in 120°C for 24 hours. The water content result from the dry test give: (222.20-187.44)/187.44 = 0.185. The weight decreased by 35 g, corresponding to 18,5 percent by dry mass. This implies that the specimen contains at least 18,5 percent moisture.

4.4.2 Wet test

The volume before and after soaking the specimen in water, did not give any notable change. According to the results from the dry test the dry weight of the specimen for the wet test could be estimated as 301.54/(1+0.185) = 254.46 g, assuming similar water content in the specimens for both dry and wet tests.

The water content in the specimen was 301.54 – 254.46 = 47.07 g, corresponding to 18.5 percent by weight of dry specimen. After the wet test, the weight increased by 16.26 g, corresponding to 6.4 percent (16.26/254.46=0,064) by weight of dry specimen.

This small increase in weight does not result in any notable increase in volume. The specimen was exposed to water for approximately 30 minutes, assuming that the specimen absorbs water quick because of the straw material. The relatively small quantity of absorbed water may indicate that the most of pores are already filled with water under the natural conditions but may also attribute to the short absorption time.

If the specimen had been exposed to water for a longer time, it would perhaps have absorbed more water. Although the quantity is small, an observation when exposing the material to water was that the specimen absorbed the water rapidly. One conclusion from this observation is that the panel is not water resistant. However, bamboo in its natural form, untreated, is resistant to water, due to its coating.

Table 4.7 Results from moisture content tests

	4.4.1 Dry test	4.4.2 Wet test
Weight before	222,20 g	301,54 g
Dry weight before	18,5 percent	18,5 percent
Moisture content before	6,4 percent	6,4 percent
Volume[1] before	$2,84*10^{-4}$ m^3	$3,65*10^{-4}$ m^3
Weight after	187,44 g	317,80 g
Moisture content after	18,5 percent	5,1 percent
Volume after	$2,40*10^{-4}$ m^3	$3,65*10^{-4}$ m^3

4.5 Water and moisture resistance

As discussed in chapter two, bamboo under natural conditions possesses very good water resistance. This is due to its outer coating consisting of silica. When the outer coating is removed, due to preparing and braiding the bamboo, bamboo loses its natural ability to resist water and moisture. Neither wheat straw is resistant to water or moisture. When performing the wet test, it could clearly be noticed that the panel absorbed water rather quickly and exposing the panel to water or moisture for a longer time, probably decreases the mechanical properties extensively.

Straw rotten easily, when exposed to moist environments. In order to create a panel that resists moisture and water, the whole panel should be covered with coating. To avoid unnecessary problems with moisture, the panel must be constructed and designed in such manner that enough ventilation is allowed. Enough ventilation is important in order to prevent moisture adhere in the panel for a longer time.

[1] Volume = dry mass/density

4.6 Limits of the validity of the results

The main idea was that all the testing and manufacturing procedures should be consistent. But the variation of temperature and relative humidity made this difficult, since there was no available laboratory where the temperature and relative humidity could be controlled.

An important factor that could affect the validity of the results could be that the specimens did not cured in the exact same oven temperature, which is normal for industrial manufacturing of panels. The curing temperature for the laboratory oven was set to rise from room temperature, between 22-26°C to 130°C for the compression and shear samples and 120°C for the bending specimens. Depending on initial room temperature the oven temperature rose to its set temperature with an inconsistent rate.

Another factor that could affect the limits of the validity of the results could depend on different rates of compression. A wheat straw core compressed for a longer amount of time probably developed a better bonding and could thereby resist greater load.

When applying load during compression, some specimens resulted in having more load transferred on one side, therefore, some specimens ended up a bit uneven. The load transferred on top of the specimen, forced wheat straw to slide up on the sides, creating an uneven specimen. The molds were not strong enough to keep the material inside the mold during compression. This resulted in wheat straw core that was a bit thicker on one edge than the other. The weak and un-tight molds resulted in that it was not as easy as expected to compress the specimens and keeping a smooth surface. Uneven specimens could be a contribution to uncertain validity of the results.

