Bamboo Composite Materials for Low-Cost Housing

by

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Abstract

Investigation into the use of bamboo in composite panels for low-cost housing is presented.

Information on the housing situation, the state of the forest resources, and the needs for low-cost housing are given for Ecuador, which is seen as representative of countries with a history of bamboo use, and potential for further development.

Specifically bamboo particleboard using *Guadua angustifolia*, *Dendrocalamus strictus*, *Phyllostachys pubescens*, and *Bambusa vulgaris* manufactured with steam injection pressing is presented.

High strength panels including waferboard made from randomly placed and oriented *Bambusa vulgaris* wafers, bamboo particleboard overlaid with woven bamboo mats, and "picada panels" were developed.

Emphasis was given to short press times, low resin contents, and low product densities in comparison with previous technology to ensure economic viability. This investigation is a unique contribution to the science of composite products and has developed a number of panel products that are both technically and economically feasible. A discussion of economic, social and environmental issues surrounding bamboo industrialisation is also presented.

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Over the course of my graduate studies a great deal has happened in my professional and personal life. First of all, I wish to thank my parents. Without their love and support the last few years would have been an impossible challenge.

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Of course the greatest inspiration of all is Dave Turcke, my supervisor and research partner for the past many years. In spite of lack of financial support from major organisations, he managed to find the means to ensure that my studies could continue. His commitment, originality, and guidance were superseded only by his patience and encouragement as I learned through experience. I am forever grateful to him for his support throughout my journey of learning.

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Notation

BS	British Standard
CBPB	cement bonded particleboard
CDN	Canadian
IB	internal bond
°F	degrees Fahrenheit
GDP	gross domestic product
MDF	medium density fibreboard
MOE	modulus of elasticity
MOR	modulus of rupture
OD	oven dry
OSB	oriented strand board
PB	particleboard
PF	Phenol Formaldehyde
psi	pounds per square inch
TS	thickness swelling
SG	specific gravity
SW	screw withdrawal force
UF	Urea Formaldehyde
USD	United States of America dollar
WA	water absorption

$\perp$ perpendicular (this normally is associated with testing of bending samples and indicates that the alignment of the bamboo in the bottom layer of the testing sample is perpendicular to the long dimension of the bending sample)

// parallel (similar to the explanation above, except the bamboo in the bottom layer of the testing sample is parallel to the long dimension of the bending sample)

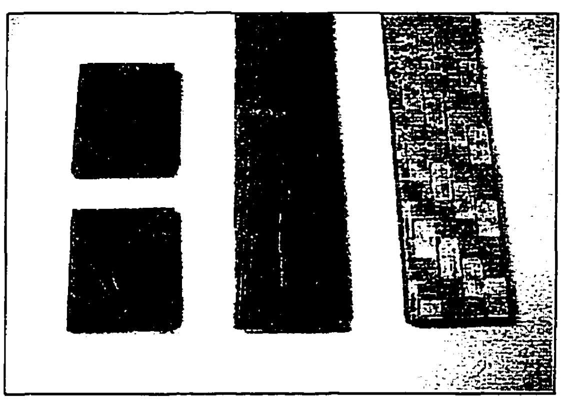
1.0 Introduction and Methodology

1.1 Introduction

This thesis, based on several years of field and laboratory investigation, is intended to fulfil several objectives. Firstly, it provides a background to bamboo and a review of much of the hard-to-find information relevant to the development of bamboo as a raw material, with specific attention given to low-cost housing.

Secondly, the specific testing conducted in the area of bamboo composites provides details of comprehensive and unique testing. While commercial operations of some bamboo panel products exist in China, they are often uneconomical and therefore have been limited in their application outside of niche markets. Through the development of economically viable products (Figure 1) that meet internationally recognised standards, this thesis provides new insight into the commercial possibilities of bamboo panel products.

Figure 1: Products Developed in This Thesis



Bamboo particleboard, bamboo waferboard, "picada panels", and bamboo particleboard overlaid with bamboo mats are depicted.

Thirdly, this work provides practical and viable alternatives to meet global pressures of low-cost housing (Figure 2), through an approach that recognises and respects environmental protection, limited fibre supply, and issues of socio-economic development in bamboo regions.

Figure 2: Low-Cost Bamboo Housing in Ecuador

1.2 Philosophy

The work presented in this thesis is intended to go beyond the conventional scope of civil engineering research in which building materials, or systems, are created and tested. Throughout the research concern has been given to the applicability of the outcomes in solving the specific problem of low-cost housing.

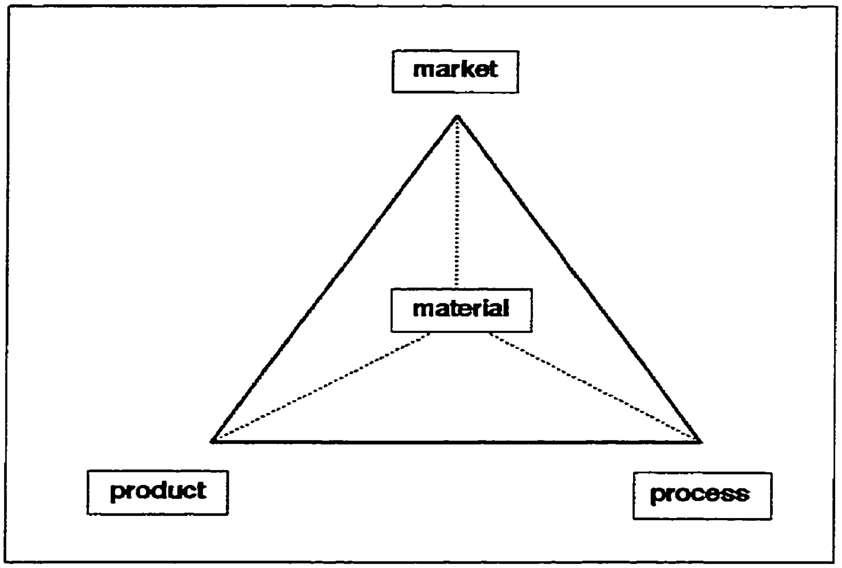
After initial research into conventional, and some might say "appropriate" technology of building with bamboo (e.g. "post and beam"), it was recognised that the material faces large obstacles before it could ever be accepted into modern building codes, thereby limiting the potential for bamboo in large-scale housing development projects.

The production of composites, however, has been shown throughout the world as useful in utilising undesirable tree species, and agricultural waste. Through controlled manufacturing processes, raw materials with large variability in properties, or simply inappropriate properties, can be converted to products of a specified size, shape, and performance level.

With that in mind, the testing results were always compared with properties of construction panels commonly available. In addition, the opportunities of export to international markets may be a critical factor in the financial viability of a commercial operation implementing bamboo composite technology, and therefore the panels developed were compared with the product standards for furniture-grade particleboards.

The Raw Material Utilisation Model (Figure 3) represents the interdependence of the competing factors in this research. Given a new raw material such as bamboo, the market, product, and manufacturing process all must be adjusted to allow for successful utilisation of the raw material. The inherent properties of bamboo (e.g. high density) can effect the major manufacturing variables, the basic properties of the product, and therefore it's application and desirability in the marketplace.

Figure 3: Raw Material Utilisation Model



Many of the well-known bamboo products, such as bamboo matboard and plybamboo, were developed based on traditional acceptance of bamboo, namely the use of "splits" long-used in weaving applications. The products that emerged have very specific characteristics (including performance well above the standards for wood products, and much higher manufacturing costs) that limit their market suitability.

The work presented in this thesis has been based on the desired application (low-cost housing) and the relevant required properties (internationally accepted material standards, and well-known economic standards of wood composite manufacturing). By recognising these constraints at the outset, the results of this research can be readily judged.

This work was conducted not only to demonstrate the commercial possibilities, although they are strong, but also to address basic questions, such as the use of resins and the impacts on worker safety (an overriding concern). While the resin used in most testing is based on petroleum products, the prudent use (less than half the amount used in commercial Chinese bamboo composite panels) will minimise environmental impact, and more importantly allow for high-quality products that are economically viable.

While the reduction of negative environmental impacts is a primary goal, the need for high-quality building materials that can be economically produced, and used with limited skills and tools to provide housing is the underlying concern.

The concerns of environmental protection, utilisation of a high-growth raw material (bamboo), and the need for new solutions to the housing crises in many countries make for a complex problem to solve. While technical solutions have long been provided by engineers, this thesis was intended to return to the true goal of civil engineering of improving the quality of life by addressing the underlying concerns of environmental protection, social acceptance of proposed technology, economic viability and public safety in addition to technical excellence and creativity.

1.3 Structure of Thesis

Because a major objective of the technical work is to provide solutions to low-cost housing, this thesis begins with a review of housing in Ecuador. Instead of simply referring to global statistics, it was decided that specific examples of the economic and housing reality in one country would better illustrate the special concerns and limitations of housing solutions.

Ecuador was selected as it has sufficient population and public infrastructure to provide reliable information. There is naturally occurring bamboo and potential for plantations to provide large volumes of bamboo for the implementation of bamboo composite solutions. While the conditions are not the same for all countries, Ecuador is seen as typical of many developing countries that suffer housing shortages and economic obstacles, while offering many factors critical in implementing solutions – skilled workers, a base level of industrial success, and a strong history of agricultural production and export.

With recent deforestation, Ecuador has serious limitations in meeting the local demand of wood products, and that concern is only expected to increase as the economically available wood supply continues to rapidly decrease.

Therefore, this thesis begins with an introduction to Ecuador in Chapter 2. The economic realities and specific references to the existing housing situation are presented including data on construction materials found in housing, the state of the housing stock, and financial concerns of the housing sector. A review of the state of the forest resources (including bamboo) is also presented to demonstrate the fact that Ecuador, a country with a strong history of wood utilisation, is facing tremendous pressures at the current time.

Much of the information on Ecuador is summarised from a study conducted by the author (Dagilis and Turcke, 1998).

Subsequently an introduction to bamboo is presented in Chapter 3. This information is relevant and important to the development of composite materials. Due to the difficulty of finding published bamboo research, an extensive review of major topics and the work by leading researchers is presented, along with complete references, so that the reader can assemble documentation on a wide-range of bamboo studies.

Because the specific goal of this research is to provide construction solutions based on bamboo, a review of bamboo panel products is presented in Chapter 4. The properties (good and bad) of bamboo matboard, plybamboo, and other bamboo panel products provides insight into the special concerns surrounding successful commercial production of bamboo panel products. Chapter 4 concludes with an overview of typical bamboo construction in Ecuador. Bamboo has been used for centuries in construction throughout the world, and the long history and continued use of bamboo in Ecuador provides an important and interesting framework for the evaluation of the current research.

With this comprehensive review complete, a study of bamboo particleboard in presented in Chapter 5. This work includes the initial testing based on *Guadua angustifolia*, and is presented in detail, along with statistical analysis of the results to provide a baseline study against which subsequent tests can be compared.

Given that there are 1300 (or more) species of bamboo, it was decided to work with other internationally known bamboo species. Three of the most important species were selected, and tested in composite panels. This phase of the research project is presented in Chapter 6, along with a comparison of the results of all four species used in bamboo particleboard against internationally recognised standards for construction and furniture-grade composite panels. Parts of this work have been published elsewhere (Dagilis and Turcke (1996 and 1997), Turcke and Dagilis (1995, 1996, 1997), and Barquero et. al. (1994))

Given the recent trends towards oriented strandboard as an alternative to plywood in Northern markets, work was conducted on developing higher strength bamboo panels, while maintaining low production costs (i.e. low resin consumption, low press times, and the reduction of manual preparation of bamboo common with bamboo matboard and plybamboo). Chapter 7 presents the work on three different approaches.

With specific reference to the conditions in Ecuador, and the results of the technical development of bamboo panel products presented earlier, Chapter 8 explains how bamboo panel technologies offer a sustainable, economical, and viable solution to the serious global concerns of low-cost housing.

Chapter 9 presents some overall conclusions, and recommendations for future work.

2.0 The Need for Alternative Housing Materials: Case Study Ecuador

2.1 Introduction to Ecuador

To understand the opportunities and obstacles for the use of bamboo in housing construction in Ecuador, it is critical to understand the social, economical and technical aspects of housing today. This chapter will deal with the social and economical aspects of housing in a broad way, leaving a review of specific construction technology and common building practices for Chapter 4.

Throughout this chapter a variety of sources are referenced, each representing different opinions, data, estimates, and projections. For that reason similar categories of data may be presented several times with differing estimates.

Ecuador is a country of approximately 12 million people (see Table 1), of which about 44.3% are economically active. Ecuador has an average population density of 44 inhabitants per square kilometre (Vicuña, 1997) and is commonly divided into three regions (Figure 4), namely the coastal zone, the Sierra (or mountain zone), and the Amazonia region (or east, or interior zone). The Galapagos region is treated as a separate case in most Ecuadorian studies, and is not included in this analysis.

Table 1 : Population and Area Statistics of Ecuador

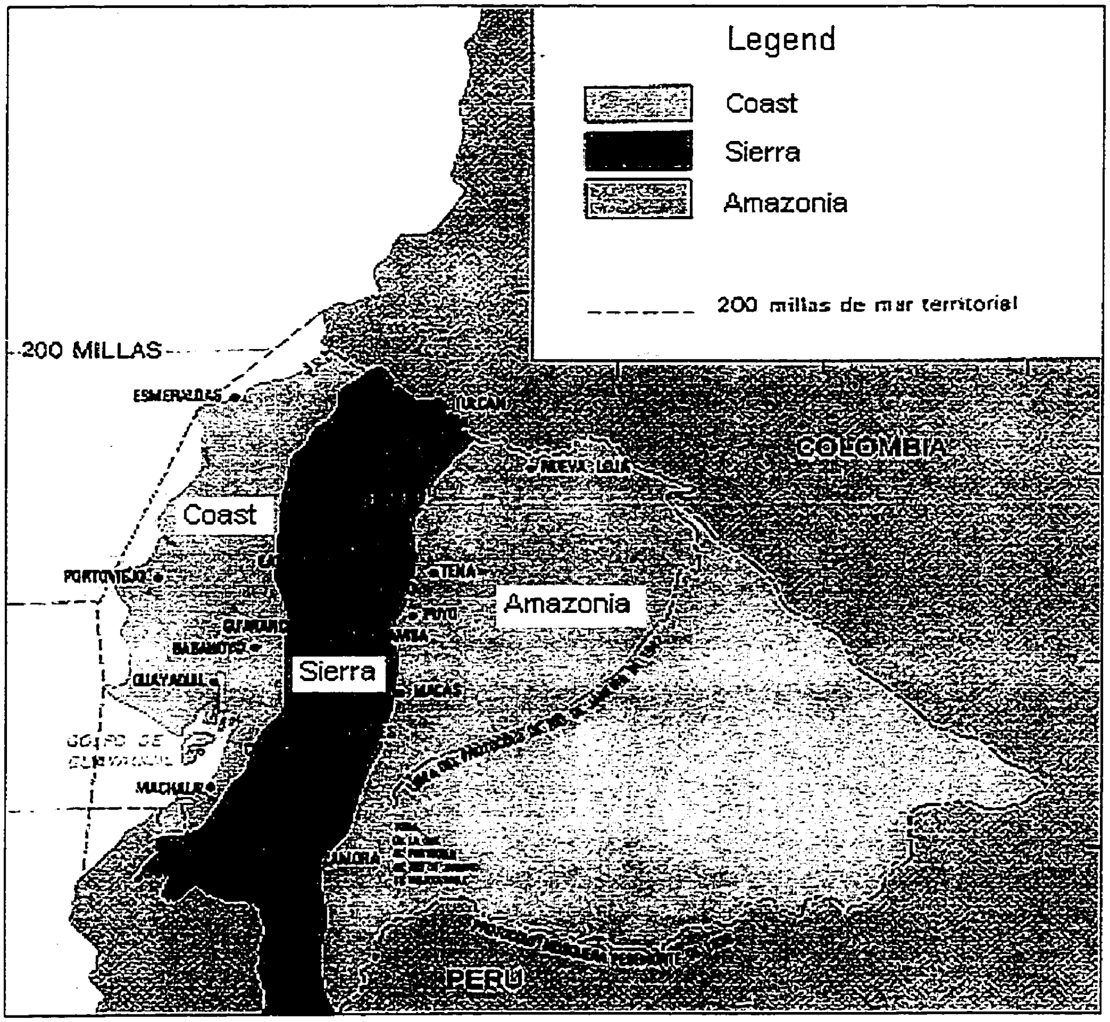
Region	Area (km²)	%	Population	%
Coast	66,600	24.65	5,957,200	49.91
Sierra	64,760	23.97	5,318,900	44.56
Amazonía	130,784	48.41	558,200	4.68
Galápagos	8,010	2.96	14,700	0.12
Total	270,154	100 [b]	11,936,900 [a]	100 [b]

Source: Vicuña, 1997

[a] There were 87,000 people living in undelimited areas.

[b] Percentages may not add to 100.00 due to rounding

Figure 4 : The Three Main Climatic Regions of Ecuador



Vicuña noted that 52% of the population lives in poverty - 35% in extreme poverty. Vicuña also estimated that approximately 67% of the rural population lives in poverty compared with 40% of urban dwellers. The per capita gross domestic product (GDP) is approximately $1500 USD per year. The minimum salary (which consists of the minimum wage, an additional 16% of minimum wage, cost of living compensation, and food and transportation additions) is approximately $165 USD per month. In many cases the "minimum wage" is not applied for agricultural work, and work agreements less than three months in duration.

Fuentes et. al. (1998) noted that in 1994 63.5% of the population lived under the poverty line, with a full 27.1% of the population below the "line of destitution" or extreme poverty.

2.1.1 The State of Housing Supply and Demand

Fernández (1996) estimated that the housing deficit will be 1.0 million houses in 2000 (see Table 2).

Table 2: Housing Deficit Statistics for Ecuador

Housing Deficit	Urban	Rural	Total
Deficit accumulated up to 1990	355,790	183,978	539,768
Quantitative Deficit	225,371	39,415	264,786
Qualitative Deficit	130,419	144,563	274,982
Expected Deficit increase 1990-2000	449,000	49,000	498,000
Projected Housing Deficit in 2000	804,790	232,978	1,037,768

Source: Ministerio de Desarrollo Urbano y Vivienda, 1994 (as cited in Fernández, 1996)

In "Construction Crisis" (Jacome, 1991), the author noted that the increase in housing demand over the last 25 years has averaged 60,000 homes a year.

Fuentes et. al. (1998) estimated the 1996 national housing deficit of Ecuador to be 1,328,000 houses, of which 980,000 were expected to be due to qualitative problems of existing housing stock.

In a paper presented at the Tenth Interamerican Housing Congress (FECC, 1991), it was estimated that of the expected 500,000 new homes needed in Ecuador from 1990-2000, 40% are in the Quito and Guayaquil metropolitan areas.

Barely 20% of the population of Guayaquil has the financial capacity for a basic home (36 m^2 house on a 72 m^2 lot) without financial assistance (FECC, 1991). With high inflation rates, and declining economic power through the 1970's and 1980's, construction as a percentage of the GDP in Ecuador fell from 7.6% in 1971 to 3.5% in 1990.

Fernández noted that the role of construction in the GDP of Ecuador fell to 2.5% in 1993 and that housing as a percentage of investment (both national and external) fell from 18.17% in 1973 to only 7.04% in 1993.

Approximately 17,000 houses per year were built through public programs (the main driving force of social housing construction in Ecuador) in the early 1990's (Fernández, 1996). This is clearly insufficient to meet the annual increase in housing stock demands, and therefore the housing deficit in Ecuador has continued to climb. Fernández estimated that an increase in construction to 50,000 housing units per year is required simply to maintain the current deficit, and that 103,000 homes must be built each year to eliminate the national housing deficit entirely within 10 years.

Bustamante et. al. (1996) noted that in Quito alone, there is an unmet demand for 8,213 housing units per year. Continued growth of the city will lead to an estimated demand for 69,591 housing units by the year 2000. According to overcrowding data (which assumed there should be no more than two residents per room), it could be said that there is a deficit of 199,450 housing units in Quito (Bustamante et. al., 1996).

2.1.2 State of the Housing Stock

Vicuña (1997) reviewed general living condition information gathered in 1994. Specifically in rural areas only 52.7% of the population has access to potable water, and only 27.7% have sanitary services, whereas in urban areas 85.9% have access to potable water, and 76.3% have sanitary services.

Data for 1982 shows that Guayaquil suffers from significant substandard housing (Table 3).

Table 3: Guayaquil Area Data of Housing Deficit, 1982

number of rooms	Houses		Occupants		number people /house	number people /room	Deficit of rooms		Deficit of houses	
	number	%	number	%			number	%	number	%
1	32,790	13.9	128,413	10.8	3.9	3.9	52,818	29	13,543	34
2	88,600	37.6	422,125	35.6	4.8	2.4	104,216	58	21,712	55
3	45,978	19.5	240,982	20.3	5.3	1.7	22,720	13	4,287	11
4	33,061	14.0	182,276	15.4	5.5	1.4				
5	18,574	7.9	105,816	8.9	5.7	1.1				
6	8,878	3.8	53,724	4.5	6.0	1.0				
7 +	7,783	3.3	52,266	4.4	6.7	1.0				
Total	235,664	100	1,185,602	100	5.03	1.74	179,869	100	39,542	100

Source: III National Housing Census, 1982 (as cited in Municipalidad de Guayaquil, 1984)

The 1982 Third National Housing Census (summarised by the Municipalidad de Guayaquil, 1984) provided further information regarding the substandard nature of the housing stock. It estimated that of the 235,644 houses in the metropolitan Guayaquil area, 22,320 (9.5%) were deficient in either roof, walls or floor, 46,908 (19.9%) were deficient in at least two components, and 25,806 (11.0%) were unacceptable for other reasons (terrain, tenure, or unexplained reasons). Only 60.0% of homes met basic standards of housing in the Guayaquil area in 1982 (numbers do not add to 100% due to rounding of percentages).

In addition, only 67.7% had access to public water supplies (51.8% in the house). The census also reported that 56.5% had exclusive sanitary services, 17.0% had communal services, 17.2% had latrines, and 9.2% had no sanitary services.

In Quito, the capital city with a population of 1,715,691 (Bustamante et. al., 1996) an estimated 42.5% of people live in poverty. The 1990 census revealed that 60% of the houses had access to potable water, and 58% access to sewerage. In the suburbs of Quito in which 68.8% live in poverty, only 51% had access to drinking water, and 24% sanitary services.

Bustamante et. al. (1996) also estimated that some 50% of the houses are in poor shape, and suffer from poor construction techniques due to self-construction, and the lack of enforced building codes and poor materials.

2.1.3 Land Tenure

Approximately half of the urban populations live in marginal zones (unserviced land subjected to flooding, erosion, etc.) (FECC, 1991). In Guayaquil, the worst situation in the country, some 58% of the population lives in marginal zones, with two out of three families living without legal tenure to the land.

Bustamante et. al. (1996) note that of Quito's 318,948 dwellings, 45.8% of housing units are owner occupied, with 43.8% rented (Table 4).

Table 4 : Housing Tenancy in Metropolitan Quito, 1990

Zone	Owner occupied	Rental	Free	Other
Urban	110,341	128,920	19,161	4,516
Suburban	35,785	10,909	9,038	278
Total	146,126	139,829	28,199	4,794

Source: INEC, 1991 (Censo de Vivienda 1990, as cited in Bustamante et. al, 1996)

2.1.4 Financial and Economic Aspects of Housing in Ecuador

The cost of construction relative to the average incomes in Ecuador is a great problem. Ultimately, it is the limited access to financial services and products such as credit, house mortgages, etc. which have the greatest effect on the poor.

Fuentes et. al. (1998) reviewed some of the financial requirements of past housing programs in Ecuador (Table 5). Although it is not useful for direct comparison as no details of the housing projects (house size, location, building materials, yard size, etc.) were given, it does show that even the lowest cost programs are beyond the reach of much of the population.

Table 5: Financial Requirements of Housing Programs in Ecuador

Housing Program	Minimum Initial Payment [1]	Initial Monthly Payment [1]
Sauces VIII (1988) (public housing project)	$ 200	$ 80
Abel Gilbert (1993) (public housing project)	$ 750	$ 90
Sauces IX (1995) (public housing project)	$ 6,667	$ 117
Samanes V (1996) (private housing project)	$ 6,060	$ 364

Source: Fuentes et. al., 1998

[1] USD values are at the reference date

Fuentes et. al. (1998) do refer to the "Un Solo Toque" program which was directed at workers in the informal economy who earn less than $106 USD per month. The customers of this housing program were expected to pay up to $15 USD per month towards the housing costs. High interest rates are also a problem. Fuentes et. al. noted (Table 6) that a number of banks have financial services directed at home-buyers, but little additional information was given as to the required incomes, assets, and other commonly requested information that banks would request before lending.

Table 6: Private Credit Markets in Ecuador

Institution	Amount Financed	Maximum Term	Interest Rate
Banco Amazonas	80% of new house 70% of used house	15 years 7 years	38% (sucres) 15% (US dollars)
Banco de Guayaquil	70% of new house	15 years 7 years	39% (sucres) 15% (US dollars)
Banco del Pacifico	70% of new house [1]	15 years	37%-42% (sucres, readjusted annually)
Banco del Pichincha	70% of new house 60% of used house 80% of construction	15 years	no rate given, readjusted annually
Banco Finec	80% of new house	15 years	46% (sucres) 16% (US dollars)
Banco La Previsora	70% of new house	15 years	46% (sucres) 16% (US dollars)

Source: Fuentes et. al., 1998

[1] Banco del Pacifico also offered up to 50 million sucres for construction costs, and 15 million sucres for remodelling.

Given that a social interest house (made from concrete) may cost $5,000 USD, it is clear that it would be difficult for most families in Ecuador to raise the 20% or 30% needed as a downpayment. Clearly, alternative, and more appropriate solutions are required.

Hogar de Cristo, a church-run housing organisation, offers credit financing to its clients. The houses (introduced in Section 2.2.3.3) are basic, and are intended to provide basic shelter to the people most in need of housing. Although the houses cost only approximately $500 USD, most people choose a Hogar de Cristo house because they offer an 18 month financing package. For the smallest house model, clients must pay an initial deposit, and the equivalent of less than 20 USD per month for 18 months. This credit payment system is the key aspect that allows them to obtain a house.

2.1.5 Summary

In this section information regarding the number of houses and state of the housing stock in Ecuador was presented. It is clear that a significant deficit of housing exists in the country, and that much of the existing housing construction is unsuitable.

This housing deficit has the greatest effect on the rural and urban poor, as they can least afford the cost (and are unlikely to have access to credit) of building a home.

Given this, it is important to reflect on the construction technologies, and the use of bamboo with specific thoughts for the urban and rural poor. This might include opportunities for "auto-construction", low-cost technologies, and financial services for the members of the informal economy.

2.2 Traditional Housing Construction Technologies in Ecuador

2.2.1 A National View

There are distinct forms of construction found in the three climatic regions of Ecuador: the Sierra; the Amazonia region; and the coastal zone (Figure 4). The Galapagos zone is separate from these, and due to the unique conditions that make it a zone with political and tourism benefits, is not referred to in this study.

In all parts of the country, concrete block construction is the most preferred form of construction today for a number of reasons. Concrete houses have superior durability against the high humidity and fungal attacks common in many parts of the country. In addition, the thick and sturdy structure is perceived to be more secure, an important consideration in a region in which crime is a problem. Moreover, concrete houses are seen as a symbol of increased social status.

But the benefits are often outweighed by the higher cost of materials and construction for many families. While most families aspire to live in a concrete home, many families building new homes today cannot afford such luxury. The poor thermal resistance of the concrete also makes them uncomfortable in hot and sunny areas, unless costly additional insulation or unique architectural features are used to avoid thermal problems.

The remainder of this section will review the predominant traditional housing techniques in the three regions of the country, with much of the information coming from AID (1985).

2.2.1.1 The Sierra

The lower Andean region is situated between 2,000 m and 3,200 m, and has an average temperature between 10 °C and 20 °C. Rainfall amounts to between 500 mm and 2,000 mm, and the relative humidity is between 65% and 85%.

Due to relatively colder temperatures of the Sierra, or mountainous zone, housing construction techniques and materials are usually chosen in part due to thermal resistance and absorption properties. The traditional construction is made of thick earth walls penetrated by few windows which provides insulation from the cold while absorbing the heat of the day to be released during the chill of the night.

In the lower valleys of the Sierra, there are dry forest regions which support the growth of Eucalyptus, Pine and other timber species, many of which were introduced into the region relatively recently. These species are used in local rural and urban construction. The soils of this region also allow for the fabrication of bricks which along with bahareque (the use of a mortar over a bamboo sheathed wall) and earth construction, form many of the walls of traditional houses.

In the higher mountainous regions over 3,200 m, average temperatures are between 7 °C and 12 °C, and the rainfall between 250 mm and 500 mm. With these conditions perennial grasses and "paja" (leaves of a common plant) provide material for thatch-style roofing, and woody shrubs some structural material. Again, earth walls are common due to the relatively low temperatures.

2.2.1.2 The Amazonia Region

The Amazonian region of Ecuador consists of two sub-zones: the high Amazonian region close to the Andes, and the lower Amazonian region further east. Much of the area has a wide range of forest resources, however some of these valuable woods are not economically accessible for exploitation due to the distances to market, and lack of infrastructure. When forests are exploited it is often unchecked, inefficient, with no replanting taking place (AID, 1985).

The high Amazonian region is far more humid than the coastal zone, with a constant humidity of 90% common in some months due to the proximity of the mountain range. As the altitudes are generally above 500m, the average temperatures do not pass 25 °C. With the serious humidity concerns, traditional construction in this region consists of a simple structure made of local woods supporting a large roof cover.

In the lower Amazonian region the average temperatures generally remain above 25 °C with a total rainfall of 2,879 mm spread throughout the year due to the lack of a dry season. Although the average humidity may be 80%, the rains help offset the heat, and with the extensive evaporation and tree cover providing shade, the region is fairly comfortable. Similar to other regions of Ecuador, the traditional construction takes advantage of local wood and bamboo material.

2.2.1.3 The Coastal Zone

The coastal zone has an average temperature of 23.5 °C and an average 209 mm of rain per year. Further inland the average temperatures rise to 25.6 °C accompanied by 1,780 mm of rain per year (AID, 1985). With a wealth of forest resources (both tree wood and bamboo), traditional house construction consists of a variety of components made from the local species.

Often, split and opened bamboo culms (the *Guadua angustifolia* is locally called "caña", or "caña guadua") are used as wall sheathing over a wooden frame. In some instances, the same opened caña (called "caña picada") is used as a floor sheathing material over a wood or bamboo floor structure that is supported on mangrove wood columns.

