

**EXAMINING THE POTENTIAL OF STRAND WOVEN BAMBOO AS  
AN ALTERNATIVE TO WOOD CONSTRUCTION MATERIAL IN JAPAN**

By

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## **Abstract**

This study examines the potential of using locally produced bamboo building material as alternative to wood constructional material in Japan. The type of bamboo building material investigated in this study is Strand Woven Bamboo (SWB). In order to know the potential of SWB as alternative to wood constructional material in Japan, this study approaches it from two perspectives, the physical properties and the availability of bamboo resources.

Firstly, this study compares the physical properties of SWB to the commonly used domestic timber, Japanese cedar. The physical properties compared include the specific gravity, tensile and compression strength, bending strength, shear strength and shrinkage rate. After that, this study explores the production potential of SWB by estimating the potential supply of bamboo resources particularly in Oita Prefecture.

From the physical properties perspective, the outcome reveals that SWB may become one potential alternative to timber under certain circumstances. While from the perspective of availability of bamboo resources, the study estimates that approximately 9651m<sup>3</sup> of SWB is potentially produced annually by using the Moso bamboo culms cultivated in Oita Prefecture under proper plantation management. However, in order to get better understanding about the potential of SWB to be used as alternative building material in Japan or other countries, further research and development is still needed.



## CHAPTER I: Introduction

In 1987, the World Commission on Environment and Development (WCED) published a report known as the Brundtland Report, and this report reaffirmed the interdependent relationship between humans and the natural environment. The natural environment provides products and services to support and maintain human life; while humans, through their existences and activities, affect the natural environment in various ways.

The report also makes a note of the interrelated problems between the environment, economic development and society. Humans, to fulfill their needs and desire, extract products and services (i.e., natural resources) from the natural environment, which consequently alters the environment to a point at which the wellbeing of human lives and societies becomes jeopardized.

One of the important outcomes of this report is the fact that it put forward the notion of *sustainable development*, which is defined as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). This is in strike contrast to times when people were left to utilize the resources for development at their free will. Mineral extraction and timber logging, land clearance for settlements and food production are few examples of natural resource exploitation. These activities have resulted in depletion of resources, but have also altered the natural environment with negative impacts such as pollution, soil degradation and loss of biodiversity.

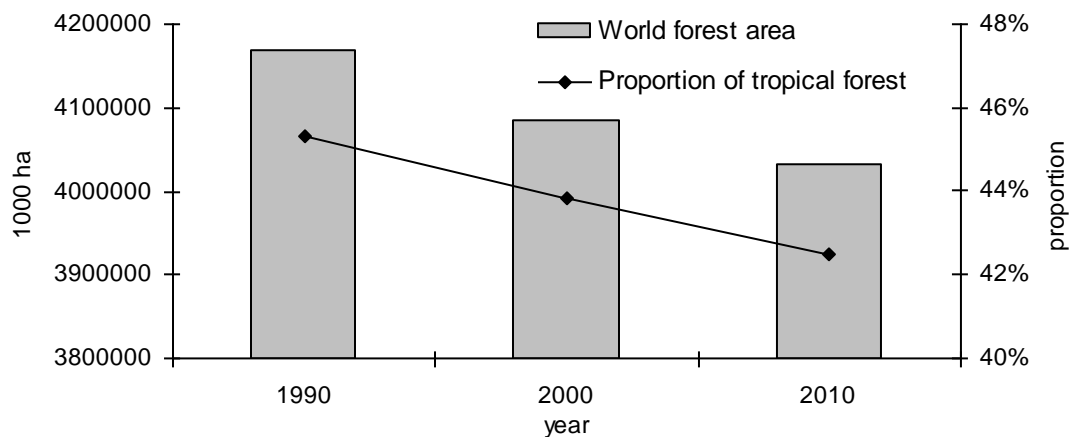
The impacts of unplanned and unlimited resource usage are far extensive as they do not only negatively affect the environment but also put human lives are at stake as well. Proper management of natural resources and active participation from every sector in human life are considered to be some basic requirements toward the sustainability and sustainable development (Perman et al., 1999).

## 1.1 Background

### 1.1.1 Deforestation and Sustainable Forestry

Deforestation is one of the most primitive human activities in exploiting natural resources and just like other human activities, it has negative impacts both on human beings and environment. However, deforestation is unfortunately still happening today regardless its negative impacts.

As it is shown in the following figure, the total world forest area is still declining even after the Brundtland Report published in 1987. Even though, the declining rate of world forest area has slightly decreased during 2000-2010 (~5210800ha/year) compared to during 1990-2000 (~8323100ha/year); this deforestation problem is still concerning, particularly in the tropics. The proportion of forest area in the tropics out of the total world forest area is keep declining which indicates that the deforestation rate is higher in the tropics compared to other regions.



**Figure 1 Change in World Forest Area and Proportion of Forest in Tropics 1990-2010**

(Source: FAO, 2010)

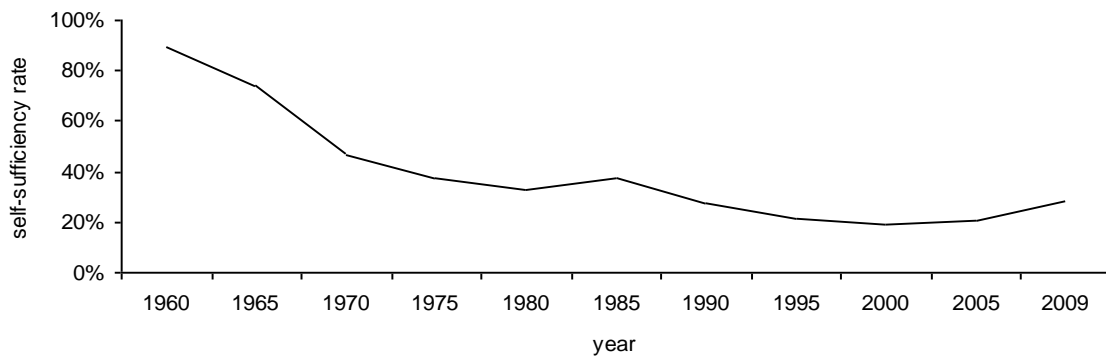
There are many causes that may directly lead to deforestation, they include timber logging (for fuel and construction material), forest clearance (for settlement and agricultural land), mining, commercial agriculture and cattle ranching, tree plantation, infrastructure development, etc. Even though there are many causes of deforestation, the

removal of timber for fuel and construction is the major cause of deforestation in rainforests which mostly located in the tropics (Domries, 1991; Salati, 1991). Further, deforestation may also be indirectly enhanced by the increase demand for forest products or forest lands to produce commercial products or establish settlements due to the increase in population either in the area around the forested area (direct consumption) or worldwide (trading).

Forest products which include timbers (for fuel, construction material, etc.) and non-timber products (e.g., foods, medicines, etc.) are essential for human lives, other products that are extracted from forests (e.g., minerals) or produced on deforested land (e.g., agricultural products) are also important for human beings. However, since the role of forests is not restricted to providing products but also environmental services which include climate regulation, soil protection, water recycling, air purification, providing habitat to maintain biodiversity and many others; a more sustainable approach in obtaining forest products which at the same time maintaining the health of forest ecosystem is needed.

### *1.1.2 Japan and Timber*

Japan is among the major importers of wood and wood products in the world regardless its vast area of forest which covers ~67% of its land area (Forestry Agency, 2011). The main reason of Japan's high import of wood and wood products is the low price of imported wood; it has caused the local producers have to keep the price of the domestic wood low although the production cost is high which results in low profitability (Iwamoto, 2002; Forestry Agency, 2010). Due to the low profitability of domestic wood, people lost their interests in wood production. As the result, the local forests in Japan are left without proper management and at the same time, this situation has led Japan to rely on imported wood for over 70% of its consumption over the past three decades as shown in the following figure.



**Figure 2 Wood Self-sufficiency Rate in Japan during 1960-2009**

Note: Self-sufficiency rate = (domestic supply / total supply)\*100%

(Source: Forestry Agency)

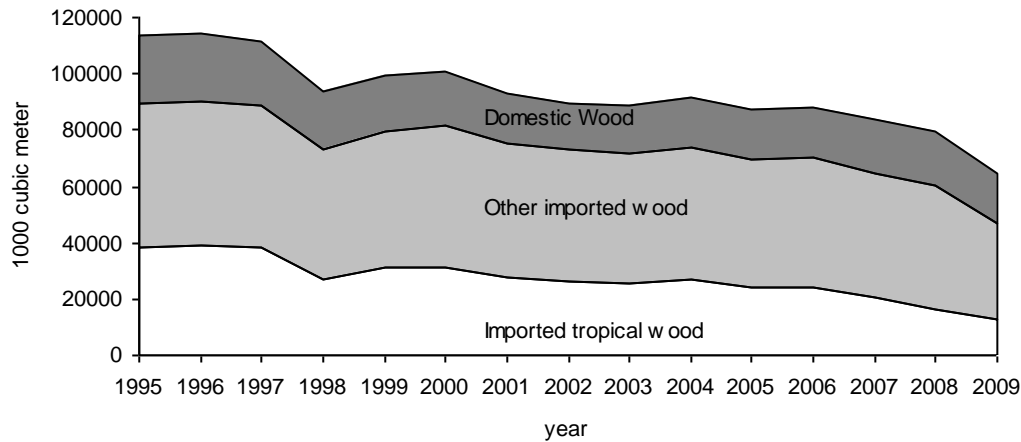
### *1.1.3 Japan and Tropical Timber*

Just like wood and wood products as a whole, Japan is also the major tropical timber importer particularly for plywood and industrial roundwood.

Japan is the top importer of tropical plywood ever since, even though the amount of import is decreasing during the last few years. In 2009, the amount of Japan's tropical plywood import was 2278860m<sup>3</sup> with Malaysia and Indonesia as the major suppliers (ITTO, 2011). In 2009, Japan also imported 442080m<sup>3</sup> of tropical industrial roundwood which make Japan as the 4<sup>th</sup> highest importer of this wood product after China (6101210m<sup>3</sup>), India (3692020m<sup>3</sup>) and Taiwan (482310m<sup>3</sup>) (ITTO, 2011). The tropical industrial roundwood that was imported to Japan in 2009 mainly come from Malaysia, Myanmar, Papua New Guinea and some African countries (FAO, 2011). While the amount of imported tropical sawnwood and veneer in 2009 was 5568000m<sup>3</sup> and 100000m<sup>3</sup> respectively.

In overall, the share of tropical wood out of the total supply in Japan can be seen in the following figure. The trend in the share of tropical wood out of the total wood supply in Japan during the past few years shows a decreasing tendency. In 2009, the share of tropical wood out of the total wood supply in Japan was 19.5% compared to 33.7% in 1995. The reason behind this decreasing tendency is more likely to be the shifting of raw

material of plywood from tropical wood to domestic coniferous wood starting from the second half of 1990s (Akahori, 2006; MAFF<sup>1</sup>). However, it was reported that the supply of domestic log for plywood production had faced difficulties in 2010 (Yamada, 30 March, 2011). This situation may result in the increase demand of tropical wood from Japan in the future which is actually undesirable since it may possibly link to the deforestation in the tropics.



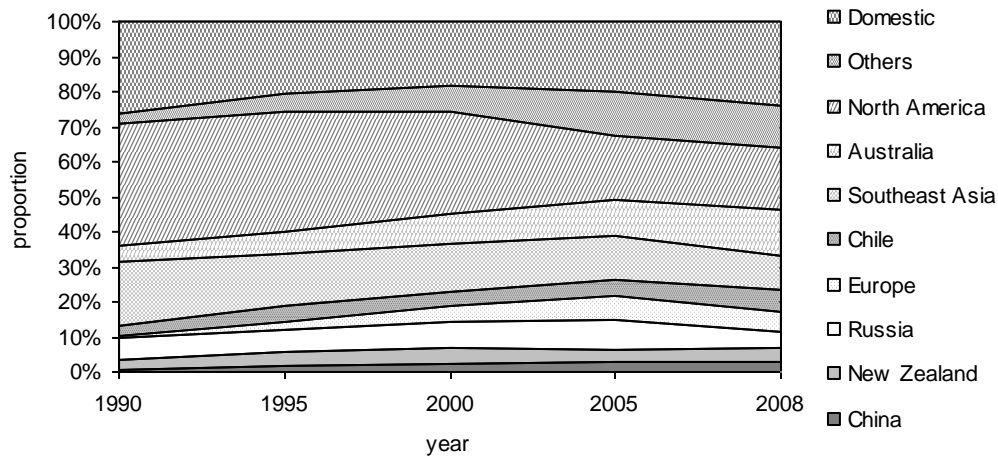
**Figure 3 Type of Wood Supply in Japan 1995-2009**

(Source: Forestry Agency & International Tropical Timber Organization (ITTO), 2011)

*Source of Imported Wood in Japan and China Factor*

As shown in Figure 4, in the beginning of 1990, imported wood in Japan was mainly supplied by North America (35%), Southeast Asia (18.4%) and Russia (6%). However, by the end of 2008, the proportion of wood supply by each supplier has become more equally distributed. The notable change during this period (1990-2008) is the change in the North American and Southeast Asian proportion of wood supply which become approximately half; while the proportion of wood supply by Australia and other countries, which include African countries, has significantly increased.

<sup>1</sup> MAFF: Ministry of Agriculture, Forestry and Fisheries of Japan



**Figure 4 Source of Wood Supply in Japan 1990-2008**

(Source: Ministry of Finance & Forestry Agency)

The change in the trend of wood supply in Japan during this period was partly caused by China's increasing demand from the same suppliers as the result of its high economic development. For example, the amount of China's and South Korea's demand for industrial roundwood from United States has been increasing started from 2005; the amount of China's demand for lumber from Canada has also been increasing during that period while at the same time, Canada's wood production has been decreasing (Ohashi, 2009). The same case was also happened for the tropical roundwood, the amount of China's demand for that product increased drastically in 2000 (ITTO, 2011). This high demand of wood from China has resulted in strict competition for wood among countries including Japan. In addition to it, the increase of log export tax in Russia has also resulted in the increase in wood price from that source (Ohashi, 2009; Forestry Agency, 2010).

#### *1.1.4 Projection of Domestic Wood Demand in Japan*

Even though the demand of wood in Japan over the past few years has shown a decreasing tendency, especially from 2008-2009 (Figure 3); in the future, the demand of wood in Japan is expected to increase.

First, the decreased in wood demand from 2008-2009 was mainly due to the impact of the worldwide economic crisis in 2008 which has resulted in the decrease number of housing

starts in the next year (Ohashi, 2009). Since the amount of wood demand is closely related to the number of housing starts; the recovery from this economic crisis, which may bring back the number of housing starts annually to its normal trend, may increase the demand of wood in the future.

Second, in 2008, Japan enacted a law about promoting the use of biofuel with wood as one of the raw materials (Law No. 45 of 2008). Later, in 2010, Japan again enacted a law concerning the promotion of the use of wood in public buildings as a part of the global warming measure and the realization of cyclical society (Law No. 36 of 2010). Based on these two conditions, the demand of wood in Japan can be expected to increase in the future.

#### *1.1.5 The Need of Alternative Material in Japan*

Considering the competition of wood from other countries particularly from China and the increase tax on log in Russia which may disturb the flow of imported wood to Japan; it is the time for Japan to assure the supply of wood domestically in addressing the projected increase of wood demand within the country.

Around 67% of land area of Japan is covered by forests. The average annual increment of the total growing stock of Japan's forests in the last 25 years (1981-2006) stays around 70-80 million m<sup>3</sup>; it is mostly contributed by the growing stock of the planted forests (Forestry Agency, 2009). The total demand of wood in Japan by the end of 2009 was around 65 million m<sup>3</sup> and the total demand of wood in the previous year (2008) before the sudden drop was around 80 million m<sup>3</sup>. If it is assumed that 60% of the cut timber ends as wood domestic supply; it is actually possible to supply as much as 50% of the wood demand in 2008 by the domestic wood (Akahori, 2009).

However in reality, not all of the harvestable wood can be obtained. One is because of the location of those forests, around 41% of the planted forests are located at slope with gradient over 30 degree (Forestry Agency, 2010). Due to that steep gradient, at present,

the forest infrastructure such as forest road network has not well developed yet; as the result, the access to forests is difficult.

In addition, the replanting of forests has faced stagnation over the past few years; consequently, maintaining the same productivity may become the challenge in the long term. It is because the trees, which commonly cultivated in Japanese planted forests (e.g. Japanese cedar, cypress and larch), require relatively long time to become suitable for timber production; it requires at least 40-50 years (Akahori, 2009).

Due to the abovementioned constraints –accessibility and time-, considering the use of alternative material may become one of the options to address the raised issues.

#### *1.1.6 The Need of Alternative Material for Construction in Japan*

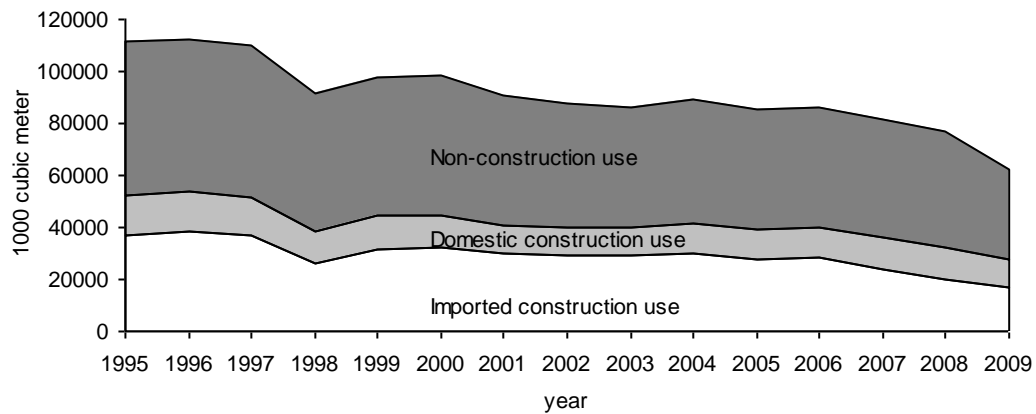
In Japan, wood is mainly used in four major industries; sawnwood industry, pulp and chips industry, plywood industry and other industries which mainly produce composite wood. The products from those industries are varied ranging from paper, packaging, and furniture to construction material.

However, as it can be seen in the following figure, constructional wood constitutes large portion of the total domestic consumption of wood in Japan. The proportion of constructional wood was estimated to account for approximately 45% of the total domestic consumption during this period (1995-2009). Further, approximately 70% of that constructional wood was estimated to be imported or produced by using imported wood material which makes the proportion of imported constructional wood is about 30% of the total wood domestic consumption.

In addition to it, according to Forestry Agency (2011), most of that imported constructional wood is used for structural purposes. The share of the imported wood in each part of traditional wooden houses in Japan is highest in beams (94%) followed by plywood for floor basis (64%), foundation poles (62%) and posts (37%) (Forestry Agency, 2011).



Due to the fact that large proportion of the imported wood in Japan is used for constructional material particularly for structural uses; and also the predicted increase in wood demand is closely related to constructional wood; if there is an alternative material that can replace constructional wood material especially for structural purposes, it will help in addressing the issue of wood in Japan in the coming years.



**Figure 5 Domestic Consumption of Wood for Construction Use in Japan 1995-2009**

(Source: Forestry Agency)

### 1.1.7 Bamboo as an Alternative Material

In term of alternative material that may replace wood construction material, there are quite a lot of possible alternatives, for example: steel, aluminum and concrete; ceramic, natural stones and earth; plastic or wood-plastic composite; or bio-based material such as bamboo, straw, hemp etc.

However, just like mentioned by Calkins (2009), based on the priority and the issue want to be addressed, the suitability of a material to serve as an alternative to the other is also different. In the case of Japan, bamboo seems to be an appropriate alternative to wood due to the following factors.

- Origin of the material

Local supply for bamboo is possible. Bamboo is local vegetation and has been cultivated for its timber and shoots in Japan. However, due to the changes in lifestyle and imported bamboo products, many of bamboo plantations in Japan are being left

and not properly managed for production. It has resulted in the encroachment of bamboo to the nearby forests and farm lands (Kondo, 2007; Uchimura, 2007; Watanabe, 2007).

- Potentiality to promote natural resource management especially in Japan

Looking at the current situation of bamboo plantation in Japan which is facing similar situation to timber production forests, using bamboo as an alternative to wood may motivate people to manage their bamboo plantations. Further, since bamboo is an integral part of forests, using bamboo as an alternative to wood may also indirectly promote forest management in Japan.