Another factor that could affect the validity of the results is the duration between the first curing phase in the oven and the other oven curing phase when adding the bamboo. The amount of time between the second curing in the oven and actual testing also varied. The amount of time varied between one day and ten days. The curing temperature and relative humidity in the laboratory also varied. The specimens were cured in the laboratory during a relative humidity of 49-62 percent and a temperature of 21,7-24,7°C (temperatures during night in the laboratory was not measured) before tested.

The amount of time between curing in the oven and actual testing could contribute to the panel developing its properties. A panel tested only 24 hours after curing in the oven might not had a chance to develop enough properties compared to a panel that was tested after ten days. The specimens which were tested a few days after manufacturing might not had developed the same moisture content as the specimens that were leaved in the laboratory for seven to ten days. The effect of curing time for the test results was never registered, so only assumptions about this can be taken.

4.7 Possible sources of error in the results

The human factor is one possible source of error. The specimens were almost totally handmade, except from using appliances to cut the wheat straw and the bamboo. All the testing, recording of deflection and applying the load was done manually and no computer was used. Carrying out all the tests manually, compared to using computerized testing machines, eventuates in less accurate testing results. The human reaction is not as accurate as computers.

Another possible source of error could be some mistakes of measuring the specimens. The specimens were measured in length, width, thickness and weight. The measurements were made with a digital caliper and a digital scale. Despite the use of digital measuring equipment, mistakes could occur. Correct readings of the deflection are needed for both compressive strength and Modulus of Rupture and incorrect readings can lead to false assumptions.

4.8 Life Cycle Analysis

A life cycle analysis is a tool deals with a products environmental impact during its entire life cycle, from raw materials to recycling. When manufacturing and using building materials, it is very important to acknowledge the whole process of its life cycle, from a sustainable point of view. A life cycle analysis of a building material should deal with environmental impacts when using raw materials, for example, what kind of raw materials, where they are extracted from and environmental consequences for extraction. A life cycle should also consider worldwide transportations. The manufacturing processes, the user stage and how the material will be taken care of after it has fulfilled its purpose is other important factors that a life cycle analyze needs to address.

The materials used in this sandwich panel should be locally available, in order to diminish worldwide transportations. The sandwich panel should be easy to manufacture with simple tools. Local people could be taught by for example Non-Governmental Organization's (NGO's) how to prepare, manufacture and build a house from with the sandwich panel.

The sandwich panel should be manufactured, prepared and constructed in the best way possible, in order to utilize user stage and durability. To prolong the user stage the panel could be treated with some type of coating so it can last longer against water, moisture and attacks from insects and pests.

After the user stage the sandwich panel should be easy and safe to dismantle. The remnants should not be managed through waste incineration. They should be recycled or composted. The panel should be recyclable and used all over again in a new shape and the remnants could be used as household items, for example baskets.

One of the main purposes with manufacturing a sustainable building material is that it should bind carbon dioxide as long as possible. Manufacturing a building material made of bamboo and wheat straw with a long durability creates opportunities to bind carbon dioxide under an extended time period.