The Municipality of Guayaquil's "Urban Development Plan" (1984) summarised the findings of the Third National Housing Census conducted by the National Institute of Statistics and Census which recorded the material used for roofing, walls, and floors. Although a total of 235,664 houses were surveyed, there were incomplete data presented in the report indicating that this information was not noted for each house in the census. Table 7 below presents the numerical findings of the survey of construction materials, and percentages based on those findings.

Table 7: Predominant Housing Building Materials in Guayaquil, 1982

Component	Material	Number of Houses	% of Houses [1]
Roof	Zinc or similar	156,826	69.8%
	Eternit, ardez, or similar	39,936	17.8%
	Concrete slab	27,797	12.4%
Walls	Brick, block, or reinforced concrete	147,889	63.8%
	Bamboo (uncovered)	43,453	18.7%
	Bamboo (covered)	26,767	11.5%
	Wood	13,697	5.9%
Floor	Wooden planks	96,873	41.4%
	Brick or concrete	72,816	31.1%
	Wood tile, vinyl, or ceramic tile	52,712	22.5%
	Earth	6,849	2.9%
	Bamboo	4,897	2.1%

Source: III Housing Census, (INEC, 1982, as cited in Municipalidad de Guayaquil, 1984)
[1] Percentages may not add to 100.0 due to rounding

The 1990 Census (INEC, 1991) found similar results. Because the detailed housing census was not completed for the entire country, data for the district of Milagro, a municipality in the Province of Guayas outside of Guayaquil, will be noted to provide an example of a typical community in the coastal region.

Of the 19,762 houses surveyed, 3,017 (15.3%) had bamboo walls that were not covered, 1,341 (6.8%) had covered bamboo walls or "bahareque" walls, and 1,202 (6.1%) had wooden walls. The most common wall construction material category was "concrete, concrete block or brick" with 14,096 (71.3%) of all houses.

Bamboo flooring was found in 1,340 homes (6.8%), and brick or cement floors in 10,331 (52.3%). Surprisingly some 4,607 (23.3%) had wooden boards as floors, and 3,184 (16.1%) had "parquet, tile or vinyl" floors.

The vast majority of houses (15,574, or 78.8%) had zinc roofing.

2.2.2 Concrete and Masonry Construction

Although the concrete block, or masonry, construction techniques used in Ecuador are similar to those used around the world, a review is presented here in order to provide a benchmark of quality and cost for the other materials and techniques to be reviewed later. Due to the nature of this study, emphasis is placed on social housing.

The Chamber of Construction of Guayaquil (Camara de Construcción de Guayaquil, 1998) provides a useful review of conventional concrete block social housing costs in their seasonal publication "Construcción y Desarrollo". In each issue, costs are provided for a standardised concrete social interest house. The house is finished with basic wiring, plumbing, windows, etc. A summary of recent data is provided in Table 8. This house provides a useful index to the cost of construction and construction materials in the Guayaquil area.

Table 8: Construction Costs of Concrete Social Housing in Guayaquil

	[1,2] Cost (USD)/m^2 Jan., 1998	[3]Index Base	Index Jan., 1998	% of total const. cost	annual % increase
Design and overhead	1.93	100	7,770.08	2%	36%
structural frame	16.66	100	8,420.37	15%	37%
masonry	43.82	100	8,265.58	39%	37%
electrical installations	3.34	100	3,653.81	7%	29%
sanitary installations	4.18	100	6,933.58	4%	35%
Eternit roofing	14.29	100	7,488.57	14%	36%
Doors	4.84	100	6,859.47	5%	35%
Bathroom fixtures	5.86	100	7,110.60	6%	36%
Painting	5.49	100	8,089.58	5%	37%
Windows and aluminum trim	2.13	100	4,685.13	3%	32%
Total	102.52				
Total construction cost (for 36 m^2 house) (USD)	$ 3,690.69				

Source: Cámara de Construcción de Guayaquil (1998)

[1] Costs are for standardised house construction (Camara de Construcción de Guayaquil, 1998)

[2] 1.00 USD = 4528.00 Sucres (January, 1998 - buying price, free market)

[3] Index base created January 1984

The construction cost for standardised concrete social housing in Guayaquil in January 1998 was therefore \$102.52 USD per m^2, with a total of \$74.77 USD per m^2 consumed by structural frame, masonry and roofing. Note that these costs do not include the development of the housing project, the infrastructure, nor any of the normally associated costs with a housing development project (another index is provided by the Chamber of Construction for those costs). The costs listed are specifically the costs of construction for a standardised, average house in a development by commercial developers.

Table 8 shows that even for "social interest" construction in Ecuador, the construction costs are substantial when compared to the minimum salary of approximately $165 USD.

2.2.3 Wood and Bamboo Frame Construction

2.2.3.1 Introduction

In terms of traditional construction technology, wood and bamboo frame construction is predominant in the coastal and Amazonian regions of Ecuador. Due to the wealth of forest resources, tree wood, mangroves, and bamboo have long been exploited for house and building construction.

Many of the buildings of the downtown core of Guayaquil are older wooden structures, that were sheathed with opened bamboo culms and covered with mortar. Even today for much of the construction in rural and poor areas, bamboo remains the main wall sheathing material. Due to the current economic pressures, it is usually left uncovered, and is sometimes used as floor sheathing as well.

In the suburban areas of Guayaquil the benefits and limitations of wood and bamboo frame housing are apparent. Firstly, many of the suburban areas are known as "invasions", as they begin as squatter's settlements (Figure 5). These communities are normally planned by a leader (known as "co-operative president" or "land trafficker") who chooses the site, and lays out the future community. Sometimes lots, roadways, and public areas for schools, parks, etc. are marked before construction begins. In as little as one or two days, the leader invades with several selected families, and their houses are built.

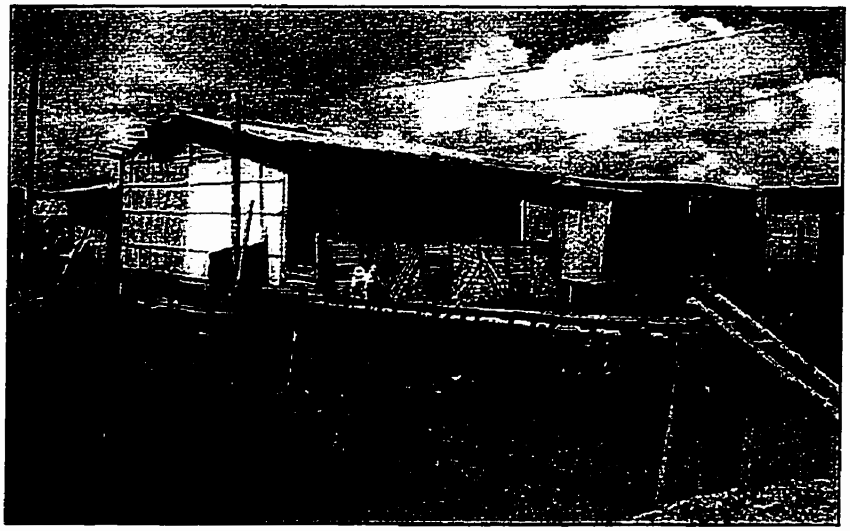
Figure 5: Invasion Subdivision

The use of a simple wooden frame allows for application of opened bamboo culms on the floor and walls, while zinc sheeting is mounted as a roofing material. These materials are all available at material deposits. Bamboo is commonly available already opened for this type of use (called “caña picada”), and it is cheaper than entire culms to transport into the metropolitan area by truck due to the smaller volume each piece occupies.

Since most bamboo houses have a lifespan of four to seven years due to the harsh humidity, heat, fungal and insect attacks, the houses require maintenance which is seldom performed. Hidalgo (1984) noted that the degradation of uncovered bamboo sheathed houses has made them a symbol of misery and poverty in Ecuador and they are therefore commonly seen as ugly and undesirable.

Due to the extreme rainfall events and the location of many of these communities in marginal areas, the houses are normally constructed on high columns. This keeps the house above the water levels, provides for shaded daytime living space and storage below, and allows for ground access to begin construction of a concrete structure on the same lot. Since bamboo houses are often seen as temporary solutions to the urgent need for shelter, an established family begins replacing the bamboo house with concrete as soon as possible. Figure 6 shows a house sheathed in bamboo, with a “concrete block” design painted on the front of the house, clearly indicating the wishes of the inhabitants.

Figure 6: A Bamboo House Painted with a Concrete Block Design



Normally, concrete footings and block structures are built on the existing house footprint as the concrete walls are built directly under the initial bamboo house (Figure 7). As the wall structures are raised to the existing floor level, it provides a rot-resistant structural support for the existing house (already extending the life of the initial housing investment).

Figure 7: A Bamboo House Being Upgraded with Concrete Block Walls

Thus, in many cases (especially in urban and suburban areas) wood and bamboo houses are seen as a first step towards the establishment of a concrete home. In this role they meet a critical need of providing cheap shelter rapidly. The materials for an average wood and bamboo frame house may cost $500 USD, and therefore is still beyond the financial savings of many families. But as the lowest cost and most simple construction system in the region, based on years of custom and tradition, it appears to have a role to play for many generations.

2.2.3.2 Bahareque

Traditionally the construction in the Guayaquil area relied on wood structures with bamboo walls covered by mortar (called "Bahareque" construction, Figure 8). Bahareque is one of the ways in which natural fibres are used with soil in housing construction. With this construction system, normally a structure of wood is loosely sheathed with cut wood, bamboo or other canes. A mortar mix is then used to cover the structure. Depending on the region, the components of the mortar mix vary, but traditionally a mixture of soil, horse hair, lime, and manure is used. Cement-based mixtures are now common.

The use of a mortar provides solid and secure walls, and greatly improves the aesthetics, durability, and suitability of the structure. Due to the high cost of mortar mixtures, this type of construction is not commonly practised in Guayaquil today as concrete blocks are now used if financial resources are available for enhanced structures.

Bahareque construction requires a supply of wood for the framing of the structure, and therefore is restricted in the locations in which it is used. The lath material may be cleanly cut pieces of wood or bamboo. In cases that a "caña picada" or opened bamboo culm is stretched and nailed to the frame to allow for a base for the mortar, the construction is sometimes referred to as "quincha" (Figure 9). For the purposes of this report, this quincha style construction is listed with bahareque due to the similarities of the processes.

Figure 8: A Bahareque Assembly (with loosely woven lath pieces)

Source: AID, 1984

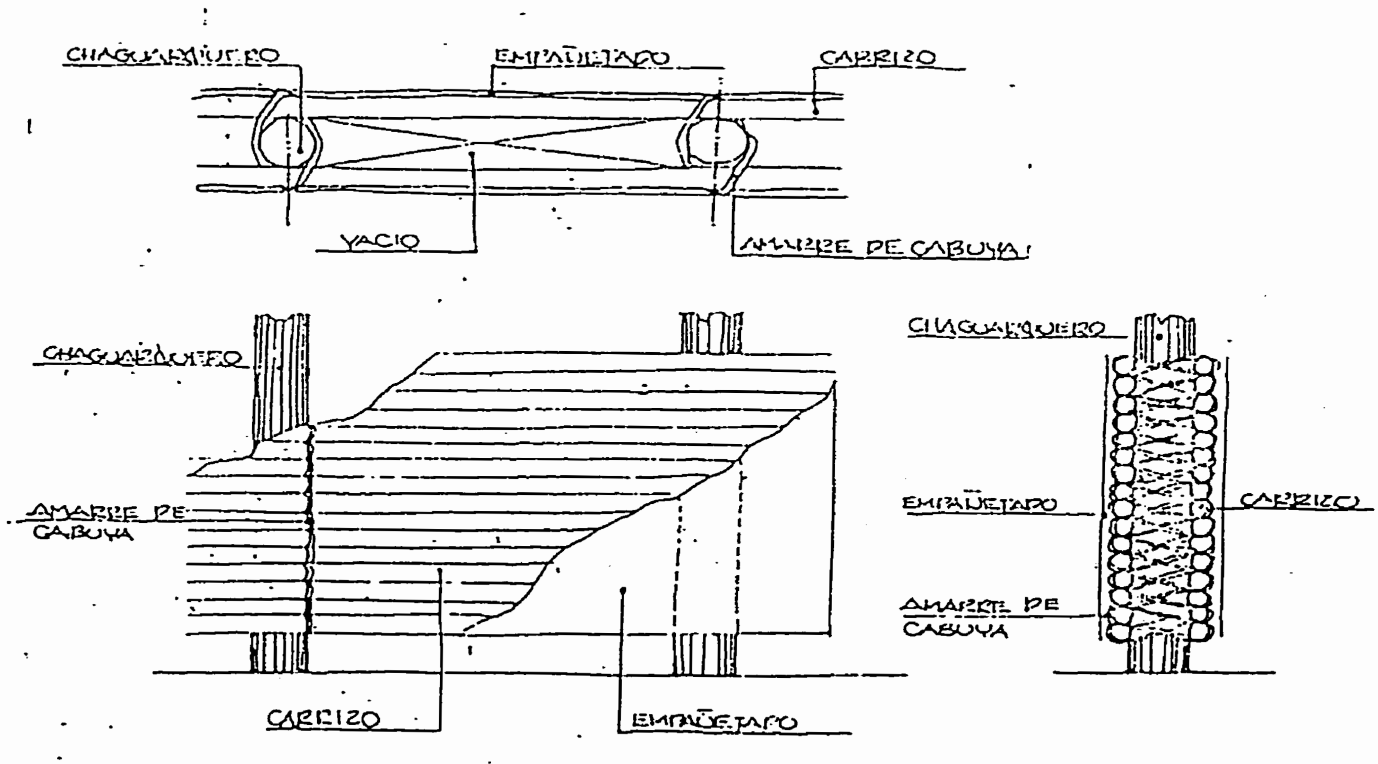
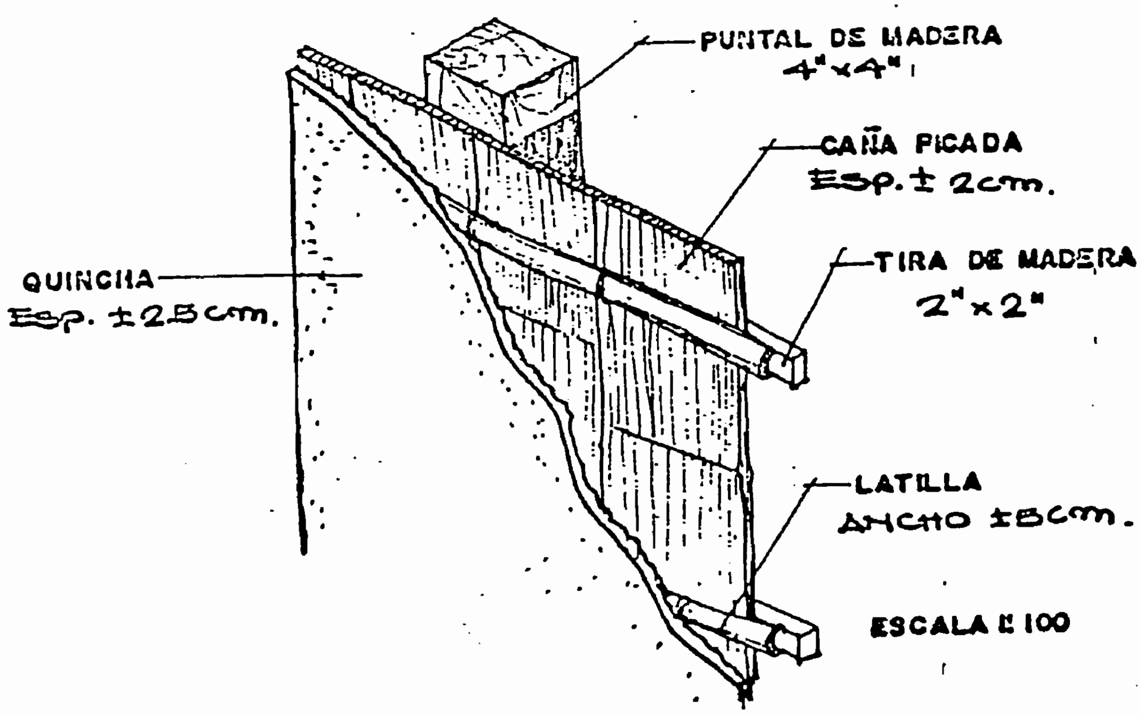


Figure 9: A Typical Qüincha Assembly

(Source: Moran, 1986)



2.2.3.3 Case Study : Hogar de Cristo's Wood and Bamboo Frame House

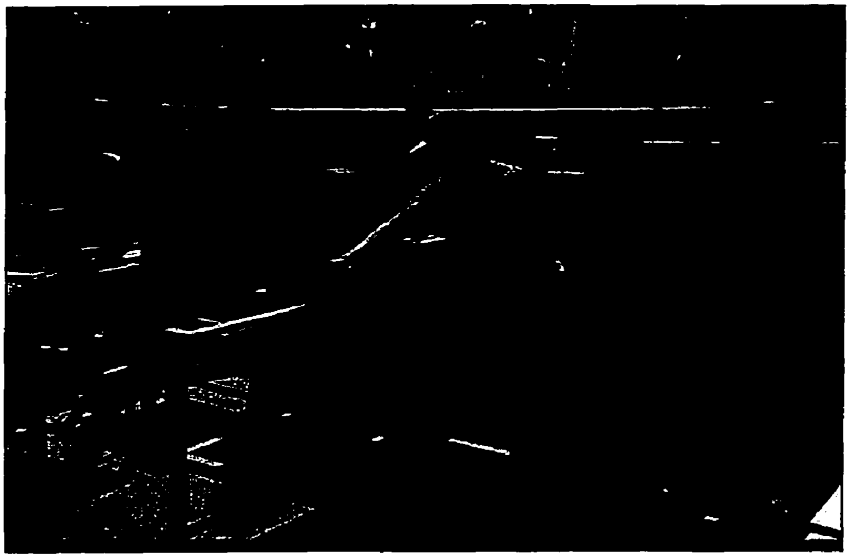
Hogar de Cristo, a private organisation run by the Catholic Church, provides prefabricated wood and bamboo frame houses to the poorest people of Guayaquil. They operate as a not-for-profit organisation, and offer financial products such as mortgages so that their clients can purchase the $500 USD house (small size) on partial credit. Aside from the efficient technical operation and sturdy houses that they produce, the financial and social services are the critical link for most clients. Since most families don't have $500 USD in savings, and are beyond the services of the traditional financial sector, the 18 month payment period allows for a poor family to have a house immediately, while making payments over an extended period of time.

Hogar de Cristo programs exist in many countries, and always search for the cheapest form of shelter to provide. That is to say, in some countries masonry is used, and in others wood is used by the local Hogar de Cristo organisation. But in Ecuador, specifically in Guayaquil, wood and bamboo houses remain the cheapest form of shelter, in spite of the fact that the bamboo is shipped several hundred kilometres to Guayaquil.

They offer two houses for sale, the main difference being size. To avoid repetition, only the smaller house will be reviewed here.

The houses are produced in the Hogar de Cristo factory in Guayaquil. Opened bamboo and large, rough wooden planks are the main raw materials purchased. While the bamboo is used as-is (i.e. no preservatives, no painting, etc.), the wooden planks are sawn and cut to a variety of sizes and lengths as needed for the different house components. Plank cut-offs are used to manufacture doors and windows (Figure 10).

Figure 10: Door Assembly at Hogar de Cristo Factory



The largest amount of wood is used for the floor structure. Normally mangrove wood is used as column material due to its superior durability. Large floor beams are covered by floor joists of 2" by 4" lumber. A floor of wooden planks is nailed on top.

The main house component is the wall assembly which consists of 6 wall panels that are made from a wooden frame of 2" by 2" lumber that is cut from larger rough planks. The frames are covered with opened bamboo to form a panel (Figure 11). Openings for doors and windows are pre-cut in the factory. These wall panels are simply lifted onto the floor platform, raised and secured.

Figure 11: Wall Panel Assembly at the Hogar de Cristo Factory

A simple structure of 2" by 2" lumber covered with 1" by 4" strapping provides a base for the zinc roof sheeting material. Doors and windows are installed in the openings, and the family completes the house by adding any porch, stairs, etc. as needed.

This entire house comes as a kit containing the floor assembly materials, the prefabricated wall panels, the wood for the roof, the zinc sheets, the doors and windows, and the necessary hardware. This entire package is lifted by a forklift (Figure 12) onto a truck that the client hires. Hogar de Cristo has arranged for a flat-fee service charge for the private sector trucks that are hired by the clients to move the house kit to their building site for approximately $13 USD. In addition, there is a similar flat-rate fee for private carpenters who erect each house for approximately $40 USD (Figure 13). Often delivery and erection are completed in one day. The other main cost to the Hogar de Cristo clients is the building lot which usually cost between $200 and $400 USD.

Figure 12: Loading a Hogar de Cristo House Kit

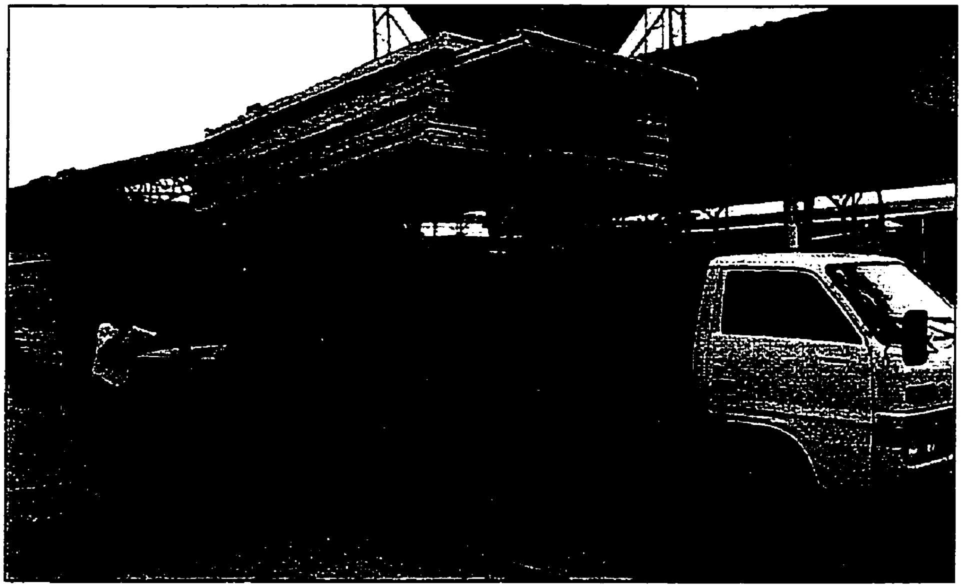
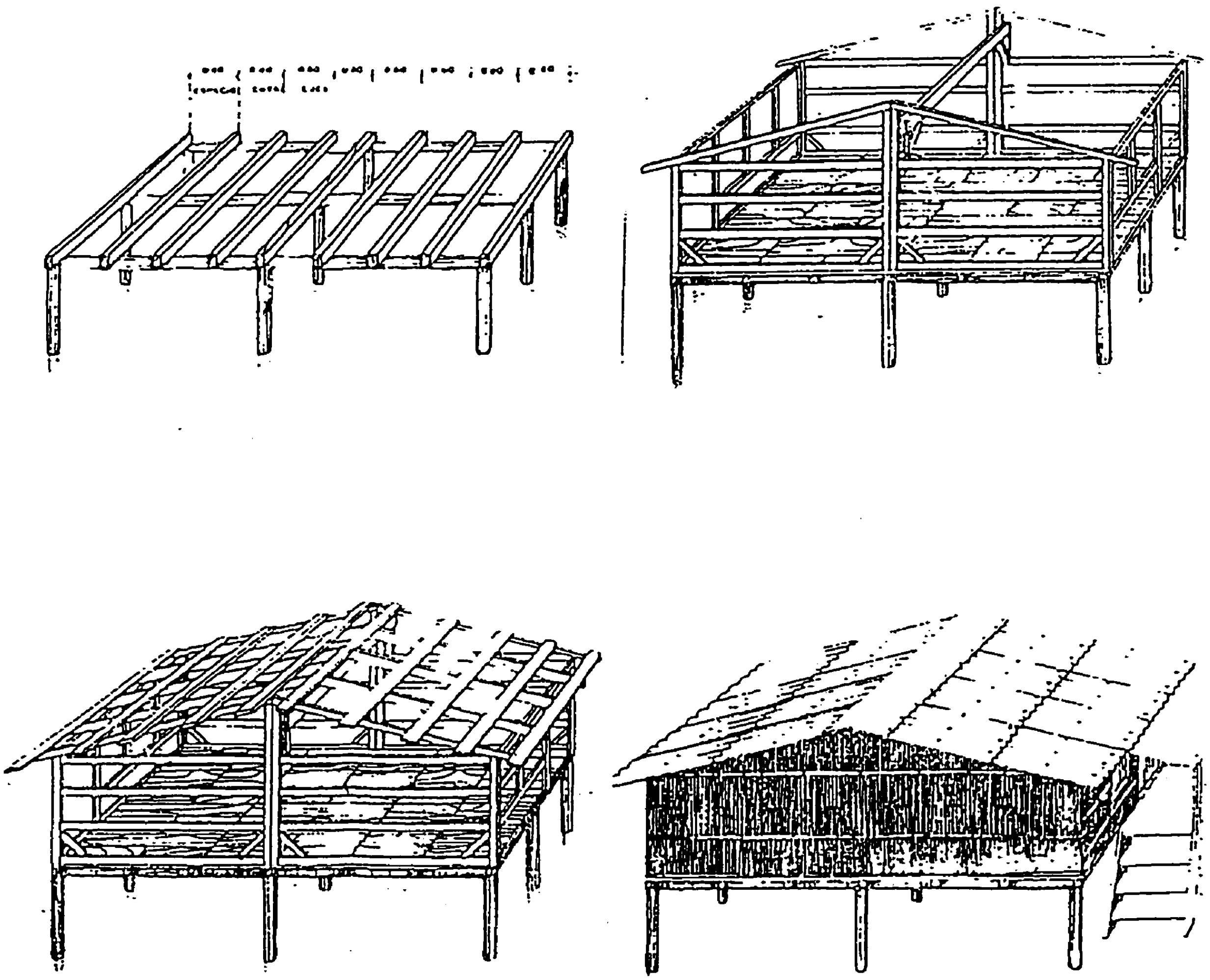


Figure 13: Assembly of a Hogar de Cristo House

Source: Rosso and Costa, 1990 (bamboo sheathing removed for clarity)



The cost breakdown of a simple Hogar de Cristo house from the factory is shown in Table 9.

Table 9: Breakdown of Costs of a Hogar de Cristo House

Component	Quantity	Total Cost (USD)
End Panels	2	$47
Side Panels	4	$103
Doors	2	$23
Windows	2	$10
Floor Assembly	1	$117
Roof Assembly	1	$30
Roofing Zinc	10	$82
Unit Cost / House Structure		$412
3.2 m Columns	9	$32
3.8 m Floor Beams	6	$17
Nails	12 lbs.	$4
Unit Cost / Base		$53
Grand Total / Complete House		$465

Source: Hogar de Cristo (1998)
Exchange May, 1998 (1 USD = 5,000 Sucres)

The house dimensions are 3.30 m x 6.40 m (approximately 21 m^2), and there are no interior divisions. The cost for the house is approximately $22 USD /$m^2$ (1998 USD). Including transportation and erection, the total cost of the house is approximately $518 USD, or $25 USD/$m^2$.

2.2.4 Summary

In this section a review was conducted of predominant bamboo construction technologies in Ecuador. In general, it could be said that the material cost information is independent of the labour costs, for which insufficient data was found. It can be assumed that large amounts of labour are required for most forms of construction (with the exception of the partially prefabricated Hogar de Cristo house). This might be expected and preferred in the self-built ("auto-construction" or "self-help") houses by rural poor, using simple materials and techniques.

This review did not take into account the "mixed" construction of wood structures with concrete block or brick wall partitions or sheathing. These are mostly adaptations of older wood-bamboo houses that were improved as the wealth and purchasing power of the inhabitants allowed for renovation. Although some of the structures in Guayaquil were initially designed and built as such, it is no longer common in new construction. If concrete, block or bricks are used as a wall material in modern construction, normally a reinforced concrete structure or frame is used.

Because of the large housing deficit in Ecuador, one would assume that larger housing projects would be of interest. Due to the lack of national attention placed on housing in past years, and with unexpected pressures on housing such as the El Niño Phenomenon, an increase in construction is expected.

Traditional builders use concrete which is more widely accepted in engineering design than bamboo and adobe construction. In addition, elements of prefabrication, long-term durability of the house, and security are also better with concrete-based construction methods in comparison to the more traditional methods. Of course, the cost of concrete houses is the limiting factor, and makes basic quality housing out of the economic reach of many families.

Clearly there are pros and cons of the existing construction materials within Ecuador, and the associated construction methods and technologies. Like in all markets, opportunities for new materials and new methods exist.

2.3 Bamboo and Forest Resources in Ecuador

If we are going to investigate the opportunities for bamboo products in the housing sector of Ecuador, it is important to understand the existing tree and bamboo resources in the country. As shown below, information and data on bamboo is scarce. But the forest data, and information of wood product markets is abundant. It provides us with a benchmark against which future bamboo growth may be compared.

2.3.1 Forest Cover Statistics

Forest statistics in Ecuador show that the country is rich in natural resources, but like many other tropical countries is suffering from unmanaged forest exploitation and deforestation. Table 10 shows the current land use for the nation.

Table 10: Land Use in Ecuador

Land Use	Area (Ha.)	%
Agriculture and Cattle	7,733,000	28.6
Saline Areas	25,000	0.1
Shrimp Production Areas	139,000	0.5
Natural Forests	11,473,000	42.4
Forest Plantations	143,000	0.5
Land with Forest Potential	2,523,000	9.3
Other Uses	5,031,000	18.6
Total:	27,067,000	100

Source: Almeida, 1996

Of the 11.5 million hectares of native forest in Ecuador, 80% is found in the Amazonia region, 13% in the coastal region, and 7% in the Sierra (STCP, 1993)

About 29% of the natural forest area of Ecuador (12% of the country) is protected. 50% of these protected areas are dry tropical forests, 46% forests of the foothills, and 4% mangroves.

2.3.2 Deforestation

Like many tropical countries, deforestation is a concern in Ecuador. STCP (1993) noted that between 1962 and 1985 deforestation due mainly to land development for agriculture and cattle was approximately 140,000 hectares a year.

Almeida (1996) stated that in the previous 30 years, the average rate of deforestation was 106,000 hectares a year.

CESA (1992) noted that exact statistics are not available, but that an estimated 200,000 hectares per year are deforested in Ecuador. This is approximately 1.5% to 2.0% of the natural forest cover disappearing each year. These statistics are conservative in comparison to other information cited by CESA.