- Easily obtainable

Bamboo plantation was traditionally planted close to human settlements as part of the agricultural system due to its role for food production (bamboo shoots). Therefore, unlike trees that are planted in deep forests, bamboos are considerably more accessible.

- Renewability of the material

Bamboo is a rapid renewable resource; bamboo can be harvested in 3~6 years depend on species and used for construction purposes (Adams, 1998). It is far different to trees (e.g., Japanese cedar, cypress and larch) which need at least 40-50 years to become suitable for timber production (Akahori, 2009).

In addition to the abovementioned factors, bamboo has longstanding history as construction material in Japan. One of the concrete examples that can still be seen today is the application of bamboo as element of thatch roof, rafter and floor in Hakogi Sennen Family House in Kobe which was built in Muromachi Period (1336-1573) (Yoshie, 2007). Considering the fact that bamboo has been utilized as construction material in Japan since long time ago; the opportunity of bamboo to be accepted as an alternative to wood construction material in Japan is considerably high.

Further, the recent development on bamboo processing has also heightened the potential of bamboo to be used in wider range of construction purposes. Previously, application of bamboo as building material was quite restricted due to its irregular tubular form. However, that recent development on bamboo processing has resulted in the ability on producing bamboo building material which form is similar to wood construction material (processed bamboo building material). The development of this new type of bamboo building material has enhanced the application of bamboo in more conventional building.

One of the examples of processed bamboo building material is Strand Woven Bamboo (SWB). It is recognized for its strength and comes in the form of lumber and board. The current main application of SWB is for flooring, paneling and decking. However, some countries, like China and United States, have already started to promote the utilization of SWB as structural construction material; it made SWB become one promising alternative to wood construction material in addressing the wood related issue in Japan.

## **1.2 Problem Statement**

Japan currently relies on imported wood for most of its wood domestic consumption. The competition for wood from other countries particularly from China and the increase in log export tax in Russia may affect the flow of wood import to Japan. Japan has considerable amount of wood stock but less accessible. While in the future, the domestic demand of wood in Japan is likely to increase. Constructional wood accounts for over 40% of total wood consumed in Japan. Approximately 70% of that constructional wood comes from imported wood and mostly are designated for structural purposes. Considering the above situation, it will be helpful if there is an alternative material that can replace constructional wood material.

Among many possible alternative materials, bamboo -which is available locally and currently not effectively used in Japan- seems to be an appropriate one, particularly in the form of Strand Woven Bamboo (SWB). However, since in order to be able to substitute wood construction material there are many requirements should be fulfilled; whether

SWB can really serve as an alternative to constructional wood material in Japan is still questionable.

In order to be able to substitute wood constructional material, a material must be able to function as wood constructional material. It requires the material to be able to perform at least the same or better than wood constructional material; address the regulation restrictions in using wood constructional material; be economically competitive; be accepted by the consumers and so on.

Even though, there are many requirements should be fulfilled, this study will only investigate two preliminary and very important premises. These are the physical properties and the availability of material of SWB. The physical properties are investigated to have insight whether SWB can perform as well as wood which is required for safety assurance. While the availability of the material is investigated to address and avoid the problem which is currently faced by wood constructional material, import dependency.

### **1.3 Research Objective**

To examine the potential of Strand Woven Bamboo to serve as an alternative to wood constructional material in Japan from two perspectives, physical properties and availability of bamboo resources.

### **1.4 Scope and Limitation**

In examining the substitution potential between bamboo and wood, this study focuses only on one type of bamboo building material, Strand Woven Bamboo (SWB), while the wood constructional material is only represented by Japanese cedar. The exploration of the SWB substitution potential is done from two perspectives, the physical properties and availability of bamboo resources; while other aspects that are also important in determining the substitution potential between those materials, such as the economics, policy, consumer preferences, etc. are not discussed in this study. In addition, this study completely relies on secondary data with there is no single experiment done to collect the

data. Further, this study uses a simplify model to estimate the substitution potential of SWB based on the availability of bamboo resources and many assumptions incorporated in the calculations.

### **1.5 Significance of the Research**

The outcome of this study is hoped could

- provide information about bamboo building material which may useful as consideration in decision making for various stakeholders,
- motivate people to properly manage forests in general and bamboo forests in particular and
- contribute in reducing environmental impacts from the construction sector in Japan and dealing with the sustainability issue worldwide.

## CHAPTER II: Literature Review

In this chapter, basic information about bamboo as construction material, particularly building material, is provided. Firstly, the current state on the use of bamboo as building material is reviewed (particularly in Japan). Second, various types of bamboo building material are introduced. Lastly, the framework of this study will be mentioned.

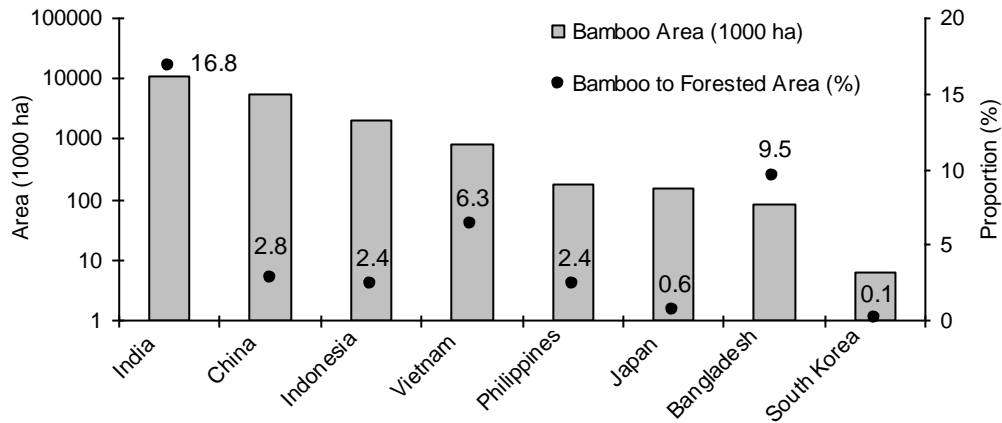
### 2.1 Use of bamboo as construction material

#### *2.1.1 Use of Bamboo as Building Material Worldwide*

Bamboo is a plant that has been used as building material in many parts of the world. Bamboo is widely distributed in tropical, subtropical and some temperate regions. In these regions, bamboo is used for various applications, including its use as building material. Using bamboo as building material has already been practiced for centuries since it can be found easily and abundantly around human settlements and because bamboo can be handled easily by one person without any sophisticated tools (Jayanetti & Follett, 2008). Countries like Bangladesh, China, Columbia, Ecuador, India and Indonesia are some examples where bamboo is still widely used or regaining the popularity as building material (Kahler, 2005; Rashid, 2007; INBAR; Kompas).

The extent to which bamboo is utilized as building material and other applications vary among locations and regions. This variation may be related to the unequal distribution of bamboo and proportion of bamboo to total forested area as shown in the following figure. In general, the use of bamboo is more remarkable in countries where the percentage of bamboo to total forested area is high. For example, although bamboo resource is abundant in Indonesia, the use of bamboo as building material is restricted to rural houses, some traditional houses and special purpose buildings. On the other hand, in Bangladesh, even though the bamboo forest extent is much less compared to Indonesia, over 70% of the houses there are constructed by using bamboo as the main building material (INBAR; Rashid, 2007). This may be partly due to the fact that the proportion of bamboo to total forested area in Bangladesh is higher than that of Indonesia. As a result, bamboo is more

accessible in Bangladesh than in Indonesia, and hence the importance of bamboo as building material is higher in Bangladesh



**Figure 6 Extent of Bamboo Forest in Some Asian Countries in 2005**

(Source: Lobovikov et al., 2007)

In addition to the unequal distribution of bamboo resources, the species of bamboo found in each region may also contribute to the unequal usage of bamboo as building material. Each bamboo species has its own specific characteristics that determine the suitability of a species to be used for certain applications. Currently there are approximately 1200 species of bamboo worldwide (Lobovikov et al., 2007), but only 65 species are known to be used for construction purposes (Jayanetti & Follett, 1998). Table 1 provides a list of representative bamboo species that have been used as building material.

**Table 1 Major Bamboo Species Used as Building Material**

Country	Species	Reference
Bangladesh	<i>Bambusa arundinacea</i> <i>Bambusa balcooa</i> <i>Bambusa burmanica</i> <i>Bambusa longispiculata</i> <i>Bambusa polymorpha</i> <i>Bambusa tulda</i> <i>Bambusa vulgaris</i> <i>Cephalostachyum pargracile</i> <i>Dendrocalamus giganteus</i> <i>Dendrocalamus hamiltonii</i> <i>Dendrocalamus longispathus</i> <i>Melocanna baccifera</i> <i>Neohouzeaua dullooa</i> <i>Oxytenanthera nigrociliata</i>	Nuruzzaman in INBAR Country Report
China	<i>Indosasa sinica</i> <i>Phyllostachys pubescens</i>	Yang et al, 1998; Yang & Xue, 1998; Yang & Hui, 2010
India	<i>Bambusa balcooa</i> <i>Bambusa bambos</i> <i>Bambusa tulda</i> <i>Dendrocalamus giganteus</i> <i>Dendrocalamus hamiltonii</i> <i>Dendrocalamus asper</i>	Rawat & Khanduri in INBAR Country Report; NMBA; Vengala et al., 2008
Indonesia	<i>Bambusa bamboo</i> <i>Bambusa blumeana</i> <i>Bambusa vulgaris</i> <i>Dendrocalamus asper</i> <i>Gigantochloa apus</i> <i>Gigantochloa atter</i> <i>Gigantochloa pseudoarundinacea</i>	Kartodihardjo in INBAR Country Report
Japan	<i>Phyllostachys bambusoides</i> <i>Phyllostachys pubescens</i> <i>Phyllostachys nigra var. henonis</i>	Locher, 2010; Uchimura, 2010
Philippines	<i>Bambusa blumeana</i> <i>Gigantochloa levis</i>	Nakamura et al., 2007; Rivera in INBAR Country Report
Latin America	<i>Guadua angustifolia</i> <i>Guadua de castila</i> <i>Guadua cebolla</i>	Adams, 1998; Kahler, 2005
Africa	<i>Bambusa arundinaceae</i> <i>Bambusa vulgaris</i>	Oteng, 2002 in Paudel, 2008

INBAR: International Network for Bamboo and Rattan  
 NMBA: National Mission on Bamboo Applications (India)



### *2.1.2 Past and Present State of Bamboo Building Materials in Japan*

Just like in other countries, bamboo has also been used as building material in Japan for centuries. But the scale of bamboo utilization as building material is quite limited compared to other bamboo-growing countries. Even though bamboo is the only non-tree plant which used as building material in Japan (Locher, 2010); due to its beauty, bamboo tends to be used as decoration in buildings rather than structural material (Murata & Black; 2000). The following provides brief information about the utilization of bamboo as building material through time.

In Japan there are approximately 600 species of bamboo, but they are limited to southern part of Japan, excluding Hokkaido (“About Bamboos”). Within bamboo’s distribution range, they were used in folk house (minka) construction. For example, the Hakogi Sennen Family House in Kobe which was built in the Muromachi Period (1336-1573) uses bamboo as element of thatch roof, rafter and floor (Yoshie, 2007). Another example is the typical style of townhouses in Kyoto during the later stage of the Warring States Period (early 16th Century); it was pictured as one-storied houses with thatched roof which used bamboo as one of the elements, bamboo breast wall and bamboo lattice windows along with bamboo blinds (Yohie, 2007).

Besides in folk houses, bamboo is also used in tea rooms or tea houses as rafters, wall’s groundwork, window’s lattice, alcove post (tokobashira), etc., and these kinds of bamboo application is still practiced in present day (Iijima & Takemae, 2002; Yoshie, 2007). Bamboo is also used in residential buildings in the modern era for wall’s groundwork on which the mud plaster applied; this type of bamboo usage is known as ‘takekomai’. This application of bamboo for mud wall was practiced even after the World War II (Watanabe, 2007); but at the present, the practice is becoming few due to the change in construction style.

Based on the above description, it is clear that the traditional way of using bamboo as building material in Japan is quite limited at present time, and is restricted to the applications in the tea ceremony rooms or houses and Japanese style rooms. The list of

those applications and the bamboo species commonly used for each application can be seen in Table 2. Aside from what is found in the list, the utilization of bamboo as building material is mainly for ornamental purposes (Murata & Black 2000), and specially design or commercial buildings.

**Table 2 List of Bamboo Species Used as Building Material in Japan and Its Applications**

<b>Form</b>	<b>Applications</b>	<b>Bamboo species (local name)</b>
Round bamboo culm	Alcove post (tokobashira)	<i>Phyllostachys bambusoides</i> (Madake)
		<i>Phyllostachys pubescens</i> (Mosochiku)
		<i>Phyllostachys heterocycla</i> (Kikkochiku)
		<i>Phyllostachys aurea</i> (Hoteichiku)
		<i>Tetragonocalamus angulatus</i> (Shihochiku)
	Rafter, ceiling pole	<i>Phyllostachys nigra var. henonis</i> (Hachiku)
		<i>Phyllostachys nigra</i> (Kurochiku)
	Window lattice	<i>Phyllostachys nigra</i> (Kurochiku)
Split bamboo culm	Takekomai	<i>Phyllostachys bambusoides</i> (Madake)
		<i>Phyllostachys nigra var. henonis</i> (Hachiku)

(Source: Locher, 2010; Uchimura, 2010)

## 2.2 Type of Bamboo Building Material

Bamboo building material is mainly derived from the culm of the bamboo plant. At present, bamboo building material can be broadly divided into unprocessed and processed bamboo building material based on the complexity of manufacturing processes.

### 2.2.1. Unprocessed Bamboo Building Material and Its Applications

Unprocessed bamboo building material refers to bamboo materials that only undergo simple processes that cause little changes on the natural form and quality of the bamboo culm. In most cases, they have been practiced for a very long time and therefore the processes themselves are done according to traditional knowledge.

In the past, unprocessed bamboo building materials were widely used in houses where bamboo is available abundantly. They were used for many purposes ranging from providing structure to the decoration of the houses. At present, the uses of unprocessed bamboo building material are restricted to traditional houses, specially designed houses or special purposes buildings.

Unprocessed bamboo material generally comes in two basic forms; round bamboo culms and split bamboo culms.

### Round Bamboo

Round bamboo culms can be considered as the most primitive form of bamboo building material. They have been used as structural material such as posts, beams, trusses, rafters, purlins, etc. in various traditional houses in the regions where bamboo is found. For example, in the coastal area in Bangladesh where flooding is the major threat; round bamboo culms are used as stilt to raise the floor of the stilt houses (Sattar, 1995). In India, they are used to provide structural framework such as posts and beams, rafter and purlins for roofing, floor joints etc.; this bamboo house construction is mainly used in earthquake prone areas (Punhani & Pruthi, 1991 in Rawat & Khanduri). In Indonesia, those applications are similar to those in India, but mostly practiced in traditional and rural houses. While in Latin American countries like Bolivia, Columbia, Costa Rica & Ecuador the application of round bamboo culms as structural material is widely practiced ranging from rural houses to complex modern buildings (Kahler, 2005). Apart from the structural functions, round bamboo culms are also used as supplementary building material for decoration purposes in the buildings especially in modern buildings as in Japan.

### Split Bamboo

Split bamboo culms are used in the form of curve split bamboo culms, flattened split bamboo culms or woven bamboo mats. Each form of the split bamboo culms are used differently. The split bamboo culms that are left curved in their natural form are used for roofing and gutter (Adams, 1998). They are also used for constructing bamboo reinforced mud wall in some countries like India, Indonesia, Japan and Latin America

(Environmental Bamboo Foundation; Janssen, 2000; Yoshie, 2007; Natigor, 2010, May 12). The flattened split bamboo culms are used for roofing, walls, and floorings. While the woven bamboo mats are used extensively for walls or room partitions, doors and ceiling in rural houses in South and Southeast Asia. For example, according to Rawat & Kanduri, woven bamboo mats made of the outer layer of bamboo culms and coated by coal tar are used for the exterior wall.

### *2.2.2. Limitation of Unprocessed Bamboo Building Material*

Unprocessed bamboo building material has been used for long time in many countries and for many applications. It is cheap and considerably strong, but some factors limit the potential of unprocessed bamboo material to become universal building material. These limitations include:

#### *- Durability*

Bamboo is a biodegradable material; therefore it can be easily attacked by insects and fungi and decay if not well treated. Untreated bamboo has an average service life span of 1-3 years where it is directly exposed to soil and outdoor environment; the service life can become as long as 10-15 years if it is used under favourable conditions (Jayanetti & Follett, 1998). There are many ways to address the issues on durability. Firstly, the bamboo culms should be harvested when the sugar content is low and mature bamboo should be given priority (Jayanetti & Follett, 1998; Oike, 2007). Second, before utilization, the bamboo culms should be well treated and preserved. Lastly, to prolong the service life of the bamboo building material, proper maintenance during the utilization is required (Janssen, 2000).

#### *- Irregular shape of bamboo culms*

The irregular tubular shape of bamboo to some extent acts as the strong point of bamboo since it allows sophisticated design. But at the same time, it makes building with bamboo more difficult compared to timber. For example, jointing which is fundamental to the structural integrity is comparably difficult due to the tubular shape of bamboo (Jayanetti & Follett, 2008). According to Adams (1998), mistakes related

to jointing of bamboo culms is one of the most common problems among new architects in Columbia when dealing with bamboo construction.

- *Quality control*

There are currently 65 species practically used as construction material (Jayanetti & Follett, 1998) and each species has different physical characteristics. Additionally, within one species, the properties also vary due to several other factors such as age and the location where the bamboo grows (Arce-Villalobos, 1993). Because of this, controlling quality of bamboo for building material is considerably difficult.

In response to the abovementioned limitations, another type of bamboo building material has been developed; processed bamboo building material. The growing concern about sustainability issues in the recent years has further hastened the research and development of processed bamboo building material and resulted in more varied types and wider applications of processed bamboo building material.

*2.2.3. Processed Bamboo Building Material Manufacturing and Its Applications*

Processed bamboo building material refers to bamboo building material that has undergone various manufacturing processes. The most notable difference between unprocessed and processed bamboo building material is its shape. The manufacturing processes convert the tubular shape of bamboo culms into standardized size panel board or lumber. The range of bamboo species used in processed bamboo building material is also different to the unprocessed bamboo building material; according to Paudel (2008), processed bamboo building material can make use of all kinds of bamboo. But at present, the most widely used species for producing processed bamboo building material is Guadua bamboo (esp. *Guadua angustifolia*) in Latin America and Moso bamboo (*Phyllostachys pubescens*) in China which is the largest producer (De Vos, 2010).

In China, bamboo-based building material is commonly made of approximately 5-year old. Moso bamboo is used because it has been historically used as timber for building houses and bridges (Fu, 2001). Moso bamboo is also given priority to be used as furniture

and building material due to its culm characteristics; high, large diameter and thick culm wall (Fu, 1998)<sup>2</sup>. While 5-year old bamboo is used because this is the age where the bamboo completes its growth and considered to reach the optimum quality (Liese, 1995 in Amada & Untao, 2001)<sup>3</sup>. Below are some examples of processed bamboo building material.

### Bamboo Mat Board

Bamboo Mat Board (BMB) is considered as the earliest type of processed bamboo building material. It was initially developed in China during World War II to replace plywood used in the interior of an aircraft (Ganaphaty et al., 1996). The technology to produce BMB was also developed in India around the same time period and became available about a decade later (Ganaphaty et al., 1996). BMB is produced from several woven bamboo mats that are glued and pressed together. Middle upper section of bamboo culm is used to make the woven bamboo mats due to the flexibility and elasticity (Zhu & Jin, 2010). The efficiency of topped bamboo culms input in producing BMB is approximately 60% (Zaal, 2008 in Van der Lugt, 2009). The major manufacturing countries of BMB are China, India, Philippines and Vietnam; BMB can be further processed into Bamboo Mat Corrugated Sheet, which is used for roofing in those countries (Ganaphaty et al., 1996; NMBA).

### Bamboo Zephyr Board

Bamboo Zephyr Board (BZB) is made of the bamboo culms which are split into strips and crushed; the resulted crushed bamboo strips are called zephyr; the zephyrs are then coated with glue and several layer of them are pressed into a board (Ganaphaty et al., 1996; Suidiyono et al., 2000; Shibusawa & Kin, 1996; Shibusawa, 2007). The difference with other types of processed bamboo building material is the size of bamboo strips used to produce BZB; the strips are wider compared to others used for Glue Laminated

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<sup>2</sup> Another reason why Moso bamboo is generally used as bamboo building material in China is because it is highly available, based on the data on bamboo resource in China 1950-1980, about 70% of bamboo forests in the country was covered by Moso bamboo (Hsiung, 1987).