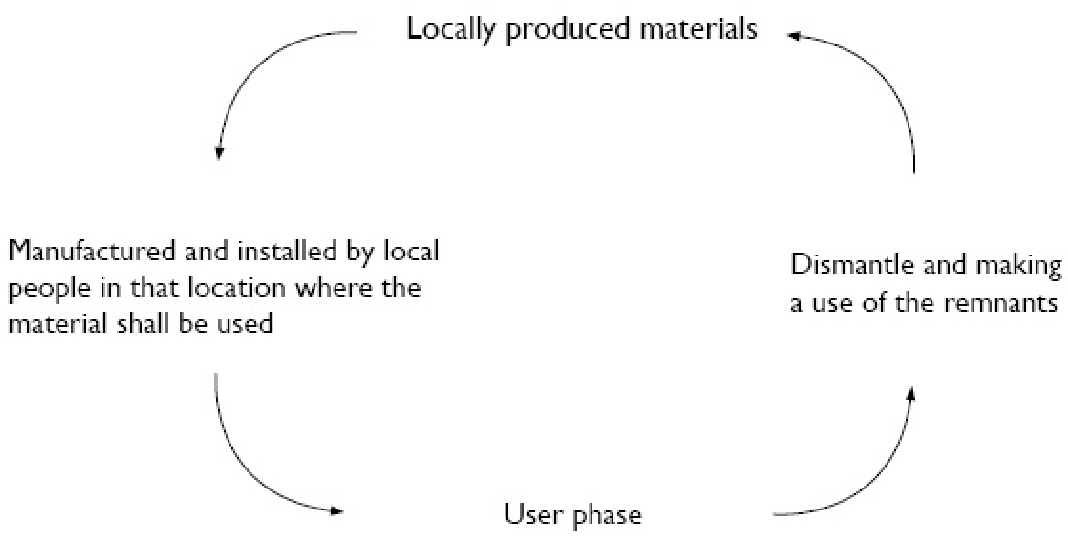

Figure 4.15 Life Cycle of the sandwich panel

Two American and German architects, William McDonough and Michael Braungart have developed the term *cradle to cradle* in their book *Cradle to Cradle: Remaking the Way We Make Things*. This concept is about making use of every component, from the very first processes of making the product, through the entire user stage and finally the recycling. The concept cradle to cradle is all about advanced ecologic intelligent design. Cradle to cradle design involves chemical benchmarking, supply-chain integration, energy and materials assessment, clean production qualification and sustainability issue management optimization.

4.9 Fire safety

As discussed in chapter two, bamboo does not possess any good fire resistance qualities. Wheat straw does not burn that easily if compressed together, as it is when manufacturing the panel made in this project. The sandwich panel needs a coating in order to be fire resistant. Without coating, it would probably burn fairly easily (even though the core probably possesses better fire resistance qualities). Regarding fire safety, the sandwich panel can be compared with any other panel made of wood. They all require a coating or some kind of treatment in order to achieve fire resistant properties. It is important that the sandwich panel should possess good fire resistance qualities, since the panel's purpose is to function as an important element of the house. Smart construction is also an important factor, which would increase fire protection.

When conventional wood is exposed to fire, mechanical properties decreases extensively. However, if the fire is put out in time and only destroys a thin surface of the wooden material, the construction can be saved and does not necessarily have to be replaced. But bamboo does not possess the same qualities and will be entirely destroyed in case of fire.

4.10 Cross laminated timber, CLT

A comparison between the bamboo sandwich panel tested in this project and a conventional panel would not provide any value to the testing results, more than stating that a conventional panel possesses better mechanical properties. There is no point in performing such a comparison, also since a lot of factors regarding manufacturing and testing procedures differs a lot. The bamboo sandwich panel is manufactured by hand and compressed manually, while a conventional panel is factory-made with advanced equipment.

An interview was made with a representative, Anders Gustafsson, from the SP Technical Institute in Sweden. The interview was performed in order to acquire some mechanical properties of a conventional sandwich panel; bending, compression and shear strength.

Cross Laminated Timber, CLT is a thick board consisting of wood (on average 70 mm thick). CLT is a conventional, modern building material that is often used as a wall component. The mechanical properties of a factory-made board are much higher, compared to the bamboo sandwich panel (Table 4.8). The bending and shear values are provided by the SP Technical Research Institute of Sweden[2]. The thickness of those specimens was 70 mm. The compressing value was presented in a Master thesis at the School of Technology and Design in Växjö, Sweden. The thickness of the specimens tested in compression was 120 mm. (Kathum et al.) It is important to notice that CLT specimens presented in Table 4.8 had a greater thickness than the bamboo sandwich specimens.

Table 4.8 Mechanical properties

Type of stress	Bamboo sandwich panel	CLT
Bending (MPa)	10,96	35,3
Compression (MPa)	9,6	3,3[3]
Shear (MPa)	18,2	190

[2] Gustafsson, Anders. Personal communication. SP Technical Research Institute of Sweden, Trätek, 2011-05-23

[3] Compression strength perpendicular to grain. (Kathum et al, 2009)

5. Discussion, Conclusions and Future Research

5.1 Discussion

This master thesis is an exploratory study upon how a sandwich panel made of bamboo and wheat straw behaves when tested under load. There was no earlier published literature to be found regarding mechanical properties of this type of configuration of bamboo and wheat straw. Therefore, this study has included significant trial and errors along the way. Many questions and practical issues were to be solved during the whole process. One of the key issues was to figure out the practical aspects regarding manufacturing and testing the panel.