Both legal and illegal colonisation of rural areas leads to deforestation (CESA, 1992), with 80-90% of cleared land in the coastal zone being used for agriculture and cattle. In the Amazonian region only 30-40% is estimated to be used in this way.

Valverde (1994), a former Director of the INEFAN (the Ecuadorian government forest institute) also stated that annual deforestation rates are 200,000 hectares per year, with 40% of the country's surface area suffering from actual and potential erosion problems. He also noted that the annual increase in agricultural land is approximately 3% per year, second only to Surinam in South America.

Carrera de la Torre (1994) examined the deforestation situation in the Amazonian region. He noted that the Amazonian region of Ecuador accounted for 31.5% of the total deforestation of Ecuador from 1980 to 1990. The causes of deforestation in the Amazonian region were: 34% for agriculture; 30% for cattle; 20% by the forest industry; and 16% for other uses such as dams, roads, mining, housing development, etc. Citing unreferred USAID statistics, he noted that by 1989 6.3% of the coastal zone natural forest found at the beginning of the century had been cleared, 25.5% in the Sierra, and 51.8% in the Amazonian region.

2.3.3 Plantations and Reforestation

The varying deforestation statistics are presented in contrast to reforestation data that suggests little replanting is done in Ecuador. CESA (1992) stated some statistics of reforestation (see Table 11). Unfortunately, CESA did not provide a complete reference for the source.

Table 11: Reforestation in Ecuador

Period	Average Annual Area Reforested in Ecuador (in hectares)
1962-1966	1,539
1967-1976	2,450
1977-1981	5,103
1982-1986	9,173

Source: "Reports of DINAF, Weber P. and J. Salina, MAG" (as cited in CESA 1992)

STCP estimated the area of forest plantations in Ecuador to be 78,000 hectares in 1993, with Eucalyptus, Pine, and exotic species making up 43%, 30%, and 27% of that area respectively. Interestingly, they note that this plantation area is spread over 6,000 sites, or an average plantation size of only 13 hectares.

Almeida (1996) estimated the area of plantations to be 143,000 hectares, 90% of which was located in the Sierra region, with the remaining 10% in the coastal and Amazonian region. From 1986 through 1995 the average increase in plantation cover was 6,230 hectares per year.

2.3.4 Bamboo Resources in Ecuador

Bamboo resource information is currently difficult to find in Ecuador. Of all of the government agencies, national institutions, and non-governmental organisations, references about bamboo as a natural resource was found in only a few documents.

2.3.4.1 Bamboo Inventory

In the 1985 report "Inventory of the Guadua Cane in the Littoral Region of Ecuador", Mantilla (1985) surveyed a limited region of the country. Unfortunately, this report is unknown to many of the people currently working in forestry in Ecuador as bamboo is not seen as a major raw material. In fact, none of the government forestry offices could provide any information on bamboo.

Mantilla (1985) stated that in the coastal zone of Ecuador, an area of 146.19 km^2 contained bamboo which was accessible and commercially exploitable. This was found in an overall area of 38,945 km^2 which contained some bamboo, or an estimated 0.38 hectares of bamboo in every 100 hectares of land. The inventory studied 61,500 km^2, accounting for most of the coastal zone with the exception of an area north of Esmeraldas and the north Manabí. Any bamboo in these areas was deemed to be economically inaccessible, or in very small quantities.

Of the 14,619 hectares of bamboo found, there were an estimated 27 million plants. Mantilla stated that this was sufficient to produce 4.5 million culms annually. Of the

75,248 bamboo plots identified, only 667 were larger than 6 hectares. The largest bamboo grove was 15 hectares. Although bamboo was found to have an average density of 1,835 culms per hectare, the density ranged between 800 and 15,700 culms per hectare.

Three major species were identified: *Bambusa guadua* (which has been since reclassified as *Guadua angustifolia* by Soderstrom and Londoño (1987)), *Bambusa aculeata*, and *Bambusa vulgaris*.

2.3.4.2 Guadua Plantation Pamphlet

The second document found (DFO, 1998) was a pamphlet, produced by Forestry Development of Western Pinchinca, which provides elementary bamboo plantation information.

For example, it recommends spacing between 6 m and 8 m between bamboo plants in large-scale plantations. It states that on a plantation of 2 years of age, with 6 metre spacing, there is an average of 2,000 to 2,500 bamboo canes per hectare (270 plants / hectare x 7-9 canes per plant).

As an example of economic viability, the pamphlet provides the following summary: Given a bamboo plantation one hectare in size, with initial plant spacing of 8 m x 8 m, there are 156 clumps of bamboo. At 4 years of age, there will be between 7 and 10 culms per clump that can be harvested (the mature culms only). This provides a total harvest of 1,092 to 1,560 culms per hectare.

Each full culm can produce one bamboo cane for construction (6 metres in length) and one "cuje" or tip used to support growing fruit bunches on banana plantations. Current market values are approximately \$0.33 USD per tip, and \$0.44 USD per construction cane. This provides a total revenue per hectare of between \$ 840.84 and \$ 1,201.20 USD.

Through informal site visits in Ecuador, similar prices were noted in June, 1998. Market prices varied, but averages prices were approximately \$0.30 per tip and \$0.40 per construction cane.

Harvesting costs (not mentioned in the DFO pamphlet, but obtained by surveying bamboo workers) averaged \$0.08 USD per section. This is to say for each marketable piece (i.e. each tip, or each construction cane), the worker had to cut, fell, trim, and extract the piece to the agreed-upon roadside pick-up location. It was also noted that most mature culms provided two full construction canes and a tip (in contrast to the single construction cane used in the pamphlet's example).

Given an average external diameter of 10 cm, a wall thickness of 1 cm, and a dry density of approximately 600 kg/m^3 , the dry mass of the average construction cane is approximately 10 kg. This gives a harvested price of \$8.00 USD per dry tonne, with the bamboo being carefully extracted in full 6m lengths.

An average worker can harvest 30 full culms (between 80 and 100 marketable construction canes and cujes) per day.

2.3.4.3 Non-Wood Forest Products Review

Released in June 1998 (Fundación CIDESA, 1998), a review of non-wood forest products of northern Esmeraldas included bamboo. The review contains highly detailed information, such as the lot number of the location of bamboo clumps along specific rivers. Unfortunately, due to the El Niño Phenomenon's destruction of roads in the area, this information could not be confirmed.

Among the findings, the report stated that the average number of bamboo plants per hectare along the Santiago, Cayapas, and Onzole rivers were 128, 96, and 47 plants per hectare along each respective river, and 4864, 1920, and 940 harvestable culms per hectare along each respective river. The final estimate of harvestable culms in the northern Esmeraldas region was 27.7 million culms.

Unfortunately, no extraction costs were given in the report, but based on market prices obtained in the Esmeraldas area, one can assume a harvesting cost of approximately $0.50 USD per 6 m construction cane. This high price is due to the fact that the bamboo must be cut, extracted, trimmed, and transported by river to the nearest road. Many of these transfer points are several hours away from the city of Esmeraldas, the largest commercial centre in the region. Although quoted commercial prices were greater than this, large scale purchase of bamboo from the source region should easily discount the price.

2.3.4.4 *Estimated Bamboo Costs*

Above, estimates of bamboo harvesting costs in the Santo Domingo area, and the Esmeraldas area were given to be $0.08 USD and $0.50 USD per 6 m construction cane respectively (price to extract bamboo to possible trucking location). After subsequent payments to the land-owner, government forest-product harvest taxes, loading, transportation, and unloading, selling prices in Guayaquil are approximately $1.00 per 6 metre construction cane (by the piece, including loading).

Gallardo (1991) provided a review of market prices of bamboo in a number of forms at the construction material deposits in the province of Manabi. Oddly, he provided prices of the purchasers and prices of the vendors, yet never stated the final selling price. His findings are summarised below in Table 12.

Table 12: Market Prices of Bamboo in Manabi at Construction Material Yards

Bamboo Product	Purchaser Price (USD, 1998)	Vendor Price (USD, 1998)	Estimated Mass (kg dry)[1]	Estimated Price by Mass[2] (USD 1998 per dry tonne)
culm, 3.5 m	0.40	0.55	5.9	93.71
culm, 4.2 m	0.50	0.67	7.1	94.56
culm, 10 m	1.58	1.97	17.0	116.15
opened (no length given)	0.51	0.71		
"cuje" or tip	0.28	0.51		

Source: Gallardo, 1991

[1] estimate assumes 10 cm outer diameter, 1 cm wall thickness, 600 kg/m^3

[2] assumes vendor price

2.3.4.5 Bamboo as an Export Product

CORMADERA (1991) noted that between 1982 and 1990 bamboo exports hit a peak in 1987 when 7,127 tonnes of opened bamboo ("bambu picada") were registered for exportation, with a value of $421,000 USD.

In 1990, the last year of statistics given, there were 1,016.5 tonnes of opened bamboo exported with a value of $62,000 USD, and 2,737.2 tonnes of bamboo construction canes ("bambu rolliza") exported with a value of $161,000 USD.

Unfortunately, CORMADERA has not published other statistics compilations, and relevant government agencies were unaware of statistics data banks of any kind for bamboo trade. It is interesting to note that given these larger shipments of bamboo the equivalent price is approximately $60 USD / dry tonne in spite of the fact that truckloads are normally bought and sold by the piece.

One owner of a plantation stated that the exportation of "bamboo" is illegal according to Ecuadorian law, but this was not confirmed. He labelled his shipments as "Caña Guadúa" (i.e. as a cane) and had no export problems.

2.3.5 Ecuadorian Wood Product Markets

STCP (1993) conducted a survey of the wood industry in Ecuador, and found that the total harvest costs (not including administration) was $16.39/m^3$, or assuming a density of 600 kg/m^3 (likely a high estimate), $27.20 USD/ dry tonne (therefore likely a low estimate).

Including administration, transportation, government harvest taxes, and the land-owner paid, wood raw material costs for small sawmills were approximately $97 USD/m^3 , for large sawmills $78 USD/m^3 , and for plywood production $134 USD/m^3. Statistics for 1992 production (STMP, 1993) of a variety of wood products is presented in Table 13.

Table 13: Production, Importation, Exportation, and Apparent Consumption of Wood Products in Ecuador, 1992

Product	Production (m^3)	Imports (m^3)	Exports (m^3)	Apparent Consumption (m^3)
Sawn Wood	1,450,000	5	45,748	1,404,252
Composites	58,000	225	17,541	40,684
Plywood	78,000	-	23,000	55,000

Source : STMP (1993)

STMP (1993) estimated that a total of 22,725 jobs existed in the post-harvesting stages of the wood industry in Ecuador. This included 4,612 jobs related to sawmills, 1,273 jobs relating to plywood, 263 jobs related to composites, 5,666 jobs related to furniture production, 5,137 jobs related to paper, with the remaining 5,774 in other industries. Overall, about 18% of these position were in administration, 5% were technical/professional positions, and 28% and 49% were skilled labour and unskilled labour positions respectively.

2.3.6 Summary

Although bamboo has a long history of traditional use in Ecuador, natural forest resources are currently limited. Although sufficient to meet current market demand, there are not large natural forests to be harvested in the future.

Given the pressures on wood resources, bamboo plantations offer an option for private and public management. Bamboo in Ecuador is harvested by hand at relatively low-cost, and is a viable alternative for wood in large-scale commercial operations, current small-scale applications and export.

Ecuador has a precedent for fibre plantations, yet there are no commercial bamboo plantations yet in production. The ideal climate and geographical features that once supported thriving natural guadua forests, yet were found unable to economically sustain agricultural and cattle production when cleared, offer unique opportunities for plantation development. Land costs are relatively cheap, labour costs are appropriate for sustainable hand-extraction of bamboo, and there is a sizeable existing domestic market for bamboo. These factors provide a base of stability for potential large-scale commercial bamboo plantations in Ecuador.

2.4 Summary

In this chapter, the current situation in Ecuador with respect to housing, bamboo construction, and bamboo resources was presented.

From the information presented above, and the information presented by Dagilis and Turcke (1998), a number of important factors influencing house construction in Ecuadorian markets can be summarised:

1. Cost: If an increase in bamboo is desired, then the construction process must be cheaper than concrete - ideally close to some of the costs for adobe, and wood and bamboo framed houses: \$25-\$30/m^2 in today's US dollars would be acceptable (concrete construction is approximately \$102/m^2).
2. Solid walls: Walls that are solid and secure are preferable to the split and opened bamboo walls for reasons of comfort and personal safety. In the Sierra region, insulated walls are required. Solid walls are beneficial as they help reduce rain infiltration, increase night-time privacy for the occupants, and reduce the infiltration of dust and insects into the house (a serious health concern in many squatter areas)
3. Durable components: Due to the high humidity and temperatures, the life of a split bamboo house is four to seven years, although houses that are well maintained and painted can last 20 years. Ideally, a construction technology would use materials that have some element of durability against humidity and fungal attack in order to increase the life-span of the building and provide a longer-term housing solution for a similar initial investment.

4. Ease of construction: Wood and bamboo are the dominant materials for self-help construction partly due to the ease of construction. The simple tools, and ease of instruction and implementation of the construction techniques is critical. The special skills and trained labour required for concrete use is the major limiting factor in its use in "auto-construction" in Ecuador.
5. Material performance: Construction materials and techniques should meet accepted standards of performance. Unfortunately, due to efforts to economise, self-help construction projects often decrease the usage of important, but costly, elements: cement and reinforcement in concrete; nails and bolts in wood connections; etc.
6. Thermal properties: In the Sierra region cold is a problem, and in other parts of the country often the heat due to high temperatures and solar radiation is a concern. Ideal construction would use materials and designs that provide for insulation from the cold/heat to improve the comfort and health of the occupants.
7. Seismic concerns: Due to the presence of seismic activity in Ecuador, construction systems that are light-weight and have sufficient strength to resist seismic loading are ideal. Currently, much of the construction does not meet seismic code requirements.
8. Aesthetics: Many of the cheaper forms of construction, such as split bamboo wall systems, are synonymous with poverty. Unique and creative stylistic approaches, and the ability to customise the house would be a benefit as the occupants gain financial resources. With increased aesthetic appeal of alternative systems of construction, people would be more open to alternative materials and house designs. Similarly, new technologies should allow for variation in style and design.

9. Roofing: The high cost of roofing suggests that unique and new ways of providing cover for houses are required. In general, the cost of the roofing material (zinc, tiles, fibercement, etc.) was from between 20% and over 35% of total construction material costs. Garcia-Rios (1992) noted that zinc roofing "causes the house to become excessively hot during the day".

These concerns provide a bench-mark against which proposed solutions to the housing situation can be compared. Ideally existing construction systems and materials can be improved to address these concerns, and new approaches will respect the limitations of the existing construction approaches and provide novel ways of addressing these concerns.

3.0 Bamboo

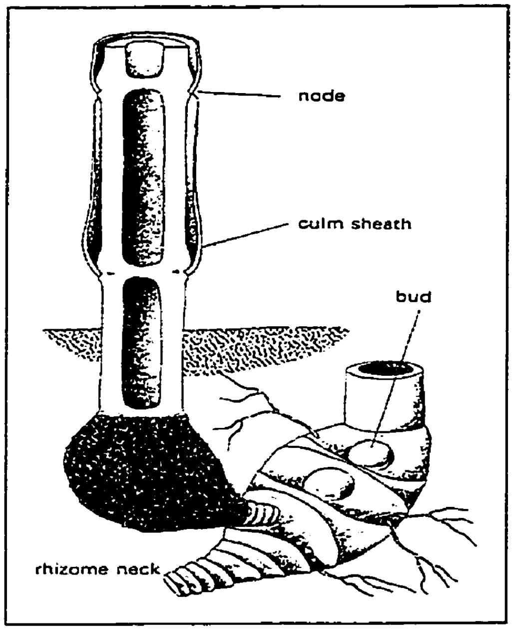
3.1 General Introduction

Walter Liese provided a comprehensive review of bamboo biology in 1985 (Liese, 1985). His information is based largely on Asian bamboos, yet it provides an excellent summary of the biology, properties, propagation techniques, etc. of bamboos in general.

Bamboo is a lignocellulosic material identified by hollow culms, branches at the nodes, and a woody wall (Figure 14). Bamboos are identified by taxonomists as members of the grass subfamily Bambusoidae, a tribe of the Gramineae. Bambusoid grasses are further divided into "woody" and "herbaceous" bambusoid grasses, the latter generally have softer culms, have shorter life spans, and experience less complex branching at the nodes (Soderstrom and Calderón, 1979).

There are two distinct varieties of bamboo, namely sympodial and monopodial, which are easily identified by the growth patterns of the root, or rhizome (Austin et. al. 1970, and Liese, 1985). In the case of sympodial bamboos (clumping bamboos as shown in Figure 15), culms shoot from the pachymorph rhizome very close to the parent, or mother culm. As additional culms grow from a single rhizome, a clump of bamboo culms are situated closely together. This growth mechanism is largely found in tropical regions.

Figure 14: Lower section of bamboo (cross-section)



Source: Recht and Wetterwald (1992)

Figure 15: ***Guadua angustifolia*** **- A Clumping Bamboo**

Monopodial bamboos (running bamboos as shown in Figure 16) on the other hand are identified by the large lateral extension of the leptomorph rhizome from the mother culm as each shoot develops. After successive shooting, the bamboo culms are sparsely distributed over a larger area, with no great concentration of culms. This is more common in temperate climates, such as much of China and Japan.

Figure 16: *Phyllostachys pubescens* (Moso) - A Running Bamboo

Growth of bamboo is rapid. In general bamboo reaches full height (which can be up to 15 to 30 m) within two to four months of shooting (Liese, 1991). Most shoots are initiated at the same time depending on species and the local climate, often coinciding with the start of a rainy season. Growth in most species is continuous and occurs night and day. It is during this time that remarkable speeds of bamboo growth are witnessed. Ueda reported that Moso (*Phyllostachys pubescens*) bamboo grew 46.8 inches (1,189 mm) in a single 24 hour period (Austin et. al., 1970).

Once culm growth has ended, branches will begin to develop. In clumping bamboos the branches are dense and begin close to the ground. Branching in running bamboos starts at a greater height from the ground. This combined with the spacious distribution of culms makes harvesting and stand management of running bamboos much easier than clumping bamboos.

Monocotyledon bamboos do not continue growth indefinitely, unlike most trees. The walls of bamboo consist of closed vascular bundles, not cambrium essential for secondary growth (Ueda, 1987). But the bamboo continues to live and provide food to the network of rhizomes that feeds the growth of subsequent culms.

Bamboo culms from recent seed or asexual propagation are of small diameter. In subsequent years, the shoots emerge at larger diameters until after approximately 5 years, all new culms are of the full diameter for the species (Venegas).

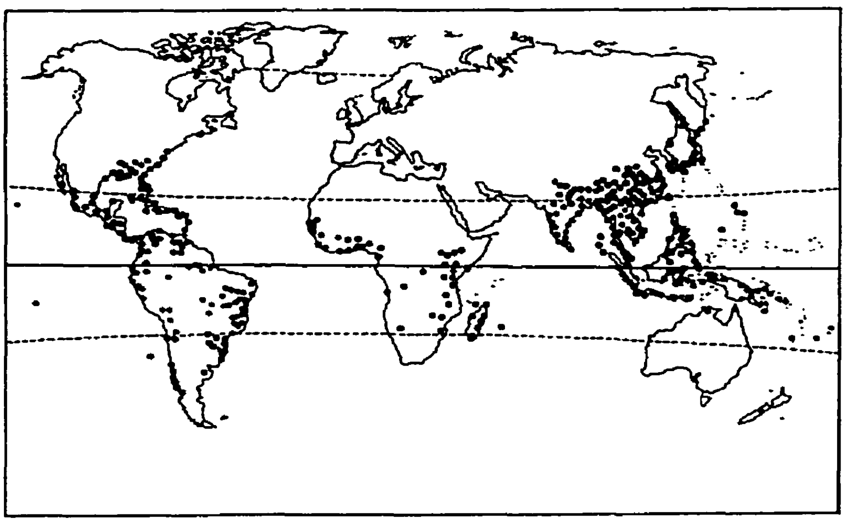
Bamboo flowers irregularly, thereby making accurate taxonomic identification difficult. It is estimated that the number of genera varies from 30 to 90, and the number of species from 500 to 1000 (Liese, 1985). It is believed that numerous species have been identified multiple times by independent researchers. The mysterious flowering of bamboo has great impacts on the propagation of bamboo.

Throughout this report, references will be made for specific species in question. Often the work will focus on *Guadua angustifolia* which is found in Latin America. There are 29 species of Guadua found in Central and South America, and the Philippines (Liese, 1985), making broad generalisations difficult given the range in climate, soils, and agricultural practices.

3.1.1 Global Distribution of Bamboo

Bamboos are generally found between 40° northern and southern latitudes. They are most commonly found in tropical and sub-tropical environments with a mean annual temperature from 20-30° Celsius (Liese, 1985), although some bamboos can survive -20° Celsius (Farrelly, 1984). Bamboos flourish at low altitudes (0 to 800 m) but can grow at altitudes as high as 3,000 metres. They grow best in well drained soil in regions with annual rainfall measuring between 1,000 and 2,000 mm.

Figure 17: Hsiung Global Distribution of Bamboo

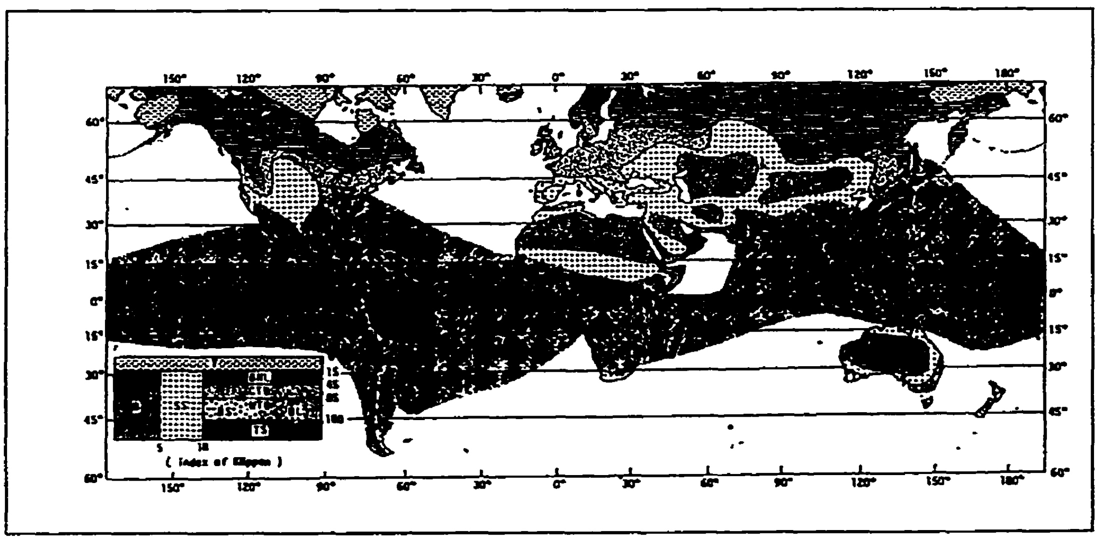


Source: Hsiung (1991)
(• indicates location of native growth bamboo)

Hsiung (1991) noted that bamboos readily propagate into deforested land when left untended, but can be easily damaged by over-harvesting. Bamboo are shallowly rooted and are therefore susceptible to damage due to changes in temperature and precipitation. Hsiung noted that the global distribution of bamboos are in a band close to the equator and covers a total area of 21 million hectares (Figure 17).

Watanabe (1987) provides another perspective of bamboo distribution based upon Kira's major ecosystems (Kira, 1976 as cited in Watanabe 1987) instead of the simplification in the past of considering mean temperatures of the coldest month, or minimum thresholds

Figure 18: Watanabe's Global Distribution of Bamboo



Source: Watanabe (1987)

of precipitation. Watanabe's work showed that bamboo growth is not limited to a simple range of latitudes, but rather climate, altitude and rainfall have a great impact on the survival of bamboo. His plot of bamboo distribution (Figure 18) closely matches the "tropical and subtropical forest" zone identified by Kira.

3.1.2 Bamboo Yields

One of the greatest benefits of bamboo as a natural renewable resource is the rate of growth and yield of material per unit area. Farrelly opens the Book of Bamboo (1984) with a paragraph stating that bamboo can produce from two to six times as much cellulose per unit area in comparison to pine. He remarks that while conventional forests increase in biomass only 2 to 5 percent per year, bamboo can increase 10 to 30 percent. These remarkable facts are of interest to researchers who are striving to understand bamboo in natural stands, and to researchers who are striving to increase productivity in order to increase profitability on bamboo plantations.

Ueda estimates that the total annual global bamboo growth is 10 million tons (Austin et. al., 1970). While this statistic shows that bamboo is of international importance, there is a wide range of estimates of the amount of fibre produced by bamboo for a given land area. Even though the estimates vary greatly, even worst case estimates are significant in comparison to the yield from conventional tree growth.

3.1.3 Total Biomass

A useful estimation of the productivity of a renewable resource is the amount of biomass per unit area of a naturally growing stand. Liese (1985) reported that the above-ground biomass for *Phyllostachys edulis* was 56 ton/ha in Taiwan (78% culms, 15% branches, 7% foliage), 50 tons/ha for a young *Phyllostachys pubescens* in Japan (60% culms, 10%

branches, 23% foliage and 7% sheaths), and 88 tons/ha for *Bambusa arundinacea* in Thailand.

It was found that *Sphaerobambos phillipinensis* had a total dry biomass of 165.3 tons/ha for flatland growth (68% culms, 9% branches, 23% leaves) and 41.0 tons/ha for hillsides (62% culms, 12% branches, 27% foliage) (Virtucio et. al., 1994).

Othman (1992) provided a comparison of an old growth natural stand of *Gigantochloa scortechnii* and a managed three year old plantation. It was found that the natural stand had 71.9 tons/ha of total biomass (74% culms, 14% branches, 13% leaves) whereas the three year old plantation had only 36.2 tons/ha (69% culms, 17% branches, 15% leaves).

3.1.4 Annual Yield

Of greater interest is the annual yield of bamboo. Considering the vast variation in moisture contents of bamboos depending on species, location, season, etc., it is assumed that all masses given are on an oven-dry basis unless otherwise noted by the researcher.

Liese (1985) provided estimates of yield for a number of species in different countries. Average annual yields ranged from 3 to 14 tons/ha (air dry). He stated that the expected sustainable yield would be 2-4 tons/ha for bamboo as understory and 5-12 tons/ha for dedicated bamboo plantations. Austin et. al. (1970), estimated "fresh weight" yields to be between 2.5 and 9.9 tons/ha. Hsiung (1991) stated that an intensively managed stand of *Phyllostachys pubescens* can yield 7 tons/ha (Japan) to 10 tons/ha (China).

The above data are from observations made in China, Japan, India, Taiwan and Thailand. While these are important estimates made by Liese and Ueda, two widely respected bamboo experts, they seem to identify a lower bound of bamboo yields per unit area. Liese has elsewhere stated that proper management and fertilisation can increase yields by more than 50% (1991).

In another study Virtucio et. al. (1994) found that hillside yields were 4.8 tons/ha (dry) and flatland yields were 18.5 tons/ha.

Smitinand and Ramyarangsi identify that there bamboo growth may occur in a two year cycle, one with a low number of shoots, the subsequent with a large number of new shoots. They identify a yearly "production" of 24.7 tonnes/ha and 5 to 8 tonnes/ha in "on" and "off" years respectively.

Guttierrez (1993) notes that 35 tons/ha per year is obtained from managed plantations in Costa Rica. These sites have large amounts of rain distributed uniformly throughout the year, and are fertilised.

A study that did not identify annual production yields specifically (Londoño, 1992), provides a reason for the highly optimistic yields identified by some people in the bamboo community. Londoño reports that a 10 year old *Guadua angustifolia* plantation had 19,031 culms/ha, and that the average diameter was 9.45 cm, and the average culm height 15 to 18 metres. Assuming a conservative wall thickness of 5 mm for *Guadua*, a height of 15 m, a density of 500 kg/m^3 (Liese (1985) estimated bamboo density as 500 to 800 kg/m^3), and 25% of standing crop harvested (after Uchimura (1987)), an annual yield is calculated to be 50.1 tonnes (dry weight) per hectare per year.

Bambusa vulgaris plantations in Brazil yield an estimated 15 to 40 tonnes per hectare per year (with "an average" of 25 tonnes per hectare per year) according to de Barros Salgado and Egashira (1992).

3.1.5 Propagation of Bamboo

The propagation of bamboo is one of the major obstacles to overcome before bamboo can replace wood on a large scale. Propagation of bamboo can occur through flowering (the creation of fruit and seeds) or asexual propagation through the use of cuttings or continued rhizome development.

In general, the flowering of bamboo is not well understood. Most species flower at large time intervals, which are often unpredictable. It appears that all culms of a species flower at the same time, in spite of differences in age or geographic location (Liese, 1985). The length of the flowering cycle can vary from 1 year, to more than 75 years (Numata, 1987).

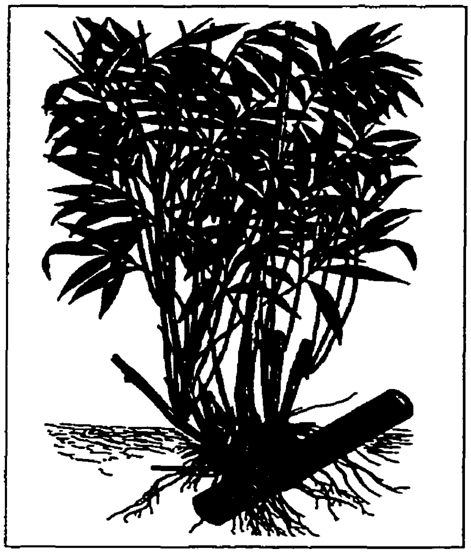
The flowering and fruiting of bamboo uses the stored energy in the rhizome and parenchyma cells in the culms (Liese, 1985). Once seeds are dropped, the bamboo becomes brittle and dies. As bamboo flowering is often gregarious, the process can have great economic impact on a region dependant on one species of bamboo. It can take up to 10 years for bamboo groves without management to once again produce full sized culms (Austin et. al., 1970).

Asexual propagation can occur by replanting a cutting of a branch, culm, or preferably a recently grown section of the rhizome (Figure 19). Austin et. al. (1970), Liese (1985) and Venegas offer good introductions to the asexual propagation of bamboo. As this is the most widely practised form of propagation for bamboo, there will undoubtedly be a great deal of research on this in the future, especially in an attempt to minimise the risks of gregarious flowering of a species.

A negative aspect of asexual propagation is the lack of genetic diversity within a plantation. This may be a liability in the battle against pests and disease.