<sup>3</sup> Another reason why 5-year old Moso bamboo is used is because 5-year old bamboo has lower shoots productivity compared to the younger one; as the result, keeping it in the plantation is not so beneficial for the plantation productivity (Oshima, 1982).

Bamboo (GLB) or Strand Woven Bamboo (SWB). Bamboo culms that are of approximately the same size are used to produce BZB are split into 2-4 strips, while at least six strips to produce GLB or SWB (Sudiyono et al, 2000; Sibusawa, 2007). This BZB has been produced in small quantity in Indonesia to be used as plywood substitution and has also been developed in Japan as construction material (Ganapathy et al., 1996; Sudiyono et al., 2000; Sibusawa, 2007).

#### Bamboo Particle Board

Bamboo Particle Board (BPB) is made out of the bamboo chips which are made from residue that comes from bamboo culms felling and strips preparation for making the other types of processed bamboo building material that are pressed together. Some critical factors in making bamboo particle board include the size of the bamboo chips and the proportion of dry to fresh bamboo chips. The length of the bamboo chips should not exceed 3cm and the proportion of dry to fresh bamboo chips should be around 40:60 in order to maintain the moisture content of the board to be between 6-13% (Ganapathy et al., 1996). The technology to produce BPB has been developed in many countries like Canada (in collaboration with Costa Rica), China, India, Japan, Malaysia and Vietnam. But in most of those countries, this particle board is only produced in limited quantity. This particle board is commonly used as an alternative to plywood or medium density fiberboard to be used as structural panel in construction (Ganapathy et al., 1996).

#### Glue Laminated Bamboo

Glue Laminated Bamboo (GLB) can be considered as the most widely marketed processed bamboo building material. It is produced from split bamboo culms which are planned into standardized size and laminated together with Lateral Force Microscopy (LFM) resin to produce one layer of GLB (Rittironk & Elnieiri, 2008). Several layers are usually combined together to make panel or lumber; because of this, GLB is also known as ply-bamboo. The size of strips to be laminated into GLB is approximately 2500mmx20mmx5mm (Van der Lugt et al., 2009). Considering this requirement, certain quality of bamboo culms especially big and thick culm is needed in order to produce GLB. For this reason, the bottom-middle section of bamboo culms is generally used since

these sections are the thickest. As the result, if the raw material input to this industry is in the form of topped bamboo culms; there is lots of unused bamboo material in the production process. According to Zaal (2008), the efficiency of raw material to make this type of bamboo building material is approximately 40% (in Van der Lugt et al., 2009).

Glue Laminated Bamboo (GLB) comes in several forms. They include panels, joists and lumber. GLB is commonly used in the form of panels for flooring, walls and ceilings world wide. It is also marketed and used as alternative to structural lumber such as for joists, beams, girders, etc. in the United States and some Latin American countries such as Columbia (De Flander & Rovers, 2008; Lamboo, Inc.). The use of GLB for structural lumber is still challenging, but some studies, like the development of new type of GLB (e.g., Xiao et al. 2008) and the possibility of using laminated bamboo as an alternative to wood lumber in residential buildings (e.g., Rittironk & Elnieiri 2008), reveal the suitability of it to be used as structural building material.

#### Strand Woven Bamboo

Strand Woven Bamboo (SWB) is a new type of processed bamboo building material. It can be used both indoors and outdoors. It is also said to have better quality compared to other processed bamboo building material. SWB is produced from bamboo strips that are coated by glue and compressed into the form of lumber. Slightly different to the Glue Laminated Bamboo which need thick culms as raw material input, SWB is produced from bamboo strips which size approximately 2000mmx20mmx3mm (Van der Lugt et al., 2009); therefore the quality of bamboo culms are less restricted in term of thickness. As the result, the culms can be used at higher efficiency. According to Zaal (2008), the efficiency of raw material in producing SWB is approximately 70% since the upper middle part of the bamboo culms can also be used in strip preparation (in Van der Lugt et al., 2009).



**Table 3 Processed Bamboo Building Material Summary**

	<b>Processed Bamboo Building Material</b>				
	<u>BMB</u>	<u>BZB</u>	<u>BPB</u>	<u>GLB</u>	<u>SWB</u>
Form of bamboo culm derivatives input	Laths	Wide strips	Chips or flakes	Strips	Thin strips
Part of bamboo culm input	Upper-Middle	Middle-Bottom	Mix whole	Middle-Bottom	Upper-Middle-Bottom
Raw material efficiency use	60%	n.a	n.a.	40%	70%
Form	Sheet, board	Sheet, board	Board	Board, lumber	Board, lumber
Utilization	Flooring, walls, doors, roofing, etc.	Flooring, walls, concrete panel, etc.	Structural panel, sub-flooring, etc.	Flooring, paneling, structural lumber substitution, etc.	Flooring, paneling, decking, structural lumber substitution, etc.

Table 3 summarizes the characteristics and properties of processed bamboo building material reviewed in this section<sup>4</sup>. From Table 3, it is clear that each type of processed bamboo building material needs different type of input, and both the unprocessed and processed bamboo building material has its own advantages and disadvantages (Paudel 2008), which may influence the suitability of using bamboo building material.

<sup>4</sup> Besides the mentioned processed bamboo building material, several other types are also available in the market (e.g., example the bamboo veneer which is mainly used for finishing, bamboo tiles, etc.).

**Table 4 Advantages & Disadvantages of Unprocessed & Processed Bamboo Building Material**

	<u>Unprocessed</u>	<u>Processed</u>
<u>Advantages</u>	<ul style="list-style-type: none"> <li>- Does not require big investment</li> <li>- Offers flexible design</li> <li>- Low technical requirements and can be done in any locations where bamboo available</li> </ul>	<ul style="list-style-type: none"> <li>- Can make use of all kinds of bamboos</li> <li>- Less wasted bamboo material (can use much of bamboo culms)</li> <li>- Can be standardized for its quality</li> <li>- Large quantity production and supply is possible</li> <li>- Can be modular and prefabricated</li> </ul>
<u>Disadvantages</u>	<ul style="list-style-type: none"> <li>- Limited species of bamboo can be used</li> <li>- Quality control problem</li> <li>- Durability depends on the quality of bamboo and preservation</li> <li>- Production and supply of houses in large quantity in a short period of time may be a problem</li> </ul>	<ul style="list-style-type: none"> <li>- Require considerable investment</li> <li>- Constant supply of raw material can be a problem</li> </ul>

(Source: Paudel, 2008)

## **2.3. Framework of the Study**

### *2.3.1 Advantages of Strand Woven Bamboo*

From the abovementioned unprocessed and processed bamboo building materials, this study chooses to focus on Strand Woven Bamboo (SWB) as the bamboo building material to be investigated due to the following advantages.

First, SWB is belonged to processed bamboo building material, therefore the issues such as prone to insects, fungi or pests attack; irregular shape and quality control of unprocessed bamboo will not become the limiting factors in using SWB in buildings.

Second, among processed bamboo building material, SWB is said to have a better quality compared to others and can be used both indoor and outdoor. Moreover, since SWB has the form similar to solid lumber; SWB can be cut to derive smaller building material in

various dimensions or shapes. Based on this characteristic of SWB, SWB possibly replace more varieties of wood material.

Third, SWB production has the highest raw material efficiency rate among other processed bamboo building materials (given that the production of each processed bamboo building material is considered as separate industries). It means with the presently available bamboo resources in Japan, there will be more wood substitution can be provided by producing and using SWB rather than other types of processed bamboo building material. Or, less environment disruption is taken place in producing and using SWB compared to other processed bamboo building materials since less extraction of resources and less wastage generated in producing and using SWB.

Fourth, the examples from other countries, like China<sup>5</sup> and the United States<sup>6</sup> where SWB has been experimentally used or already marketed as alternative to structural lumber, show that SWB might possibly serve as alternative to wood structural construction material in Japan. Therefore, if using SWB is possible in Japan, it will consequently decrease the demand of imported wood constructional material which is designated for structural purposes.

In shorts, by using SWB, it may contribute in addressing the issue related to wood (esp. imported wood) in Japan which largely used in construction.

### *2.3.2. Advantages of Using Bamboo*

While in general, using bamboo as wood substitution is beneficial due to the following.

- Bamboo is rapid renewable resource; it can be harvested on a 3~6 year cycle and used for construction purposes (Adams, 1998). Considering the fast cycle of bamboo, the same given area can produce more accumulated amount of material if it is used to plant bamboo rather than tree in the long term during the same period of time under appropriate management.

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<sup>5</sup> Bamboo house in the Moso Bamboo Modern Technological Park in Anji County, Zhejiang Province

<sup>6</sup> One example of company that markets SWB as alternative to structural lumber in USA is Cali Bamboo

- Bamboo is widely distributed in the developing regions where there is high demand for building material and wood fuel. Therefore, using bamboo instead of wood for those needs may also help to slow down deforestation. As the result, it is likely possible to maintain the health of forests ecosystem and enhance the other roles of forests.
- Using bamboo as building material or other products can provide direct employment opportunities to the local communities through cultivation, management, pre-processing and processing stages (Paudel, 2007). Particularly in developing countries, this aspect may not only empower the community; but also may reduce the tendency of generating income by using unsustainably extracted natural resources.

Utilization of bamboo in Japan or other countries where bamboo is available locally may contribute to minimizing the undesirable impacts on the environment due to irresponsible wood extraction. Particularly in Japan, utilizing bamboo may motivate people to again manage their currently abandoned bamboo plantations; thereby in the long term, it may promote better management of natural resources. Apart from it, local supply of bamboo may also help reduce environmental impacts due to transportation and reduce cost at the same time.

### *2.3.3. Research Questions*

As explained in the previous two sections, using SWB or bamboo instead of wood in general may potentially come out with positive results. However, whether using locally produced SWB instead of wood construction material in Japan is possible is still unclear.

There are many factors should be considered in determining the possibility of this material substitution. Some of those factors include:

- Physical properties of the materials, whether SWB can perform at least the same or better than the wood constructional material to be replaced.

- Production factors; whether production of SWB is possible in Japan which is much affected by the availability of sustainable supply of the raw material, human resources, capital, technology, etc.
- Regulation restrictions; whether SWB can also address the constraints which come from the regulatory aspects, such as building standard law and regulation in Japan, in using wood as construction material.
- Economic factors; whether the price of SWB is competitive compared to wood construction material to be replaced or other potential alternative and whether SWB can meet the consumer preferences.

It can be seen that there are many factors affect the potential of SWB to be able to serve as an alternative to wood construction material. In order to do so, SWB should be able to fulfill the requirement related to those factors. However, this study will only examine the very fundamental and important premises that are required to determine whether Strand Woven Bamboo (SWB) can be an alternative to wooden constructional material; the physical properties of SWB (comparison with wood material) and the availability of the bamboo material. The physical properties are investigated to have insight whether SWB can perform as well as wood which is required for safety assurance. While the availability of the bamboo material is investigated to address and avoid the problem which is currently faced by wood constructional material, import dependency.

Therefore, to meet the objective of this research which is *“to examine the potential of Strand Woven Bamboo (SWB) to serve as an alternative to wood constructional material in Japan from two perspectives, physical properties and availability of bamboo resources”*.

The next two chapters will address the following research questions:

1. *“Can SWB substitute wooden constructional material from the perspective of the physical properties in Japan?”*
2. *“What is the substitution potential of SWB from the perspective of the availability of bamboo resources in Japan?”*

## **CHAPTER III: Strand Woven Bamboo Substitution Potential - Physical Properties**

Strand Woven Bamboo (SWB) is one type of processed bamboo building material. It comes commonly in the form of lumber or board. In Japan, SWB has been limitedly used in the form of panel for flooring and wall paneling (INBAR Trade Database of Bamboo and Rattan Products, 2008). While in other countries like the United States and China, SWB has already been marketed in the form of lumber as alternative to wooden lumber for structural purposes. Considering the low wood self-sufficiency in Japan which is less than 30% for over the past three decades (Forestry Agency) and the problem of bamboo encroachment to the nearby forests and farmlands (Kondo, 2007; Uchimura, 2007; Watanabe, 2007); introducing the latter utilization of SWB may contribute to the mentioned issues by motivating people to manage their bamboo plantations and at the same time provide alternative to wood. But the problem is whether SWB can be used as alternative to structural lumber in Japan is still questionable. For this reason, this chapter tries to explore the potential of SWB to serve as substitution to structural lumber in Japan particularly from the perspective of the physical properties.

### **3.1 Substitution Potential ~ Physical requirements<sup>7</sup>**

Wooden building material, just like any other building material regardless the type of material they are made of, can be broadly classified into four categories based on their utility. Those categories are groundwork building material, structural building material, fittings and fixtures, and finishing material.

All of those building materials share similar basic requirements regardless which category they are belonged to. These requirements include strength, durability and dimensions' stability (Akaori, 2006; Iwamoto & Ozawa, 2009). Beside the mentioned requirements, aesthetic is also important especially for the finishing material (Iwamoto & Ozawa, 2009, p.76). However, although the basic requirements are similar, the degree and type of strength, durability and dimensional stability needed for each category is different.

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<sup>7</sup> See Appendix 2 for details

In general, groundwork and structural building material require higher degree of strength, durability, and dimensional stability compared to fittings and fixtures and finishing material. One of the basic reasons is because the function of groundwork and structural material are to support and bear the loads. Other reason is because groundwork and structural material in most cases are located inside the building structure which makes it difficult to visualize and to replace.

According to the abovementioned explanation, it is obvious that the basic characteristics of wooden structural building material must be strong, durable and dimensionally stable. And these three characteristics can be said to be the minimum criteria of structural building material that may give idea about the suitability of that building material to be utilized in a particular condition.

### *3.1.1 Criteria and Indicators of the Suitability to Serve as Structural Building Material*

#### Strength of the Building Material

How much strength required and what kind of strength needed for each of the components might be different depending on various factors such as, the type of construction, the structural position of the component within the building structure, the function of the building, the location of the building and many others.

One indicator to identify the strength of building material is the *specific gravity* of the building material. It is the ratio of the density of the material to the density of water. The specific gravity of wood in general is positively related to its strength (American Wood Council, 1993).

In term of the type of strength, in general the following types of strength are used as reference to indicate the strength in relation to deformation and other physical characteristics of building materials. Those types of strength basically include *tensile strength*, *compression strength*, *bending strength*, and *shear strength*. Other indicators that are also useful to give idea about the strength of certain building material may include *modulus of elasticity (MOE)* and *modulus of rupture (MOR)* (American Wood

Council, 1993). For all of the type of the strength and strength parameter, the degree of strength of the building material mainly depends on the nature of the material itself which later may be altered through some processes when it is used to make different building material components.

### Durability of the Building Material

Another criterion used in assessing the suitability of a certain building material is to serve as structural building material is durability. Since, the durability of a building material depends on many factors; the internal factors such as the material itself and the external factors such as the environment where the building located, building design, maintenance, etc.; it is quite difficult to determine whether a building material is durable or not. For this reason, looking at the definition of ‘durability’ might give better idea on how to indicate a building material as durable.

“Two definitions of durability and definition of a related concept, serviceability, which appear in the standards prepared by ASTM Committee E-6 on Performance on Building Construction are:

- Durability: the safe performance of a structure or a portion of a structure for the designed life expectancy. (From ASTM Recommended Practiced for Increasing Durability of Building Construction against Water-Induced Damage (E241-77)).
- Durability: the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time. (From ASTM Recommended Practiced E632).
- Serviceability: the capability of a building product, component, assembly or construction to perform the function(s) for which it is designed and constructed. (From ASTM Recommended Practiced E632).”

(Frohnsdorff & Masters, 1980)

From the above definitions, the durability of a material is indicated by a time span during which the material able to function well and perform safely. In terms of structural



building material, the main function is to provide structure to the building and bear loads. Therefore, if the structural building material can provide the structure to the building and bear loads without harming the existence of the building; that structural building material can be considered as durable.

By considering the function, one approach to determine building material durability is by using the *building material's life expectancy* as the indicator. If the structural building material is assumed to be fixed without any replacement during the life span of the building, then the life expectancy of the structural building material must be longer than the life expectancy of the building in order to perform well and safely.

#### Dimension Stability of the Building Material

Dimension stability of the building material represents the behavior of the material toward the changes in the environment like humidity and temperature. This criterion is important to be taken into consideration on determining the suitability of a certain material to serve as structural building material since the dimensional change of a certain component of structural building material may affect the whole structure functionality. In addition, the strength of wooden material is closely affected by the temperature and relative humidity. “Wood increases in strength when cooled below normal temperature and decreases in strength when heated” (American Wood Council, 1993). Increase in relative humidity tends to cause increase in wood moisture content and result in the decrease of wood strength, while the decrease in wood moisture content result in increase of wood strength (American Wood Council, 1993).

In order to know how stable a certain material is, especially wood; the *shrinkage rate for every one percent change in moisture content* is commonly used as an indicator. The size of the material changes along with the change in moisture content; when the moisture content decrease the material tends to shrink and decrease in size and the same way oppositely. This indicator gives the idea on the ability of a certain material in maintaining its size in response to the change in moisture content. The lower the shrinkage rate for every one percent change in moisture content indicate the more stable the material.

## **3.2 Methodology**

### *Method*

In order to know the potential of SWB to serve as substitution to structural lumber in Japan, basically the information that indicates its physical properties should be known. Then by using that information, the physical properties of SWB is compared to the requirement standard for structural lumber in Japan in order to understand the SWB substitution potential.

Since the requirement standard is varied depended on the species of wood, the type and function of the building, the location of the building etc.; this study adopts the physical properties of the most commonly used domestic wood for building material in Japan as the benchmark. In shorts, this study uses a comparative analysis method in order to examine the potential of SWB to substitute structural lumber in Japan. Therefore, the physical properties of SWB to the physical properties of the most commonly used domestic wood for building material in Japan are compared.

### *Data*

The basic requirements for structural building material are strong, durable and dimensionally stable (Akahori, 2006; Iwamoto & Ozawa, 2009). And the indicators for each of the requirement are specific gravity, tensile strength, compression strength, bending strength and shear strength for the strength; building material life expectancy for the durability; and shrinkage rate for the dimensional stability. Since the durability of the building material depends largely on external factors such as the type of preservation, the way of utilization and maintenance of the product etc. (Frohnsdorff & Masters, 1980; Garden, 1980); the durability aspect is not discussed here. Instead, this chapter only discusses the strength and dimensional stability as the criteria for comparison. Based on the above explanation, the data needed in this study includes the specific gravity, tensile strength, compression strength, bending strength, shear strength and shrinkage rate for both the SWB and the most commonly used domestic wood for building material in Japan.

Apart from the above data, the information about the tree species commonly used for building material in Japan is needed to identify the type of wood used as benchmark. The information about the raw material input of SWB is also required since the quality of a product is influenced by its raw material.

The data and information used in this chapter are collected from academic journals and books related to the physical properties of wood and bamboo, Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), etc. Due to the limited information on the SWB, the data related to the physical properties of SWB has to rely on the data provided by the manufacturer or wholesaler who did tests on their product for marketing purposes.

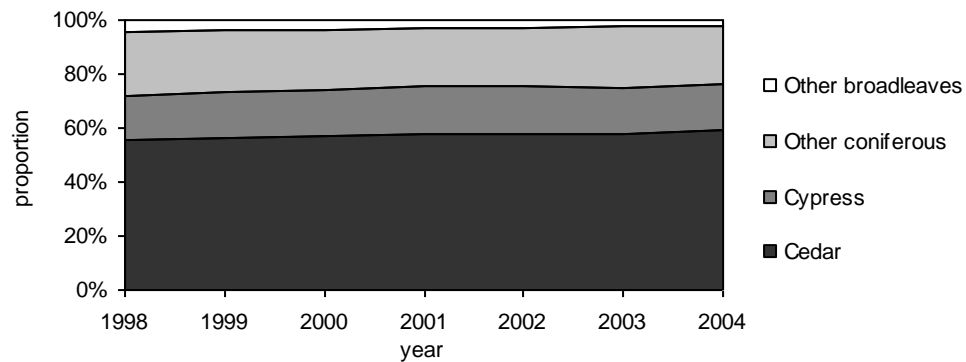
A brief outline about this chapter, this chapter firstly gives an overview about the domestic wood used for building material in Japan; followed by the information related to SWB raw material input. Next, this chapter compares the physical properties of raw material of SWB and the commonly used domestic wood for building material. In the last part, this chapter compares the physical properties of SWB and the commonly used domestic wood for building material in Japan to understand the substitution potential of SWB in term of the physical properties. Beforehand, the last part of this chapter first discusses some possible explanations behind the differences on the physical properties between SWB and its raw material that might be useful in improving the physical properties of SWB in the future.