One practical issue was to investigate which type of equipment available for compression. As described previously in section 3.3 owing to the practical reason the only available old type of universal compressing machine was used for all testing (bending, compression and shear), however different settings for each test was used.

Preparing the wheat straw core was accomplished with the assistance of mechanical engineering student Evan Nishimura, who prepared and tested wheat straw cores in his project report *Manufacture and Properties of Soy Protein Resin Wheat Straw Boards*. The same recipe for the wheat straw core and the same equipment for manufacturing the core were used.

The mechanical properties of the panel were expected to increase through adding bamboo mats to the wheat straw core. However, the test results did not improve, compared with the results from the wheat straw core in Mr. Nishimuras research report.

In Mr. Nishimuras project, the specimens were compressed and cured under the same phase in an advanced laboratory oven. In addition, the specimens were also cured under a higher temperature. Compressing and curing in the same phase is an important factor for achieving good mechanical properties.

The global deforestation makes it important to consider where to grow bamboo with as little impact on the environment as possible. There are several areas in the world where forest has been cut down, in favor for cultivations of crops or other demands for available land. The use of bamboo should not require a massive logging of forests. Regarding expansion of plantations it is important to thoroughly consider areas where bamboo could be cultivated without any extermination of plants or habitat. If supplies from plantations are not enough, there should be an extensively planning for where the plantations can be expanded without interfering on any habitat.

It is important that building materials are culturally acceptable wherever they are going to be utilized. Some materials have a perception to be considered “poor” and have a “bad quality”. Bamboo and wheat straw are well-known vernacular building materials that should be accepted for its unique qualities and should not be interpreted as poor. People are aware about the qualities of bamboo; among others the tensile and flexure properties, that it is easy to work with and its good tactile qualities. Despite all these good qualities of bamboo, bamboo is still interpreted as “poor man’s timber”. Presenting a quote from a traveler in Asia a century ago;

"What would a poor man do without bamboo? Independently of its use as food, it provides him with the thatch that covers his house, the man on which he sleeps, the cup from which he drinks and the chopsticks with which he eats. He irrigates his field by means of a bamboo pipe; he gathers his harvest with a bamboo rake; he sifts his grain through a bamboo sieve and carries it away in bamboo baskets." (Sunstar, 2011)

Figure 5.1 Bamboo and palm house on stilts, Inle lake, Burma. (Vellinga et al. 2007)

In order to manufacture a sustainable building material, the components should have as low negative impact on the environment as possible. This results in important requirements, especially when concerning carbon dioxide emissions. One idea with introducing the sandwich panel made from bamboo and wheat straw is that all components for the panel should be locally available in order to reduce unnecessary transportations. The sandwich panel made in this research project is solely considered to be used in those parts in the world where bamboo and wheat straw grows locally.

A sandwich panel made from bamboo and wheat straw could be used as a building material in temporary camps in those parts of the world where bamboo and wheat straw grow natively, for example in parts of Africa and Asia. Parts of these continents are suffering from climate disasters like drought, typhoons, earthquakes, hurricanes, flooding and tsunamis and also human disasters such as war, conflicts and poverty, which create a critical need for cheap and available building materials.

Bamboo is a light weight material, which reduces damages if it falls apart during an earthquake or a hurricane. Wood based sheeting materials as MDF boards are suitable to use when building earthquake safe, a flexural panel of bamboo and wheat straw could also be suitable to use as earthquake resistant building material. It would moreover be a cost saving and environmentally friendlier alternative.

Future visions for a sandwich panel like the one created in this study, is that it should be possible to fabricate the panel by the house owner on site. The panel should be user friendly and offer potential for people to self-reliance, through building their own home with a durable panel. The panel should be easy to fabricate for anyone who wishes to build a house. The techniques for manufacturing the panel should also be easy so that through workshops people can be taught how to manufacture the panel and taught how to build a durable and safe house, using the panel. The panel should also be manufactured and built with available, simple and cheap tools. The panel should moreover be cheap to construct, in order to make it available for low income groups.