More recently efforts have been made to propagate bamboos from undifferentiated cells (Woods and Woods, 1994). Given high labour costs for asexual propagation, this will likely be the method of choice for large-scale plantings for commercial bamboo operations.

Figure 19: Asexual Propagation of Bamboo



Source: Farrelly (1984)

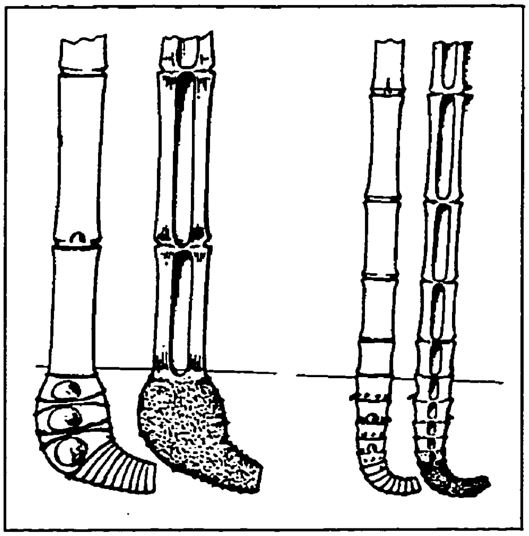
3.1.6 Summary of Bamboo as a Raw Material

Bamboo offers a lignocellulosic alternative to conventional tree-wood. The production rates per unit area can be excellent, and the quick growth, young age of harvesting, and extensive rhizome network makes bamboo ideal for soil conservation. Bamboo culms are small by timber standards, and therefore low-cost machinery can be used for harvesting. These factors combined make bamboo an excellent alternative for plantation or natural growth production of fibre.

3.2 *Anatomy*

Bamboo culms are hollow and erect. The culm consists of alternating nodes and internodes along its length (Figure 20). Bamboo is a monocot, and therefore no cambrium layers exist for secondary growth.

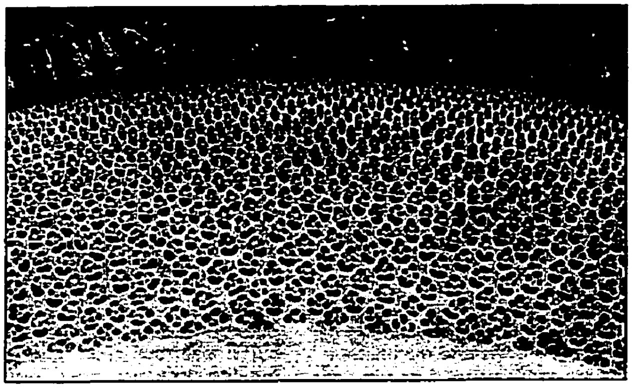
Figure 20: Different Bamboo Species with Differing Internodal Properties



Source: Farrelly (1984)

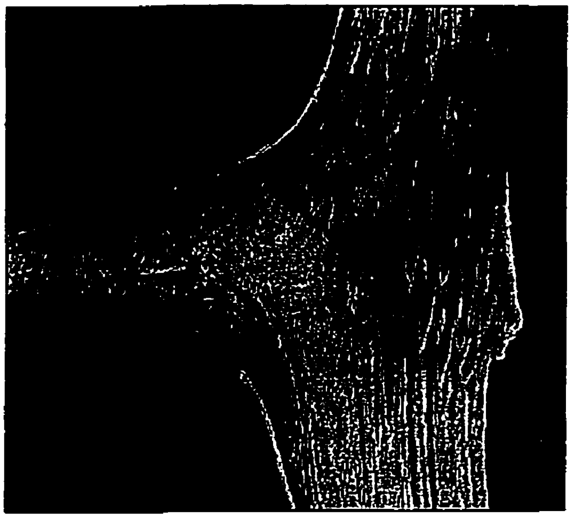
There are no lateral, or radial, elements (Figure 21), such as rays found in wood. Cells are axially oriented throughout the internode. Near and within the nodes, the vessels branch and extend throughout the node (Figure 22), providing paths for transverse conduction of water and nutrients throughout the entire culm (Liese, 1985).

Figure 21: Horizontal Cross-Section of Bamboo Culm



Source: Arce (1993)

Figure 22: Vertical Cross-Section of a Bamboo Culm



Source: Arce (1993)

3.2.1 Exterior

The exterior of the culm consists of a cuticular layer that is made up of cutin and epidermis wall material (Hsieh and Wu, 1994). More specifically, the hydrophobic cutin is distributed between the exterior waxy covering and the epidermis. This layer serves as a useful retardant to water movement and assists in cell protection. As cutin is indigestible, it provides protection against fungi and bacteria.

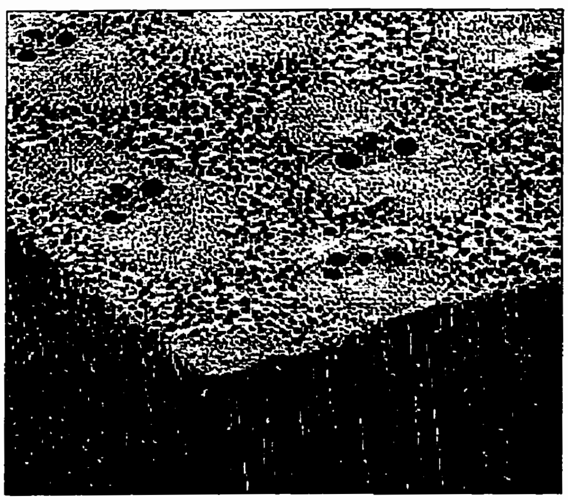
In addition, the epidermis layer itself consists of cork and silica cells. The silicon dioxide in the silica cells strengthens the epidermal layer, and provides protection from the environment and is analogous to bark in dicotyledons (Hsieh and Wu, 1994).

3.2.2 Culm Composition

The density of the culm and the total number of vascular bundles is greatest at the exterior of the culm, and decreases towards the inner wall of the culm. Likewise, the density of the culm and the number of vascular bundles increase towards the upper reaches of the bamboo culm (Liese, 1985).

The overall composition of the culm (Figure 23) consists of approximately 50% parenchyma, 40% fibre, and 10% conducting tissues (Liese, 1985). Although there are minor variations within species, the inner parts of the culm generally have a higher number of parenchyma and conducting cells (vessels and sieve tubes) than the exterior part of the culm where the presence of fibres is greater. Similarly, the amount of fibres increases and the amount of parenchyma decreases towards the top of the culm.

Figure 23: Bamboo Culm Wall



Source: Liese (1985)

3.2.3 Fibre Properties

Bamboo has been used for many years in the production of paper. As fibre properties are critical in the production of high quality paper, it is of no surprise that the recent studies on bamboo fibres detail long, strong fibres in many bamboo species.

Haun et. al. (1966) found that bamboo fibres are approximately the same length as hardwood fibres (i.e. shorter than most softwood fibres). Of great interest is the high length-to-width ratios of bamboo fibres, indicating that they are strong and flexible, and not stiff and brittle. For example, it was found that the *Bambusa vulgaris* had an average fibre length of 2.28 mm, and a length-to-width ratio of 240:1. Other species of interest include *Guadua angustifolia* (1.60 mm and 148:1) and *Phyllostachys pubescens* (1.3 mm and 140:1).

These findings are in keeping with Liese's recent work. He found (1985) that length-to-width ratios varied between 150:1 and 250:1. Average fibre lengths ranged from 1.3 mm (*Phyllostachys pubescens*) and 4.3 mm (*Dendrocalamus membranaceus*).

While the above values are significant in comparison to wood, it is the variability of fibre length of bamboo that is of concern. Liese and Grosser (1972) identified a large variation in the fibre length within each internode. Specifically, for *Bambusa vulgaris* they found that the fibres reached a maximum size near the centre of the internode (2.7 to 2.8 mm long), and decreased drastically near the nodes (1.2 to 1.3 mm).

In addition, they noted that the fibres decreased in length from the exterior towards the interior of the culm wall, and that fibre length decreased with increasing height of the culm.

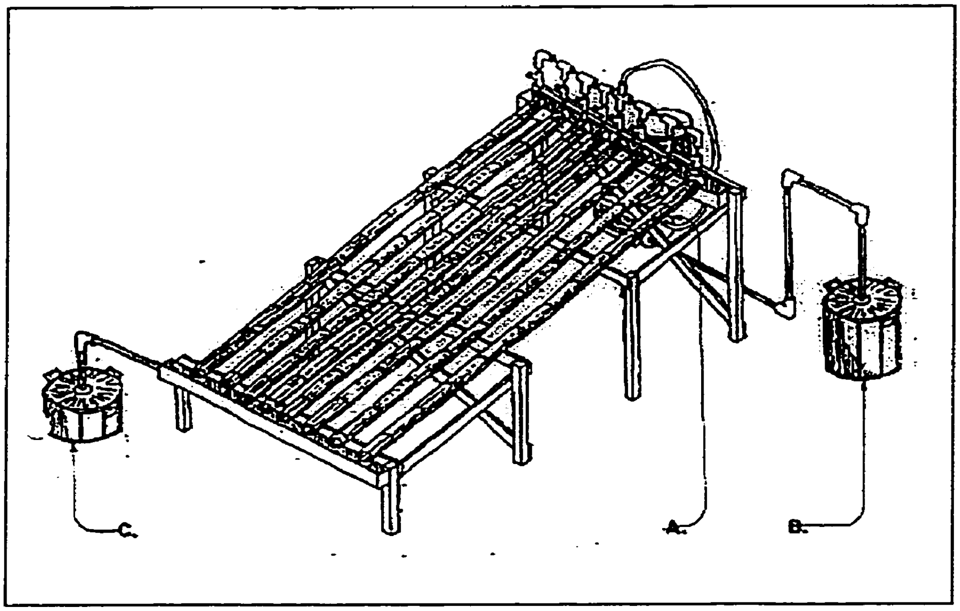
The fibres have a high tensile strength due to thick polylamellate wall structure which is not common in fibre cell walls in wood (Liese, 1985).

Within one growing season the lignification of the bamboo culm is complete. Therefore, for pulp and paper applications, bamboo is normally harvested at a very young age. For structural applications, older bamboos (3 to 5 years) are normally harvested (Espiloy, 1994).

3.2.4 Preservation of Bamboo

Due to the longitudinal alignment of the vascular bundles (i.e. lack of ray tracheids and ray parenchyma), and the impermeable exterior of the culm (due to cutin and silica), the preservation of bamboos is difficult. Bamboo culms can not be simply submersed in a preservative in order to displace sap with the preservative. The alignment of vascular bundles requires the preservative to be applied from a cut end of a culm. Liese (1985) has modified the Boucherie method that was originally developed for wood preservation, and adapted it for the preservation of bamboo in rural areas. Currently, this "Modified Boucherie" method (Figure 24) is in use at the National Bamboo Project of Costa Rica (González et. al., 1991).

Figure 24: Boucherie Preservation Method



Source: González et. al.(1991)
A – pump, B – tank of preservative to be forced through culm, C – tank containing outflow

In essence, a mixture of boron preservatives are forced through one end of a recently harvested bamboo culm. This requires an adaptable flange that is capable of withstanding the 80 to 120 kPa pressure required. If too great a pressure is used, the preservative may be expelled at the nodes. An additional concern is that any air entered into the system can block vascular bundles, thereby blocking passage of the preservative. The concentration of preservative in the effluent can be measured to determine when the preservative has sufficiently replaced the sap.

While this is a long and complex procedure for preserving bamboo culms, it demonstrates that the decay of bamboo can be treated with methods similar to those used to preserve wood.

3.3 Material Properties

3.3.1 Testing Standards

The mechanical material properties of bamboo are widely variable for many reasons. Firstly, there is a lack of standardised bamboo testing procedures which leads to incompatible test results from individual researchers. Although there has been much discussion on the development of an international standard for testing bamboo culms, this remains a concern. The lack of testing standards for bamboo is in sharp contrast to other construction materials such as tree-wood, concrete and steel for which standards are widely accepted and utilised.

In general, bamboo is strong in all physical-mechanical tests, with the exception of shear. It is difficult for direct comparison between studies, as they generally use different testing methods created by each researcher.

To begin with, no distinction is made in many reports of which form of bamboo is being tested, namely the entire culm, or a "split" (a section of the bamboo wall derived from longitudinal cuts of an entire culm).

3.3.2 Culm Mechanical Properties

The hollow nature of bamboo makes it an obvious choice for applications in bending or compression as the moment of inertia is high in comparison to beams or columns of wood given the same mass. Janssen presented (1981) testing procedures, and discussed the impact of moisture content, the sample's location within the culm (i.e. bottom, middle or top), the presence of a node in the testing sample, etc.

Janssen's (1981) dilemma of testing bamboo in tension relates some of the obstacles faced by bamboo researchers. Bamboo is generally recognised to have a tensile strength of 200 to 300 MPa. When attempting to verify this, Janssen was unable to properly conduct the tests due to failure of the bamboo in transverse compression at the grips. He noted that through empirical studies the failure of bamboo in tension is not of concern. Normally shear failure influences overall performance, and as Janssen rightly points out, even when considering bamboo as reinforcement in concrete the bond strength remains the limiting factor, not the tensile strength of the bamboo itself.

As with other bamboo properties, the measurement of specific gravity depends greatly on the location within the culm. In general, strength properties vary more in the horizontal direction than in the vertical direction. A lower moisture content of bamboo leads to higher strength. For this reason, the effects of seasoning bamboo is much more pronounced with young culms, as younger culms have a much higher standing moisture content (Liese, 1985)

Janssen (1981) found the compressive strength of bamboo culms to generally range from 60 to 110 MPa. He stated that the strength of bamboo culms and split bamboo pieces (tested in compression) did not vary significantly. The average ultimate bending stress for culms was found to be 84 MPa, and the average bending MOE for culms was 20.5 GPa. Failure in bending was generally noted as a shear failure along the neutral axis.

Urrutia (1983) studied six Guatemalan species of bamboo. Testing samples for compression were culm sections with and without nodes. Tension tests, however, measured performance for splits only (again for sections with and without nodes). No bending tests were performed. The test results are presented in Table 14.

3.3.3 Mechanical Properties of Splits

Lee et. al. (1994) found that for *Phyllostachys bambusoides* the strength increased between the bottom and top of the culm. They also found that air-dry samples tested much higher than green bamboo in compressive strength, tensile strength, modulus of elasticity, and modulus of rupture. In addition they noted that the presence of a node had little effect on the modulus of elasticity, but greatly affected the compressive strength, the tensile strength, and the modulus of rupture.

The testing results for bamboo, and some representative wood values are provided in Table 14.

These results, and those of many other researchers, constitute a great deal of the "bamboo in construction" scientific literature available. Unfortunately, this information is of little benefit to the present study as the results are not standardised. In addition the very small imperfections in each culm, and in splits of culms, makes it difficult to use the macroscopic properties in the prediction of composite panel performance presented later. In reality, even the macroscopic properties measured are of little assistance in determining the mechanical properties of other culms as the properties vary tremendously between species, and between samples of the same species.

Table 14: Mechanical Properties of Bamboo and Selected Wood Species

Species	Density (kg/m^3)	Bending MOR (MPa)	Bending MOE (GPa)	Tension MOR (MPa)	Compression MOR (MPa)
Phyllostachys. bamusoides (Lee et. al., 1994) (splits)	0.52 (SG[2])	102.7	10.7	120.0	42.1
Bambusa guadua (Urrutia, 1983)	620	NA	NA	100.4 [3] 163.8 [4]	53.9 [3] 49.9 [4]
Bambusa vulgaris (Urrutia, 1983)	690	NA	NA	129.8 [3] 183.6 [4]	38.7 [3] 39.4 [4]
Bambusa blumeana (Janssen, 1981) (culms)	660	84.0	20.5	NA	60 to 110
Bambusa guadua (Atlantico) (Sotela) (culms)	698	75.7	23.2	NA	41.8
Bambusa guadua (Sur) (Sotela) (culms)	704	109.2	27.2	NA	41.2
Douglas Fir[1]	480	83.0	13.7	130	51
Pine, Eastern White[1]	350	59.0	8.6	78	33
Teak[1]	670	131.0	13.7	118	65

[1] From Tsoumis, 1991
[2] SG = Specific Gravity
[3] sample without node
[4] sample with node

In most studies bamboo is very strong in comparison to wood. However, the natural variation of individual bamboo culms makes it difficult for an efficient design procedure to be developed for maximising efficiency and safety in construction.

3.4 Summary

In this chapter, basic information critical to the understanding of bamboo was presented. In recent years bamboo has been heralded as a plant that will help minimise the effects of deforestation, global warming, erosion, and many other concerns.

Bamboo has material properties that make it a potential alternative fibre source (fast growing, high yielding, easily manageable, and a strong lignocellulosic raw material).

4.0 Traditional Uses of Bamboo

4.1 General Overview of Bamboo With Respect to Construction

In Chapter 2 an introduction was provided into the traditional construction with bamboo in Ecuador where the current applications are basically a continuation of the traditional construction practices developed over hundreds of years, and are almost entirely conducted without engineering design or analysis. This chapter will provide an introduction to the technical concerns regarding the use of bamboo in construction. Applications include post-and-beam construction, bamboo used as reinforcement in concrete, and the more recent development of panel products found mostly in Asia.

4.2 Traditional Construction with Bamboo

Bamboo is a peculiar material. For centuries it has been used for paper, construction, furniture, and a wide variety of tools and small-scale applications as noted by Farrelly (1984).

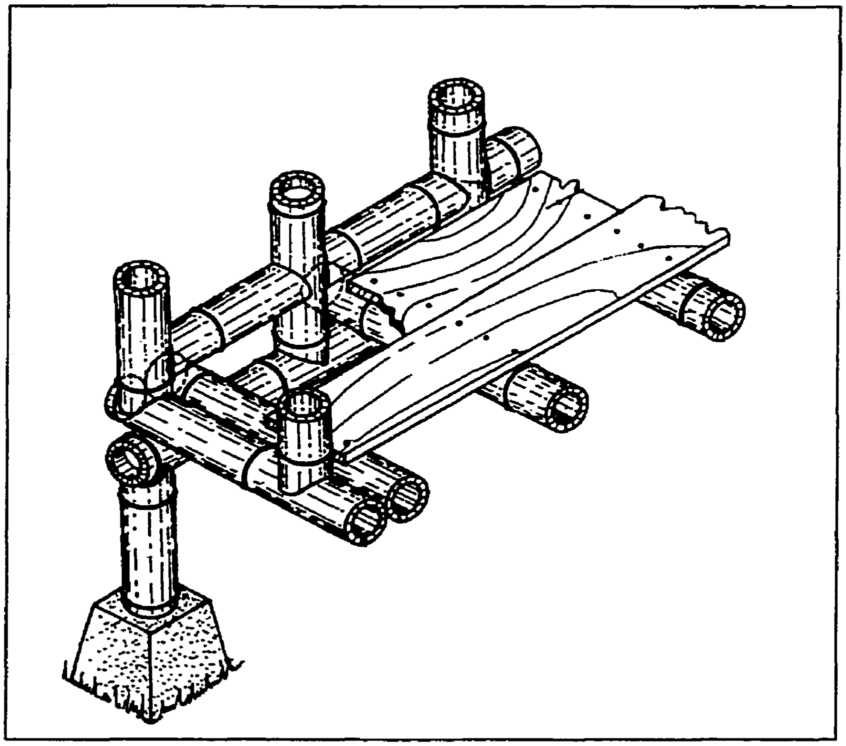
Unfortunately, bamboo has not been a priority for either the large international forestry organisations nor the international agricultural organisations, as bamboo is a grass and falls outside of the direct area of interest of major international organisations. The collection of relevant research information is scattered, and incomplete. Often research results are not widely published.

This has made a complete review of bamboo very difficult. Through continuous literature searches, and more successful direct personal contact with researchers, a significant collection of relevant information has been gathered. These findings are presented in this thesis, with the hope that due to the rapid increase in bamboo technology and information technology, the appropriate literature will be more accessible and complete in the future.

Traditional uses of bamboo in construction have been primarily simple post and beam construction (Figure 25). Due to the physical properties of bamboo discussed earlier, bamboo naturally grows in a form that lends itself for use as columns and beams. Common connection methods include simple tying of joints with string, rope, bamboo strips or metal wire (Figure 26). This small-scale form of construction is favoured by many sustainable development enthusiasts as it requires very little investment in equipment, tools and resources. The techniques can be easily copied thereby providing potentially strong housing at very low cost in rural areas where bamboo and labour are readily available.

Duff (1941) provided an excellent overview of bamboo, including the state-of-the-art of bamboo construction in China. He also introduced his methods for testing the mechanical properties of bamboo. He offered a review of bamboo construction practices, along with a list of potential limitations cited by other researchers, and proposals for overcoming these problems. As is common with many bamboo researchers, he seemed taken with the outstanding mechanical properties, and the variety of uses of the material. Limitations such as the "very bad fire record" were glossed over, in spite of the knowledge that traditional lashed joints are easily burned, thereby causing catastrophic early failure of the structure. The lack of effort in overcoming these serious limitations of bamboo in practical applications such as housing perpetuate the concept that bamboo in traditional applications is a last resort for poor people.

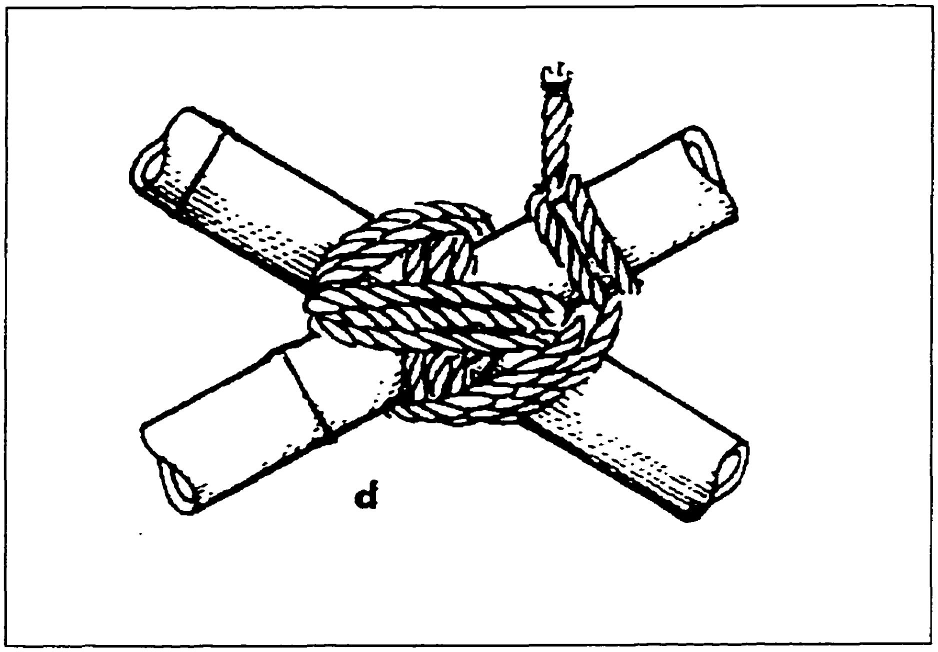
Figure 25: Bamboo Post and Beam Construction



Source: Hidalgo (1981)

F. A. McClure, the infamous bamboo researcher who spent many years in China and in Latin America studying and identifying numerous bamboos, prepared a small review in 1953 entitled "Bamboo as a Building Material" (McClure, 1953). It provides an introduction to bamboo construction and numerous photographs of sample houses and building components. While this review is of limited use by today's standards, it clearly shows that even McClure (a pioneer bamboo botanist and taxonomist) was inspired by bamboo for its beauty and its practicality.

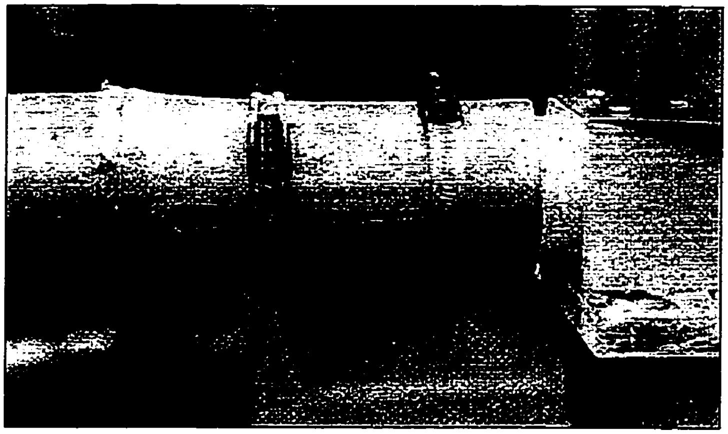
Figure 26: A Typical Connection



Source: Hidalgo (1974)

Hidalgo Lopez released a comprehensive review of bamboo cultivation, technology and applications in 1974 (Hidalgo, 1974). This often-referenced work provided a complete review of traditional bamboo construction practices common in South America with specific reference to Colombia.

Figure 27: An Engineered Joint



Source: Arce (1993)

More recently, Janssen (1981, 1988) and Arce (1993) have focused much attention on the joining process. Through comprehensive laboratory studies of single joints and truss systems, they have developed several proposals to improve the efficiency of joints. Several joints and joining methods have been suggested by Arce in the hopes of promoting a standardised construction procedure. An example is provided in Figure 27. Unfortunately, the level of formality and technology, and therefore cost, of bamboo construction would become prohibitive to most natural bamboo users, primarily the rural poor.

The limitations of traditional joining practices are of great concern. Due to the uniqueness of each culm of bamboo, the joining process is difficult to replicate properly. If a joint is well made, it is sufficiently strong to exhaust the mechanical strength of the bamboo it joins (Janssen, 1981 and 1984). Janssen tested his engineered joints through full scale mechanical testing, and through numerical modelling of truss assemblies calibrated by empirical studies. Unfortunately, there is a large variation of the quality of joints in most construction as they are highly dependant on the carpenter or artisan who carries out the construction.

Due to the difficulty in estimating the strength of a bamboo joint, structures are often over-built in order to err on the side of safety. This leads to increasing construction costs due to the wasteful use of extra bamboo material, and the labour required in the construction process.

As bamboo rich regions benefit from increased economic activity and growth, there are demands placed on many facets of the nation to meet international standards of construction. Ideally standards provide safe and affordable housing and general-use structures for the general population given the environmental, physical and social factors that affect loads on structures. Due to the variability of traditional bamboo lashed joints, traditional natural bamboo post and beam construction will face great challenges in gaining approval under responsible and comprehensive building codes of most nations.

Given the wide distribution of bamboo in poor countries, a reliable, affordable joining system would make a significant impact on low-cost housing supply in many areas of the world. Given the flexible, light-weight nature of this form of construction, it is preferable in earthquake susceptible regions. Unfortunately, due to the lack of commercial opportunities in supplying this target market, the funding of such pure and applied research falls to the non-governmental organisations, and organisations with specific objectives in providing such information and services.

4.3 The State of the Art of Bamboo in Construction and Bamboo Composites

It has been noted that bamboo rivals wood in terms of mechanical properties. But how is it used? Each bamboo culm is of a different shape with minor irregularities. Due to the hollow nature of most bamboo species, it is not practical to cut or mill bamboo to change its cross-section as is commonly performed with wood to make lumber and timber members of standard cross-sectional sizes.

In order to overcome these difficulties many novel methods for utilising bamboo have been developed. While many are impractical with wood, the ease with which bamboo splits are formed offers unique potential products, albeit requiring additional processing stages. This section will therefore focus on the unique methods by which bamboo strength is captured for use in composite products and applications.

First, a review of bamboo reinforced concrete will be presented. While this has not been found highly practical (mostly due to bond failure and decay), it demonstrates the efforts that have been undertaken to exploit the high tensile strength of bamboo in a more readily useable and adaptable form for general construction purposes.

Second, a variety of composite products formed from split bamboo will be presented. These approaches show that innovation directed towards obtaining standardised shapes from the culm can lead to products that can be mass produced, and meet international standards (in shape and performance).

Finally, bamboo composite panels will be introduced. The advancements in this area have been quite recent, and show great promise. Refining the bamboo into small uniform particles that are blended with resin, and formed into a desired product offers an ideal solution to the irregularity of each bamboo culm.

4.3.1 Bamboo Reinforced Concrete

The original bamboo composite work dealt with the use of bamboo as reinforcement in concrete. Although previous work had been completed, it is Glenn's 1950 report "Bamboo Reinforcement in Portland Cement Concrete" that receives a great deal of attention. His work provides a thorough review of the anatomy of bamboo, and details the testing improvisation that was required to test the material properties of bamboo, and required to test the various aspects of bamboo in concrete.

Glenn (1950) found that bamboo reinforced concrete beams were capable of carrying more than five times the load carried in unreinforced beams of the same cross-sectional area. The optimum amount of reinforcement was 3 to 4 percent of the cross-sectional area of the member.

Much effort was directed towards improving the bond conditions between the bamboo and concrete. It was found that seasoned bamboo culms coated with an asphalt emulsion carried greater loads than unseasoned culms, and untreated culms. The asphalt mixture helps prevent the swelling of bamboo by limiting the absorption of water during the concrete curing process. Of concern is that too great an amount of emulsion can lubricate the bonding surfaces, thereby causing failure.

Geymayer and Cox (1970) noted that while the tensile strength of bamboo is very high, the modulus of elasticity is less than 10% that of steel reinforcement. Therefore large deflections and wide cracks are expected in bamboo reinforced beams. While this is of concern in the direct replacement of reinforcing steel, it should be remembered that in most regions where bamboo grows, the desire for low cost construction might outweigh the concern of bamboo reinforced concrete not meeting current serviceability limit states.

They also note that the longitudinal thermal expansion of bamboo can be 33% that of concrete, and the lateral thermal expansion can be more than 10 times that of concrete. This contributes to the cracking of the concrete cover thereby leading to bond failure between the bamboo and concrete.

Kankam et. al. (1988) found that bamboo reinforced concrete beams subjected to three-point loading failed at approximately 2.4 times the theoretical shear strength of unreinforced concrete. The subsequent use of bamboo stirrups did increase the strength, but not as much as they had expected. All beams tested failed in shear and their recommendations deal with the bond strength of the bamboo tensile reinforcement. They do note that the design of the beams was based on a nodal tensile strength of bamboo (104 MPa) not the internodal tensile strength (280 MPa). In a disappointing conclusion they recommend that the maximum permissible design moment should be calculated based on the concrete section alone in the interests of meeting serviceability and cracking limit states. They suggest that the bamboo reinforcement should only offer a factor of safety in design, something that has little benefit to most of the potential bamboo reinforcement users.