### **3.3 Discussion**

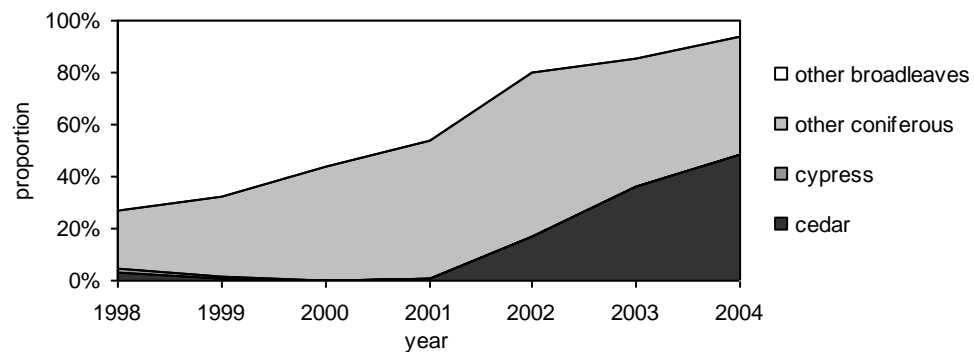
#### *3.3.1 The Most Commonly Used Domestic Wood for Building Material in Japan*

The wood used for building material in Japan is mainly come from two wood-based industries. They are sawmill industry and plywood industry. The following figures show the proportion of domestic raw material input to each industry based on tree types during the period 1998-2004 in Japan. As it can be seen, over 55% of the domestic raw material used in sawmill industry was merely comprised of Japanese cedar during that period (Figure 7). While the plywood industry which previously relied mainly on broadleaves domestic wood has started to shift to coniferous domestic wood (Figure 8). On the

previous stage, the plywood industry shifted to wide range of coniferous domestic wood for the raw material input; but started from 2001, Japanese cedar has become one of the main type of raw material for this industry and Japanese cypress remains insignificant (Akahori, 2006; Ministry of Agriculture, Forestry and Fisheries (Figure 8)). Considering this fact, “Japanese cedar” (*Cryptomeria japonica*) is chosen as the representative of the most commonly used domestic wood for building material in Japan and used as the comparison to the Strand Woven Bamboo and its raw material.



**Figure 7 Proportion of Raw Material Used in Sawmill Industry based on Tree Types in Japan**  
(Source: Ministry of Agriculture, Forestry and Fisheries)



**Figure 8 Proportion of Raw Material Used in Plywood Industry based on Tree Types in Japan**  
(Source: Ministry of Agriculture, Forestry and Fisheries)

### 3.3.2 Raw Material Input of Strand Woven Bamboo

At the present, China is the major exporter of bamboo products including the Strand Woven Bamboo (SWB). During 2001 to 2008, China bamboo products export in terms of quantity accounts for at least 50% of the total export of bamboo products worldwide (INBAR Trade Database of Bamboo and Rattan Products). For this reason, this study uses the SWB made in China as the reference product.

In China, bamboo-based building material including SWB is commonly made of “Moso bamboo” (*Phyllostachys pubescens*). Moso bamboo is used as raw material for this product and for other bamboo-based building material in general because it has been historically used as timber for building houses and bridges (Fu, 2001). Moso bamboo is also given priority to be used as furniture and building material due to its culm characteristics; high, large diameter and thick culm wall (Fu, 1998). Moreover, based on the data on bamboo resource in China 1950-1980, about 70% of bamboo forests in the country was covered by Moso bamboo which indicates the high availability of Moso bamboo resources in China to be further developed (Hsiung, 1987).

Specifically, the raw material input for SWB production is the bottom-middle-upper part of approximately 5-year old Moso bamboo culm which split into thin bamboo strips (Van der Lugt et al., 2009; Zhu & Jin, 2010). The bottom-middle-upper part is used mainly because the wall thickness is not considered as the restriction for SWB raw material input. While 5-year old bamboo is used because this is the age where the bamboo completes its growth and considered to reach the optimum quality (Liese, 1995 in Amada & Untao, 2001). Another reason is because 5-year old bamboo has lower shoots productivity compared to the younger one; as the result, keeping it in the plantation is not so beneficial for the plantation productivity (Oshima, 1982).

After looking at the information related to the most commonly used domestic wood for building material and the raw material of SWB which are the Japanese cedar and approximately 5-year old Moso bamboo culm, the next part presents the physical properties of those two materials.

### *3.3.3 Physical Properties of Moso Bamboo and Japanese Cedar*

This part provides some physical properties of the Japanese cedar and approximately 5-year old Moso bamboo culms which is used as raw material of SWB. The physical properties presented here aims to give some insights into the strength of SWB raw material. Indicators that are presented here include specific gravity, tensile and compression strength, bending strength, shear strength and shrinkage rate (Table 5).

The values used as the indicator in this part are not the precise values but merely the average values obtained from experiments done by some researchers using different methods and under different conditions. For example, the values from Experimental Forestry Station (1983) was obtained through tests done according to the Japanese Industrial Standard; JIS Z 2102 for specific gravity test; JIS Z 2111-2114 for compression, tensile, bending and shear test; and JIS Z 2103 for shrinkage rate test. While, the experiment done by Chung and Yu (2002) was performed according to the method developed by Janssen (1999). Another experiment done by Li (2004) was performed based on the ASTM-D1037-94, the American standard method to evaluate the properties of wood based fiber and particle panel. In that experiment, the samples were air-dried until they reached Equilibrium Moisture Content (EMC) of about 10% before tested. And, the moisture content of bamboo specimens used in Lo et al. (2004) study was ranged between 12.5 % and 13%.

Apart from the experiments' method and condition, the specimens used in each experiment were also not exactly 5-year old. In some experiments, the age of the culms was determined through visual inspection, like the specimens used by Chung & Yu (2002) and Lo et al (2004). The culms used by Experimental Forestry Station are most likely to be the culms cut for timber, which is around 6 to 7-year old (Oshima, 1982). In addition, those bamboo culms were also grown under different environmental condition. Considering the effects of the methodology, moisture content (American Wood Council, 1993), age (Sekhar et al., 1960; 1962 & Espiloy, 1994 in Lo et al., 2004; Liese, 1995 in Amada & Untao, 2001; Li, 2004) and environmental condition (Oshima, 1982; Lou, 2009)

on the physical properties of the bamboo culms, it is common to find out that the results of those experiments are varied as it is shown in the table.

**Table 5 Physical Properties of Japanese Cedar and Moso Bamboo Culms**

<b>Physical properties</b>	<b>Japanese cedar</b>	<b>Moso bamboo (5-year old)</b>
Specific gravity	0.38 <sup>1</sup>	0.76 <sup>1</sup> 0.763 <sup>2</sup> 0.794 <sup>3</sup>
Tensile strength parallel to the grain (MPa)	88.2 <sup>1</sup>	172.5 <sup>1</sup>
Compression strength parallel to the grain (MPa)	34.3 <sup>1</sup>	51.5 <sup>4</sup> 75 <sup>3</sup> 76.4 <sup>1</sup> 88.7 <sup>2</sup>
Compression strength perpendicular to the grain (MPa)	-	34.3 <sup>2</sup>
Bending strength (MPa)	63.7 <sup>1</sup>	88 <sup>3</sup> 141.1 <sup>1</sup>
Shear strength (MPa)	5.9 <sup>1</sup>	16.7 <sup>1</sup>
Tangential shrinkage rate for every 1% change in moisture change (%)	0.25 <sup>1</sup>	0.27 <sup>1</sup>
Radial shrinkage rate for every 1% change in moisture change (%)	0.10 <sup>1</sup>	0.25 <sup>1</sup>

(<sup>1</sup>Experimental Forestry Station, 1982; <sup>2</sup>Li, 2004; <sup>3</sup>Chung & Yu, 2002; <sup>4</sup>Lo et al., 2004)

As it can be seen in Table 1, the specific gravity of Moso bamboo culms ranged between 0.76 and 0.794; which on average is close to double of the specific gravity of Japanese cedar. According to the American Wood Council (1993), the specific gravity of different woody materials under the same condition in most cases can be used as an index for the

strength of the materials and shows a positive relationship with the strength. The data from the Experimental Forestry Station (1982) confirms the theory mentioned by American Wood Council (1993); all Moso bamboo culms' physical strengths shown in the table are greater than the physical strengths of the Japanese cedar.

The compression strength parallel to the grain of the Moso bamboo culms ranged widely between 51.5MPa and 88.7MPa. The compression strength parallel to the grain obtained from the study done by Lo et al. (2004) is considerably low compared to results from other studies. It might be caused by the higher moisture content of the specimens compared to moisture content of other studies' specimens. On the other hand, compression strength parallel to the grain obtained from Li's experiment shows the highest value among others. It might be because the specimen used in this experiment was said to be 5-year old where the bamboo culms are about the mature age with optimum strength (Liese, 1995 in Amada & Untao, 2001).

In the case of the bending strength, the result from Chung & Yu is lower compared to the result from Experimental Forestry Station. It might be because of the different age of the culms samples their use and the moisture content of the specimen. Chung & Yu used 3-6-year old culms and the moisture content of the specimen was (5-30) %; while the Experimental Forestry Station most likely used 6-7-year old culms and the moisture content of the specimen was conditioned to be about 5%.

Even though the values indicating the physical strengths of the Moso bamboo culms shown in the table are varied; in overall, the physical strengths of the Moso bamboo culms are superior compared to the physical strengths of Japanese cedar. In other words, if the physical strengths of SWB is assumed to be same as the physical strengths of its raw material and only the physical strengths which taken into consideration to determine the possibility of using SWB as alternative building material; SWB can be considered one possible option.



However, in terms of the dimensional stability, the shrinkage rate indicates that Moso bamboo seems to be more easily affected by the changes in the environment especially moisture compared to Japanese cedar. Since the physical strength and moisture content of the material are in general negatively related (American Wood Council, 1993); this physical property of Moso bamboo may restrict SWB potential as alternative building material regardless its strength performance.

Further, considering the production of SWB which includes so many processes (Appendix 3); the SWB is expected to have different physical properties to its raw material. For this reason, the next part discusses the differences between the physical properties of Moso bamboo culms and SWB; and how the SWB physical properties compared to Japanese cedar.

### 3.3.4 Physical Properties of Strand Woven Bamboo and Japanese Cedar

As shown in the Table 6, the physical properties of Strand Woven Bamboo (SWB) are different to the physical properties of its raw material, the approximately 5-year old Moso bamboo culms. Some of the physical properties of SWB have better performances compared to those of its raw material; while some others have less.

**Table 6 Physical Properties of Japanese Cedar, Moso Bamboo Culms and SWB**

Physical properties	Japanese cedar	Moso bamboo (5-year old)	SWB
Specific gravity	0.38 <sup>1</sup>	0.76 <sup>1</sup> 0.763 <sup>2</sup> 0.794 <sup>3</sup>	1.08 <sup>5</sup> 1.1-1.2 <sup>6</sup>
Tensile strength parallel to the grain (MPa)	88.2 <sup>1</sup>	172.5 <sup>1</sup>	105 <sup>6</sup> 105.4 <sup>7</sup>
Compression strength parallel to the grain (MPa)	34.3 <sup>1</sup>	51.5 <sup>4</sup> 75 <sup>3</sup> 76.4 <sup>1</sup> 88.7 <sup>2</sup>	52 <sup>6,7</sup>
Compression strength perpendicular to the grain (MPa)	-	34.3 <sup>2</sup>	17.7 <sup>7</sup> 18 <sup>6</sup>
Bending strength (MPa)	63.7 <sup>1</sup>	88 <sup>3</sup> 141.1 <sup>1</sup>	93.8 <sup>6</sup>
Shear strength (MPa)	5.9 <sup>1</sup>	16.7 <sup>1</sup>	19.4 <sup>6</sup>
Tangential shrinkage rate for every 1% change in moisture change (%)	0.25 <sup>1</sup>	0.27 <sup>1</sup>	0.14 <sup>7</sup>
Radial shrinkage rate for every 1% change in moisture change (%)	0.10 <sup>1</sup>	0.25 <sup>1</sup>	

(<sup>1</sup>Experimental Forestry Station, 1982; <sup>2</sup>Li, 2004; <sup>3</sup>Chung & Yu, 2002; <sup>4</sup>Lo et al., 2004; <sup>5</sup>Van der Lugt et al., 2009; <sup>6</sup>HCZY & Sinochon; <sup>7</sup>Bamboo Industries, 2008)

As it can be seen in the Table 6, the specific gravity of SWB is around one and a half of the specific gravity of its raw material. It is the result of the compression process during its production. However, contrary to the general specific gravity and physical strength relationship (American Wood Council, 1983); the data in Table 6 shows that the tensile strength, compression strength and bending strength of the SWB are comparably inferior compared to its raw material.

The tensile strength of SWB is about two third of the tensile strength of the bamboo culms. The SWB's compression strength in both directions is also not as good as the compression strengths of the raw material. But the difference between the compression strength of the SWB and the compression strength of the bamboo culms is relatively greater in the perpendicular direction. The parallel compression strength of the SWB is about 59% of the greatest parallel compression strength of the Moso bamboo culms; which means still lies on the range of the parallel compression strength of the Moso bamboo culms. On the other hand, the perpendicular compression strength of the SWB is only about half of the perpendicular compression strength of the Moso bamboo culms. Further, since bending stress is the combination of tensile stress and compression stress; just like tensile strength and compression strength, the bending strength of the SWB is also comparably lower than the bending strength of its raw material. It is approximately two third of the bending strength of the raw material.

The mentioned strength inferiority of SWB compared to its raw material might be related to or caused by the following steps during the production:

- *Removal of the outer layer of the bamboo culms.* Since the fibers are highly concentrated on the outer layer of the culm (Liese, 1992; Amada et al., 1997; Li, 2004) and the fibers are the one which provide most of the strength to the bamboo culms (Nogata & Takahashi, 1995; Amada & Untao, 1997, 2001); consequently, the removal of the outer layer of the bamboo culms results in the decline of the strength (Li, 2004; Yu et al., 2008).

- *Splitting of bamboo culms into strips and compression of strips into lumber in the perpendicular direction to the grain.* These processes might change or damage the structure of the fibers and lead to the degradation of those fibers.
- *Boiling of the bamboo strips to remove the sugar content.* The study done by Li (2004) shows some correlations between the chemical content and mechanical strength of the bamboo culm. For example, the cellulose content is positively correlated to the mechanical strength which might be related to the fact that bamboo fiber is mainly constructed out of cellulose (Lakkad & Patel, 1980 in Li, 2004). This boiling process may alter the chemical characteristics of the bamboo strips and lead to some changes in the strength properties.

On the other hand, the SWB's shear strength is about 16% greater than shear strength of the approximately 5-year old Moso bamboo culms. The shrinkage rate of SWB is also lower than its raw material. These better performances in shear strength and shrinkage rate of SWB might be related to the glue application as mentioned by Sumardi et al. (2006).

By looking at the physical characteristics of SWB and its raw material shown in the Table 6; it can be understood that most of the physical strengths of the SWB are not as good as its raw material, the approximately 5-year old Moso bamboo culms. This outcome is most likely to be the consequences of the production processes as mentioned previously.

However, by looking further on the physical properties of SWB and comparing them to the physical properties of Japanese cedar; it can be seen that the physical strengths of SWB are still considerably stronger than those of Japanese cedar. The dimensional stability of SWB is also comparable to the Japanese cedar's. Therefore, if the requirement taken into consideration is only the mentioned physical properties; it can be simply said that SWB has the potential to substitute Japanese cedar.

## **CHAPTER IV: Strand Woven Bamboo Substitution Potential -Availability of Bamboo Resources**

Considering the wood related issue in Japan, at the beginning of this study (Chapter 1), bamboo is suggested to be one possible alternative to wood construction material in Japan. The reason is because bamboo is a local rapidly renewable material which currently not utilized effectively in Japan and has led to another problem like bamboo encroachment. Therefore, using bamboo as an alternative to wood construction material is hoped to be able to address the problem of wood in Japan and at the same time, also address the problem of bamboo plantation abandonment in Japan. However, even though, bamboo is available in Japan; the available amount of bamboo resources and the amount of bamboo building material which is potentially supplied to replace wood construction material is needed to clarify to determine the actual substitution potential of bamboo.

Since this study focuses on Strand Woven Bamboo (SWB); this chapter tries to examine the potential of SWB as alternative to wood construction material from the perspective of the availability of bamboo resources in Japan and takes Oita Prefecture as a case study. Specifically, this chapter tries to estimate the amount of production potential of SWB in Oita Prefecture.

### **4.1 Substitution Potential ~ Availability of Bamboo Resources**

The availability of bamboo resources in a region can be considered as the amount of bamboo material that can be used in manufacturing bamboo-based products. This bamboo resources availability mainly depends on the available production area (bamboo plantation area) and the productivity of that bamboo production area. The larger the production area and the higher the productivity of a unit production area, the more bamboo resources can be produced and available for bamboo-based products manufacturing.

The extent of bamboo cover in a region naturally depends on the adaptability of bamboo to the environmental condition. However, the available area for bamboo production is in general the outcome of the decision made in designating land use which is influenced by

the ownership of the land, socio-economic development plan, political factor, etc. This makes increasing availability of bamboo resources by expanding bamboo production area may require complicated legal processes. On the other hand, increasing bamboo resources availability by improving the productivity of the bamboo plantation is considered to be more relevant given that the production area is limited and sufficient information related to the bamboo plantation productivity is available.

The productivity of a bamboo plantation is basically the result of interactions between the bamboos in the plantation and the environmental conditions within and surrounding the plantation that affect the growth of those bamboos. According to Kleinhenz and Midmore (2001), in order to enhance the productivity of a bamboo plantation, it can be done by manipulating the growth and development of the bamboo in the plantation or managing the environmental conditions in the plantation.

Since each species of bamboo acts differently, this study only discusses about Moso bamboo which the raw material of SWB. The following are some factors that affect the productivity of bamboo plantation, particularly Moso bamboo plantation.

#### *4.1.1 Factors Affecting Productivity of Moso Bamboo Plantation*

##### Moso Bamboo Life Cycle

Moso bamboo (*Phyllostachys pubescens*) is classified into monopodial bamboo considering its rhizomes which grow apart toward fertile soil underground and result in the scattered distribution of bamboo culms aboveground (Oshima, 1982). It reproduces through both generative and vegetative reproduction; however, vegetative reproduction is more common (Qui Fu-geng, 1982). It is because generative reproduction is less beneficial due to the seldom flowering of bamboo; and even when it does flower, the produced seeds are considerably weak and cannot stay fertile for long period (Hui, 2002; Uchimura, 2007). For this reason, vegetative reproduction is more preferable for propagation. Vegetative reproduction mostly relies on the development of buds on the rhizomes into new shoots which further grow into mature culms and participate in the new shoots production in the later years.

On the first development stage, a bud has to rely completely on its mature parent culm for nutrient supply until it becomes young culm, sheds its sheaths and develops its leaves (Oshima, 1982; Li et al., 1997). The leaves expand as soon as forty days to two months after the shoot emerges; and starting from the leaves expansion, the culm starts to produce its own nutrient through photosynthesis (Ueda 1960 in Li et al., 2000; Oshima, 1982). After the shooting period in spring, the culm starts to develop rhizomes system underground in June, on which the new buds of the next years grow and through which the nutrient for the new buds supplied (Oshima, 1982).

In the next year, just before shooting period which is around the end of January to early February; the culm sheds its leaves (Dreckmann, 1995 in Kleinhenz & Midmore, 2001). This leaves shedding can be considered as one of the mechanism for shooting preparation in terms of controlling soil temperature and moisture. However, it should be realized that not all culms shed their leaves at the same time since the leaves have different life span. According to Bamboo Research Institute of Nanjing Forestry University (1974), the leaf life span of Moso bamboo is two years among over one-year old culms and one year among one-year old culms (In Li, 1997, 2000; Kleinhenz & Midmore, 2001).

While the culms which shed their leaves before shooting period contribute to provide suitable micro-environment for the new shoots; the culms which do not shed their leaves actively photosynthesize to provide nutrient for the new shoots. According to Li et al. (1997), the number of culms which do not shed their leaves before the shooting period and the number of new shoots produced every year and the survival of those new shoots in a plantation are positively related.