Especially the compressing part of manufacturing the panel can be difficult to perform in rural areas, where there is no access to advanced equipment. One suggestion could be manufacturing the panel in household ovens. The panel can be manufactured in smaller pieces, in order to fit inside the oven and after curing in the oven, pieces can be assembled in a desired size. The woven bamboo does not necessarily need to be cured in an oven and the mat should be braided in a traditional way. After curing the wheat straw panel in the oven, the woven bamboo mat can be attached to the core with bamboo nails. Know-how and assistance in preparing, manufacturing and building with the bamboo sandwich panel could be provided by local Non-Government Organizations or other organizations that are working with shelter and housing projects.

There are several practical possibilities for a home-made sandwich panel. The sandwich panel can be also be used as furniture, for example; bed frames, cabinets for storage, tables or as an unloading bench.

Bamboo is easily recycled, compared to conventional wooden materials. This is due to the high tensile strength of bamboo. Bamboo is also easier to repair, compared to conventional wood. When wood starts to fail, it is often useless. If bamboo starts to fail, it can be repaired with ropes or nails. One of the main purposes with an environmentally friendly sandwich panel is that it should have none negative impacts on the environment during its whole life span.

In parts of Southeast Asia (for example Indonesia), where the climate is very humid, building with breathable and light materials is an essential part of local building tradition. Many traditional buildings consists therefore mostly of available grass types like bamboo. The walls often consist of thin, braided bamboo mats. The wind can travel through the small holes in the bamboo mat and a type of self ventilate system is created. The sandwich panel made in this project is too thick and heavy for being suitable in a country with such a humid climate as for example Indonesia.

If a sandwich panel of bamboo and wheat straw was to be used as a main component for a housing structure, for example as walls, it would be very important that the design and construction of the house allows the material to ventilate properly (Figure 5.3). If humid air stands still inside of the sandwich panel under a longer time, the panel will eventually rotten.

A bamboo sandwich panel like the one constructed in this project, would be suitable to use in climates that have cold night and warmer days. The wheat straw core would insulate against cold during night and heat during days.

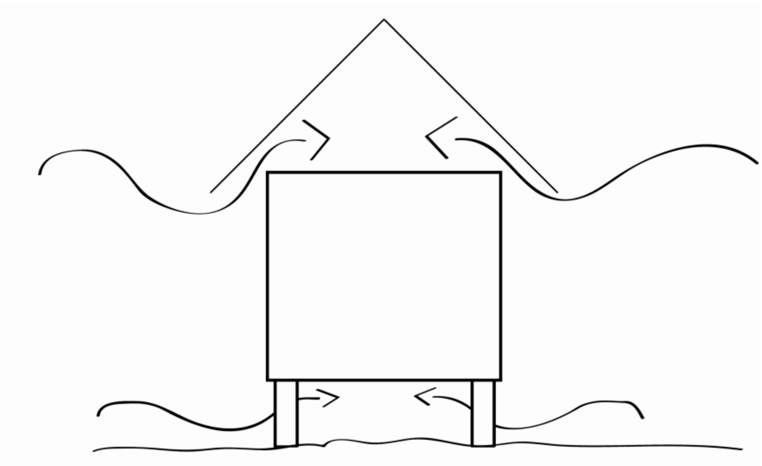

Figure 5.3 Building with bamboo sandwich panel as walls, illustrating necessary ventilation

In order to create the panel with desired thickness and to obtain a compact core, the wheat straw core was compressed by a universal testing machine. This was the part of the manufacturing procedures that was the most time consuming. Several factors from the compressing procedure probably limited the validity of the results. One factor was that the amount of time compressing the specimens was not consistent. Some specimens were compressed for a longer time than others, depending on how rapidly the manually applied load was controlled. It could be noticed that specimens that had been compressed for a longer time accomplished better test results.