It should be noted that some resistance against slippage is provided by the outer perimeter of the nodes, and the tapering of the bamboo culm (in the case of small diameter culms used in their entirety, in place of steel reinforcement). Additional mechanical attachment of bamboo has been suggested by Hidalgo and others. As with original steel-based ferrocement, the bamboo reinforcement in bamboo ferrocement is dispersed throughout the member, often in a fine mesh, and then covered with cementitious material. Of course, the natural durability of bamboo in concrete applications is of concern, especially in terms of long-term degradation which can lead to failure of the structure.

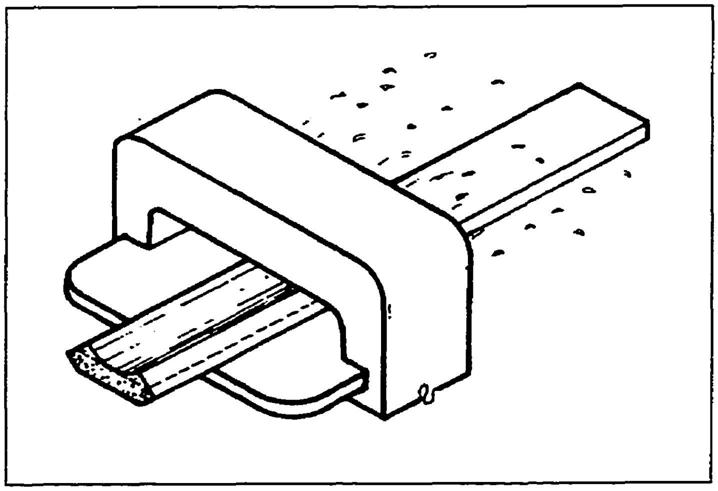
Another application of bamboo reinforcing cement is that of cement-bonded particleboard. There is little work done in this area, and will be discussed alongside conventional bamboo particleboard.

4.3.2 Bamboo Strip Composites

Some of the first advances in bamboo in construction were taken from the well-developed crafting industries. Bamboo has long been split into long, thin pieces (Figure

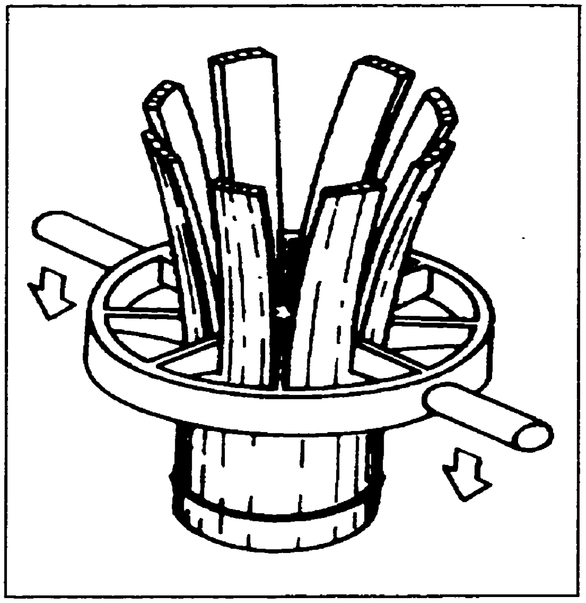
28, Figure 29) and combined in numerous fashions in the production of baskets, covers, mats, etc. The weaving of large bamboo splits through wood uprights forms simple non-loadbearing walls in many parts of the world. This can also form the basis of Quincha type construction seen in Colombia and other Latin American regions. Quincha construction is similar to modern ferrocement approaches, and consists of loosely spaced members (thin bamboo culms, canes, or bamboo splits) that are subsequently covered with concrete. This is the dominant form of construction used by the National Bamboo Project of Costa Rica (Ham, 1990).

Figure 28: Modern Splits are Planed and Squared



Source: Hidalgo (1981)

Figure 29: Traditional Method of Cutting Splits



Source: Hidalgo (1981)

4.3.2.1 Bamboo Mat Board (BMB)

The weaving of thin bamboo strips has long been used as internal partitions, shutters, and decorative material. The high strength of this hand-made product was further investigated as a potential alternative to thin plywood in Asia. In India there has been a great deal of work dedicated to the optimisation of this product, bamboo matboard (Figure 30), but it has failed to gather significant international interest in spite of its outstanding performance. Most data of mechanical properties refer to a three layer panel, or a panel formed by pressing together three individual mats. The mats are dipped (or soaked) in a phenol formaldehyde mixture before pressing at 140-145° Celsius for six minutes (for a three layer panel).

Figure 30: Bamboo Matboard

Bamboo matboard of a density of 750 kg/m^3 has excellent mechanical properties (IPIRTI, 1994). The MOR and MOE for bending are 50.8 MPa and 3.68 GPa respectively. The shear modulus is 5875 MPa.

Of concern is the economics of this product, and other mass produced bamboo products. According to a relatively recent economic investigation (IPIRTI, 1992) the bamboo mats can be purchased for 16.88 Rupees per mat (4' by 8'), or \$ 0.50 USD (assuming exchange rates of 34.8 R=\$ 1 USD). Assuming a suggested selling price of \$3.00 USD (103 R) per finished panel, there remains only \$1.50 USD to cover the costs of mat transportation to the facility, drying, impregnation with resin, manufacture of resin, forming (three layer), pressing, cooling, trimming and factory overhead.

It is reported that this recent research has reduced the amount of PF resin required to 0.33 kg/m^2 (down from 1.3 kg/m^2 in previous research efforts), or approximately 1 kg per three layer panel. At international prices, PF resin sells for approximately $0.65 USD to $0.90 USD per kg solids. Unfortunately, no details were given in the recent research as to how the reduction in required resin amount was achieved, nor the effects the changes had on the material properties of the panels.

Further limitations of bamboo matboard are the non-uniform bonding due to inadequate application of resin on all bonding surfaces, poor appearance due to surplus resin staining on surfaces, and low durability. Some of these issues have been addressed by IPIRTI with limited success, although only Zoolagud and Rangaraju (1994) mention that changes were made, although no details were provided. Most of their work focused on the quality of resin used. In most Indian bamboo matboard applications, it appears that resins are manufactured on-site.

Bamboo matboard has been widely supported by Indian research agencies, and the International Network of Bamboo and Rattan. Due to much different labour conditions, and the lack of government subsidised bamboo plantations in other countries, the production of this product has had limited success in regions outside of India.

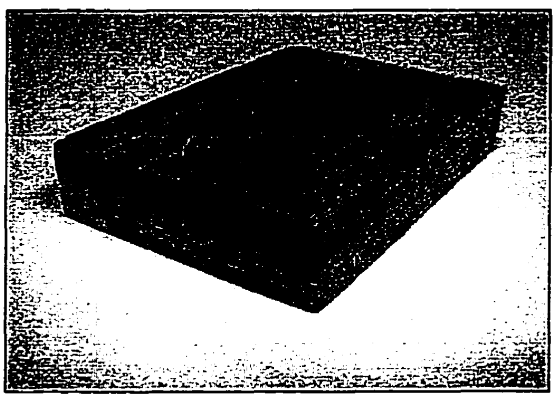
Automatic weaving machines have been used in China to reduce costs in mat production. However, the economics still dictate that thick panels have little opportunity to compete directly with wood products. The excellent mechanical properties, and attractive appearance make bamboo woven mats an ideal exterior laminate on panels, and are used in China to cover particleboards to enhance bending properties and appearance.

4.3.2.2 Plybamboo

Larger, thick-walled bamboos are more readily split into sections yielding fairly flat "splits". Obviously, the larger the diameter the original bamboo, the less curvature there is across a split. Similarly, narrower splits have less curvature. Recognising this, large timber bamboos such as *Phyllostachys pubescens* (often referred to as Moso), have been exploited for splits.

Various Chinese researchers have created bamboo products analogous to plywood by laying bamboo splits in layers. For example, two surface layers of splits might be aligned longitudinally, and the centre layer laterally in a three layer plybamboo (or bamboo plywood) panel. This provides great strength, especially in the longitudinal direction.

Figure 31: Plybamboo With Adjacent Layers of Bamboo Placed Orthogonally



Occasionally bamboo splits are connected in a similar fashion to bamboo blinds. When several layers are coated in resin, and formed as with plybamboo, a product called bamboo "curtain board" is manufactured. The main benefit of this approach is a more efficient layout of the product in the final application of resin and in the forming stage.

This approach exploits the great mechanical properties of bamboo by utilising splits, not fibres or smaller cuts of bamboo. Each split itself has remarkable properties, and therefore leads to excellent performance which surpasses the properties of most tree-wood plywoods. Some of the limitations are that the product requires a high quantity of resin to properly bond surfaces, and the flattening of splits is labour intensive and difficult to mechanise (Zhang, 1992).

There has been a great deal of research done on plybamboos, and has been swiftly commercialised in China. Zhang (1992) estimated in 1992 that there were 13 plybamboo factories each with an annual production capacity of about 2,000 m^3 (Zhang, 1992).

Shen (1992) indicated that a survey of 18 plybamboo factories in Zhejiang Province found that the average plant employed 59 workers, yet had an average annual production of 1000 tonnes per year (approximately 1175 m^3). Only three of the 18 mills were making a profit. Shen cites the "unripe" technology that leads to high product densities and high production costs.

Zhang (1992) noted that for bamboo plywood of 850 kg/m^3 density, there was a longitudinal bending strength of 98 MPa for panels under 15 mm thickness, 90 MPa for panels between 15 and 25 mm thickness, and 80 MPa for panels thicker than 25 mm.

As mentioned earlier, the manufacturing process for plybamboo is long and complicated. As with wood products, the pressing stage is the most critical as the capital investment for press equipment is the greatest for any single piece of machinery in a typical plant. The plybamboo mentioned above is pressed at 145° C under 3 MPa of pressure for approximately 1.1 minutes per mm of panel thickness. That is, for a conventional panel of 15 mm thickness requires a 16.5 minute press time. Panels designated for use as truckbeds are, in fact, often pressed for a second time with additional PF resin on one or both surfaces. A metal screen is inserted on either face of the panel. This final procedure is intended to increase the wear and weathering resistance of the product while offering a textured surface for increased traction.

Zhang (1992) goes on to describe plybamboo for use as formwork. This is essentially the same product as before, but it is overlain with resin impregnated paper in order to provide increased water resilience and a smooth finish. Subsequently the edges are sealed to inhibit water penetration. For a product density of 950 kg/m^3 and 12 mm thickness he notes a longitudinal MOE of 10 GPa and MOR of 98 MPa, and lateral MOE of 7.0 GPa and MOR of 68 MPa. For thicker panels, values are slightly higher. Unfortunately few manufacturing details are provided.

Concrete formwork has a large market demand in China, and other tropical bamboo-rich countries where concrete housing and construction is often viewed more favourably than wood-frame construction due to wood deterioration from insect attack and weathering, and other cultural reasons which identify wood and bamboo housing with poverty.

Zhao and Yu (1992) introduced a similar product also intended for use as forms for concrete. For a 12 mm panel of 920 kg/m^3 (also covered with impregnated paper) they obtained a MOE of 13.5 GPa and MOR of 127.4 MPa. It should be noted that there is no indication of whether this product is made from woven mats, or from bamboo curtains, or other approaches. The pressing cycle required 45 minutes to press a single 12 mm panel. The cycle slowly raised the press temperature from 50 to 135° C. This final temperature was maintained for 1.5 to 2 minutes per mm of final product thickness. Subsequently the temperature was reduced to 50° C. There is no estimation of the PF resin consumed, but mention is made of the application of PF resin by a "special dipping device".

Of interest in the products mentioned above is that all are manufactured using phenol formaldehyde resin. PF resins are generally considered to be expensive, yet are used to improve dimensional stability when required. PF resins are normally used with bamboo in order to overcome the high silica contents of the bamboo. However, this seems redundant for both bamboo matboard and plybamboo as the interior pith and the exterior skin is removed. PF resins have a much lower formaldehyde emission than UF resins that are commonly used in particleboards. This leads to a wider market acceptance for PF bonded products due to fewer health concerns in comparison with UF bonded products, and leads to a safer working environment in the manufacturing facilities.

Sulastiningsih and Sutigno (1992) made "plybamboo" made from 1 mm thick veneers. No information was provided as to how the veneers were obtained. They used urea formaldehyde (UF) resin and reported that for a density of 800 kg/m^3 a three layer panel had a longitudinal MOR of 100.3 MPa, and a lateral MOR of 9.7 MPa. Comparable values for a five layer panel were found to be 129 MPa and 34 MPa respectively. Pressing was performed at 110° C and 1.5 MPa for 2 minutes for three layer panels, and 4 minutes for five layer panels. Unfortunately no final product thicknesses were provided, and the details of resin quantity were unclear.

The limitation of plybamboo is similar to that of bamboo matboard: economics. Although the *Moso* bamboo yields large and fairly uncurved splits, they must be refined in numerous ways to make them suitable for use in plybamboo. This complexity in manufacturing requires large capital investment, large labour resources yet yields only small production capacities. In addition the resin contents of these products are seldom reported, and based on field investigations are normally extremely high. These factors lead to expensive products.

4.3.3 Bamboo Composite Panels

4.3.3.1 Bamboo Particleboard

Bamboo particleboard suffers much the same reputation as wood particleboard: it is seen as a lower quality product, and has therefore received little attention. Clearly the refinement of bamboo into small particles limits the product's potential for taking advantage of the macroscopic strength of bamboo. But as discussed above, the fibre characteristics of bamboo are superb. Therefore, the mechanical properties of bamboo particleboards should be comparable to tree-wood particleboards.

One advantage of particleboards over plybamboos (and other bamboo products) is that the great local variability of bamboo properties within a culm is controlled. The effects of strength variations from the top to the bottom of the culm, or from the interior to exterior of the culm, can be randomly distributed throughout the panel.

There are several limitations to the use of bamboo as furnish for particleboard. The exterior skin of the bamboo causes problems in two critical stages of production. Firstly, the tough skin makes refinement more difficult than for wood. The highly localised silica found on the exterior of bamboo culms can prematurely dull saws, knives and flakers. But on a more important note, the silica makes adequate bonding with resins difficult to achieve.

The benefits of particleboard are a simpler manufacturing method that can be mechanised to a level consistent with local labour conditions. Also, the fact that particleboards are an engineered product allows for the adjustment of manufacturing parameters (density, resin content, particle size, etc.) to adjust product performance (and manufacturing costs) to meet market demands.

In many bamboo-rich regions there are numerous small-scale manufacturing enterprises that produce a great amount of waste bamboo. As in the wood industry, this could provide the basis of the raw material supply to a bamboo particleboard plant.

Chew et. al. (1994) produced particleboards of *Bambusa vulgaris* alone and in combination with other materials. Each test panel was produced with 8% UF resin, and a target density of 700 kg/m^3 . Panels of individual fibre types were produced, as well as bamboo in combination with these other fibres. All panels of combinations of fibre were produced using 50% by mass of each fibre type.

Although the bamboo and oil palm fibre used have high silica contents, no mention of this is made. No indications of resin additives or modifications are given. Test panels were tested according to British Standards BS 5669. Results are presented in Table 15.

Table 15: Bamboo Particleboard Results

Type of UF board (all samples are 19 mm thick)	Density (kg/m^3)	MOR (MPa)	IB (kPa)	SW (N)	TS (%)
Bambusa Vulgaris (BV)	690	21.3	740	697	4.4
rubberwood	682	25.3	680	1303	3.3
BV / rubberwood	700	29.3	860	820	5.0
oil palm stems	675	13.6	410	470	7.7
BV / oil palm stems	702	25.5	870	650	10.5
industrial wood waste	690	12.9	380	560	4.2
BV / industrial wood waste	699	14.9	620	567	9.0
acacia manguim	645	30.8	710	827	4.4
BV / *acacia manguim*	706	28.8	1120	898	3.5
yemane	639	22.9	490	516	2.5
BV / *yemane*	726	33.3	950	862	4.9

Source: Chew et. al. (1994)

Mr. Xue of the Shi Tai Bamboo Products Factory offered technical details of the manufacturing process and product performance (Xue, 1995). The manufacturing plant was still in the final stages of start-up, but limited production runs were performed daily. Bamboo particleboard was to be produced in three thicknesses after the final start-up of the plant.

Press temperature fluctuated between 170° C and 200° C. Panels of 16 mm thickness were pressed in approximately 10 minutes, although the entire cycle (loading, closing, pressing, opening and unloading) required 12.5 minutes. All panel thicknesses were produced with 10% PF resin.

The mechanical properties of the panels, which are given in Table 16, were determined using the Chinese Particleboard Standard GB/T4897-92.

Table 16: Chinese Bamboo Particleboard Properties

Thickness (mm)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (kPa)	TS (%)
12	975	37.5	3020	600	5
16	925	36.0	3210	580	6
19	915	35.0	3650	500	7

Source: Xue (1995)

While the mechanical properties of these one layer particleboards appear good, the high resin content and long press cycles make the manufacturing costs prohibitive. According to Mr. Xue, current production costs (estimated for 8.3 RMB = $1 USD) are $360 USD/$m^3$, which is comparable to the product's market price in the region. It is expected that production costs will drop to $240 to $290 USD/$m^3$. The best estimate production cost remains well above the international wholesale price for conventional tree-wood particleboards of approximately $150 USD/$m^3$. It should be noted that the technical development of this product, and many other bamboo panel products in China (including plybamboo), was conducted by the Bamboo Engineering Research Centre at Nanjing Forestry University.

In 1995 the International Network of Bamboo and Rattan (INBAR) prepared a draft of a manual that provides details of some bamboo products under development in various countries (INBAR, 1995). Although no information of which researchers or which research organisations are involved in the development, the information will be included here as an attempt to provide some additional background to current research in progress. In spite of the limited detail of the information, it is unfortunate that this document has not been widely distributed.

A Malaysian bamboo particleboard is introduced. Although no resin quantity is provided, it is stated that UF resin is used. Panels were pressed for 6 minutes at 160 ° C. Results, which were determined using British Standard BS:5906-1989, are given in Table 17. All panels were produced from *Bambusa vulgaris*. No information on panel thicknesses was provided.

Table 17: Properties of Malaysian Bamboo Particleboards

Sample number	Resin (%)	Density (kg/m^3)	MOR (MPa)	IB (kPa)	SW (N)	TS (%)
1	6	550	12.7	150	489	7.6
2	6	610	17.6	270	671	9.3
3	6	710	27.9	360	777	9.5
4	8	840	11.8	310	418	4.0
5	8	610	16.9	490	528	5.2
6	8	690	21.3	740	697	4.4
7	10	610	20.7	520	650	5.7
8	10	660	27.3	620	670	6.3
9	10	720	27.4	850	881	7.6

Source: INBAR (1995)

In addition, INBAR (1995) details a bamboo particleboard in development in Vietnam. Again, no direct references are provided. The product is blended with 9 to 11% UF resin, and pressed for 12 minutes for a panel of 18 mm thickness at a press temperature of 120 to 140 ° C. For a density of 650 to 720 kg/m^3 it is estimated that the MOR is 16.5 to 17.3 MPa, the MOE is 4150 MPa, and the IB is 1050 to 1500 kPa. No reference is made to the species of bamboo used, nor whether the resin is modified to bond with the high silica particles.

These examples highlight attempts to develop a bamboo particleboard. While some of the mechanical properties appear excellent, the limiting characteristics remain a long press time, and high resin content. The hot press is the single largest capital investment in a particleboard manufacturing line, and the resin often the largest ongoing expenditure. Therefore, there clearly needs to be further work done to reduce resin amounts and press times before bamboo particleboard can become economically viable for large scale manufacturing, and brought within conventional production standards for tree-wood based particleboards (i.e. densities between 550 and 700 kg/m3, resin contents between 3% and 5% for PF resins and between 8% and 11% for UF resins, and short press times which depend on product thickness).

4.3.3.2 Bamboo MDF

Yusoff et. al. (1994) provided an introduction into bamboo medium density fibreboard (MDF). Using 1 and 2 year old *Gigantochloa scortechinii*, they pressed 12mm MDF panels using 9% and 13% UF resin at 170 C for 4 minutes.

Their samples ranged in density from 629 to 659 kg/m3, and had MOR results from 8.8-15.3 MPa, MOE results from 1074-1687 MPa, IB results from 216-363 kPa, and thickness swelling results from 16% to 23%. They noted that a Japanese standard ("JIS A 5906 – 150 type") requires a MOR of 14.7 MPa, an IB of 294 kPa, and a thickness swelling under 12%, and that the bamboo MDF they developed had worse properties than MDF made from rubberwood (commonly used in Malaysia for MDF production).

4.3.3.3 Bamboo Waferboard

Lee et. al. (1996) published results from their preliminary tests on bamboo strandboard made from *Phyllostachys pubescens* (Moso bamboo). They produced a series of test panels 7/16" thick (approximately 11.1 mm) that were pressed at 700 psi and 400°F for 6 minutes. Some panels were made with 2.5% powder PF resin, and others with 3.5% powder PF resin. Unfortunately they only state that their target density was 46 lbs/ft^3 (approximately 737 kg/m^3), but do not provide data plots nor analysis to demonstrate how successful they were in achieving their aim. A summary of their most interesting results (converted to metric for this presentation) is presented in Table 18.

Table 18 : Waferboard Produced with *Phyllostachys pubescens*

Resin Content (%)	Flake Orientation	MOR (MPa)	MOE (MPa)	IB (kPa)	24 hr. Thickness Swelling (%)
2.5	random	36.9	3647	512	6.81
	oriented (//)	38.0	6074	434	6.51
	oriented (⊥)	25.1	1786	471	
3.5	random	43.7	4392	603	5.62
	oriented (//)	54.1	7095	596	4.93
	oriented (⊥)	30.0	1813	623	

Source: Lee et. al. (1996)

Another project produced a composite panel with varying ratios between *Phyllostachys pubescens* strands (dimensions 100 x 10 x 0.75 mm) on the faces and lauan fibres (average length 4.6 mm, average diameter 0.15 mm) in the core (Zhang et. al., 1996). In this study it is interesting to note the results of panels made with 100% "face" material. The 6 mm thick test panels were made with bamboo strands blended with 8% polymeric isocyanate resin, and pressed at 160 C for 2.5 minutes. The approximate results (their results were presented only in graphical format) are: MOR (//) = 82 MPa, MOR (⊥) = 4 MPa, MOE (//) = 8,800, and MOE (⊥) = 800 MPa. The researchers did not state which testing standard had been used.

4.3.3.4 Other Composite Panels

The INBAR report (1995) presents numerous composite panels, such as "bamboo net board", "bamboo mat and bamboo curtain board", and "bamboo strip, bamboo particle and wood veneer". As there are no direct references given in that report, it is not of immediate interest to present the mechanical properties. Let it be stated that there is on-going research on bamboo composites, but these products are not presently in wide application.

Although the development of bamboo composites has barely been initiated, there is a high level of interest. By exploiting the strength of bamboo in products which are engineered to meet desired size, shape, and performance criteria, the potential of bamboo can be realised on a greater scale than is currently the case.

4.4 Summary

In this chapter a number of different approaches in using bamboo were presented. Traditional bamboo construction allows for use of bamboo with little transformation or processing necessary, but is limited by the difficulties of using bamboo in engineered designs. Bamboo's tensile strength has long been tested in concrete, but until the concerns about decay and bonding are overcome, it will remain only a minor interest.

With the tremendous strength of bamboo splits, products such as plybamboo and bamboo matboard are likely to play an ever-more increasing role in the use of bamboo. With increasing economic openness in China, India and other countries engaged in heavily subsidised production, the challenge is to maintain the excellent product characteristics while decreasing the excessive manufacturing costs of today.

Bamboo composite panels such as waferboard and particleboard can likely play the largest role in increasing the use of bamboo. Due to the potentially automated manufacturing processes, the successful introduction of manufacturing facilities is not dependent on cheap labour, subsidised bamboo, and other incentives necessary for maintaining production of other bamboo products.

Unfortunately, bamboo has a higher density than most tree-wood species used to make composite panels. This means that composite panel production will lead to high density panels since composite manufacturing normally compacts the raw material to a density slightly higher than the density of the original raw material. High density panels are undesirable due to increased raw material consumption (fibre and resin), higher shipping costs, handling limitations, etc.

Bamboo also has a high silica content which can prematurely dull knives and other equipment, and negatively impact the bonding between resin and the natural fibre, or furnish.

As shown by the work of others presented in this chapter, the most advanced research on bamboo panels suffers from panels with high resin contents, long press times, and high densities. Due to the lack of uniform testing standards, the actual mechanical properties can not be directly compared, but due to the strength of bamboo they can be assumed to be excellent as most researchers indicate.

As shown in this chapter, there was relatively little work conducted and published internationally (unlike research for tree-wood composite panels) in 1992 when the current research project into bamboo composites for low-cost housing began.

The novel work conducted in the course of the current study will be presented in Chapters 5, 6, and 7.

5.0 Bamboo Particleboard: Baseline Study

5.1 Introduction

As shown earlier in this thesis, bamboo lends itself as a raw material for composite production: it is fast growing; it has high yields per unit area of growing land; the fibre properties are excellent; macroscopic mechanical properties are good, etc. There are two limitations of the use of bamboo. The high density of most bamboo species (and the range of densities within species, and within each culm) leads to products of high density since most composites require a densification of the natural fibre above the natural density of the raw material. The ratio of product density to raw material density, or compaction ratio, generally must be greater than 1.0 to ensure that adequate pressure exists to allow for bonding between particles. As the compaction ratio increases, generally the better the panel properties will be.

Bamboo also has an exterior layer of silica and wax which increases tool wear and inhibits effective bonding of most resins, thereby adding cost due to increased maintenance and resin utilisation.

With this in mind, a research program was initiated in an attempt to develop bamboo composite panel products that could be used for low-cost housing construction, and for export to international markets. Therefore, the goals of the work were to develop bamboo panel products that meet international performance standards with economically viable production parameters.

It was decided to begin with particleboards because mechanically breaking bamboo into the "lowest common denominator" - fibres or particles – the macroscopic and microscopic variability of bamboos are then randomly distributed throughout the composite panel. The bamboo culm exterior, which contains a high amount of silica and is difficult to remove, is also randomly distributed, an effective solution to countering the negative effect of silica on the proper bonding of resins.

The process of engineering products from particles is well suited to bamboo due to the complexity of each culm's cross-section, and the high fibre strength. But there are greater benefits that can be obtained. A composite material can be made into almost any shape. This allows for the creation of bamboo products that meet internationally accepted standard shapes and sizes, in addition to specified performance standards.

In the manufacturing process there are numerous factors that affect the product performance. All have an impact on final product cost. Therefore, the research and development of products must consider the following:

- desired product shape (panel size and thickness, lumber length and cross-section) ?
- desired product performance (modulus of elasticity (MOE), modulus of rupture (MOR), water resistance, density, nail holding capability, etc.) ?
- costs of manufacturing (press time, resin type and amount, energy demands, equipment, labour, etc.) ?

Of the numerous bamboo applications under development, many rely on the availability of inexpensive labour, a resource that is in decline as bamboo-rich regions (generally developing tropical countries) develop economically. Therefore, there is a need to pursue a product that can be produced with minimal amounts of labour. This, however, does not exclude production with high amounts of labour, but rather creates the economic option of investment in equipment and perhaps a higher-skilled workforce, or a lower initial investment with higher on-going labour costs. Depending on the priorities in the region of production and of the funders of such a manufacturing plant, either alternative should remain open.

That is to say, products that require excessive hand processing were not pursued in this study as the limit for their commercial success is dubious in open markets. This eliminated bamboo matboard and plybamboos from consideration because for many stages of production, automation is impractical.

The need for high quality materials that meet international market demands is desirable. This would provide a source of foreign currency for manufacturing countries, and provide a source of standardised, high performance products for local use. This approach is quite distinct in the world of bamboo products.

As shown in Chapter 4, many bamboo products (such as plybamboo and bamboo matboard) exhibit properties far in excess of existing international structural panel standards (Appendix A). While this may give products additional boasting rights, it does not change their use (assuming they are being directly substituted in structural design codes, for example). The development of new design codes based on new product standards is costly and difficult, and not an easy way of introducing bamboo products to the marketplace. By engineering products to meet international standards (as opposed to far surpassing them), it is expected that the manufacturing costs could be reduced.

Particleboard, strandboards, and fibreboards, are therefore obvious choices. The processes associated with these products refine the raw material into particles of uniform shape and size. Resin is added to the particles (or "furnish"). The mixture is then formed into panel-sized mats. In order to densify the mat to ensure bonding between particles and to cure the resin, the mats are hot-pressed. In these products, the manufacturing variables can be altered to control product cost, and product performance. Product development is directed towards the creation of a manufacturing process and product that is economical (greatly controlled by density, resin content and press time), and meets target product performance for modulus of elasticity (MOE), modulus of rigidity (MOR), internal bond (IB), screw withdrawal (SW), etc. In addition, the dimensional stability of composites is of concern in many applications. As the manufacturing variables all play a role in the level of dimensional stability, there is a wide range of testing parameters.

5.2 Aims of This Study

The overall aim in the initial phase of the experimental work was to develop an economical bamboo composite panel that meets performance criteria for a structural panel. This would allow for use in low-cost housing structural applications such as sheathing for floors, walls and roofs. In addition the structural panels could be used in other commercial application including the production of shipping containers, etc. A smooth surface is also desirable for furniture applications so that veneers and melamine layers can be applied.

The overall practicality of this approach had been previously unknown with respect to bamboo, and therefore a range of manufacturing parameters were selected to identify major trends in product performance with the intention that future studies could better identify exact production and processing variables.

After unsuccessful tests to produce wafers, strands, and other refined furnish, it was decided to pursue composite panels based on particles. While the attempts to refine wafers and strands did yield some desirable results, the variability in particle size, shape and thickness was great which makes board manufacturing difficult. In addition there was a large amount of fines which consumes large amounts of resin and may lead to the reduction of mechanical properties of the panel.

It was decided that for preliminary testing particles would provide the most practical furnish. The use of particles, which were uniform and produced approximately 40% fines (suitable for a three layer particleboard), ensured that the product development could have immediate industrial applicability, and be potentially directly substituted for existing tree-wood based panels. Three layer particleboards are preferable over one layer particleboards because the fine particles in the two exterior layers provide smooth faces (an important trait in furniture manufacturing). The separation of the larger coarse material for use in the core allows the core material to be blended separately with less resin on a per mass basis due to less surface area of the particles in comparison with the face particles. Separate blending of the core and face also allows for specialised resins to be used. Resins which cure quickly are used in the core to allow for bonding as quickly as possible. Slow curing resin is used for the face layers that are adjacent to the hot plattens and therefore increase in temperature quickly in order to reduce over-cure of the face resins.

Particleboard was selected in part because it is not necessarily a labour intensive process, an essential factor in the application of the technology in developing countries with rising labour costs.