The ratio of total number of newly emerged shoots to total number of adult culms (per capita birth rate) and the ratio of total number of surviving new shoots to total number of adult shoots (per capita survival rate) were 1.32 and 0.29 respectively; however, with only respect to the total number of adult culms carrying new leaves (2-, 4-, 6-year old culms), the ratio became 2.41 and 0.53 respectively (Li et al., 1997). One reason behind it is because the new leaves which are less than one-year old tend to have higher

photosynthesis rate up to three times compared to old leaves which are more than one-year old (Huang, 1986; Huang et al., 1989; Qiu et al., 1992 in Kleinhenz & Midmore, 2001).

Besides the leaves age, the culm age is also an important factor affecting the per capita birth and survival rate which collectively indicate the productivity of the plantation. As generally known, young adult tends to have better productivity compared to older adult. The application of this general idea can be seen through the selection of stock plant age for producing bamboo shoots. “Kanda says that one-year old bamboo plants are the best for stocks, while two-year olds may be adequate but are not best. While Abe believes that the optimum age for stocks is one full year and bamboo plants over three-year old are useless” (Oshima, 1982).

Based on the information about the leaves life span and its relation to photosynthesis rate; Kanda and Abe said as previously mentioned might be because:

- One-year old plants would turn into two-year old in the following year in which the productivity reaches the highest and still quite productive for next few years.
- Two-year old plants would turn into three-year old in which the productivity is much lower compare to the two-year old and by the time they reach four-year old, the productivity increase slightly but not as good as those two-year old plants.
- Three-year old plants would turn into four-year old in the following year with considerably low productivity and in the next few years those plants would become too old to produce new shoots.

Therefore, in terms of productivity of new shoots (P), it can be assumed that productivity of two-year old moso bamboo ( $P_2$ ) is the highest, followed by productivity of four-year old bamboo ( $P_4$ ) and productivity of one-year old bamboo ( $P_1$ ); while three-year old and older bamboo have lower productivity compared to one, two, four-year old bamboo. ( $P_2 > P_4 \cong P_1 \cong P_3 \cong P_5 \dots$ )



### Age Structure in the Moso Bamboo Plantation

The productivity of bamboo plantation is also affected by the age structure of the bamboo culms in the plantation. A plantation with high proportion of productive culms tends to grow exponentially if there is no limiting factor. On the other hand, a plantation with high proportion of old culms tends to diminish since old culm is relatively low in productivity. Old culm is also weaker compared to young culm which causes them easily attacked by insects or pests (Oike, 2007). Since plantation is a limited area and yield is expected, maintaining an equilibrium stock to produce sustain optimum yield is desired. For this reason, studies related to age structure of bamboo plantation have been done. Those studies came out with some hypothetical optimum age structure ratio, such as equal ratio for all age structure or equal ratio for even and odd age structure (Zhou, 1988; He, 1993 in Zheng et al., 1998). But because the yield from a plantation is also influenced by many other factors, the optimum age structure for every plantation is different among each other.

### Standing-Culm Density in the Moso Bamboo Plantation

Density of the bamboo culms in the plantation has become one interesting subjects among bamboo cultivators since the number of culms in the bamboo plantation is one of the limiting factors to the productivity of the plantation. For this reason, bamboo cultivators usually try to maintain a particular standing-culm density which is varied based on the purpose of the plantation, whether the plantation used to produce shoots, culm timber, or both. As the result, various standing-culm densities are suggested by different studies, for example about 1482 culms/ha for shoots plantation (Oshima, 1982); 1800-3300, 10500-12000, 18000 culms/ha for producing large-, medium-, small-size bamboo shoots (Hui, 2002); 2700-3000 culms/ha for culm timber plantation under ordinary management (Chen, 1992); 1500, 2300 and 3000 culms/ha for annual timber yields of <3.5, 3.5-7, 7-10 t/year (Fu & Banik, 1995 in Kleinhenz & Midmore, 2001). While Uchimura (1980) suggested that plantations which have (3000-4000) culms/ha; (4000-6000) culms/ha and (6000-8000) culms/ha culms density retained after harvest as high, middle and low quality sites.

### Climatic Conditions that Affect Moso Bamboo Growth

Temperature is one important factor to the growth of bamboo particularly during the shoots development. According to Oshima (1982), warm temperature is needed for Moso bamboo to grow well; “regions in which the minimum summer temperature goes below 15 degree Celsius are not suitable.” While Uchimura (1980) states that “Moso bamboo is better grown in the area where the temperature is never lower than 3 degree Celsius and never higher than 33 degree Celcius”.

Water availability is another important growth factor to bamboo and the demand of water is different depends on the growth stage of the culms (Kleinhenz & Midmore, 2001). In terms of precipitation, according to Fu (2001), the optimum rainfall for the Moso bamboo growth is around 400-600mm during the shooting time.

Further, since the root systems of Moso bamboo is relatively shallow, mostly concentrated up to 30 cm below ground; Moso bamboo growth are prone to wind storm (Oshima, 1982; Kleinhenz & Midmore, 2001).

### Topography and Location of the Moso Bamboo Plantation

Although Moso bamboo is used for soil erosion prevention and largely planted on hillsides in China (Kleinhenz & Midmore, 2001); considering the shallow root systems of Moso bamboo, too steep land can be considered as undesirable for Moso bamboo plantation. However, certain degree of slope can be beneficial for the growth of the bamboo since it may increase the amount of sunlight that reaches the ground and warm the soil, especially the land sloping toward the south direction (Oshima, 1982). From the management point of view, land on the slope provides natural irrigation and drainage. According to Oshima (1982), the optimum slope should be 7-8 degree and it should not more than 15 degree. Other study done with *Phyllostachys nidularia* also showed negative relation between slope and yield; 10.6t/ha at slope less than 10 degree, 7t/ha at slope 10-30 degree, and 3.6t/ha at slope more than 30 degree (Zhang et al., 1996 in Kleinhenz & Midmore, 2001). Besides, the distance of the bamboo plantation to roads

and human settlements may also affect the level of management received by the plantation which may also affect the production of the plantation.

#### Soil Conditions in the Moso Bamboo Plantation

Even though, Moso bamboo is believed to be able to grow well even on poor soil condition; suitable soil condition results in better productivity of the bamboo plantation. For example, study done by Li et al. (2000) reveals that the number of new shoots emergence increased with the application of fertilizer. Uchimura (1980) also suggests that fertilizer application may be needed when the natural nutrient supply by soil and precipitation is not enough. Further, according to Fu (2001), the most suitable soil conditions for Moso bamboo is “over 60cm (23½ inches) deep fertile loam; pH = 4.5 to 7.0; moist but not soaked”.

## **4.2 Methodology**

### *Method*

In estimating the amount of SWB substitution potential, a simplified model which is assisted by modeling program called STELLA is used in calculation. As the first step, a model to estimate the substitution potential of SWB is developed by considering the factors that influence the amount of SWB production potential.

On the second step, the parameter values of factors which affect the SWB production potential (the amount of bamboo material needed to produce a unit amount of SWB and the production potential of bamboo resources, particularly the Moso bamboo resources, by the plantations in Oita Prefecture) are estimated.

The amount of bamboo material required to produce a unit SWB is estimated by first reviewing the manufacturing process of SWB which includes collecting data related to the material input for each manufacturing stage and the manufacturing output (SWB Lumber). Next, by using this information, the amount of Moso bamboo material needed to produce one cubic meter of SWB will be estimated.

The production potential of Moso bamboo resources in Oita Prefecture is estimated by first reviewing the current condition of bamboo plantation in the prefecture. Then, by referring to the information about factors affecting Moso bamboo plantation productivity, the factors which currently inhibit the production potential will be identified and used to develop scenario in estimating the production potential of Moso bamboo resources in Oita Prefecture; the parameter values will also be identified.

On the next step, by using the developed model and the parameter values, the amount of substitution potential of SWB under several scenarios will be estimated. It will be followed by the estimation verification by referring to the bamboo culms production historical data in Japan and other supporting information.

#### *Model Development*

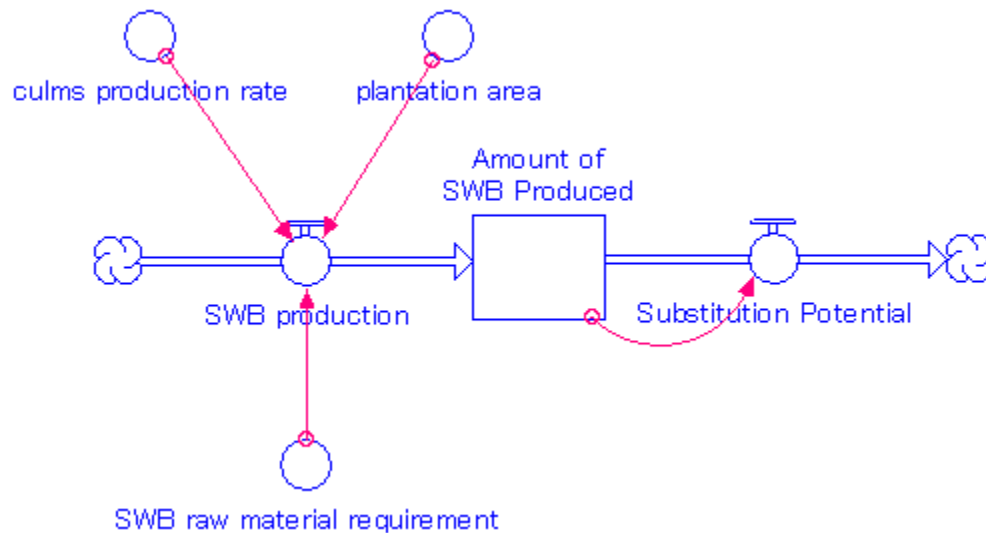
The amount of SWB substitution potential is determined by the amount of SWB potentially produced in a region. The production potential of SWB in a region is simply affected by the availability of bamboo resources, particularly Moso bamboo resources which provide raw material for SWB manufacturing, in that region and the efficiency of raw material usage during the SWB manufacturing.

Since this chapter tries to explore the SWB substitution potential from the perspective of the availability of bamboo resources; the model emphasizes on estimating the production potential of SWB by manipulating the factors that are related to the availability of Moso bamboo resources. For this reason, the factors that may affect the amount of SWB production potential which are related to the SWB manufacturing processes are neglected and assumed to be constant.

As mentioned previously, the availability of bamboo resources depends on the availability of production area and the productivity of that production area. The production area is the bamboo plantation area. Bamboo plantation in this model is assumed to be designated only for culms production and harvested by adopting the selective cutting procedure to provide raw material for SWB.

The productivity of the production area is represented by the culms production rate and is affected by the abovementioned factors (life-cycle of the bamboo, age-structure in the plantation and standing-culm density in the plantation, location of the plantation, climatic condition and soil condition). The location of the plantation and the climatic condition are assumed to be the same for all plantations in a certain region.

As for the calculation (in the case of Oita Prefecture), the annual amount of Moso bamboo culms production in Oita Prefecture (soku/year) can be calculated by multiplying the total area of Moso bamboo plantation in Oita Prefecture (in hectare (ha)) by the annual average Moso bamboo culms production rate in Oita Prefecture (in soku/ha/year). While the annual amount of SWB production potential in Oita Prefecture ( $\text{m}^3/\text{year}$ ) can be calculated by dividing the annual amount of Moso bamboo culms production in Oita Prefecture (soku/year) by the amount of raw material required to produce each cubic meter of SWB ( $\text{soku}/\text{m}^3$ ). The annual amount of SWB production potential in Oita Prefecture ( $\text{m}^3/\text{year}$ ) is equal to the annual SWB substitution potential ( $\text{m}^3/\text{year}$ ). The flow of these calculations is illustrated in the following figure (Figure 9).

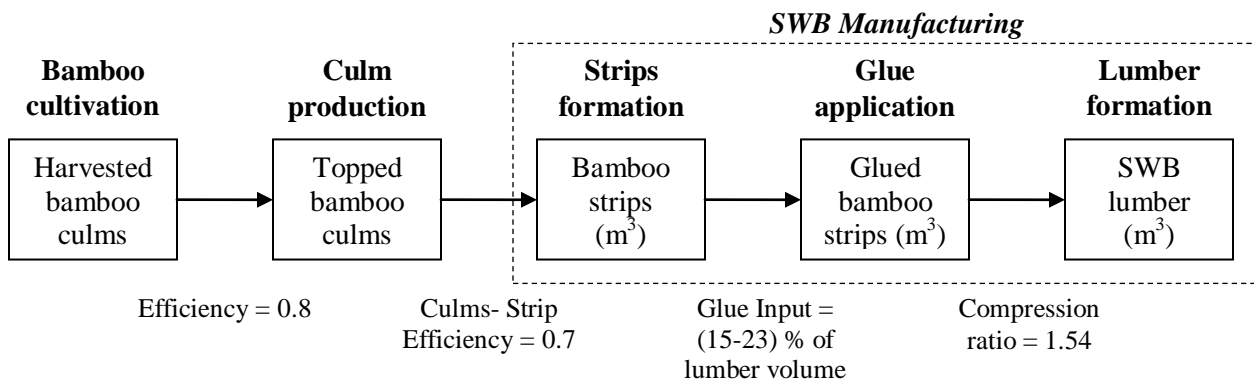


**Figure 9 SWB Substitution Potential Model**

### 4.3 Review and Analysis

#### 4.3.1 Strand Woven Bamboo Raw Material Requirement

Just like mentioned in the previous chapter (Chapter 3), this study uses Strand Woven Bamboo (SWB) made in China as reference. The raw material used as input in SWB manufacturing is the bottom-middle-upper part of 5-year old Moso bamboo culms (Van der Lugt et al., 2009; Zhu & Jin, 2010). The following figure shows the simplify flow of SWB production process (Appendix 3).



#### SWB Production Process

(Source: Van der Lugt et al., 2009)

Based on the information about the SWB manufacturing process, it can be estimated that approximately  $1.30\text{m}^3$  and  $1.18\text{m}^3$  of bamboo strips is needed to make  $1\text{m}^3$  of indoor and outdoor SWB lumber respectively (Appendix 4).

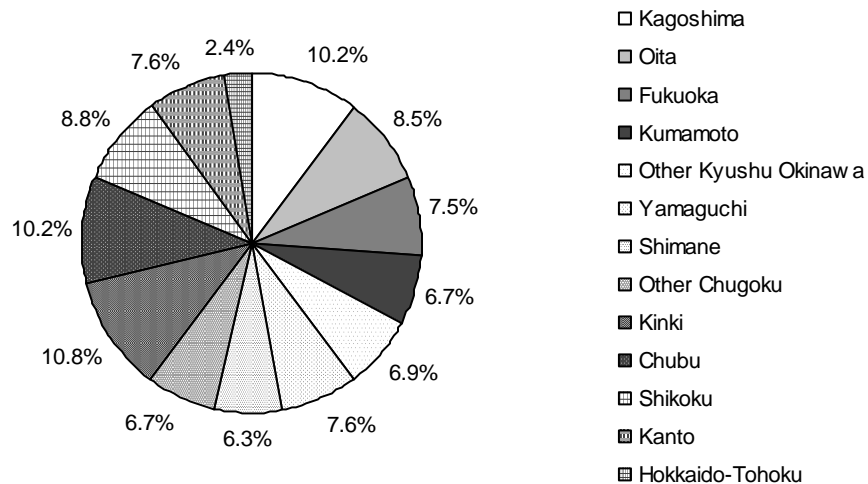
However, bamboo is not counted in volume ( $\text{m}^3$ ). In Japan, ‘soku’ is used as a unit in counting bamboo material (in form of topped bamboo culms); one soku is approximately equal to 25 kg of air-dried bamboo culm(s) (Kondo, 2007). According to Experimental Forestry Station (1982), the average specific density of air-dried Moso bamboo in Japan is  $760\text{kg}/\text{m}^3$ . By using that value, the volume of each soku of bamboo is estimated. Then assuming that the bamboo culms that are sold in soku are all used as input for the manufacturing process; the amount of Moso bamboo required to produce  $1\text{m}^3$  of SWB in Japan is estimated to be about 51.55 soku for outdoor SWB and 56.84 soku for indoor SWB (Appendix 4).

#### 4.3.2 Current Condition of Bamboo Plantation in Oita Prefecture

##### Current Condition of Bamboo Plantations in Oita Prefecture

Oita Prefecture is famous for its bamboo handicraft and has become one of the top producers of bamboo culms together with Kagoshima and Kumamoto Prefecture in Japan for years (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009).

In Oita Prefecture, bamboo covers 13465ha of Oita Prefecture's land area which accounts for 8.5% of total bamboo covers in Japan (Figure 10) (Forestry Agency, 2007; Oita Prefecture Statistical Yearbook, 2009). The main species of bamboo cultivated in Oita Prefecture is Madake (*Phyllostachys bambusoides*) and Moso (*Phyllostachys pubescens*). Madake (*Phyllostachys bambusoides*) covers around 80% of bamboo cultivation area, while Moso (*Phyllostachys pubescens*) covers around 13% of bamboo cultivation area in the prefecture (Forestry Agency, 2009). Madake is cultivated mainly for the culms which are used in producing daily goods, handicrafts or used as building material; while Moso is cultivated to produce bamboo shoots and bamboo culms (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009).



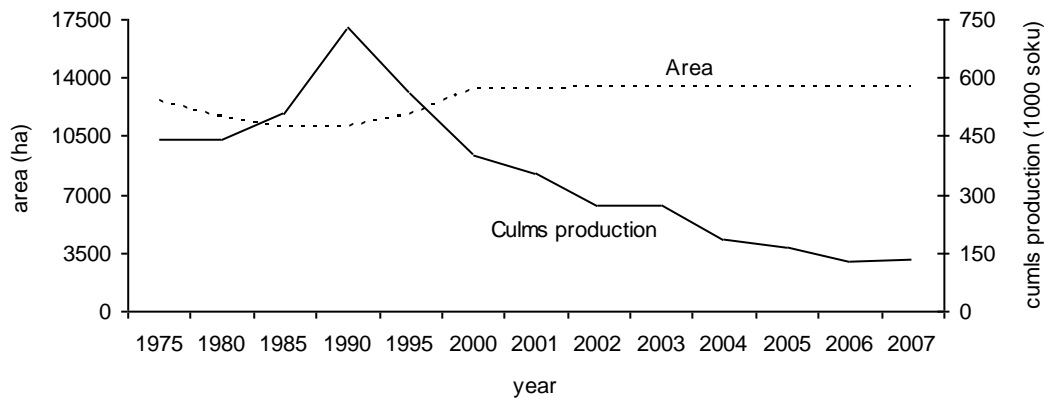
**Figure 10 Distribution of Bamboo Cover in Japan 2007**

(Source: Forestry Agency, 2007)

However, just like in other area in Japan, due to the increase popularity of plastic goods around 1960s and further by the high import of bamboo shoots especially from China in early 1990s, people has started to lose their interest to cultivate bamboo due to the low

competitiveness of domestic bamboo products (Kondo, 2007; Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009). As the result, many bamboo plantations in Oita Prefecture are abandoned.

The abandonment of bamboo plantations in Oita Prefecture can be seen through the decreasing production of bamboo culms although at the same time the bamboo area remains relatively unchanged in the prefecture (Figure 11).



**Figure 11 Bamboo Culms Production & Bamboo Cover Area in Oita Prefecture 1975-2007**

(Source: Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009 (for Bamboo culms production); Oita Prefecture Statistical Yearbook 1975-2007 (for Bamboo area))

In addition, field research done by Oita Prefecture Agriculture, Forestry and Fisheries Department (2009) also reveals the abandonment of bamboo plantations in the prefecture. From fifteen sample study plots in three areas, Kunisaki, Oita and Usuki; seven of the plots are abandoned (5 Moso plots, 2 Madake plots); three of the plots are partly managed (3 Moso plots) and the rest 5 plots are managed (1 Moso plots, 4 Madake plots). However, regardless the plots are under management or abandoned, all of the plots are reported to be invading the next lands. Moreover, the sample plots also have high density of culms; the density of Madake plots range from 22000 to 31000 culms per hectare. While the density of Moso plots range from 9000 to 24000 culms per hectare.