The setting of the compression (Figure 5.4) and the available molds resulted in difficulties in compressing the specimens into an even surface. A metal lid was placed on top of the mold and under the lid metal cylinders were placed on top of every specimen. This setting was the most suitable one that could be made from machines and items at hand in the laboratory. On some of the specimens the load transferred uneven during compression, causing some wheat straw to be forced outside the mold resulting in an uneven product. This is an unwanted effect of the molds not being entirely fixed. As discussed in 4.6, uneven specimens could be a contribution to uncertain validity of the results.

Figure 5.4 Compressing

After compressing the wheat straw cores, clamps were attached to the molds (Figure 5.5). This was done in order to keep the specimens compressed and hinder them from rising back to initial thickness. The thickness of the specimens directly increased after removing load. Since the specimens strived towards original thickness, it was difficult to clamp them back to compressed thickness and this required a lot of strength.

Various clamps were used. Some clamps were better than others, which resulted in some clamps keeping some specimens together better than other clamps. Using clamps of the same type would have contributed to a more consistent testing procedure.

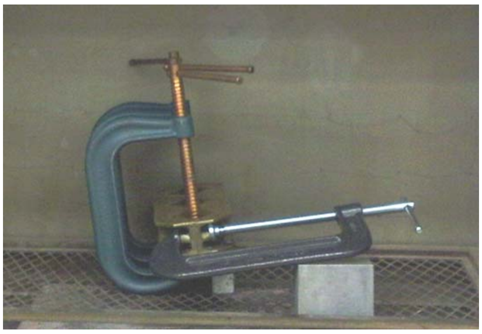

Figure 5.5 The clamps

The sandwich panel was not compressed after adding the two bamboo mats, but put in the oven directly after gluing the mats to the core. Also compressing the specimens after adding the bamboo mats, might had increased the mechanical properties of the specimens.

What was critical for testing was the rate of strain, which did not vary while applying load during testing. The rate of moment was fixed, therefore, the load was not varied and it was a constant strain load application of load. Once the load was opened, the pristine was moving with the same rate. The readings were recorded while continuously loading. All the specimens for each and every testing were exhausted with the same rate.

Soy resin as a binder used in this project is an environmentally friendly binder, although it seems not strong enough. It is so far difficult to find a stronger binder without any chemically substances. A stronger binder should instead be used, in order to achieve a better binding between the bamboo mats and the wheat straw core.

5.2 Conclusions

Due to an increasing population, amongst others, there is a greater demand for wood. Our planet is going through rapid changes and it is exhausted for a huge stress. Solutions for how to mitigate these activities are becoming critical in order to adapt to the environmental changes in a sustainable direction. Using bamboo as a substitute instead of conventional wooden building material would be an environmentally friendly alternative. Bamboo is a vernacular building material that has been used for centuries in parts of the world where bamboo grows natively. Bamboo possesses many advantages to be used as a building material. With its high tensile and flexural strength it creates a strong, adaptable and light weight material that could be used as wall, roof and floor material. Bamboo is suitable to be used as a shear wall, where seismic stress can be resisted. Bamboo is also easy to work with and only simple tools are needed in order to create a building component.

Wheat straw is also a vernacular building material that is used in many parts of the world, often as roofing material. Wheat straw is a green building material that also possesses many good properties. It is possesses good thermal and acoustic insulation properties. It keeps the building cool under warmer periods and it keeps the building warm under colder periods.

Combining bamboo and wheat straw into a sandwich panel and making a use of their qualities would be an alternative to create an environmentally friendly sandwich panel. As far known, there is no earlier research on creating a sandwich panel made from bamboo and wheat straw. The panel created in this thesis work is an experimental study, in which most parts of the testing have been set up exclusively for this specific study. It was only the bending test that followed a testing method according to ASTM. Even though the sandwich panel did not reach expected test results, the panel is still functional as several building components. The panel has qualifications to be developed into a stabile and durable building material. However, the panel should not be placed in a building as a load bearing wall in order to take up essential loads (for example load from the roof). In order to use the panel as a load bearing wall, modifications needs to be implemented, in order to improve mechanical properties.