A decision was made to use PF (Phenol formaldehyde) resins over UF (Urea Formaldehyde) resins (either pure, or modified with isocyanate binders). UF resins are already limited in their scope of use due to concerns of formaldehyde emissions in Europe and North America. Products bonded with UF resins alone suffer from poor dimensional stability, and therefore are not applicable in exterior, or high humidity applications. As most bamboo often grows in humid countries, the option of using a UF resin was easily eliminated in the present study. In addition, the high silica content of the bamboo complicates the bonding processes of UF resins, making UF bonded bamboo products expensive as the exterior silica layers would have to be removed for successful bonding to occur.

Preliminary prototype tests yielded excellent results using isocyanate-modified UF resins. While products made with isocyanate modified UF resin have cheaper manufacturing cost in comparison with products bonded with PF resins, the industrial use of isocyanates has many safety issues, few of which are likely to be addressed in initial commercial operations in developing countries. Given the highly toxic nature of isocyanate-based resins, it was decided to pursue other resins that are more in keeping with the overall strategy of environmental sustainability, worker safety, and product life-span.

Phenol formaldehyde is seldom used for industrial non-structural particleboard production as it often leads to high cost products because the PF resin is expensive, and it requires long press times, thereby decreasing the production capacity of given manufacturing installations. The research program endeavoured to develop a bamboo particleboard that would address all of these concerns. It should be noted that many structural panels (plywood, waferboard, oriented strand board) are manufactured with PF resins, and that most particleboards are made with lower strength properties and are intended for internal (dry) applications.

In order to decrease press times and improve dimensional stability, a steam injection pressing cycle was used. Steam injection pressing involves the injection of steam into the face of the panel directly from one (or both) of the press platens. Subsequently the panel surface is exhausted to remove moisture from the panel. As shown by Hsu (1990) and others, steam injection pressing has many advantages over conventional pressing, especially due to the rapid transfer of heat, thereby reducing press times for slow-cure resins such as PF resins.

The initial tests were performed using *Guadua angustifolia* provided by the Proyecto Nacional de Bambu (now named FUNBAMBU) in Costa Rica. The bamboo was harvested from their managed plantation at approximately 4 or 5 years of age. The bamboo was shipped by air to Canada and testing promptly performed.

Guadua angustifolia, commonly referred to as "Guadua" throughout Latin America, has been used for centuries in housing and plays a major role in rural housing in Colombia and Ecuador (Velez, 1993, Moran, 1985). McClure (1993) and Judziewicz et. al. (1999) provide outstanding botanical and application information of this species.

Guadua can be distinguished from other bamboo genera by large culms, existence of thorns, and white bands of hairs in the nodal region (Judziewicz et. al. 1999). *Guadua angustifolia* is characterised by large culms commonly 18 m high (sometimes up to 30 m) with a diameter of 10 to 15 cm (sometimes up to 20 cm) (McClure, 1993).

Due to its predominance in northern South America, and it's desirable qualities (size, and wood quality) it is the most economically important bamboo in the region, and therefore has received a lot of research attention.

5.3 Research Program

As was mentioned, *Guadua angustifolia* from Costa Rica was used in this study. Both the lower sections and the upper reaches were used. The bamboo was conditioned to air-dry, and refined using a hammermill with a screen consisting of 0.25 inch diameter holes. The particles were then mechanically sieved into coarse and fine material as separated by a number 20 mesh. This refining and sieving procedure yielded excellent core and face particles, with approximately 40% by mass for use as face material which is similar to the amount used in conventional tree-wood particleboard production.

Particle moisture content was found to be approximately 4%, and deemed acceptable for the study. Maloney (1993) and many others have demonstrated that the moisture content of the mat is critical to successful pressing, and that a range of 2% to 5% for conventional pressing is common. Due to the use of a steam injection pressing cycle, the moisture content of the mat was not as important since steam injection pressing is known to allow for more variability in mat moisture content.

Core resin contents of 3%, 4%, and 5% by mass were used on test panels ranging in target density from 690 to 750 kg/m^3 . Face resin contents were increased by 1% over core resin contents. Face and liquid resins were the same liquid PF resins. Different resins for face and core were not required due to the curing mechanisms of steam injected pressing.

Maloney (1993) noted that in the USA panels are produced with 6-10% UF resin, 5-7% liquid PF resins, or 1.5-5% powder PF resins. The range of resin contents used in the present study are therefore within the range of commercially viable operations now in production in the USA.

The target panel densities are greater than is commonly found in wood-based composites because of the higher density of bamboo.

The particles were blended in a rotary blender with the liquid PF resin and wax (1%), which was included to improve dimensional stability as is commonly done in the production of wood composites. Mats were hand formed in three layers, with the product mass being divided 40% / 60% between the faces (fine material) and core (coarse material) respectively.

All test panels were 610 by 510 mm (the maximum size available in a test press with steam injection capability), with a target thickness of 16 mm (a common panel thickness for furniture production), and were pressed for three minutes using steam injection (Hsu, 1990) with a press temperature of 215 ° C. Panel thickness was controlled by the use of metal spacers. However, it was expected that final product thickness, and therefore density, would vary due to springback of the particles.

Nine sets of panels were produced representing the combinations of three resin contents and three target densities. Each set consisted of three panels, each of which yielding three bending samples, six internal bond samples, and two water soak samples.

5.4 Testing Program & Results

All panels were trimmed, and cut for testing (Figure 32) according to Canadian Standards Association (CSA) standard CAN/CSA O437.1 "Test Methods for Strandboard and Waferboard". The density of the testing samples was measured. Although numerous tests can be performed on any product, three tests that are critical in determining product performance were identified and performed:

1. A three point bending test (Figure 33) provided data on modulus of rupture (MOR) and modulus of elasticity (MOE). These strength and stiffness results allow for easy assessment of the suitability of the panel in structural applications.
2. An internal bond test (Figure 34). This test is performed by pulling the sample apart in tension by attaching grips to the faces of the test sample. A high internal bond, which is an excellent indicator of the bonding effectiveness across the panel cross-section, is sometimes achieved at the expense of bending performance through careful manipulation of the pressing cycle. For that reason IB performance is normally considered with bending performance to properly assess the panel quality.
3. A 24 hour water soak test was used to determine thickness swelling and water absorption of the test panels. Thickness swelling is an important indicator of dimensional stability of the panel. Since water absorption is not specified by testing standards, it will not be presented in this thesis.

Figure 32: Testing Samples

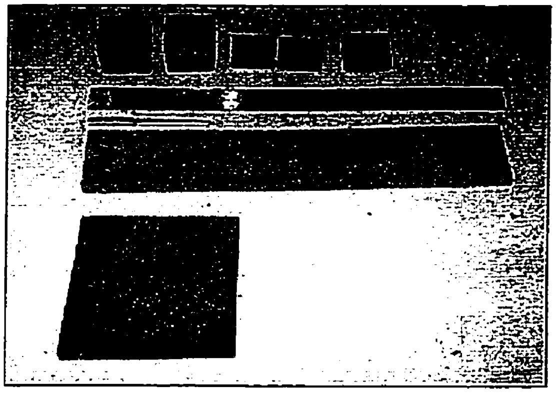


Figure 33: Bending Test

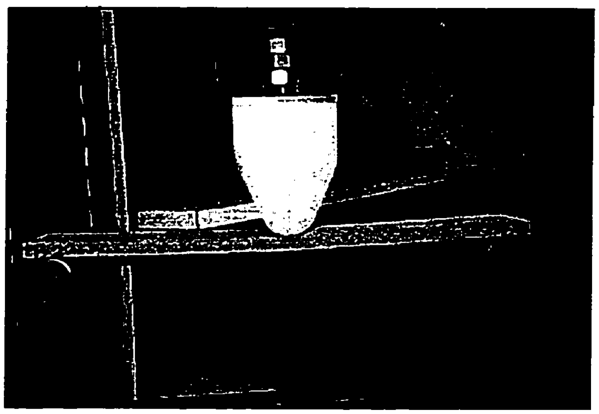
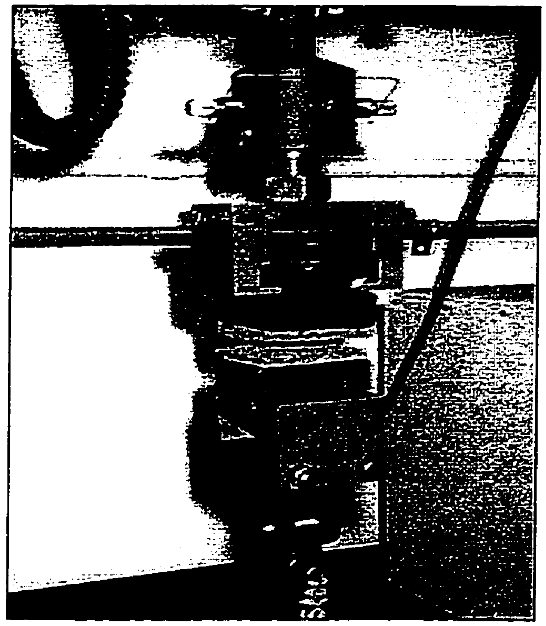


Figure 34: IB Test



Other tests, such as screw withdrawal, were not performed due to the small panel size, and limited raw material available. Since the internal bond tests demonstrate the bonding effectiveness through the entire panel thickness, meeting the performance standard for IB is an approximate indicator that the panel will meet screw withdrawal requirements.

As shown in the following plots, the MOR (Figure 35) and MOE (Figure 36) increase with greater product density, and with increasing resin content. As these are two critical factors in a cost analysis of a composite manufacturing method, it is important to note that at a density of 750 kg/m^3, and a resin content of approximately 4% the bending and IB values set by waferboard standards are met. The current standards for particleboards and structural composite panels (waferboard and oriented strandboard) are included in Appendix A. Specifically, the MOE and MOR standards for R-1 waferboard are achieved (3100 MPa and 17.2 MPa respectively), and the internal bond (Figure 37) is greater than 345 kPa.

Thickness swelling tests reveal that the range of values given the density and resin contents are between approximately 11% and 15% (Figure 38). At a density of 750 kg/m^3, and a resin content of approximately 4% the thickness swelling is more than the 10% required for grade R-1 waferboard. Dimensional stability of panel products is a major focus of on-going composite enhancement, and it is expected that this trait could be improved with further development work on the current bamboo particleboard. Figure 35 through Figure 38 display a linear regression analysis based on density as discussed in the following section, Section 5.5.

Figure 35: *Guadua angustifolia* MOR Results

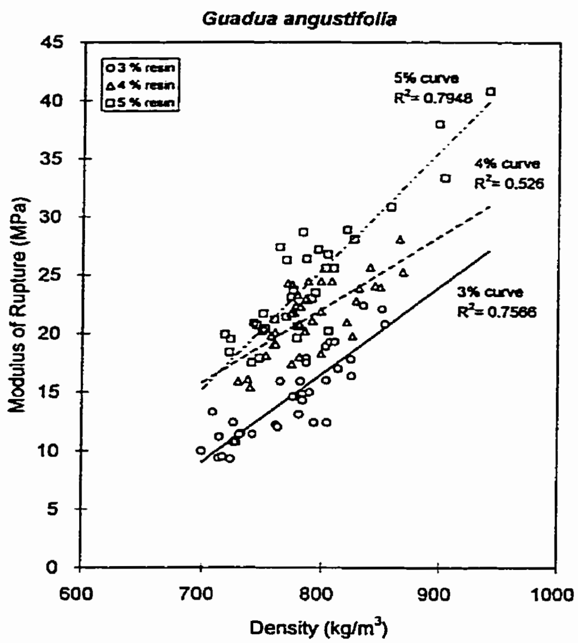


Figure 36: *Guadua angustifolia* MOE Results

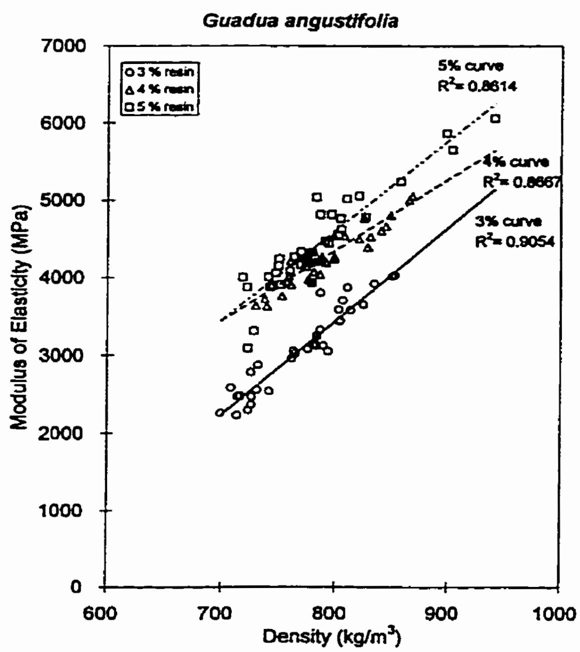


Figure 37: *Guadua angustifolia* IB Results

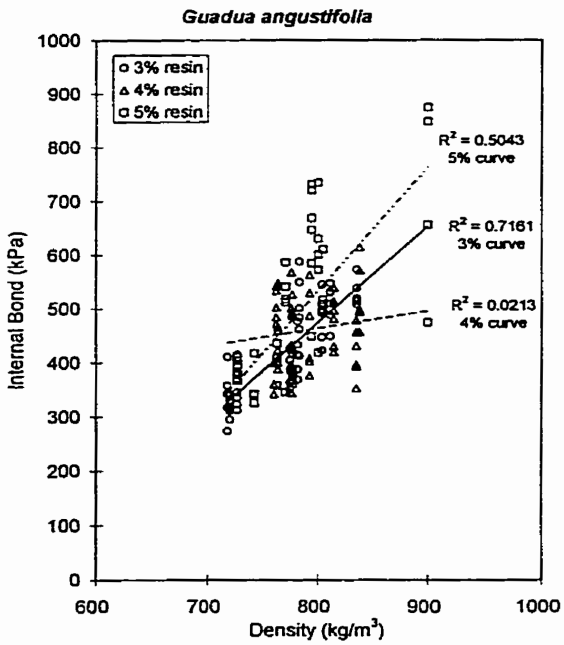
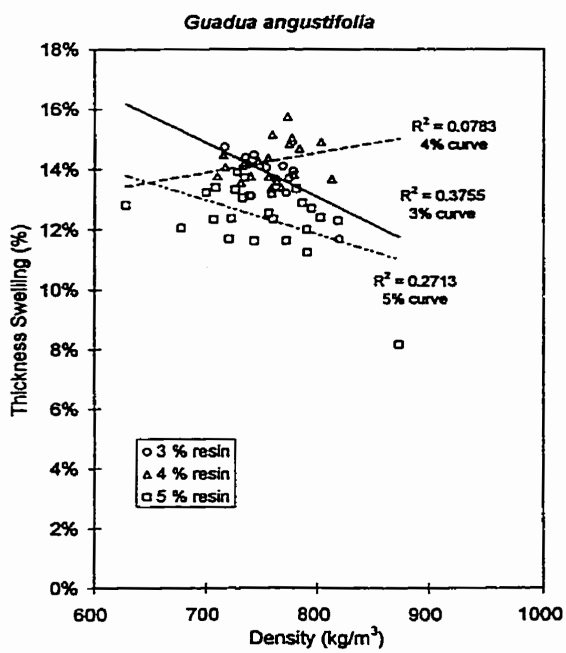


Figure 38: *Guadua angustifolia* Thickness Swelling Results



5.5 *Statistical Models of Bamboo Particleboard Performance*

Statistical models for the bamboo particleboard were developed in the interests of better understanding the effect of the two major manufacturing variables (resin content and product density) on the properties tested.

A variety of plots were initially made to provide an overall view of trends. These were identified in the previous section, Section 5.4.

Subsequent efforts were directed towards more traditional linear regression using SYSTAT (a commercial statistical analysis package). A series of mathematical models were developed for each panel property as follows:

$$\text{property} = \text{constant} + a(\text{resin}) + b\,(\text{density}) + c\,(\,\text{density}^{\wedge}2) + d(\text{resin}^{\wedge}2) + e\,(\text{resin} * \text{density}) \tag{5.1}$$

Research in wood composites has shown that mechanical properties are usually linearly related to density and resin content. The second-order terms were included in this initial mathematical modelling in order to test the conventional linear approach.

This initial model provided a variety of statistical information. The p-values for each variable were noted in comparison to 0.05 (the 5% threshold value often used to indicate statistical significance). In all cases, density was measured in kg/m^3, resin content was either 3, 4, or 5 (%). MOE and MOR were measured in MPa, and IB in kPa.

In each case, the significant variables were determined from an initial regression performed as shown in the equation above, and the "complete model" was obtained. Subsequent models were developed using variables with p-values less than 5% (i.e. significant). In all cases models were developed for resin and density alone in order to provide a comparison with wood and other bamboo work. The following information was obtained:

MOR

None of the variables in equation 5.1 were significant.

Using only the resin and density variables, the following model was determined:

$$MOR = -64.5 + 4.23\,(resin) + 0.086\,(density) \qquad (5.2a)$$

$$R^2 = 0.839$$

MOE

The variables in equation 5.1 with p-values less than 5% (i.e. the significant variable in that model) were resin, density, and $resin^2$.

Using these significant variables, the "complete model" was developed, as shown below:

$$MOE = -12786.0 + 3487(resin) + 11.3\,(density) - 361.9\,(resin^2) \qquad (5.3a)$$

$$R^2 = 0.944$$

Using only the resin and density variables, the following model was determined:

$$MOE = -7638.2 + 592.3\ (resin) + 11.8\ (density) \qquad (5.3b)$$

$R^2 = 0.897$

IB

None of the variables in equation 5.1 were significant.

Using only the resin and density variables, the following model was determined:

$$IB = -879.9 + 10.7\ (resin) + 1.65\ (density) \qquad (5.4a)$$

$R^2 = 0.687$

In this model, only the constant and density were significant (i.e. p-values were less than 5%). An additional model was developed using only these variables:

$$IB = -879.9 + 1.70\ (density) \qquad (5.4b)$$

$R^2 = 0.678$

TS

The variables in equation 5.1 with p-values less than 5% (i.e. the significant variable in that model) were resin, density, $resin^2$ and $density^2$.

Using these significant variables, the "complete model" was developed, as shown below:

$$TS = -0.7468+0.08112(resin)+0.002061(density)-0.01091(resin^2)-1.4E\text{-}6(density^2) \qquad (5.5a)$$

$R^2 = 0.660$

Using only the resin and density variables, the following model was determined:

$$TS=0.2308-0.008(\text{resin})-8.5E\text{-}5\ (\text{density}) \quad (5.5b)$$

$R^2 = 0.352$

In this model, only the constant and resin content were significant (i.e. p-values were less than 5%). An additional model was developed using only these variables:

$$TS = 0.1653 - 0.00767(\text{resin}) \quad (5.5c)$$

$R^2 = 0.281$

This work shows that the resin content and the product density are highly significant in estimating the MOE and MOR of bamboo particleboard. In addition, product density is also relevant in the estimation of IB while resin content is not significant in the estimation of IB. The low R^2 values for the IB and TS models indicate that these models are relatively poor estimators of these properties.

Subsequently, three dimensional plotting was attempted. Plotting the individual data points proved of little use, and therefore full three dimensional surface plots were attempted (Figure 39 through Figure 42). These clearly demonstrate the importance of resin content and product density on the performance characteristics tested, and are useful representations of the results shown in Figure 35 to Figure 38. Note that the density scale of Figure 42 was reversed to facilitate plotting.

Figure 39: *Guadua angustifolia* MOR Regression Surface (Equation 5.2a)

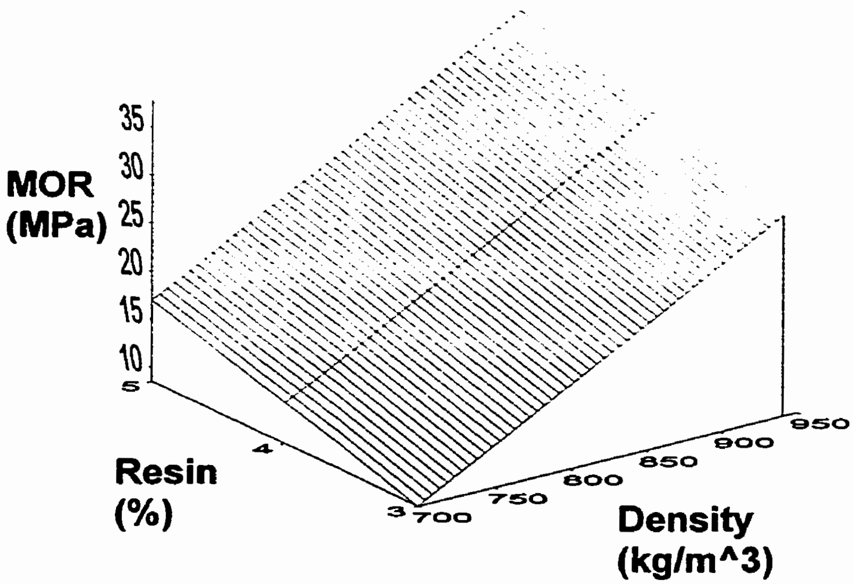


Figure 40: *Guadua angustifolia* MOE Regression Surface (Equation 5.3b)

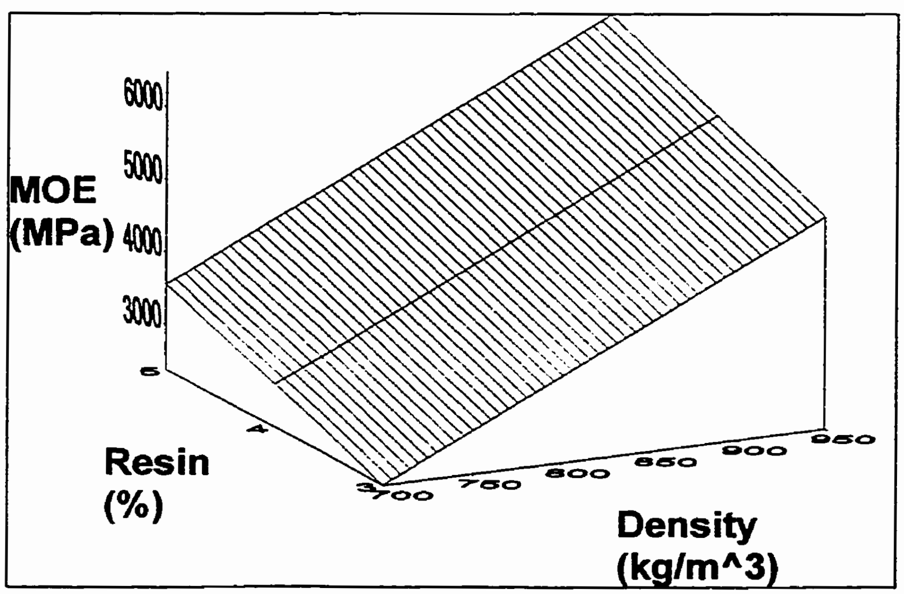


Figure 41: ***Guadua angustifolia*** **IB Regression Surface (Equation 5.4a)**

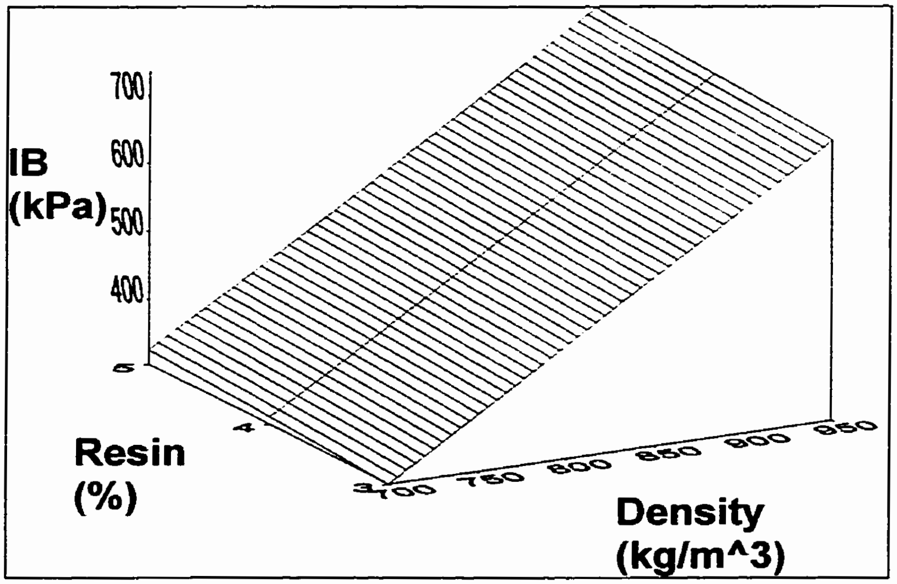
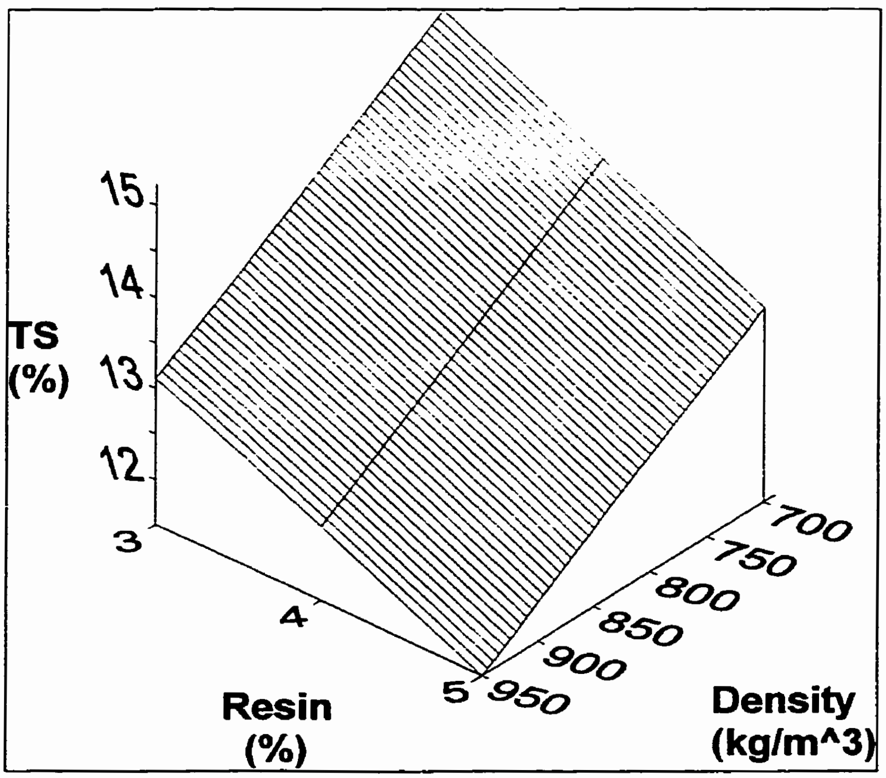


Figure 42: ***Guadua angustifolia*** **TS Regression Surface (Equation 5.5b)**



5.6 *Discussion of Results*

The mechanical properties of the bamboo particleboard presented here, which has been named "BamBoard", are comparable to waferboard, as mentioned earlier. The resin and density required for BamBoard to meet the waferboard standard is presented in the following table (Table 19), along with mechanical performance results of common wood-based products, and the requirements of some standards.

Table 19: Initial Bamboo Particleboard Results in Context

Product Name	Country	MOE (MPa)	MOR (MPa)	IB (kPa)	Resin Cont. (%)	Density (kg/m^3)
BamBoard[1]	Canada	3100	17.2	345	4% PF	750
Bamboo particleboard prototype[2]	Canada	3644	22.4	1124	5% PF	847
Waferboard (R-1)	Canada	3100	17.2	345		
Pine, Eastern White[3]	N. America	8600	59.0	NA		350
OSB (O-1)	Canada	4500 (//) 1300 (⊥)	23.4 (//) 9.6 (⊥)	345		
Bamboo flakeboard[4]	Malaysia	NA	21.3	740	8% UF	690
Bamboo PB[5] (16 mm)	China	3210	36	580	10% PF	925
Bamboo Cement Bonded PB[6]	Indonesia	NA	11.8	NA		1100

[1] The required BamBoard resin content and density required to meet R-1 standard are presented
[2] Bamboo particleboard prototype values were obtained from initial laboratory tests not presented in this study
[3] Tsoumis, 1991 (solid wood)
[4] Chew et. al., 1994 (press time 6 minutes for 19 mm panel, UF resin)
[5] Xue, 1995 (press time 10 minutes for 16 mm panel, PF resin)
[6] Askaboard (1995)

Of these results, only the Canadian and USA results are directly comparable, as other panels are tested according to different procedures. These values are given for interest only, and can not be used as an indication of product inferiority, nor superiority.

Performance characteristics for BamBoard have been selected to be equivalent to the Canadian Waferboard (R-1) values. This was selected as the optimum product given the parametric ranges used in this study. That is to say, waferboard was the highest performing, widely accepted product standard that was within the range of the preliminary bamboo particleboard research. The required density and resin contents were then identified based on this desired performance. Throughout the testing program, the three minute steam injection pressing cycle was maintained.

Aside from the differences in methods of product evaluation, one must consider the density and resin contents of the products. Put simply, these are engineered products, and specific product performance standards can be achieved with greater product density, and greater resin content. Unfortunately, this vital information is not available for all products to allow for comprehensive comparisons.

The most interesting competing bamboo panels presented in Section 4.3.3.1 are those by Chew et. al. (1994) and the panels in commercial production in China (Xue, 1995). The use of UF resins by Chew et. al. allow for a press time of 6 minutes, relatively low compared with some other bamboo panel work, but unfortunately they do not discuss whether they modified the resin, removed the exterior of the bamboo, or how they addressed the well-known concerns of the silica on bamboo interfering with the UF bonding process.

It is also unfortunate that no MOE data was provided as MOE has been identified as a critical limitation in bamboo composites. Overall, their work is interesting.

The panels in commercial production in China (Xue, 1995) suffer from high resin content (10% PF), long press time (approximately 10 minutes for 16 mm panel), and high density. The final products are clearly in a product performance category that is far different than conventional wood particleboard as the strength characteristics are extremely high. This commercial enterprise is suffering due to higher prices in comparison with wood particleboard available in the same region. Clearly modifications of density, resin content and press time would be of benefit in their efforts to reduce production costs.

Resin losses in the blending process were estimated to be less than 5% of intended resin mass due to a small quantity of resin remaining in the pump lines after blending was completed. This loss would be reduced in larger scale tests and commercial production, thereby further improving panel performance.