### *Moso Bamboo Plantation in Oita Prefecture*

Since, the raw material of Strand Woven Bamboo used as reference is Moso bamboo culm; this part discusses further about the condition of Moso bamboo plantation in Oita Prefecture. Moso bamboo plantation area comprises considerably small area of the total area of bamboo plantation in Oita Prefecture if compared to Madake plantation. In 2009, it is reported that the area of Moso bamboo plantation in Oita prefecture was 1776.8 ha which comprised of 13.5% of the total bamboo plantation area (Forestry Agency, 2009). However, Oita Moso bamboo plantation area accounts for 15% of the total Moso bamboo plantation area in Japan which is the second largest Moso bamboo plantation within the country after Kagoshima Prefecture (65%) (Forestry Agency, 2009). In terms of the average production of bamboo culms, it is considerably low compared to the country average. In 2009, the average production of Moso bamboo culm in Oita Prefecture was 15.2soku/ha which equal to 0.38ton/ha; while the country average was 59.4soku/ha which equal to 1.485ton/ha (Forestry Agency, 2009).

#### *4.3.3 Scenario for Bamboo Resources Production Potential Estimation*

Considering the current condition of Moso bamboo plantation in Oita Prefecture, the following factors should be given priority in estimating the Moso bamboo culms production in the prefecture. Those factors are:

- Soil condition; due to the lack of management for some times, the soil condition in the plantations at the presents might not be in the ideal condition to support optimum growth of the bamboo in the plantations.
- Standing-culm density; as it was mentioned previously, the present standing-culm density in the bamboo plantation, including the Moso bamboo plantation, in Oita Prefecture are considerably too high. Therefore, removing some amount of bamboo culms may enhance the production of the plantation.
- Age structure; since the plantations in Oita Prefecture are not well managed or abandoned, it can be expected that the age structure in those plantations is relatively old. However, as previously explained, the old culms has lower productivity rate compared to the younger ones; for this reason, the old bamboo

culms should be removed to maintain the desired age structure to produce certain amount of yield.

By taking the soil condition factor, age structure of the bamboo plantation and standing-culm density factors into consideration to improve the productivity of Moso bamboo plantations in Oita Prefecture; the productivity of Moso bamboo plantations in Oita Prefecture are predicted to become one of the following scenarios:

- Scenario 1 → The management of Moso bamboo plantation stays the same as the present condition; as the result, the culms production rate remains unchanged from the present production rate, 15.2soku/ha/ year (Forestry Agency, 2009).
- Scenario 2 → Moso bamboo plantation managers in Oita are assumed to do some efforts to increase their plantation productivity so that the culms production rate in the prefecture can be equal to the country average culms production rate 59.4soku/ha/year (Forestry Agency, 2009).
- Scenario 3 → Moso bamboo plantations in Oita Prefecture are maintained so that the plantations have ideal soil condition and optimum age structure. The plantations are also managed under extensive management with standing-culms density of ~1500culms/ha; as the result the culms production rate becomes as high as 3.5t/ha/year which equal to 140soku/ha/year (Fu & Banik, 1995).
- Scenario 4 → Moso bamboo plantations in Oita Prefecture are maintained so that the plantations have ideal soil condition and optimum age structure. The plantations are also managed under mid-level management with standing-culms density of ~2300culms/ha; as the result the culms production rate becomes as high as 7t/ha/year which equal to 280soku/ha/year (Fu & Banik, 1995).
- Scenario 5 → Moso bamboo plantations in Oita Prefecture are maintained so that the plantations have ideal soil condition and optimum age structure. The plantations are also managed under intensive management with standing-culms density of ~3000culms/ha; as the result the culms production rate becomes as high as 10t/ha/year which equal to 400soku/ha/year (Fu & Banik, 1995).

#### 4.3.4 Estimation of SWB Substitution Potential under Different Scenarios

In estimating the SWB substitution potential, the following parameter values are adopted:

- Initial amount of SWB produced: 0 m<sup>3</sup>/year
- Plantation area: 1776.8ha
- Culms production rate (Scenario 1): 15.2soku/ha/ year
- Culms production rate (Scenario 2): 59.4soku/ha/year
- Culms production rate (Scenario 3): 140soku/ha/year
- Culms production rate (Scenario 4): 280soku/ha/ year
- Culms production rate (Scenario 5): 400soku/ha/ year
- SWB raw material requirement: 51.55soku/m<sup>3</sup> (for outdoor SWB production)

By using the developed model, the amount of SWB substitution potential in Oita Prefecture -assumed that the Moso bamboo production area remains constant as in 2009 (1776.8ha) and managed according to the five scenarios- was calculated and presented in Figure 12.

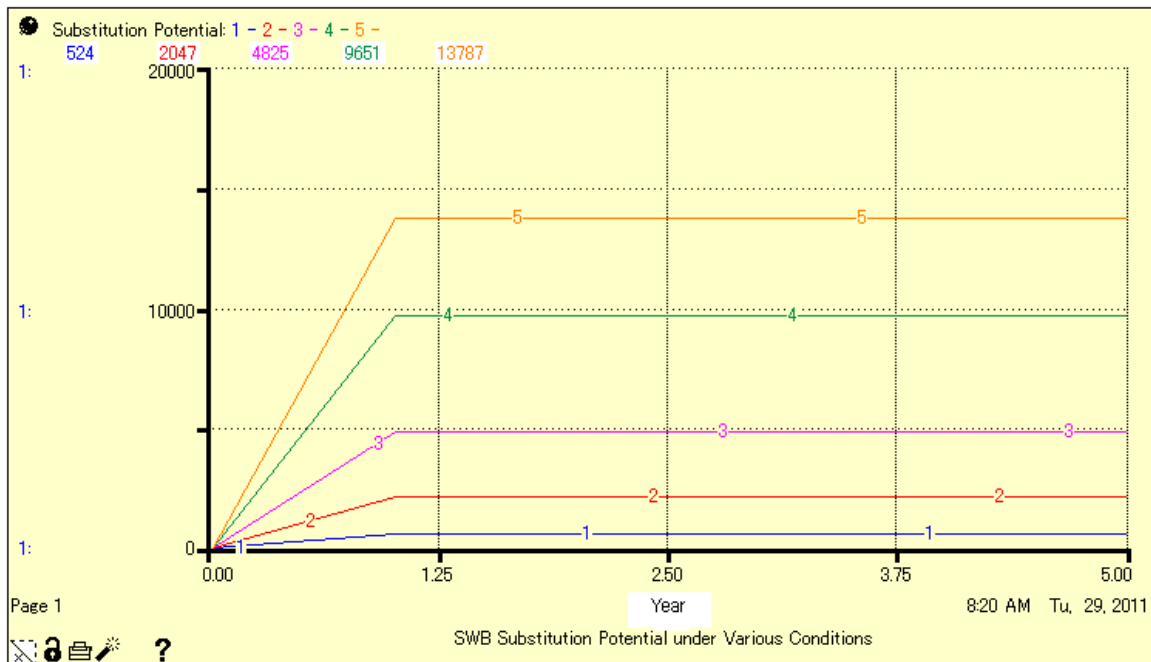


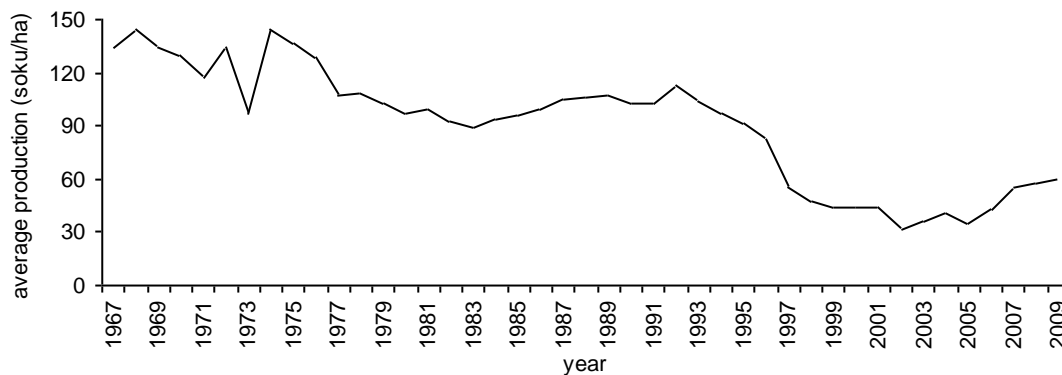
Figure 12 The Amount of SWB Substitution Potential under Different Scenarios

As explained previously, Scenario 1 is assumed to be based on the present way of managing Moso bamboo plantation in Oita Prefecture and the SWB substitution potential under this condition is estimated to be 524m<sup>3</sup>/year. While in Scenario 2 where Moso plantations in Oita are managed to achieve the same average culms production as the country average, the estimated SWB substitution potential may increase to 2047m<sup>3</sup>/year. Under Scenario 3, 4 and 5 which based on the extensive, mid-level and intensive management of Moso bamboo plantations in China, the amount of SWB substitution potential is estimated to become 4825m<sup>3</sup>/year, 9651m<sup>3</sup>/year and 13787m<sup>3</sup>/year respectively.

#### *4.3.5 SWB Substitution Potential Verification*

Out of the five scenarios, it can be understood that Scenario 1 and 2 are where the Moso bamboo plantations do not receive proper management considering the current problem of bamboo plantations abandonment in Japan. Therefore, the amount of SWB substitution potential in Oita Prefecture should be more than the potential under the second scenario which is 2047m<sup>3</sup>/year.

According to Uchimura (1980), Moso plantations designated for culms production is considered to have high quality if the density of the culms after harvest is (3000-4000) culms/ha which is relatively similar to the plantations under Scenario 5, the intensive management. However, since the standard in determining the quality of the plantation is not known; it cannot be directly assumed that the SWB substitution potential under Scenario 5 is the most suitable one. In addition to it, several studies done in China show that intensive management of bamboo plantation particularly the one done through monoculture has negative impacts on the biodiversity and shows declining productivity in the long term (Fu, 2001; Lou, 2009; Lou & Henley, 2010).



**Figure 13 Average Production Rate of Moso Bamboo Culms in Japan 1967-2009**

(Source: Forestry Agency)

Further, from Figure 13, it can be known that before 1975, the period where bamboo plantations were still receiving proper management; the highest recorded average Moso bamboo culms production rate in Japan was 144soku/ha. Since that value (144soku/ha) is the average value, it means that some places in Japan may produce more than the average value while some others produce less. According to Oshima (1982), Moso grows better in Kyushu region due to the warm climate condition; since Oita Prefecture is located in Kyushu, it can be assumed that the Moso culms production rate in Oita is supposedly higher than the country average at that time. Moreover, Moso bamboo plantations in Oita have been cultivated to produce both shoots and culms (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009); therefore if the plantations only used to produce culms, the production rate should also have been higher during that period. From the explanations; it can be predicted that under proper management, the average Moso bamboo culm production rate in Oita Prefecture may be higher than the production rate in Scenario 3 and more likely close to Scenario 4.

Therefore, based on the above explanations, it can be understood that the amount Strand Woven Bamboo (SWB) substitution potential in the Oita Prefecture might be enhanced by putting efforts on managing the plantations. The amount of SWB substitution potential is estimated can be enhanced up to twenty six times of the current substitution potential by improving the plantation management system as it is under Scenario 5. However,

considering the impacts of high yield management system and historical data on the production of Moso bamboo culms in Japan; the amount of SWB substitution potential in Oita Prefecture is more likely to be lower than the substitution potential under Scenario 5 (13787m<sup>3</sup>/year) and higher than the substitution potential under Scenario 3 (4825m<sup>3</sup>/year). For this reason, the amount of SWB substitution potential in Oita Prefecture is estimated to be most likely close to the substitution potential under Scenario 4.

Considering, the average of sawnwood demand in Oita Prefecture in during the last decades (2000-2007) which is approximately 720000m<sup>3</sup>/year (Oita Prefecture Statistical Yearbook); the most likely estimated amount of SWB substitution potential in Oita Prefecture which is 9651m<sup>3</sup>/year is comparable to 1.3% of the average demand of sawnwood in the prefecture.

## CHAPTER V: Discussion & Conclusion

In the beginning of this chapter, some possible implications if the potential of SWB as an alternative to wood construction material is really developed in Japan will be discussed. It will also discuss some factors that may hinder the development of SWB potential as an alternative to wood construction material and some other factors that should be considered to have more comprehensive understanding about SWB substitution potential. In the last part, this chapter will provide the conclusion of this study.

### 5.1 Discussion

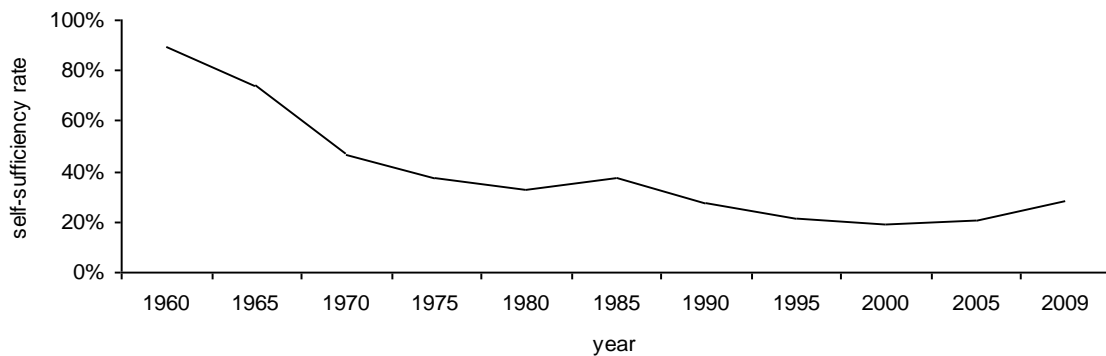
#### *5.1.1 Possible Implications of SWB Potential Development*

##### SWB Potential Development and Forest and Forestry Revitalization Plan

One of the possible implications of the development of SWB potential in Japan is its contribution to the accomplishment of Japan's Forest and Forestry Revitalization Plan. The plan which was established in December 2009 by the Ministry of Agriculture, Forestry and Fisheries is based on three fundamental principles. They are to revitalize forestry and wood products industry by fully utilizing regional natural resources; to contribute to the realization of "low-carbon society" through expanding wood use for both material and energy; and to provide and sustain the multifunctional roles of forests (Forestry Agency, 2010). Since bamboo plantation is part of the forest ecosystem and bamboo products are generally categorized into non-timber forest products; the management of bamboo plantation as the result of the development of SWB potential will supposedly work according to those principles.

First, the development of SWB potential may contribute to the resource security in Japan. The development of SWB potential may replace some of the wood products that are presently imported from other countries by utilizing the local bamboo resources. This replacement of wood products by SWB may reduce the demand of those imported wood products. Besides that, the management of bamboo plantation which is the basic requirement in developing SWB potential may also address the problem of bamboo encroachment to the neighboring forests. As the result, the productivity of those forests

may also increase and lead to increase supply of domestic wood. In consequence, the dependency on imported wood products as shown in Figure 14 may be reduced. At the same time, the lowering dependency on imported wood products may also contribute to meeting the target of the Forest and Forestry Revitalization Plan to increase wood self-sufficiency to more than 50% by 2020 (Forestry Agency, 2010).



**Figure 14 Wood Self-sufficiency Rate in Japan during 1960-2009**

Note: Self-sufficiency rate = (domestic supply / total supply)\*100%

(Source: Forestry Agency)

Second, the development of SWB potential in Japan will promote the management of currently abandoned bamboo plantations across the country. As the result, the plantations will become more productive and able to provide raw material to produce other bamboo products apart from SWB since each bamboo product requires specific part of the bamboo plants as raw material input (Table 7). For example, even though SWB, mat and blind require the middle-upper part of the bamboo culm for production; SWB uses the middle layer, while mat uses the green outer layer and blind uses the inner layer of the culm as raw material input. The fact about different utilization of each part of bamboo plant combines with the proposed ‘Eco-Plantation Product System’<sup>8</sup> in producing bamboo products by Kotani (1999) may practically contribute to bamboo resource security and opening the opportunity to revitalize of bamboo industry in Japan.

<sup>8</sup> Eco-Plantation Production System refers to the production system in which the harvested material (i.e., harvested bamboo plants) is collected to a central preliminary processing factory to be sorted and processed into raw materials for various products. The prepared raw materials are then sent to the manufacturing factories to be processed into various products which later are marketed to the consumers. This system also adopts a near closed-loop system where it incorporates recycling processes to minimize waste in this system. (Kotani, 1999)



**Table 7 Utilization of Different Parts of Bamboo Plant in China & Japan**

<b>Part of Bamboo</b>	<b>Usages in China*</b> <b>(as industrial inputs)</b>	<b>Usages in Japan</b> <b>(particularly in Kagoshima)</b>
<b>Leaves</b>	Manure, fodder, coloring agents, medicine, beverages	Food wrapping, short-handled broom
<b>Twigs</b>	Broom, clothes	Broom, handicraft
<b>Culms</b>	<i>Top part</i> Sticks (toothpicks, skewers), bamboo poles, scaffoldings	Pulp, baseball bat, charcoal, fodder, fuel, vinegar, fiber, particle board, flooring, handicraft
	<i>Middle upper part</i> Blinds, mat, woven articles, handicraft, lumber, pulp, charcoal, fuel	
	<i>Middle lower part</i> Laminated furniture, flooring, lumber, pulp, charcoal, fuel	
	<i>Base part</i> Charcoal	
<b>Shoots</b>	Vegetable	Vegetable
<b>Sheaths</b>	Handicraft	Bamboo hat, food wrapping, handicraft
<b>Rhizomes</b>	Handicraft	Bag handle, walking stick, handicraft

(Source: Hamada, 2009; Kondo, 2009; Matsuda, 2009; Nakanishi, 2009; O'ishi, 2009; Shibusawa, 2009; Tani, 2009; \*Zhu & Jin, 2010)

Next, due to the fast-growing characteristic, bamboo and its products may act as good carbon storage. However, the short life cycle of bamboo -in which the culm reaches its maximum height and size within the first three months of its growth<sup>9</sup>, reaches maturation at around 5-8 year old and starts to decay few years after the maturation- may let bamboo

<sup>9</sup> The length of early growth period is different among species, temperate bamboos (incl. Moso and Madake) generally require 50-60 days to reach their maximum culm height and size, while tropical bamboos generally require 90-100 days (Uchimura, 2007). There is no further enlargement of culm size since bamboo has no cambium. Therefore, the size of the culm remains the same until it start to decay. In the later stage of development, the product of the photosynthesis is accumulated in leaves which fall periodically, used for rhizome development and transported to the new shoots.

as ineffective carbon storage if the bamboos are left unused in the plantation. For this reason, sustainable management of bamboo plantation which incorporates regular harvesting and utilization of harvested bamboo to produce long life-span products are suggested to optimize the capacity of bamboo to store carbon (Lou et al., 2010). Even though bamboo is not tree, the ability of bamboo stand in storing carbon in the long term is as good as or even better than tree stand as shown in Table 8. Therefore, the development of SWB potential in Japan which will promote the management of bamboo plantation and store the carbon in the product for considerably long period of time, combine with the by-products of charcoal and fuel (ethanol), may contribute to the realization of low carbon society in Japan.

**Table 8 Carbon Storage Capacity of Teak and Moso**

Plant species	Mean annual increment of carbon (tC/ha/year)	Total biomass carbon storage at maturation (tC/ha)	Total est. carbon storage incl. products (tC/ha)	Reference
Teak ( <i>Tectona grandis</i> )	3.15	126 (mature in 40 years)	191 (after 40years)	Boateng, 2005
Moso ( <i>Phyllostachys pubescens</i> )	8.62-13.79	92 (mature in 5-8 years)	159.4 (after 20 years)	Isagi et al., 1997

(Source: Widenoja, 2007)

In addition to the already mentioned implications, the development of SWB potential or other bamboo products in general, either in Japan or other regions where bamboo are able to provide various ecological services through the sustainable management of the bamboo plantation. One example is to maintain biodiversity by providing habitat and food source for some endemic species such as panda in China and bamboo lemur in bamboo plantation area as long as the plantations' condition is maintained to be close to its natural condition where bamboo, shrubs and some other broadleaves tree grow together (Lou & Henley, 2010). Another example is the well-managed bamboo plantation

will result in beautiful landscapes that provide amenity service and may also attract tourists and generate income to the community.

#### SWB Potential Development and Deforestation

At the same time, among the timber exporting countries counterpart, the development of SWB potential in Japan or other countries may contribute to the reduction of deforestation due to the decrease demand of timber. However this possible implication may also work oppositely due to the general relationship between price and demand. Because of the declining demand of timber which generally results in declining price, the more timber is needed to earn the same amount of income as previously or it may also lead to the land use change such as conversion into bamboo plantation or other uses which are thought to be more profitable. Considering these undesired possibilities, increasing awareness about the importance and holistic roles of forest ecosystems may become one of the fundamental approaches in addressing deforestation.