Suggestions for possible application areas:

- Doors for kitchen cabinets and other cabinets used in a home
- Inner-door
- Non-bearing partition wall
- Room divider
- Wind-protection for wall constructions
- Insulation for wall constructions

The panel possesses good interior qualities, it is comfortable to touch and it is nice to look at. In other words the panel possesses tactile qualities that make it suitable to use in a building. The panel could be used as doors for kitchen cabinets or other cabinets in a home. It would also be possible to use the panel as an inner-door. The sandwich panel could moreover be used as a wall or as a part of a wall, as long as no essential load is transferred on the panel. Another suitable application area for the panel would be as partition walls (non bearing) or as a room divider. For example the panel could be used as mobile inner walls for temporary room division. This would create a practical choice of design for families that are in need for a home with mobile configuration of room settings.

The panel is not load bearing, but it can still fulfill other functions in wall constructions due to its configuration of compressed wheat straw and braided bamboo. The sandwich panel could for example be used as wind-protection or insulation in wall constructions. Solely the wheat straw has very good noise and insulation properties and is used for its superior thermal and acoustic insulation qualities.

The bamboo sandwich panel could also be used as shear wall that can resist seismic stress. The mean maximum test result for testing the specimens in shear parallel to the plane was 9,268 MPa. A particle board should resist between 3-15 MPa in shear load, according to Swedish National Board of Housing (standards could vary, depending on country). (Boverket, 1999). The specimens tested in shear perpendicular to the plane achieved 18,193 MPa as maximum strength. However, these specimens were tested with the bamboo facing the testing surface and thereby the specimens achieved greater test results. Bamboo can of course resist more stress than wheat straw.

One of the main conclusions is that the sandwich panel did not achieve as good material performance as expected. This is probably due to weak soy protein resin, used as binder for the wheat straw core and also used as bonding between the bamboo mat and the wheat straw core. When testing the specimens, two types of early failure were occurring: The bamboo mat separated from its core, probably due to the fact that the soy protein resin used as glue was too weak to hold the bamboo mats intact with the wheat straw core. The other failure was that the wheat straw core failed in an early stage. If a stronger resin was used, the wheat straw core would probably have resisted more stress.

As known, there are no binders made from natural products (for example soy beans), that could be comparable in strength to chemically based binders. If a chemically based binder would be used, the panel would probably achieve better material performance. The main purpose of creating an environmentally friendly sandwich panel would be lost, if using chemically based substances.

When lacking a strong green binder, there could be other solutions preventing an early failure. In order to utilize the tensile property of the bamboo mat, the wheat straw core would need some kind of reinforcement that keeps the core intact with the bamboo. Using a type of bamboo nails could be one solution for keeping the sandwich panel intact. Another possible solution preventing an early failure would be mixing bamboo fibers into the wheat straw core, which could increase the mechanical properties of the core and especially increase tensile strength.

Since the results from testing did not turn out as good as expected, as stated earlier, it is important to reflect what can be improved and possibilities to reconfigure the sandwich panel. Redesigning the sandwich panel, would be an option of improving the mechanical properties. Reconfiguration of the panel could appear in several ways. Adding more layers to the panel would probably create a stronger sandwich panel. The thickness of the wheat straw would then be thinner in order to make room for more layers. One suggestion would be having two layers of wheat straw and three layers of bamboo mats (Figure 5.2).

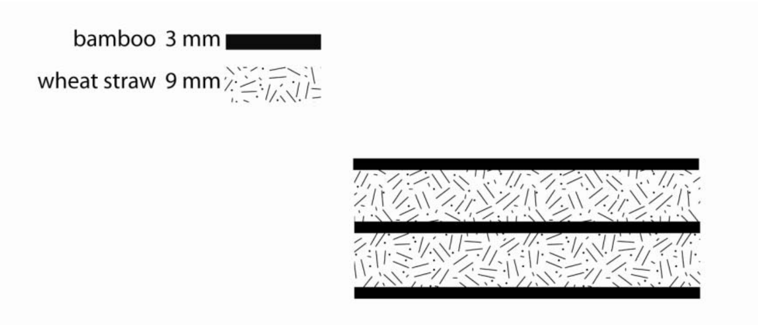

Figure 5.2 reconfigured sandwich panel

Redesigning the sandwich panel into a panel with solely one layer could also be an option for creating a stronger panel. Creating a bamboo and wheat straw sandwich panel with only one layer would require that bamboo is mixed into the wheat straw. Reconfiguration of the panel should also involve using a mechanical stronger binder, both for binding the wheat straw core and also as a stronger glue between the core and the mats.