5.7 Conclusions

Bamboo composites offer strategic advantages in the advancement of bamboo as an alternative to wood and other construction materials. Through this study, a preliminary bamboo product was developed to meet international structural panel (waferboard) standards. Due to the use of relatively fine particles (smaller than a 20 mesh screen for surface layers) it could be used for construction, packaging, and furniture and other traditional particleboard and MDF (medium density fibreboard) applications.

The original research presented in this chapter details the production of bamboo particleboard. A panel of 750 kg/m^3 density, with 4% liquid PF resin, and a three minute press time meets Canadian waferboard (R-1, see Appendix A) standards for MOR, MOE and IB. Thickness swelling was between 10% and 15%, slightly above the current standard of 10%. The short three minute press time, low resin contents, and low densities (all in comparison to other bamboo particleboards) are significant improvements to the economical production of bamboo particleboard. This research therefore provides an important contribution in understanding bamboo particleboard, and an important contribution to enhancing the economic viability of bamboo particleboard in low-cost housing. As was expected, increased resin content and panel density improved panel performance.

The economic (and environmental and social) aspects of these production criteria will be reviewed in Chapter 9 at which point a more elaborate discussion will be presented regarding the impact of resin quantity, panel density, and pressing time on overall production manufacturing costs.

Based on the success of these preliminary tests it was decided to produce panels using other important bamboo species, and to attempt other panel types using bamboo. These related research activities are presented in the following chapters.

6.0 Particleboard Made with Other Globally Important Bamboo Species

6.1 Introduction

After the success of initial research efforts with *Guadua angustifolia* from Costa Rica, it was decided that other, globally important bamboo species should be investigated as potential raw material for bamboo particleboards.

The species selected were as follows:

1) *Dendrocalamus strictus*. Bennet and Jain (1990) estimate that *Dendrocalamus strictus* is found in 53% of the bamboo area in India, and occupies between 75% and 85% of the bamboo area in the predominately tropical states of India. While it is often used for pulp and paper in India (McClure, 1993), it has also recently been used in bamboo mat-board products discussed earlier.

The *Dendrocalamus strictus* samples used to make the test panels were of small diameter (less than 3 cm in diameter) from Vietnam. No history of the growth, management, harvest or storage of the culms was available.

2) *Phyllostachys pubescens*. The bamboo supplied was grown in the USA although *Phyllostachys pubescens* is a predominant leptomorph bamboo species from China. It is estimated that 74.2% of bamboo forests in China are *Phyllostachys pubescens* (Zhu et. al., 1994), and it is the mostly commonly used bamboo species in industrial applications

in China. Commonly referred to as "Moso" bamboo, it is desired for plybamboo and flooring applications due to the relatively large diameter, and the light colour of the fibre (i.e. whitish colour of the woody wall).

3) *Bambusa vulgaris*. This species is one of the most common bamboo species in the world. McClure (1993) noted that *Bambusa vulgaris* is noted for its high strength, ease of vegetative propagation, and high yield of fibre. It is seldom used in construction due to its very high susceptibility to powder-post beetle attack. The samples provided were young (harvested at an estimated at 1-2 years of age) and came from Ecuador.

Unfortunately for all the bamboo samples used in this research there is not a well-documented management history.

This lack of information such as growing location (and associated characteristics), age, harvesting details, etc. is a limitation in drawing conclusive findings of this portion of the study. These growth and harvesting factors all play a role in the performance of bamboo in macroscopic physical-mechanical testing (Liese, 1985). Also, due to financial limitations only small amounts of material could be obtained. Therefore the testing was not further optimised, and instead the results should be taken only as an initial, but important, indicator of the potential for these species in composites.

The intention was to maintain similar production characteristics as those that were successful with the *Guadua angustifolia* presented in the previous chapter. In that study the pressing time, resin content, and density were all within the general parameters of commercially viable products useful as both housing construction material, and furniture stock. Therefore, the values of these parameters were maintained for testing in this chapter.

6.1 Testing Program

The bamboo was refined using a hammermill with a screen consisting of 0.25 inch diameter holes. The particles were then sieved into coarse and fine material using a 20 mesh screen. Length, width and thickness measurements of a representative sample of the core particles for the various raw materials are presented in Table 20. Of specific interest, the core particles from *Phyllostachys pubescens* were more varied in thickness and width. Visual inspection revealed that the *Phyllostachys pubescens* core particles were irregular in shape and not smooth when compared with the other raw materials.

Both the *Dendrocalamus strictus* and the *Bambusa vulgaris* provided particles that were smooth, uniform, and deemed well-suited for composite production.

Table 20: Physical Characteristics of Bamboo Core Particles

Species	Average Length (mm)	Average Thickness (mm)	Average Width (mm)	Density of Species' Samples (kg/m^3)
Dendrocalamus strictus	7.70 (3.84)[1]	0.29 (0.12)	0.75 (0.33)	500
Phyllostachys pubescens	6.81 (3.50)	0.43 (0.30)	0.96 (0.47)	760
Bambusa vulgaris	8.79 (6.28)	0.34 (0.21)	0.66 (0.33)	780
Guadua angustifolia	7.51 (2.98)	0.32 (0.12)	0.53 (0.19)	530

[1] Values in brackets are the standard deviations

The particles were blended with a PF resin and wax (1%) in a rotary blender. Mats were hand formed in three layers, with the product mass being divided 40% : 60% between the faces (fine material) and core (coarse material) respectively.

The *Dendrocalamus strictus* panels had core PF resin contents of 3%, 4%, and 5% by mass in order to maintain testing parameters similar to the tests presented in Chapter 5. Three target densities were selected.

Due to the small amount of *Phyllostachys pubescens* raw materials, only two resin contents (3% and 5%) and two target densities were chosen. As shown later, the low IB results for the *Phyllostachys pubescens* panels were of concern. For that reason, for the subsequent testing with *Bambusa vulgaris* core resin contents of 3.5% and 5% were selected. It was hoped that this slight increase of resin content would allow for improvements in panel properties while maintaining resin quantities in an acceptable range for economical commercial production.

For the same reasons mentioned in Chapter 5, target densities ranged from 700 to 900 kg/m^3 and all test panels were 610 by 510 mm, with a target thickness of 16 mm. Face resin contents were increased by 1% over core resin contents.

All panels were pressed for three minutes using steam injection, and a press temperature of 215°C. A thermocouple was inserted during forming in order to measure temperatures within the panel during pressing. Panel thickness was controlled through the use of metal spacers. It was expected that final product thicknesses, and therefore densities, would vary due to springback of the particles upon termination of the press cycle, but due to the limited amounts of raw materials no adjustment of the spacing bars was conducted.

In all cases commercially available OSB face resins were used. Due to the time span covered by this study (1993-1999), no two species were tested with identical resins because the commercially produced resins are constantly being improved, and therefore they are slightly altered. Although the resins used were supposed to be improved versions of the previous resin, the impact of the changes on panel properties is unclear.

Further testing is necessary to compare bamboo species from plantations with well-documented management programs, and to use identical resins so that direct comparisons about fibre differences, and their impact on board quality can be drawn. Financial support was the only restriction to this happening in the current study.

The same testing program outlined in Section 5.4 used for the *Guadua angustifolia* panels was used for the tests of the panels made from the three species presented in this chapter. Each test set consisted of three panels, from each of which three bending samples, six internal bond samples and two water soak samples were cut. Nine sets were produced from *Dendrocalamus strictus* (three resin contents and three target densities), and four sets were produced from both *Phyllostachys pubescens* and *Bambusa vulgaris* (each species with two resin contents and two target densities).

6.2 Results and Discussion

The results of MOR, MOE, IB and TS are presented in Figure 43 through Figure 54. The results for each species are presented on separate plots to avoid an excessive number of data points and regression curves on any one plot.

A linear regression analysis was performed on the data for each resin content, and representative curves are plotted on each graph. This allowed for two dimensional plotting which demonstrated the impact of density and resin content on the performance property in question for each species.

Through the work presented in Chapter 5, it was determined that three dimensional plotting did not increase the understanding of the role of resin and density on panel performance. Two dimensional plots in which the panels made with different resin contents are presented as different data series were deemed to be adequate for presenting the testing results.

Figure 43: *Dendrocalamus strictus* MOR Results

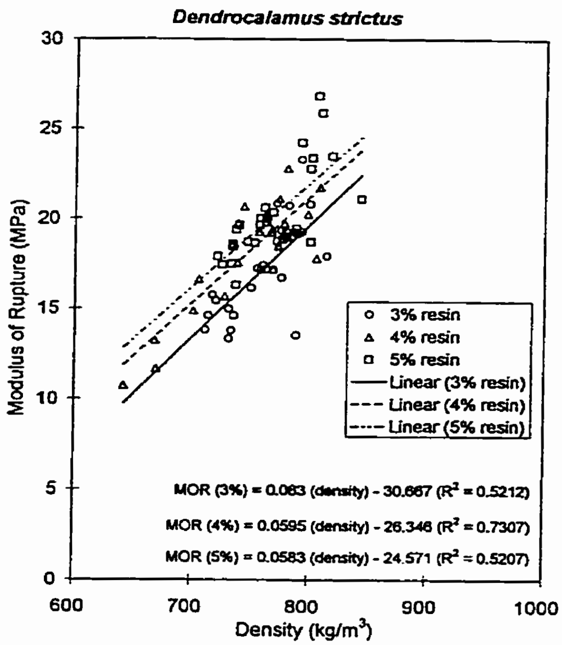


Figure 44: *Dendrocalamus strictus* MOE Results

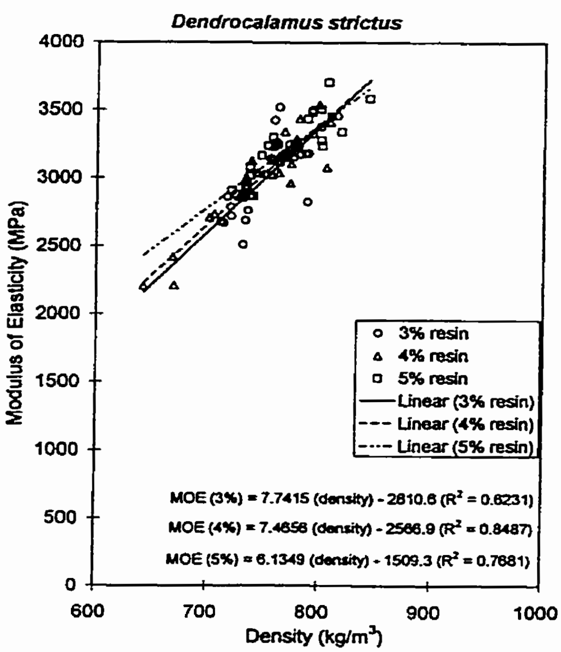


Figure 45: *Dendrocalamus strictus* IB Results

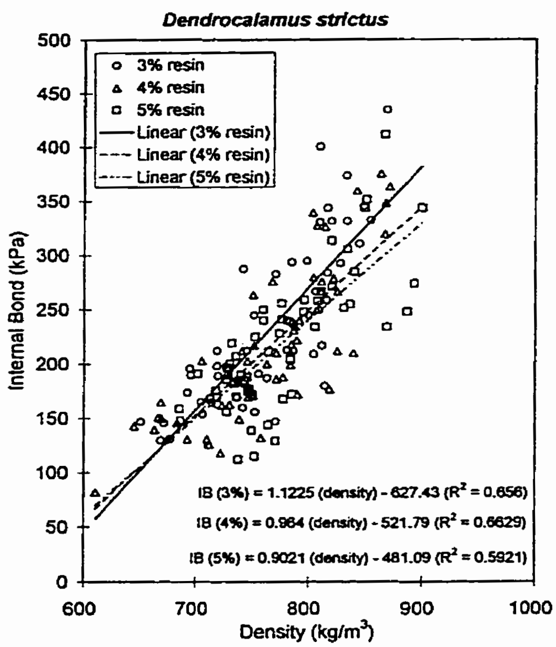


Figure 46: *Dendrocalamus strictus* Thickness Swelling Results

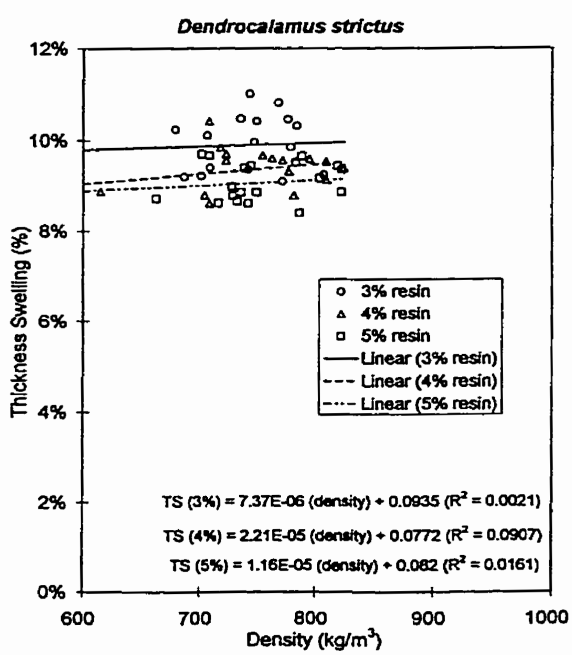


Figure 47: ***Phyllostachys pubescens*** **MOR Results**

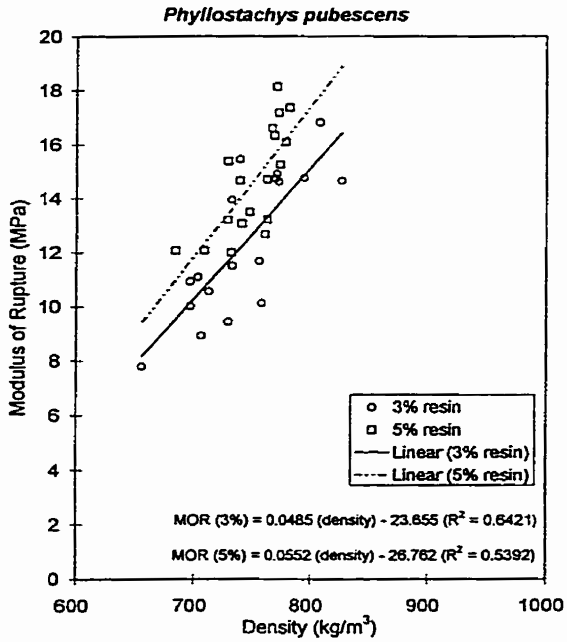


Figure 48: ***Phyllostachys pubescens*** **MOE Results**

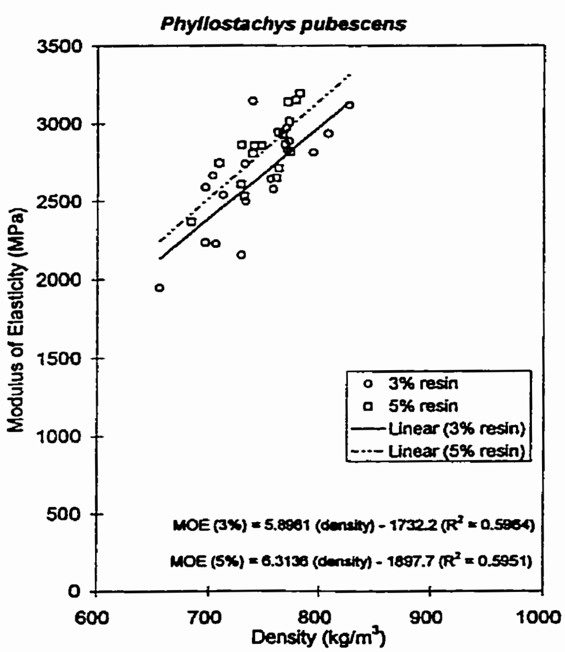


Figure 49: *Phyllostachys pubescens* IB Results

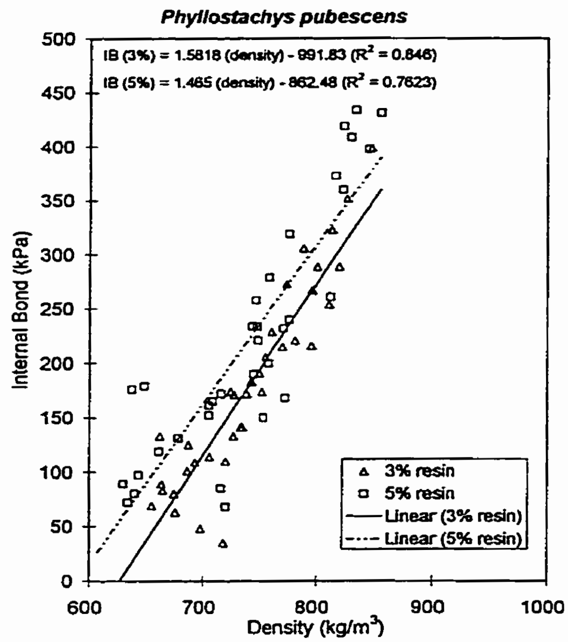


Figure 50: *Phyllostachys pubescens* Thickness Swelling Results

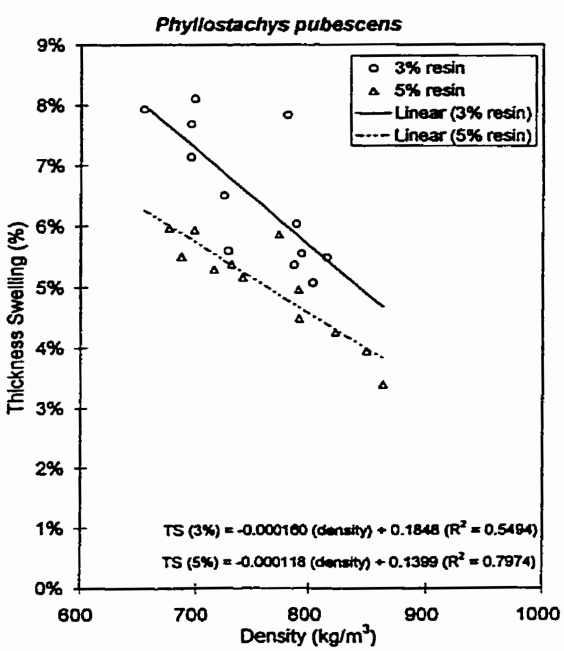


Figure 51: *Bambusa vulgaris* MOR Results

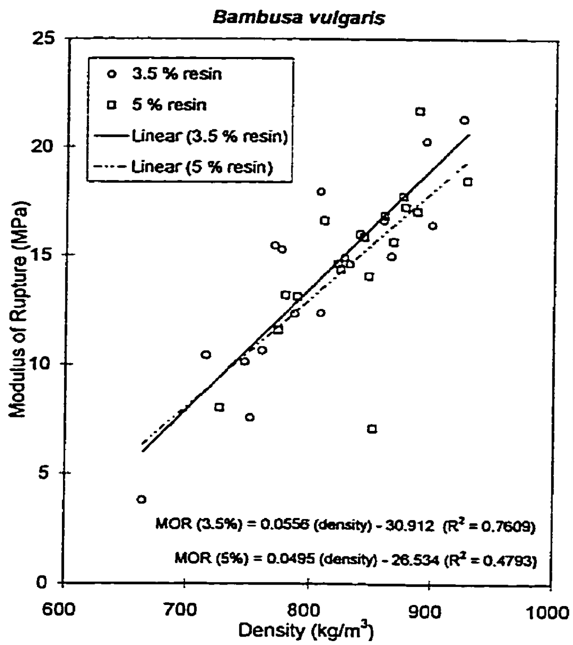


Figure 52: *Bambusa vulgaris* MOE Results

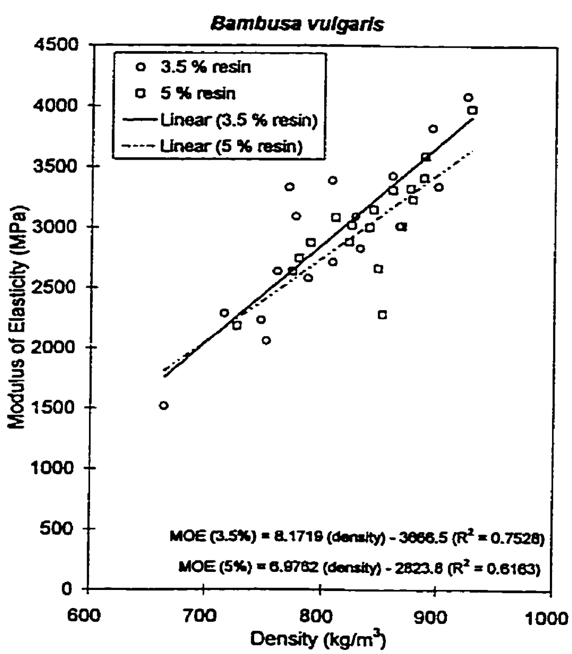


Figure 53: *Bambusa vulgaris* IB Results

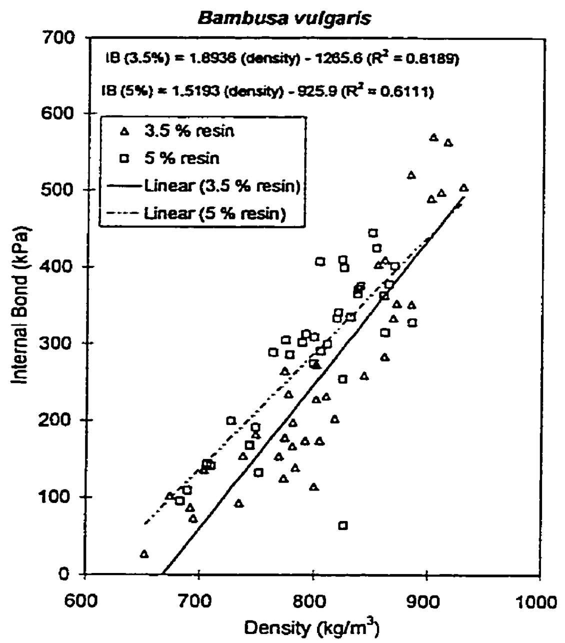
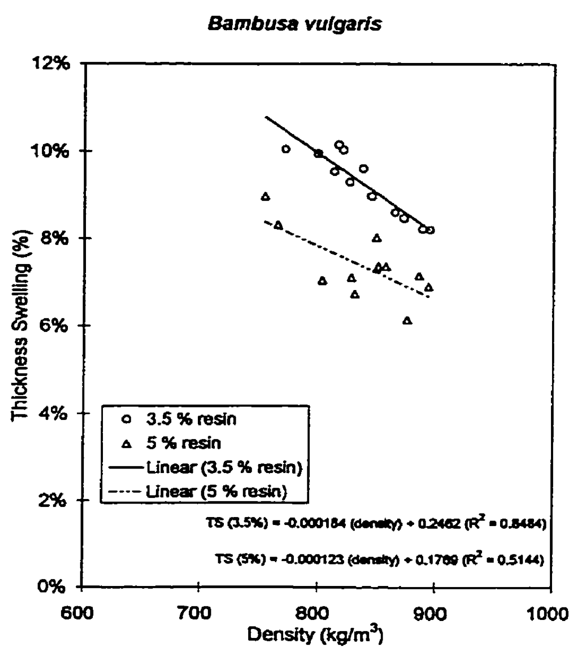


Figure 54: *Bambusa vulgaris* Thickness Swelling Results



In all of the cases above, a statistical analysis of the results was conducted following the pattern of the initial tests (presented in Chapter 5). The linear regression results are shown graphically on the figures, and the resulting regression equations are also presented. As mentioned earlier, it was decided to use two dimensional plots, and therefore the data representing testing results of panels made with different resin contents were presented as different data series, each with an independent linear regression analysis performed.

These curves show that density is an important factor in panel performance. However, the role of increasing resin is less pronounced than in previous tests (Chapter 5). This could be due to ineffective bonding with the bamboo (perhaps due to higher silica and wax contents, or due to low compaction ratios). The small difference between performance characteristics at different resin contents could also demonstrate that the bamboo itself failed, not the resin bond between particles.

The R^2 values show the success of the models in representing the chosen performance characteristic. Some R^2 values, such as those for the thickness swelling results for *Dendrocalamus strictus* (Figure 46) show that the linear regression models are poor estimators of the performance for that specific testing series.

As before, MOR and MOE are increased with greater board density. Higher resin contents had less impact on bending performance than shown for *Guadua angustifolia* presented in Chapter 5. Internal bond results are largely influenced by density, and less influenced by resin content. Thickness swelling results were close to or below the permissible levels of wood composite panel standards.

Results for the panels are presented in Table 21 in which values for each property tested were averaged for different resin contents. Therefore, the average (and standard deviations) for the test properties and sample densities are provided, along with the properties of several product standards. Results for *Guadua angustifolia* panels presented in Chapter 5 have also been included to facilitate comparisons.

The tests conducted with the alternative species produced panels with acceptable bending properties, although the internal bond results were low. That is, the panels meet several conventional particleboard standards for bending MOR and MOE, however fail to meet the minimum standard required for IB. As noted in Chapter 5, the results for *Guadua angustifolia* panels meet performance standards (with the exception of thickness swelling) at 4% resin content.

The low internal bond results are likely a symptom of the high density of the raw material, and the relatively low panel density (leading to a low compaction ratio as discussed later). This lead to panels with a flat density profile across the panel thickness (i.e. the density measured at different points across the panel cross-section are similar to the average panel density) indicating that little variation can be obtained by altering the pressing cycles without increasing the average panel density. Due to limited supplies of raw material, no further work was conducted to overcome the IB short-coming.

Table 21: Summary of Bamboo Particleboard Properties

	Resin %	MOR (MPa)	MOE (MPa)	IB (kPa)	TS (%)
Dendrocalamus strictus	3%	17.2 (2.6)[1] [760.1 (29.8)][2]	3073.6 (292.2)	232.4 (75.0) [766.0 (54.1)][3]	9.9% (0.6%) [746.9 (37.5)][4]
	4%	18.28 (2.9) [749.8 (41.6)]	3030.7 (337.1)	215.9 (71.3) [765.3 (60.2)]	9.4% (0.6%) [744.4 (64.3)]
	5%	20.2 (2.6) [768.9 (32.2)]	3207.5 (225.1)	218.6 (62.8) [775.6 (53.6)]	9.1% (0.4%) [751.3 (45.3)]
Phyllostachys pubescens	3%	12.3 (2.7) [741.5 (43.9)]	2639.7 (335.3)	179.9 (91.0) [740.8 (52.9)]	6.5% (1.1%) [747.2 (53.3)]
	5%	14.6 (2.0) [749.8 (26.5)]	2835.9 (217.2)	222.2 (112.4) [735.4 (69.1)]	5.0% (0.8%) [761.7 (63.1)]
Bambusa vulgaris	3.5%	13.8 (4.4) [805.0 (69.8)]	2912.2 (657.2)	257.2 (151.5) [804.2 (72.4)]	9.3% (0.7%) [836.9 (37.2)]
	5%	15.0 (3.5) [838.3 (49.5)]	3024.2 (439.5)	286.8 (103.8) [798.2 (53.4)]	7.4% (0.8%) [836.2 (43.9)]
Guadua. angustifolia	3%	14.5 (3.7) [772.8 (42.5)]	3114.3 (537.5)	425.8 (86.4) [772.6 (40.8)]	13.8% (0.7%) [758.0 (24.7)]
	4%	21.5 (3.0) [790.9 (34.7)]	4272.3 (342.7)	461.9 (66.5) [794.1 (29.6)]	14.3% (0.7%) [758.2 (28.7)]
	5%	24.1 (5.9) [785.5 (51.9)]	4441.4 (652.4)	491.6 (140.5) [781.9 (43.5)]	12.4% (1.1%) [750.6 (51.2)]
[5]R-1		17.2	3100	345	10% (thicker than 12.7 mm)
[6]M-1		11.0	1725	400	
[6]M-S		12.5	1900	400	
[6]M-2		14.5	2250	450	
[6]M-3		16.5	2750	450	

[1] Values in round brackets are standard deviations
[2] Values in square brackets under MOR values are the density values (average density and standard deviation) for bending samples (kg/m^3)
[3] Values in square brackets under IB values are the density values (average density and standard deviation) for internal bond testing samples (kg/m^3)
[4] Values in square brackets under TS values are the density values (average density and standard deviation) for thickness swelling testing samples (kg/m^3)
[5] Canadian standard for randomly oriented waferboard (O437.0 – 93), a structural panel used for floor, wall, and roof sheathing in building codes in Canada and the USA.
[6] ANSI A208.1-1993 Particleboard standard. M1, M-2, M-S and M3 are all medium density particleboards used for range of applications including furniture manufacture. shelving, countertops, kitchen cabinets, etc.

The results of the panels made from with *Dendrocalamus strictus* are clearly much better than the performance of the panels made with *Phyllostachys pubescens*. Liese (1992) noted that *Phyllostachys* bamboo have Type I vascular bundles with a lower fibre content than *Dendrocalamus* bamboos which are identified as having Type IV vascular bundles. As he noted "these basic differences in the anatomical make-up must affect a number of properties like density, strength, bending behaviour, splitting and shrinkage. A detailed comparison, however, is still to be done, albeit much needed." This vascular bundle difference can likely explain part of the difference between the quality of the particles of *Phyllostachys pubescens* and the other species. In addition, the density of the *Phyllostachys pubescens* material used was very high, as shown in Table 20. The high density of the Moso raw material (and therefore the low compaction ratios in this range of tests), combined with thicker particles suffering from uneven surfaces, could lead to inadequate contact between particles, and therefore unsuccessful resin bonding.

In general the performance properties improve with increasing density. The density ranges of this study were kept below the high density ranges (e.g. 900 to 1000 kg/m^3) used in Asia for commercial bamboo particleboard production in an attempt to pursue economically viable processes (high density requires greater raw material bamboo and resin usage), so no direct comparisons can be made. By using the regression analysis to estimate properties at the high end of the density range of the tests (850 kg/m^3), an approximation of panel performance can be obtained, as shown in Table 22.

Table 22: Regression Estimates for Particleboard Properties (850 kg/m^3, 5% resin)

	MOR (MPa)	MOE (MPa)	IB (kPa)	TS (%)
Dendrocalamus strictus	25.0	3705	286	9.1%
Phyllostachys pubescens	20.2	3469	383	4.0%
Bambusa vulgaris	15.5	3106	365	7.2%
Guadua angustifolia[1]	30.6	5194	648	11.3%

[1] Regression equations for *Guadua angustifolia* testing results based on density for each resin content are not provided in this thesis, but are used to plot regression curves in Figure 35 through Figure 38

Table 21 and Table 22 show that the results for bamboo particleboards of different species are promising. The properties for all species at 850 kg/m^3 surpass requirements of R-1 (waferboard) standards, with the exception of the *Dendrocalamus strictus* IB results, and *Guadua angustifolia* TS results. With small improvements in IB for *Dendrocalamus strictus*, *Phyllostachys pubescens*, and *Bambusa vulgaris*, the panels would meet the M-1, M-S, and M-2 particleboard standards.