#### SWB Potential Development and Rural Area Development

While in general, the development of SWB potential or other bamboo products may contribute to rural area development. First, it may become one of the sources of income generation for the community. As mentioned before, from the harvested bamboo, various parts of it can be used to produce lots of specific product (Table 7).

Further, since most of bamboo industries are labor-intensive; bamboo industries provide huge employment opportunities. The development of bamboo industries also affects the development of other related industries such as construction, machinery, packaging, tourism industry, etc. and other sectors in the society such as communication and transportation.

As the result, bamboo related industries have been used as a mean for poverty alleviation and rural area development in some places. For example is the case of poverty alleviation in Lin'an, China where bamboo shoots industry is the main industry; in early 1980's (before the bamboo shoots industry development in 1985) the annual per capita net income was less than US\$50, however in 2002, the annual per capita net income became

US\$654 (Zhu & Yang, 2004). Another example is rural area development in Anji, China where bamboo panels industry is the main industry (Zhu, 2010).

### SWB Potential Development and Culture

Bamboo industries may also contribute in nurturing the bamboo culture in the regions where bamboo inhabits. Bamboo which usually grows or is planted close to human settlements has embedded to people's daily life. Many of the cultural aspects of community who lives in bamboo growing countries are related to bamboo. It can be seen through many of traditional music instruments, handicrafts and toys are made of bamboo; traditional dishes use bamboo shoots as the ingredient or are prepared by using bamboo culms, leaves or sheaths; some cultural practices (i.e., tea ceremony in Japan) use bamboo as the material for the equipments. With the advancement in the society, the demand of those traditional or cultural goods tends to be declining; however, development of bamboo industries which may ensure the availability of bamboo material which is used to make those goods may enhance the possibility of the culture to be passed to the next generation.

Those are some of the possible implications and benefits of bamboo products potential development especially the Strand Woven Bamboo (SWB). However, several constrains may hinder the potential development.

#### *5.1.2 Constraints toward Development of Strand Woven Bamboo Potential*

In Japan, bamboo plantations are currently being abandoned in many places due to the change in life style and the availability of cheap imported bamboo products (Kondo, 2007). The abandonment of bamboo plantations that has taken place for long time<sup>10</sup> has caused those plantations to be overly dense and have low productivity. Considering this situation, in order to develop the SWB potential, restoring and managing those bamboo plantations thereby they can provide sustainable supply of bamboo material is the basic requirement. However, some factors such as availability of human resource and

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<sup>10</sup> For example, in Oita Prefecture the abandonment of bamboo plantation has started since 1993 (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009)

economic factors may inhibit the restoration of those plantations and later development of SWB potential.

One constraint in restoring the plantation is the lack of qualified human resources. According to the survey done in Oita Prefecture, most of the owners or managers of the bamboo plantations are advanced in age and they have no successor (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009). As the result, even though they are willing to manage their plantations, the manageable area is limited; especially the bamboo plantations which are located on steep slope are difficult to be managed. In addition, the fact that they have no successor may affect the result in restoring and managing the bamboo plantations, particularly in the areas where are unmanaged by the elders, since managing bamboo plantation requires knowledge and skill that can only be obtained through experience (Kotani, 1999). The absent of successor may also affect the ability to ensuring sustainable supply of bamboo resources in the future if the industry is developed.

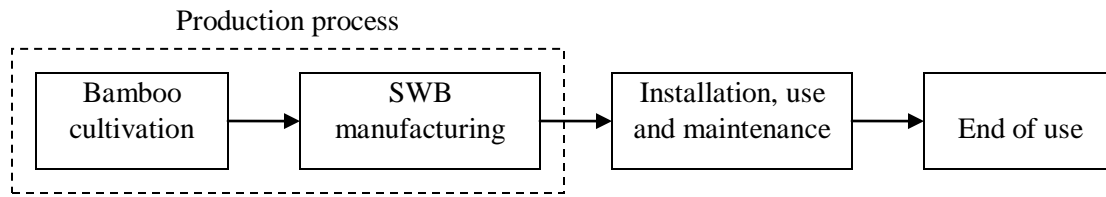
Another constraint is the availability of initial investment. First, considerable amount of cost is required in order to restore the bamboo plantations; it may include the cost for labour, transportation to remove the culms, fertilizer, wild boar prevention<sup>11</sup>, etc. Further, in order to establish the industry, initial capital which may include land, machinery, etc. is also needed. However, the profitability of developing SWB potential in Japan is still unclear; as the result people may be hesitate to make investment to develop this potential.

### *5.1.3 Cautions in Developing Strand Woven Bamboo Potential*

In developing Strand Woven Bamboo (SWB), some aspects related to the current production process of SWB (particularly in the origin country, China) should also be re-examined and improved. It is because some practices in the current production process bring negative impacts to human beings and the environment along its life phases.

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<sup>11</sup> According to the survey done in Oita Prefecture, the bamboo shoots are frequently eaten by wild boars (Oita Prefecture Agriculture, Forestry and Fisheries Department, 2009).



### **Strand Woven Bamboo Life Phases**

#### Monoculture Bamboo Plantation

First point to be re-examined in the current production process is the way of bamboo cultivation. At present, most of the bamboo plantation in China are managed to produce high yield of bamboo products through monoculture plantation system (Lou & Henley, 2010). This monoculture practice incorporates clearance of other vegetations including tree saplings, shrubs and undergrowth to provide greater space, nutrients and water for bamboo; this clearance is usually done twice a year. In addition, topsoil tillage, chemical fertilizers and pesticides application are also done on regular basis.

Even though this monoculture practice raises the yield of the bamboo plantation in the beginning; adopting this practice should be reconsidered since this type of practice brings negative impacts both to the environment especially in term of biodiversity and to the plantation itself in the long term.

The negative impact of this monoculture practice toward the biodiversity for example is the lower diversity of shrub and grass in monoculture bamboo plantation (31 species) compared to the polyculture bamboo plantation (58 species) due to the clearance (Lou, 2009). The number of bird species that can be seen in monoculture bamboo plantation is also lower compared to the polyculture bamboo plantation; in Hunan, 15 species of bird were observed in monoculture plantation compared to 35 species in the nearby polyculture plantation; while in Sichuan, 12 species were observed in monoculture plantation compared to 34 species in nearby the polyculture plantation (INBAR Bird Diversity Project in Lou & Henley, 2010).

Monoculture practice is also not good to the plantation itself; the conversion into monoculture plantation has disturbed the interactions among the organisms in that ecosystem. As the result, monoculture bamboo plantation is more prone to pests attack since the natural competitors of those pests may have been removed together with other vegetations during the clearance. According to the study done by Zhang et al (2000) in Fujian Province; monoculture bamboo plantation is more prone to mite infestation compared to polyculture bamboo plantation. Mite damage in the monoculture plantation (35%) was on average twice as high as that in the polyculture plantation (17.5%) (Zhang et al, 2000).

In addition, monoculture plantation is more prone to extreme weather condition such as wind and snow; and soil erosion (Lou & Henley, 2010). Moreover, the soil quality in monoculture plantation is not as good as in the polyculture bamboo plantations (Zhou et al., 2006; Lou, 2009). This relatively poor soil condition in monoculture plantation leads to the application of fertilizer. However since the soil in monoculture plantation is easily eroded, the fertilizer application cannot work effectively; on the other hand, it may cause another environmental problem such as eutrophication.

In the long term, those changes in biodiversity and soil quality lead to changes in productivity of the bamboo plantation. Study done by Fu (2001) in Jianyang, Fujian Province found out that Moso bamboo produced in mixed stand with broadleaf trees had mean diameter 5-15% bigger than in the pure bamboo stand. The mean height and commercial height of Moso bamboo culms were also 4-14% and 9-21% higher in the mixed forest types compared to the pure bamboo stand (Fu, 2001). Study done by Lou (2001) in Anji, Zhejiang Province and Jianyang, Fujian Province also revealed that an 11 year old monoculture bamboo plantation declined in productivity by 25% (in Lou, 2009).

#### SWB Manufacturing Processes

The manufacturing stage of SWB can be specified into bamboo strips preparation which includes cutting and splitting of the bamboo culms, preservation etc.; and lumber

formation which includes gluing of the strips, moulding and so on (Appendix 3). The following are some points in the manufacturing process that are potentially improved.

#### Energy Consumption

The manufacturing process of SWB in overall is energy and labour intensive. Each of the steps in the manufacturing processes consumes energy to run the machines and human power. However the energy consumed in each steps is different between one and another. According to the study done by Van der Lugt et al. (2009), the drying process, which is done after the boiling process for preservation or heat-pressure treatment for carbonization (colouring), consumes the highest energy relative to other steps within the manufacturing process.

#### Hazardous Substances

At present, Phenol Formaldehyde resin (PF) is used to glue the bamboo strips together in making SWB. PF is considered as hazardous partly due to the formaldehyde contain. Formaldehyde is toxic to some aquatic animal and has been shown to cause cancer in animals (US EPA; WHO, 1991).

While among human, the effects of exposure to formaldehyde are varied depends on the level of exposure and the individual health condition; the effects range from eye, nose, and throat irritation; wheezing and coughing; fatigue; skin rash; severe allergic reactions; or even cancer (US EPA). Due to the health hazard of PF resin, the workers in the SWB manufacturing may be at risk if the working environment does not provide good air-circulation and they do not take appropriate protective measure.

The use of PF resin in SWB also affects the consumers during its utilization phase since the installed SWB continues emitting the hazardous gas (i.e., formaldehyde) even though the amount of emission declines through time.

Beyond, the use of PF resin may also affect the fate of SWB in the end of its first service life. The utilization of SWB in its next life may be restricted to re-using it for similar



applications; recycling SWB especially which includes combustion process may be harmful since it will emit toxic and carcinogenic gas. In other words, disposing SWB in the end of its life may require complicated methods in order to minimize its negative impacts.

#### *5.1.4 Other Factors Affecting SWB Substitution Potential*

##### Substitution Potential ~ Durability

In assessing the substitution suitability between two or more building materials, durability is another important aspect that must be taken into consideration, particularly for groundwork and structural building material. The durability of a building material depends on many factors; the internal factors such as the material itself and the external factors such as the environment where the building is located, building design, maintenance, etc.; as the result, it is quite difficult to determine whether a building material is durable or not. For this reason, looking at the definition of ‘durability’ might give a better idea on how to indicate a building material as durable.

“Two definitions of durability and definition of a related concept, serviceability, which appear in the standards prepared by ASTM Committee E-6 on Performance on Building Construction are:

- Durability: the safe performance of a structure or a portion of a structure for the designed life expectancy. (From ASTM Recommended Practice for Increasing Durability of Building Construction against Water-Induced Damage (E241-77)).
- Durability: the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time. (From ASTM Recommended Practice E632).
- Serviceability: the capability of a building product, component, assembly or construction to perform the function(s) for which it is designed and constructed. (From ASTM Recommended Practice E632).”  
(Frohnsdorff & Masters, 1980)

Based on the above definitions, it can be understood that the durability of a material is indicated by a time span during which the material is able to function well and perform safely. In terms of structural building material, the main function is to provide structure to the building and bear loads. Therefore, if the structural building material can provide the structure to the building and bear loads without harming the existence of the building; that structural building material can be considered as durable.

By considering the function, one approach to determine building material durability is by using the building material's life expectancy as the indicator. If the structural building material is assumed to be fixed without any replacement during the life span of the building, then the life expectancy of the structural building material must be longer than the life expectancy of the building in order to perform well and safely.

In the case of Japan, the average life expectancy of residential buildings is approximately 30 years (Akahori, 2009). However, this life-expectancy is not the actual service life expectancy of those residential buildings; it is the time-span between the construction and the dismantling of that building. The short life expectancy of residential building in Japan is mainly driven by how the real estate company put value on old residential buildings and the change in family structure (Akahori, 2009). Therefore, it is highly possible that the condition of those dismantled buildings is actually still livable. With the increasing awareness on the environment, the life expectancy of the buildings in Japan is more likely to be extended in the future. For this reason, in order to understand the substitution potential of SWB particularly to serve as an alternative to structural wooden building material more comprehensively, this aspect should also be examined.

#### Substitution Potential ~ Regulatory Restrictions

Another factor that affects the potential of building materials substitutability is the ability of those building materials to meet each other's regulatory restrictions. Since this study focuses on examining the SWB and wood substitution potential, only regulations that are related to wooden building material are discussed here.

## Building Standard Law and Regulation

### *Fire Safety*

The application of wood in buildings is restricted by various characteristics of it. Since wood is a combustible material, the use of wood as building material or building structure is restricted by the law and regulation related to fire safety. The ability to withstand fire and heat for a designated period may indicate the fire-safety quality of one building material. Based on the length of the time a certain material is able to withstand heat and fire; building materials are categorized into incombustible material (at least 20minutes<sup>12</sup>), quasi-incombustible material (at least 10 minutes<sup>13</sup>) and fire resistant material (at least 5 minutes<sup>14</sup>). Since the level of fire-safety requirement depends on type of application, building function, location etc.; the ability of each material to withstand heat and fire is also different; detail information is needed in examining this aspect of substitutability.

### *Indoor Air Quality*

Sick House Syndrome (SHS) or usually known as Sick Building Syndrome (SBS) in the West refers to “a temporary phenomenon in which the building occupant experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified” (Friis, 2007). It is possibly caused by one or the combination of inadequate ventilation, the presence of biological contaminants and chemical contaminant from outdoor or indoor sources. In addition to the mentioned possible causes of SBS, the risk of SBS occurrence may increase by inappropriate building designs, hazardous building material and occupants’ lifestyle especially which lead to insufficient ventilation and increase the contaminants level (Yoshida & Ikada, 2007). As part of the measure toward this SBS, the Japanese government enacted law and regulation<sup>15</sup> that aims to control the prevalence of SBS by restricting the use of building materials that emit chlorpyrifos and formaldehyde<sup>16</sup>.

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<sup>12</sup> Building Standard Law Chapter 2 (9) (建築基準法第2条第9号)

<sup>13</sup> Enforcement Order No.1 Article 5 (建築基準法施行令第1条第5号)

<sup>14</sup> Enforcement Order No.1 Article 6 (建築基準法施行令第1条第6号)

<sup>15</sup> Building Standard Law Chapter 28 Section 2 (3) (建築基準法第28条の2第3号);  
Enforcement Order No.20 Article 7 & 8 (建築基準法施行令第20条7号&8号)

<sup>16</sup> Chlorpyrifos used to be used as anti-termite treatment for wooden flooring; while formaldehyde is contained in most of composite wood since where it is used as adhesive (Takagi, 2009).

Based on that law and regulation, any building material that contains chlorpyrifos is prohibited to be used in habitable space. While the restriction of using formaldehyde contained building material goes together with the classification done by Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and JAS (Japan Agricultural Standard) related to the amount of emission of formaldehyde emitted by each building material. The building materials that belong to Class I are prohibited to be used in buildings. Building materials that belong to Class II and Class III are restricted to be used in habitable space under certain circumstances related to the ventilation system.

**Table 9 Classification of Building Material based on Formaldehyde Emission**

<b>Classification by MLIT</b>	<b>JAS Marking</b>	<b>Amount of formaldehyde emission (mg/m<sup>2</sup>/h) in summer season</b>
Class I	JAS ☆	More than 0.12
Class II	JAS ☆☆	0.02-0.12
Class III	JAS ☆☆☆	0.005-0.02

(Source: Takagi, 2009)

#### *Quality and Size*

In order to assure the safety of the building, the Law and Regulation in Japan provides the calculation method to determine the minimum requirement of structural strength of a certain building in bearing load. As generally known, the minimum structural strength requirement between one building and another are different depends on the type of the building, the material, location, etc. In order to simplify the method in examining the minimum quality requirement of the wooden structural material, physical appearance and size inspection of the timber is adopted.

The following are some of the minimum quality requirement of wood used for structural purposes:

- The wood used for structural purposes must be flawless such as those related to knots, decay, grain, wane etc<sup>17</sup>.
- The horizontal structural member (e.g. beams, girders, etc.) must be flawless in and around the middle part<sup>18</sup>.
- The size of brace exposed to tensile force must have the thickness and width of more than (1.5cmx9cm); while the size of brace exposed to compression force must have the thickness and width of more than (3cmx9cm)<sup>19</sup>. In addition to it, the wood material used for the brace must be flawless.
- The dimension of the small diameter of the posts in wooden structure must be relative to the distance between two the horizontal structural members (e.g. beams, girder, etc.) as shown in the following table<sup>20</sup>.

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<sup>17</sup> Enforcement Order No. 41 (建築基準法施行令第41条)

<sup>18</sup> Enforcement Order No. 44 (建築基準法施行令第44条)

<sup>19</sup> Enforcement Order No. 45 (建築基準法施行令第45条)

<sup>20</sup> Enforcement Order No. 43 (建築基準法施行令第43条)

**Table 10 Dimension of Small Diameter of the Post Relative to the Distance between Two Horizontal Structural Members**

Type of Construction	Posts			
	Posts that attached to two horizontal structural members which are apart for more than 10m or posts of buildings designated for specific purposes*		Posts of other than mentioned in the left column	
	Posts of the top floor or one-storey house	Posts of other storey	Posts of the top floor or one-storey house	Posts of other storey
1. Big construction**	1/22	1/20	1/25	1/22
2. Light construction*** and other than (1)	1/30	1/25	1/33	1/30
3. Other than (1) and (2)	1/25	1/22	1/30	1/28

\*Building designated for specific purposes include school, gymnasium, theater, cinema, entertainment hall, public hall, assembly hall, commercial store (with total area more or equal to 10 square meters) or public bathhouse.

\*\*Big construction → constructions with thick wall such as timber structure with mud plaster finishing.

\*\*\*Light construction → constructions covered with light material such as metal plate, slate, asbestos, wooden board, etc.

(Source: Takagi, 2009)

#### Construction Material Recycling Law

In order to contribute to the realization of circular society particularly to ensure the efficient use of material, Construction Material Recycling Law was enacted in May 2000 (Ministry of Environment). This law requires the contractor to sort out and recycle the specified construction material; one of the materials specified is wood construction material. The sorted wood material should be recycled either by using it as material input for other industries or by thermal recycling (waste to energy); however the former is given priority.

### Substitution Potential ~ Marketability

Marketability gives an insight about the practical substitution potential of SWB from the economic point of view and the ability to meet the consumers' demand competitively is essential. Particularly for substitution goods, the competitiveness of two or more substitution goods in meeting the consumer demand is influenced by the following factors; the functionality and the price of the goods compared to one and another, and consumer preference (Tian, 2011).

The functionality factor is the basic requirement for two or more substitution goods to have in common. In the case of substitution potential between SWB and wood in Japan, the functionality factor is basically the ability of the two materials to perform as building material in relatively the same way.

On the other hand, the price (along with the availability of supply) can be considered as the main economic factor that drives the substitution event to happen. For example, in the case of SWB and wood, when the demand of wood rises, the price of wood will also rise; as the reaction, the consumers try to look for possible substitutions that can function in the same way as wood and have price within the consumers' affordability range. If the function and the price of the SWB can meet the consumers' demand, then it can become one of the substitutions for wood. This substitution may repeatedly happen on both sides until it reaches equilibrium at a certain point. However, this study emphasizes on the substitution of locally produced SWB and wood, therefore the price of that locally produced SWB should not only be competitive to the wood price but also to the imported SWB. It should also consider other potential alternatives that may substitute wood in Japan.

Another factor that affects product substitution potential in terms of marketability is the consumer preference. This factor brings in another aspect besides the function and the price in determining the substitution potential since consumer preference is also influenced by other consumer's background which includes sex, age, health, education, knowledge and also the changes in the society. According to the study done by Wahl et al.

(1999) regarding the wood use in Japanese residential windows and flooring; apart from the design, the health and environment aspect are the criteria in choosing building material. Based on this information, it can be understood that the health and environmental aspect of SWB may become significant factors in determining its substitution potential in term of marketability.

## **5.2 Conclusion and Recommendation**

This study focuses on examining the potential of Strand Woven Bamboo (SWB) as an alternative to wood constructional material in Japan from two basic perspectives, the physical properties (Chapter 3) and the availability of bamboo resources (Chapter 4). The outcomes from examining the SWB potential from those two perspectives are as follows.