For achieving the best material performance, a reconfigured bamboo sandwich panel should be manufactured and prepared in a laboratory oven where compressing and curing evolves simultaneously. The maneuvering of a modern laboratory oven is computerized and minimizes therefore errors due to the human factor. The panel will probably achieve better mechanical properties when curing and compression is done under the same stage. The temperature should also be increased.

The panel will develop better mechanical properties if it is compressed under a high temperature. In this testing the curing temperature was on average 128°C. The curing temperature could be increased to 150-170°C. For example MDF boards develop their mechanical properties under curing in advanced laboratory ovens where compression during various time spans is made under high temperatures, between 180-200°C. The amount of pressure applied and the time spans varies, depending on the thickness of the MDF board. The highest amount of pressure applied is 13 MPa.[4]

[4]Bergström, Peter. Personal communication, Karlit AB, 2011-06-09

The panel is not waterproof. It needs a coating in order to develop impermeable properties. If the panel is exposed to water for a longer time it may lose its mechanical properties. There is also risk for the wheat straw core to rot, if exposed to moist environments during a longer time. It is therefore important to keep in mind good ventilation, when designing with a bamboo and wheat straw sandwich panel. The panel is neither fire resistant. Therefore also a coating against fire is required. Bamboo burns fairly easily once it is on fire. Compressed wheat straw does not burn as easily, but once exposed to very high temperatures, the wheat straw will also burn.

The sandwich panel made of bamboo and wheat straw that was manufactured and tested in this master thesis research project, has a lot of potential and should be further developed. The sandwich panel is strong enough and without any improvements, can be used as a shear wall. Developing alternative building materials to be used instead of conventional wooden materials, would mitigate to the stress on forests and the environmental consequences following deforestation.

5.3 Future Research

Developing any building material is a process that could continuously be improved. Components can be replaced with more affordable, more efficient, more energy saving and mechanically stronger components. Materials can always be reconfigured and a continuous search for environmentally friendlier alternatives should always be present.

The sandwich panel manufactured in this research thesis enables possibilities for future research. One main suggestion for future research would be to come up with a stronger binder which would improve its mechanical properties and thereby expand application possibilities. The specimens in this report indicated that they were not cured properly. It is also necessary to investigate whether the core is curing properly or not. And if the core is not curing properly, what kind of solutions would be applicable to this problem. It is also important to explore the relationship between the curing of the binder and mechanical properties of the specimen.

Before a sandwich panel is introduced on the market it needs to go through different tests in order to become an approved building material. For example, it needs to be tested for moisture and fire. Regarding fire testing, it needs to be tested in order to determine if it releases any toxic substances when burning. Another suggestion for future research would be to develop a type of coating for the panel that protects it against moisture and fire.

A suggestion for future research would be to manufacture the panel under different temperatures and different compressing load in order to explore what kind of effects curing temperature and compressing has for the mechanical properties.

Another suggestion for future research would be to investigate suitable reinforcements for the sandwich panel. A type of reinforcement would prevent the bamboo mat separating from the wheat straw core during load. Two types of reinforcements are suggested as suitable to perform as future research: bamboo nails hammered into the wheat straw core or bamboo fibers mixed in the core.

Mixing bamboo fiber in the wheat straw core could be another suitable type of reinforcement. Adding bamboo fibers would create a stronger core with better mechanical properties and better tensile strength. Bamboo fibers are 100 percent made from bamboo and are therefore environmentally friendly and biodegradable. Bamboo fibers are used in the textile industry. The fibers are added to fabrics, in order to create clothing with better properties. Bamboo fibers possess good anti bacterial property and are therefore used for underwear, socks and tight t-shirts. Adding bamboo fibers to textiles creates garments that absorbs moisture and ventilates. Bamboo fibers breathe very well and keep a cooler temperature. Bamboo fiber will make the product resistant against mold due to damp. Therefore bamboo fibers are also possible to use as wall papers, sofa covers or curtains. (Swicofil, 2010)

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