In terms of physical properties, SWB may potentially become an alternative to wood constructional material in Japan under certain circumstances. While from the perspective of availability of bamboo resources, the study estimates that approximately 9651m<sup>3</sup> of SWB is potentially produced annually by using the Moso bamboo culms cultivated in Oita Prefecture under proper plantation management.

The development of SWB potential in Japan or other countries may potentially bring some positive outcomes and contribute to relieving the deforestation issue. However in order to develop the SWB potential either in Japan or other countries, some tasks are still needed to do beforehand.

First, regarding the constraints to the development of SWB potential; the location of bamboo plantation, the availability of labor force to restore the bamboo plantation and engage in the production activities, way to motivate people to engage in bamboo related industry and the cost-benefit analysis of SWB development are some factors should be clarified to address the constrains.

Second, as mentioned previously, some of production processes of SWB may be harmful to human beings and the environment; with the current production system the advantages



of SWB may become insignificant due to the negative impacts come during its production process. For this reason, further study related to the environmental performance of SWB should be done to provide better idea which will be useful in decision making.

At the same time, improvement by promoting more responsible production processes is also required to minimize the undesirable impacts. For example, in cultivating bamboo, rather than practicing monoculture plantation which produces short term benefits and bring negative impacts to the environment, it is better to practicing mixed plantation or intercropping which produces long term benefits. Another example, when fertilizer application is needed, organic fertilizer should be given priority; or just like being practiced in some places in China, instead of using fertilizer, they rely on the poultry excrement which raised in the plantation to fertilize the soil. However, since the suitability of each practice is different for each area; selectively incorporating the local practice and traditional knowledge and the new idea may become one of the approaches.

Another improvement should be done to SWB manufacturing process is to minimize the energy consumption during the whole process. First is by re-examining the significance of each step to the whole process and the outcome of the product. Second is by indicating the high energy consumption steps (i.e., the drying process) and trying to adopt less energy way if possible. Further, to minimize the environmental impacts come from the production process, it is suggested that renewable energy should be used whenever possible.

Next, since manufacturing process of SWB uses hazardous substances (PF resin) especially when it is not handled properly; the replacement of this resin by other less hazardous one as preventive measure is recommended. However, since the resin also influences the physical properties of the material; research is needed to identify the suitable replacement of the resin.

Lastly, since this study relies completely on secondary data in exploring the physical properties of SWB and the availability of bamboo resource; experimental based research on the physical properties of SWB and field research related to the availability of bamboo resources might be required to have better understanding about these two aspects. Moreover, to understand the SWB substitution potential more comprehensively, examining the substitution potential from other perspective such as policy aspect, economic aspect, social aspects etc. should be done.

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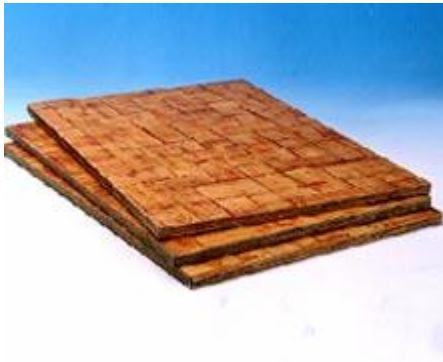
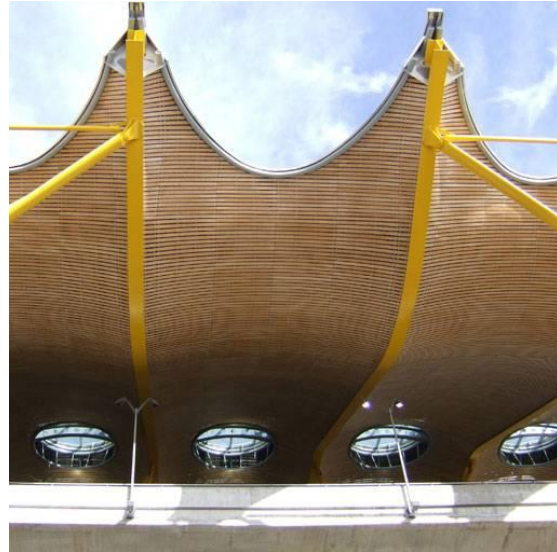
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## Appendix 1: Pictures of Bamboo Building Material



**Bamboo Ceiling in Terminal 4 Barajas Airport, Madrid, Spain**  
(Source: MOSO Group)



**Bamboo Mat Board**  
(Source: National Bamboo Mission, India)



**Bamboo Mat Corrugated Sheet**  
(Source: IPIRTI, India)



**Bamboo Zephyr Board**  
(Source: Sibusawa & Kin,1996)



**Bamboo Particle Board**  
(Source: Shibusawa & Kin, 1996)



**SWB as Structural Building Material in the Bamboo House, Anji County, China**

Reference:

Bamboo Ceiling Terminal 4 Barajas Airport, Madrid, Spain  
MOSO Group <http://www.moso-bamboo.com/>

Bamboo Mat Board  
National Bamboo Mission, Department of Agriculture & Cooperation, Ministry of  
Agriculture India <http://nbm.nic.in/glossary.html>

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## **Appendix 2: Criteria and Indicators of Building Material Physical Properties**

### *Characteristics of Structural Wooden Building Materials*

Wooden building material, just like any other building material regardless the type of material they are made of, can be broadly classified into four categories based on their utility. Those categories are:

1. Groundwork building material

Building materials in this category are used to make the foundation of the building. The main function of groundwork building material to provide support and base on which the building constructed.

2. Structural building material

The main function of building materials belonged to this category is to provide structure and shape to the building. Structural building material should be able to bear the load of the building itself and also additional loads which might be added during the utilization of the building and the environment load such as wind, snow, earthquake, etc. Structural building material includes components like groundsill, post, beam, and also boards for wall and floor (Akahori, 2006, p.62; Ching, 1998, p.327)

3. Fittings and fixtures

Fittings and fixtures include any material other than groundwork and structural building material; they are usually installed after the structural framework of the building well constructed and before the finishing material applied. Some example of fittings and fixtures are door and door frame, window and window frame, etc. (Akahori, 2006, p.66).

4. Finishing material

Finishing material is any material applied during the last stage of building construction. Each of the finishing material may have its own specific function, but in overall finishing materials have role to protect the building

from outside exposure and provide better appearance to the building. Finishing material include finishing floor, finishing wall, ceiling, etc (Akahori, 2006, p.64).

To enhance their performance, all of the building materials must share similar basic requirements regardless of which category they are belonged to. These requirements include strength, durability and dimensions' stability (Akahori, 2006; Iwamoto & Ozawa, 2009). Beside the mentioned requirements, aesthetic is also important especially for the finishing material (Iwamoto & Ozawa, 2009, p.76). At the same time, although the basic requirements are similar, the degree and type of strength, durability and stability needed for its components are different based on their own utility.

In general, groundwork and structural building material require higher degree of strength, durability, and stability compared to fittings and fixtures and finishing material. One of the basic reasons is because the function of groundwork and structural material are to support and bear the loads. Other reason is because groundwork and structural material in most cases are located inside the building structure which makes it difficult to visualize and to replace.

According to the descriptions above, it is obvious that the basic characteristics of wooden structural building material must be strong, durable and dimensionally stable. And these three characteristics can be said to be the minimum criteria of structural building material. Further, the indicators for each criterion are explained in more detail below.

### *Criteria and Indicators of the Suitability to Serve as Structural Building Material*

#### Strength of the Building Material

As stated earlier, the strength of building material is an important consideration in choosing structural building material. How much strength required and what kind of strength needed for each of the components might be different depending on various factors such as, the type of construction, the structural position of the component within

the building structure, the function of the building, the location of the building and many others.

One indicator to identify the strength of building material is the specific gravity of the building material. It is the ratio of the density of the material to the density of water. The specific gravity of wood in general is positively related to its strength (American Wood Council, 1993).

In term of the type of strength, in general the following types of strength are used as reference to indicate the strength in relation to deformation and other physical characteristics of building materials.

- Tensile strength

Tensile strength is the capacity of certain material to resist force that is applied perpendicular to the cross-sectional area; the force tends to elongate it in and tears it apart (American Wood Council, 1993; Ching, 1998, p.210; Serway & Vuille, 2007, p.206). For fibrous building material, tensile strength can be differentiated into ‘tensile strength parallel to the grain’ and ‘tensile strength perpendicular to the grain’ according to the direction the loads applied relative to the orientation of the fibers of the material (American Wood Council, 1993).

- Compression strength

Compression strength is the capacity of certain material to resist force that is applied perpendicular to the cross-sectional area; the force creates tendency to compress the material and crushes it (American Wood Council, 1993; Ching, 1998, p.210; Serway & Vuille, 2007, p.207-208). As is the case for the tensile strength, compression strength can also be differentiate into ‘compression strength parallel to the grain’ and ‘compression strength perpendicular to the grain’ for fibrous building material (American Wood Council, 1993). High compression strength parallel to the grain is usually demanded for building material components which are positioned vertically to support the loads put on it such as the column (American Wood Council, 1993; Scott, 1991, p.82). On the other hand,

compression strength perpendicular to the grain is highly demanded for building materials which are positioned horizontally such as building material used as groundsill.

- Bending strength

It refers to the capacity of certain material to resist force that is applied perpendicular to the cross-sectional area; the force creates tendency to compress the material in one side and at the same time elongate it on the other side (American Wood Council, 1993; Ching, 1998, p.211). High bending strength is especially important for material used horizontally and to support loads such as beam (American Wood Council, 1993; Scott, 1991, p.29).

- Shear strength

Shear strength is the capacity of certain material to resist force that is applied parallel to the cross-sectional area; the force tends to cause one section of the material slide along the other section of the material in parallel direction (American Wood Council, 1993; Ching, 1998, p.211; Serway & Vuille, 2007, p.207).

Other indicators that are useful to give idea about the strength of certain building material may include modulus of elasticity (MOE) and modulus of rupture (MOR) (American Wood Council, 1993).

Modulus of elasticity (MOE) is the parameter of stiffness of certain material; the larger the number of MOE, the more rigid and difficult to be deformed (Serway & Vuille, 2007, p.205). MOE can be calculated by dividing the force applied per unit area by the deformation caused by it. The force applied is usually in the form of tension, compression or shearing. MOE is usually constant within the elastic limit for each material. An object undergoes deformation within the elastic limit of the material and tends to return to its original form; deformation taken place beyond the elastic limit tends to be permanent (Serway & Vuille, 2007, p.207).

Modulus of rupture (MOR) is the measure of brittleness of a certain material; the larger the number of MOR, the more difficult the material to be broken apart. Just like MOE, MOR is also calculated by dividing the force applied per unit area by the deformation caused by it. The force applied usually refers to the breaking stress (Scott, 1991, p. 282).

For all of the type of the strength and strength parameter, the degree of strength of the building material mainly depends on the nature of the material itself which later may be altered through some processes when it is used to make different building material components.

#### Durability of the Building Material

Another criterion used in assessing the suitability of a certain building material is to serve as structural building material is durability. Since, the durability of a building material depends on many factors; the internal factors such as the material itself and the external factors such as the environment where the building located, building design, maintenance, etc.; it is difficult to determine whether a building material is durable or not. For this reason, looking at the definition of ‘durability’ might give better idea on how to indicate a building material as durable.

“Two definitions of durability and definition of a related concept, serviceability, which appear in the standards prepared by ASTM Committee E-6 on Performance on Building Construction are:

- Durability: the safe performance of a structure or a portion of a structure for the designed life expectancy. (From ASTM Recommended Practiced for Increasing Durability of Building Construction against Water-Induced Damage (E241-77)).
- Durability: the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time. (From ASTM Recommended Practiced E632).



- Serviceability: the capability of a building product, component, assembly or construction to perform the function(s) for which it is designed and constructed. (From ASTM Recommended Practiced E632).”  
(Frohnsdorff & Masters, 1980)

#### Building material’s life expectancy

From the above definitions, the durability of a material is indicated by a time span during which the material able to function well and perform safely. In terms of structural building material, the main function is to provide structure to the building and bear loads. Therefore, if the structural building material can provide the structure to the building and bear loads without harming the existence of the building; that structural building material can be considered as durable.

By considering the function, one approach to determine building material durability is by using the building material’s life expectancy as the indicator. If the structural building material is assumed to be fixed without any replacement during the life span of the building, then the life expectancy of the structural building material must be longer than the life expectancy of the building in order to perform well and safely.

#### Dimension Stability of the Building Material

Dimension stability of the building material represents the behavior of the material toward the changes in the environment like humidity and temperature. This criterion is important to be taken into consideration on determining the suitability of a certain material to serve as structural building material since the dimensional change of a certain component of structural building material may affect the whole structure functionality. In addition, the strength of wooden material is closely affected by the temperature and relative humidity. “Wood increases in strength when cooled below normal temperature and decreases in strength when heated” (American Wood Council, 1993). Increase in relative humidity tends to cause increase in wood moisture content and result in the decrease of wood strength, while the decrease in wood moisture content result in increase of wood strength (American Wood Council, 1993).

## Shrinkage rate

In order to know how stable a certain material is, especially wood; the shrinkage rate for every one percent change in moisture content is commonly used as an indicator. The size of the material changes along with the change in moisture content; when the moisture content decrease the material tends to shrink and decrease in size and the same way oppositely. This indicator gives the idea on the ability of a certain material in maintaining its size toward the change in moisture content. The lower the shrinkage rate for every one percent change in moisture content indicate the more stable the material.

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### Appendix 3: Strand Woven Bamboo Production Process

#### 1. Planting-harvesting

The top part of harvested bamboo culms where most of the branches located is cut; it results in ~8m in length topped bamboo culms which serve as the input on the next process (Van der Lugt et al., 2009)

#### 2. Strips Preparation

- a. stocking of bamboo culms
- b. cutting the bamboo culms into three sections of 2.66m in length based on Chinese bamboo industry standard (Van der Lugt et al., 2009)
- c. splitting of the bamboo culms
- d. removing the green outer part and the inner nodes- result in relatively same measure of rough bamboo strips (2630\*23\*8mm (Van der Lugt et al, 2009))
- e. splitting strips into half thickness
- f. carbonizing and preservation
- g. cooling and drying
- h. crushing of the split strips

#### 3. Moulding the Strips into Lumber

- i. gluing
- ii. pressing strips into beams (compressing factor: 1.54 (Van der Lugt et al., 2009)
- iii. deforming prevention
- iv. taking out from the cast
- v. trimming and sanding

Cutting lumber into planks (to be used as flooring or paneling)  
- cutting and sanding  
- lacquering and UV sealing

The above processes are the major processes relating to the formation from bamboo culms into lumber or planks in producing Strand Woven Bamboo. However, in between the above processes, there are many other processes involved such as transportation, selection, etc.

#### Reference:

Bamfox, Hangzhou bamfox bamboo products Co., Ltd. 63 Lindong Road, Jincheng Town, Lin'an Hangzhou, Zhejiang Province 311300, China. <http://bamfox.com>

Van der Lugt, P., Vogtländer, J. & Brezet, H. (2009). Bamboo, a Sustainable Solution for Western Europe: Design Cases, LCAs and Land-use. INBAR Technical Report 30.

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## Appendix 4: Raw Material Requirement of Strand Woven Bamboo

Data obtained from:

Van der Lugt, P., Vogtländer, J. & Brezet, H. (2009). Bamboo, a Sustainable Solution for Western Europe: Design Cases, LCAs and Land-use. INBAR Technical Report 30.

Density of bamboo material:  $700\text{kg/m}^3$

Density of Strand Woven Bamboo (SWB):  $1080\text{kg/m}^3$  (Moso International)

Compression ratio = Density of SWB/ Density of bamboo material  
=  $1.08/ 0.7$   
= 1.5428

SWB beam dimension: (1.9m x 0.11m x 0.140m)

SWB beam volume:  $0.02926\text{m}^3$

Composition of SWB beam based on use:

- Outdoor use: 77% of the SWB volume is bamboo, 23% of the SWB volume is Phenol Formaldehyde (PF) resin

- Indoor use: 84.9% of the SWB volume is bamboo, 15.1% of the SWB volume is PF resin

(Assumption: density of PF resin is equal to the density of SWB)

Volume of bamboo strips needed for outdoor use SWB beam:

$(77\% * 0.02926) * 1.54 = 0.03469\text{m}^3$

Volume of bamboo strips needed for indoor use SWB beam:

$(84.9\% * 0.02926) * 1.54 = 0.03825\text{m}^3$

Raw material of bamboo to strips efficiency: 70% (Zaal, 2008 in Van der Lugt et al., 2009)

Raw material of bamboo: bottom-middle-upper part of the culm with length around 8m

*Japan's case:*

One soku = 25kg of bamboo culms (Kondo, 2007)

One soku of moso contains of 1-3 bamboo culms with (7-8) m in length and (0.08-0.13) m in diameter. (Fujihira Takeya)

Average density of moso bamboo material:  $760\text{kg/m}^3$  (<sup>1</sup>Experimental Forestry Station, 1982)

Assumption:

All culms in each soku are used as raw material for producing strips.

No material loss except for the conversion from culms to strips.

Volume of bamboo strips needed to produce one cubic meter of outdoor use SWB beam  
= (1/ volume of SWB beam) \* volume of bamboo strips needed for outdoor use SWB beam

=  $(1/ 0.02926) * 0.03469$

$$= 1.1856\text{m}^3$$

Volume of bamboo strips needed to produce one cubic meter of indoor use SWB beam  
= (1/ volume of SWB beam) \* volume of bamboo strips needed for indoor use SWB beam

$$= (1/ 0.02926) * 0.03825$$
$$= 1.3072\text{m}^3$$

Volume of bamboo strips can be produce from each soku of moso bamboo

= (weight of one soku/ average density of moso bamboo material)\* raw material to strips efficiency

$$= (25/ 760)*0.7$$
$$= 0.023\text{m}^3$$

Number of soku needed to produce one cubic meter of outdoor use SWB beam

= Volume of bamboo strips needed to produce one cubic meter of outdoor use SWB beam/ Volume of bamboo strips can be produce from each soku of moso bamboo

$$= 1.1856/ 0.023$$
$$= 51.55\text{soku}$$

Number of soku needed to produce one cubic meter of indoor use SWB beam

= Volume of bamboo strips needed to produce one cubic meter of indoor use SWB beam/ Volume of bamboo strips can be produce from each soku of moso bamboo

$$= 1.3072/ 0.023$$
$$= 56.84\text{soku}$$

Japan (2009)

Production of moso bamboo: 703000soku

Total area of moso bamboo plantation: 11837.6ha

Productivity of the plantation: 703000/ 11837.6 = 59.38soku/ha

Possible amount of Outdoor-SWB production by every hectare of bamboo plantation

$$= 59.38/ 51.55$$
$$= 1.15\text{m}^3$$

Possible amount of Indoor-SWB production by every hectare of bamboo plantation

$$= 59.38/ 56.84$$
$$= 1.04\text{m}^3$$

Total possible production of Outdoor-SWB in Japan (2009) = 13637.24m<sup>3</sup>

Total possible production of Indoor-SWB in Japan (2009) = 12368.05m<sup>3</sup>

Kyushu (2009)

Production of moso bamboo: 588000soku

Total area of moso bamboo plantation: 10001.7ha

Productivity of the plantation: 588000/ 10001.7 = 58.79soku/ha

Possible amount of Outdoor-SWB production by every hectare of bamboo plantation

$$= 58.79/ 51.55$$
$$= 1.14\text{m}^3$$

Possible amount of Intdoor-SWB production by every hectare of bamboo plantation

= 58.79/ 56.84

= 1.03m<sup>3</sup>

Total possible production of Outdoor-SWB in Kyushu (2009) = 11406m<sup>3</sup>

Total possible production of Indoor-SWB in Kyushu (2009) = 10344.83m<sup>3</sup>

Oita (2009)

Production of moso bamboo: 27000soku

Total area of moso bamboo plantation: 1776.8ha

Productivity of the plantation: 27000/1776.8 = 15.2soku/ha

Possible amount of Outdoor-SWB production by every hectare of bamboo plantation

= 15.2/ 51.55

= 0.29m<sup>3</sup>

Possible amount of Indoor-SWB production by every hectare of bamboo plantation

= 15.2/ 56.84

= 0.26m<sup>3</sup>

Total possible production of Outdoor-SWB in Oita (2009) = 523.76m<sup>3</sup>

Total possible production of Indoor-SWB in Oita (2009) = 475.02m<sup>3</sup>

Reference:

Forestry Agency

Van der Lugt, P., Vogtländer, J. & Brezet, H. (2009). Bamboo, a Sustainable Solution for Western Europe: Design Cases, LCAs and Land-use. INBAR Technical Report 30.

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