In Table 21 and Table 22 the low IB value for *Dendrocalamus strictus* is of note, especially as the bending properties appear good. Examination of the plots of results show that the resin content had little impact on IB. Because the bending properties show reasonable strength (indicating that the bamboo must have acceptable inherent fibre strength), the low IB values are an indicator that variations in the pressing cycle are required to alter the density profile of the panel in order to enhance IB performance. Density profile analysis revealed that face density may have been obtained at the expense of core density. Low core density is detrimental to internal bond performance as sufficient contact to allow for bonding might not occur.

Generally speaking, a rapid press closing time will densify the faces, and core density may remain low producing a non-uniform density profile across the panel thickness. In contrast, slow press closing time usually produces a more uniform density profile. For this reason, a balance between bending and IB properties must be struck. Meeting performance standards for both bending and IB is the goal.

The age of the culm sample is also important. Lignification continues over time, and the fibre cell walls thicken during maturation and in later years (Liese, 1998), which is a factor in the increasing density in culms as they age. There is little published information on the levels and properties of the wax and silica present on the exterior of culms, although Liese (1998) noted that it can be felt "especially on young culms".

In spite of the promising results of this study, few firm conclusions should be made at this point regarding the preference of these species for panel production for a number of reasons. First of all, the bamboo was provided by third parties, and therefore the age of the bamboo, the time since cutting, and the storage of the culms was difficult to ascertain. These factors all play a role in the performance of bamboo in macroscopic physical-mechanical testing (Liese, 1985).

Secondly, the condition of raw material culms, such as those mentioned above, have an influence on the bamboo fibre. The impact of these conditions on the refining of particles, as well as on panel performance (MOR, MOE, IB, TS) could be conducted.

Thirdly, a major influence on composite panel performance is the compaction ratio used in composite production (i.e. the panels are required to be higher in density than the natural draw material in order to allow for adequate bonding and obtain sufficient values of selected mechanical properties). Due to the significant variation of density within species (and individual culms), the compaction ratio is not consistent. For example, Gnanaharan (1994) notes that the density of *Dendrocalamus Strictus* ranges from 540 to

780 kg/m^3. Given conventional particleboard compaction ratios of 1.3 : 1.0, a range of possible panel densities exists from 702 to 1014 kg/m^3. Density of bamboos has been shown to vary greatly for a species depending on growth location, climate, soils, etc., and since it plays an important role in the production of composites, tests should be replicated with species samples from managed, and well-documented, plantations or natural sources.

It is important to note that a press time of 3 minutes used in this research is very fast for PF bonded particleboards. Currently bamboo particleboards (of comparable thickness) bonded with PF manufactured in China require 10 minutes (Xue, 1995), decreasing the profitability of the enterprises, and therefore decreasing the opportunity for replacing bamboo for wood.

The bamboo particleboards developed use PF resin, which can be up to 100% more expensive than Urea Formaldehyde (UF) but is used in much smaller quantities (i.e. 3% to 5%). Chew et. al. (1994) used 8% UF in the development of bamboo particleboards, and commercial production of particleboard in China uses 10% PF resin. Given the increase in water resistance, and the decrease of formaldehyde emissions, PF bonded composites will grow in market importance in the near future.

This research is useful in that panel products meeting international bending and thickness swelling standards for structural panels and industrial particleboard were developed with a short (three minute) press cycle for a 16 mm panel. Although focus on increasing internal bond strength is required, the work presented shows that the major parameters of bamboo particleboard production that affect production costs (resin content, press time and panel density) can be improved beyond the levels now seen in commercial bamboo panel production and shown by other bamboo research projects. The impact of these production parameters will be further discussed in Chapter 8.

6.3 Conclusions

Particleboard panels were manufactured from *Dendrocalamus strictus* and *Phyllostachys pubescens* and *Bambusa vulgaris*. The age, time of harvest, and storage conditions of the bamboo samples were unknown. It is reasonable to assume that as a result the bamboo was not ideally suited to composites production.

In spite of these challenging circumstances and less than ideal samples of raw material, the test panels met international standards for bending performance within the range of manufacturing parameters used in this study, albeit at high densities. While the internal bond was weak for the panels, there are many factors in the preparation of the raw material and in the manufacturing process which can be altered to improve this performance characteristic.

In general, the panels made from these species were inferior to the initial results obtained with *Guadua angustifolia*, however the results were promising. The range of manufacturing parameters show that economically viable bamboo particleboard panels can be manufactured using the world's most common bamboos, although further work (suggested in Chapter 9) is required. In general, panel performance improved as resin content and panel density were increased.

This research into economically viable bamboo particleboards made from a variety of species has provided a unique contribution to the understanding of composite bamboo panel performance, and addresses the concern of the economic viability that has surrounded bamboo products manufactured with existing technologies.

7.0 High Strength Panels

7.1 Introduction

The previous work showed that bamboo composites are viable in the simplest form using particles, small discrete pieces of bamboo that are easily produced through mechanical processes. By reducing the entire bamboo culm to particles, the undesirable wax and silica on the outer layers was reduced to pieces of small surface area that were randomly distributed throughout the product, which ensured no localised failures due to bonding of large pieces covered in part by large silica regions. While this showed that the products are generally feasible in terms of reaching internationally accepted standards for panel performance, improvements can be made.

In general, the larger the pieces of a lignocellulosic material that are used in a composite, the higher the performance properties, and lower the production cost will be. This is because large pieces of raw material have less surface area for the same mass of raw material when compared with small pieces of raw material, and fewer bonding locations are required since fewer surfaces need to be bonded together. Due to the large surface available with particles, for example, the resin provides bonding only at randomly distributed locations and is therefore sometimes referred to as "spot-welding" the particles together. Plywood, on the other hand, has less bonding surface area within a panel of equal dimensions, however the resins can be effectively and economically applied to the entire bonding surface.

Many structural applications now use plywood and oriented strandboard, panel products with significantly higher bending resistance in comparison with particleboards. Therefore, effort was directed towards developing a higher strength, yet still economical panel with pieces of bamboo larger than the particles used in Chapters 5 and 6.

Three approaches were taken. Firstly, waferboards were investigated. This product is manufactured from wafers cut from the bamboo raw material. Generally waferboards (and similar strandboards) have high strength, low resin usage, and lower density than composite panels made from finer particles which require a greater compaction ratio.

The second approach involved covering the basic particleboard developed earlier with an overlay. It was intended that by bonding a high-strength overlay, the particleboard core would provide a low-cost and easily manufactured substrate for the overlay.

The third approach was to use bamboo in its largest form, namely an opened culm of bamboo. Layers of opened culms were covered with resin, stacked, and hot-pressed producing a laminated-type product. Although this product is very rough in terms of surface quality and appearance, it was hoped that high mechanical properties and low resin usage would create a high performance panel at low cost for applications in which appearance and surface roughness are not an issue.

This final approach is based in large-part on the availability of "caña picada" (opened bamboo culms) in Latin America, and therefore will be referred to as "picada panels". It varies greatly from plybamboo and laminated bamboo lumber in that the bamboo was not planed (a process used to remove the soft interior pith and silica exterior, but necessarily removes significant amounts of fibre from the strong exterior portions of the bamboo pieces). Processing without planing would dramatically reduce processing costs in large-scale operations.

7.2 Waferboard

7.2.1 Background

By refining the bamboo into larger pieces, more of the macroscopic strength of the bamboo could be captured in the final product shown in Figure 55. This has been clearly shown as advantageous through the excellent properties exhibited by bamboo matboards, plybamboos, etc. The key is to find a middle ground between processes based on small particles, and those based on "splits" which require costly processing.

Cutting bamboo wafers is a complicated affair as the hollow nature of most bamboos makes direct use in conventional (i.e. tree wood) wafer cutting machinery complicated. In addition, wafers from the exterior sections of the culm are often covered with silica and wax which provides a poor bonding surface that could cause localised failures. Of course, due to the hollow nature, there is a large variation in wafer size.

A number of trials with *Guadua angustifolia* from Costa Rica were conducted. A variety of moisture contents, knife spacing, and orientation with respect to the cutting knife were tested. All results were deemed unacceptable due to the inferior quality of the resulting wafers. Specifically, the wafers were torn, had inconsistent thickness, and the resulting wafers were not symmetrical, varying in width, length and thickness. These negative wafer properties are detrimental to board properties, and can increase production costs.

Subsequent trials with *Bambusa vulgaris* from Ecuador were conducted. The resulting wafers were greatly improved over the wafers from the previous tests, and were deemed sufficient to test preliminary applications of the wafers in waferboard panels. A summary of their physical properties is presented in Table 23.

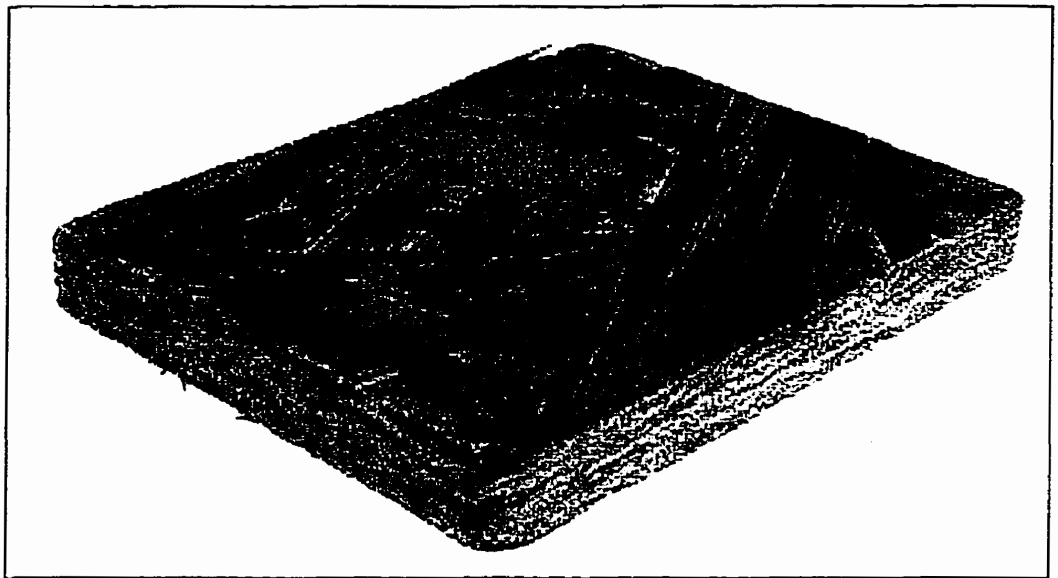
Table 23: Physical Properties of Bamboo Wafers

Species	Average Length (mm)	Average Thickness (mm)	Average Width (mm)	Density of Species' Samples (kg/m^3)
Bambusa vulgaris	119.9 (23.1) [1]	0.59 (0.34)	18.82 (11.1)	780

[1] Values in brackets are the standard deviations

The large variation in wafer width was expected as the cutting of wafers from a hollow, round material such as a bamboo culm will necessarily produce wafers of differing widths. The variation of wafer thickness is likely due to the nature of bamboo, and the alignment of the cutting blade. Bamboo refinement has long been seen as problematic, and the wafers produced in this study were greatly improved over previous attempts mentioned earlier.

Figure 55: Bamboo Waferboard



7.1.2 Testing Program and Results

Four sets of *Bambusa vulgaris* waferboard panels were produced, with each set consisting of three panels. All panels had a target thickness of 7/16" (approximately 11.1 mm, a common thickness for waferboard and oriented strandboard panels), and a target density of 800 kg/m^3, a relatively high value which was chosen to ensure that sufficient inter-wafer contact would take place to allow for resin bonding.

For all waferboard produced, the wafers in the core and face were the same. They are distinguished in this chapter only because when conventionally pressed different powder PF resins were applied to the core and face to optimise resin cure (i.e. a slow cure resin was used in the face).

The first two sets were three-layer panels (40% face / 60% core by mass) blended with powder PF resins and conventionally pressed. One set had 2.5% powder PF resin in the core and face, and the other set had 3.5% powder PF resin in the core and face.

A three minute and fifteen second pressing cycle was used. Press temperature was 215 °C, and metal spacers were used to produce a panel of the desired target thickness.

In addition, one set of panels was blended with 3.5% liquid resin, and pressed using steam injection. These wafers were formed in a single-layer mat (i.e. only one liquid PF resin was used) and pressed with a three minute cycle. Steam injection pressing is normally used to decrease pressing times on thick panels. Because the waferboard produced had a thin target thickness of 11.1 mm, steam injection pressing was not intended to decrease press time. This set of steam injection pressed panels was made to allow for a comparison between the *Bambusa vulgaris* particleboard and waferboard, and to see if the steam injection pressing had other effects on board properties. The same pressing details used for the particleboards in Chapter 5 and 6 were used for this set of bamboo waferboard.

The final set of panels were three layer panels blended with 3.5% powder resins (different resins for the core and face). During forming the wafers were aligned by hand in orthogonal directions in adjacent layers.

Wax was added to all batches in the amount of 1% by mass.

The results for the first three sets of waferboard are presented in Figure 56 through Figure 59. Figure 60 through Figure 63 show the results for the oriented panels.

The properties tested (MOR, MOE, IB, TS) are in accordance with panel performance standards (Appendix A) and indicate the suitability of the panels in structural applications.

The panels with oriented wafers were expected to have increased bending performance when the face wafers were oriented parallel to the longer dimension of the bending sample, and are labelled as "parallel" or "//" in this presentation. The bending performance of the panels in the orthogonal direction are identified as "perpendicular" or "⊥" in this study.

Several of the IB testing samples failed due to the presence of a large wafer of bamboo with the exterior silica layer intact. This was not unexpected as the waferizing process was not successful in producing consistent wafer sizes, especially at the initial and final cuts of the bamboo culm (where one would expect wafers with larger sections of silica intact). This fact suggests that a "debarking" process may be required to remove the silica prior to waferizing as part of the manufacturing process for bamboo waferboard panels.

Figure 56: *Bambusa vulgaris* Waferboard MOR Results

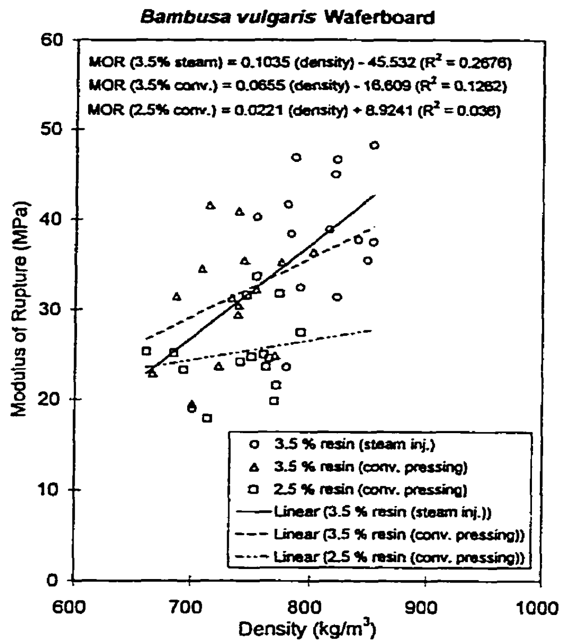


Figure 57: *Bambusa vulgaris* Waferboard MOE Results

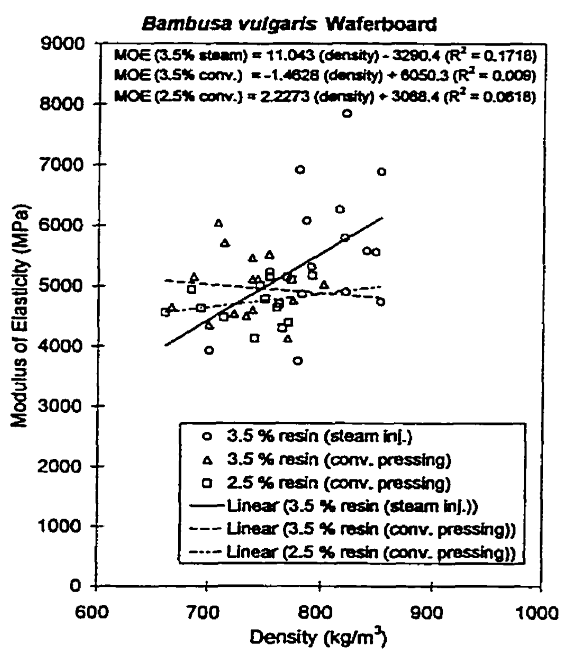


Figure 58: *Bambusa vulgaris* Waferboard IB Results

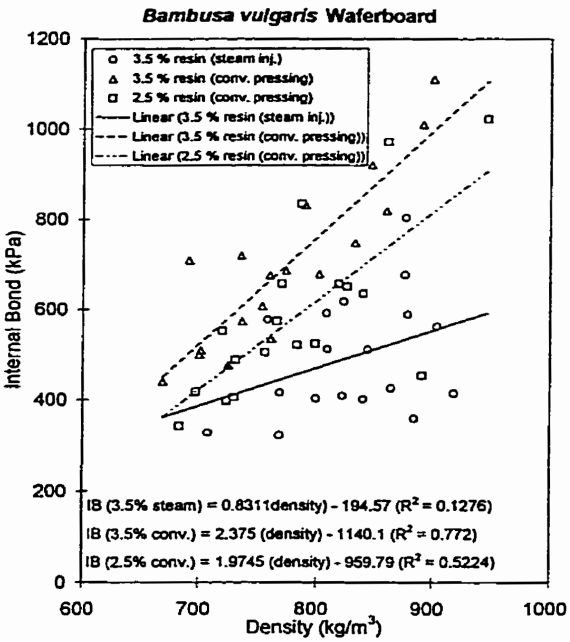


Figure 59: *Bambusa vulgaris* Waferboard Thickness Swelling Results

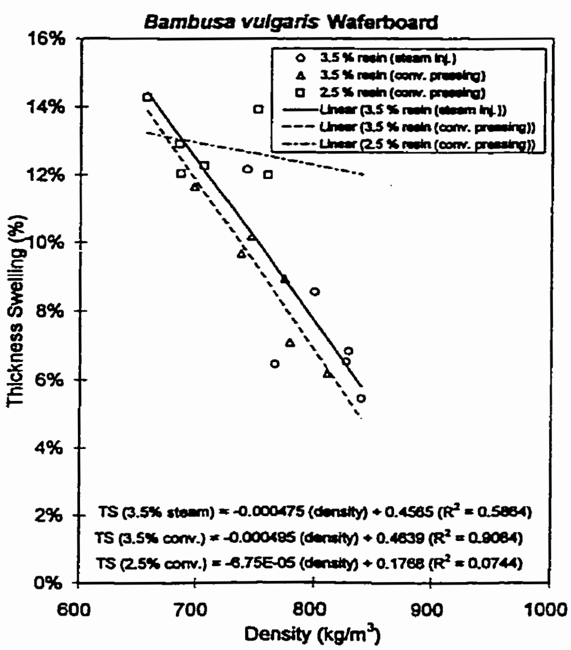


Figure 60: *Bambusa vulgaris* Oriented Waferboard MOR Results

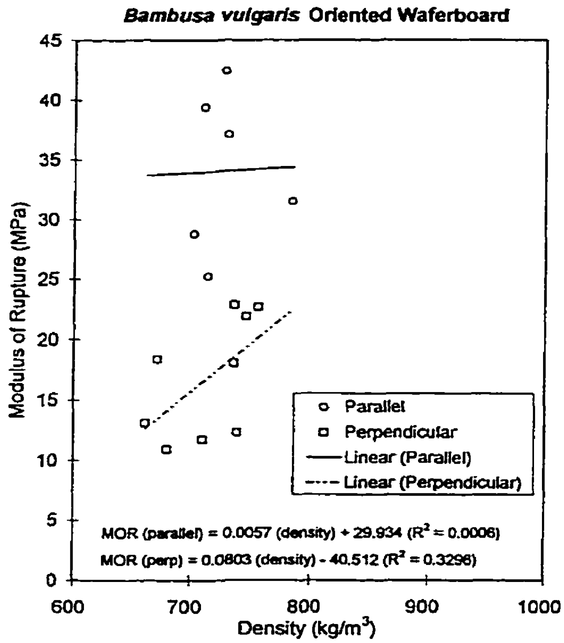


Figure 61: *Bambusa vulgaris* Oriented Waferboard MOE Results

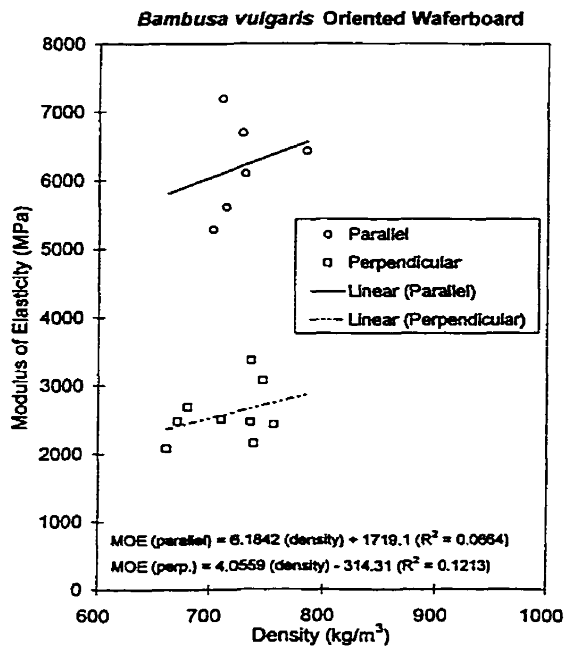


Figure 62 : *Bambusa vulgaris* Oriented Waferboard IB Results

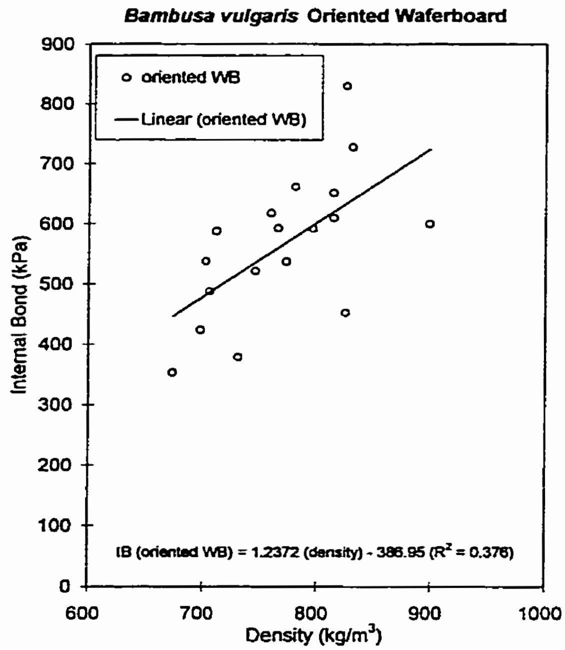
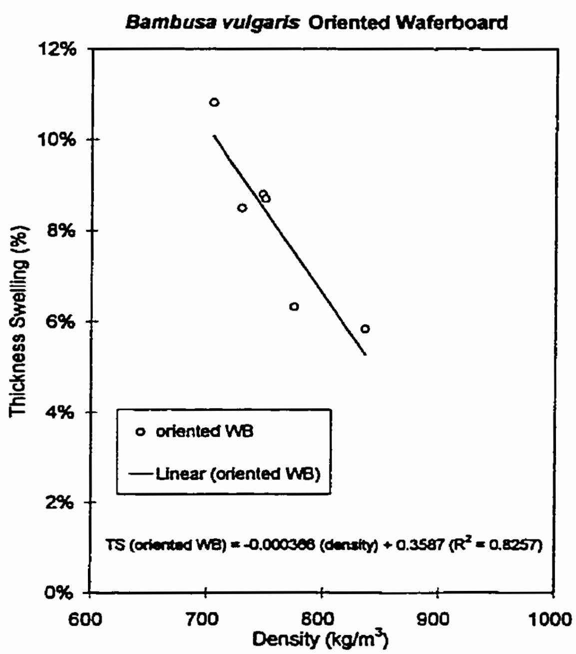


Figure 63: *Bambusa vulgaris* Oriented Waferboard TS Results



The results show that bamboo waferboard (with both randomly placed and oriented wafers) have excellent properties. The regression curves have a much lower R^2 value than for the particleboard presented earlier. The scatter in the data is mainly due to the presence of wafers with large areas of silica. This had been previously expected, and was confirmed after testing by visual inspection of several failure planes.

For each distinct panel series, average values of testing results were averaged and are presented in Table 24 along with the average density for the test samples.

Table 24: Summary of Bamboo Waferboard Properties

Testing Series		MOR (MPa)	MOE (MPa)	IB (kPa)	TS (%)
2.5% resin conventional pressing		25.3 (4.4)[1] [742.3 (37.4)][2]	4741.7 (335.3)	589.5 (190.4) [784.6 (69.7)][3]	12.9% (1.0%) [707.2 (39.8)][4]
3.5% resin conventional pressing		31.3 (6.5) [732.6 (35.0)]	4978.6 (541.1)	697.2 (187.1) [773.6 (69.2)]	8.9% (2.0%) [756.9 (39.0)]
3.5% resin steam injection pressing		37.6 (8.3) [802.8 (41.7)]	5575.5 (1111.4)	495.7 (131.2) [830.6 (56.4)]	7.7% (2.4%) [800.0 (39.1)]
oriented 3.5% conventional pressing	(//)	34.1 (6.6) [728.1 (29.3)]	6221.7 (704.0) [728.1 (29.3)]	564.9 (119.5) [769.4 (59.2)]	8.2% (1.8%) [757.0 (45.2)]
	(⊥)	16.9 (4.9) [715.1 (35.4)]	2586.1 (412.1) 715.1 (35.4)		
[5] R-1		17.2	3100	345	10% (thicker than 12.7 mm)
[5] O-1	(//)	23.4	4500	345	10% (thicker than 12.7 mm)
	(⊥)	9.6	1300		
[5] O-2	(//)	29.0	5500	345	10% (thicker than 12.7 mm)
	(⊥)	12.4	1500		

[1] Values in round brackets are standard deviations

[2] Values in square brackets under MOR values are the density values (average density and standard deviation) for bending samples (kg/m^3)

[3] Values in square brackets under IB values are the density values (average density and standard deviation) for internal bond testing samples (kg/m^3)

[4] Values in square brackets under TS values are the density values (average density and standard deviation) for thickness swelling testing samples (kg/m^3)

[5] Canadian standard O437– 93 (CSA, 1993)

Given the low R^2 values and the small number of data points, no distinct conclusions can be made differentiating the conventionally pressed and the steam injection pressed panels. While scatter of results for the oriented panels was great, they clearly show the impact of aligning the wafers to achieve improved bending performance in the "parallel" direction.

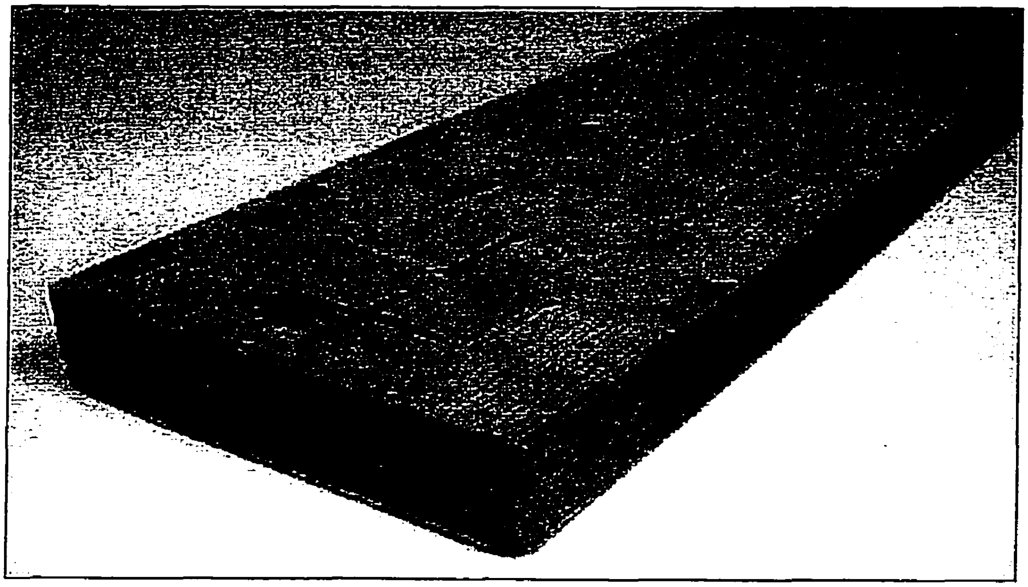
Unfortunately, limitations in raw material supply prevented opportunities for further testing.

7.2 Overlaid Bamboo Particleboard

7.2.1 Background

The bamboo particleboard developed in Chapters 5 and 6, in some cases, met international requirements for structural panels, such as waferboard. For all species tested some major international bending standards for particleboard products were met. In structural applications the internal bond requirements are less than for furniture applications (i.e. 345 kPa compared with 400 or 450 kPa for particleboards depending on the chosen standard, as shown in Appendix A), and therefore efforts were made to enhance the bending performance for structural uses by overlaying the particleboard with woven bamboo mats as shown in Figure 64.

Figure 64: Bamboo Particleboard Overlaid with Woven Bamboo Mats



In order to improve the commercial viability of a bamboo particleboard operation, ideally a plant would be able to produce exterior-grade panels that could be used in two distinct applications: construction sheathing; and furniture manufacturing. This would require adjustment of the pressing cycle to improve IB performance (likely at the cost of reducing bending performance, as discussed in Section 6.2).

In order to improve flexural properties, the particleboard was taken as a substrate on which an overlay would be applied. In keeping with the investigation of bamboo, it was decided that bamboo woven mats would be applied. Again, waferboard standards were seen as a desirable benchmark.

Bamboo mats are commonly woven by hand, dipped in PF resin and pressed to form bamboo matboard (BMB) in India. Some commercial operations are in existence in India, China, Thailand, etc. These products have excellent performance, but due to the costly nature of the woven mats, the products are seldom economically desirable beyond 5 layers thick (approximately 5 mm thick). By using a cheaper particleboard substrate, it was hoped that excellent bending properties could be obtained at the smallest possible manufacturing cost. Commercial production of bamboo particleboard overlaid with bamboo mats does exist in China.

7.2.2 Testing Program and Results

Tests were conducted to determine the performance of woven bamboo mats on particleboard made from *Guadua angustifolia* from Ecuador. The particleboard used here as a substrate was not assumed to be identical to the particleboard made with *Guadua angustifolia* from Costa Rica, and was therefore tested separately as shown in Table 25. Woven bamboo mats were coated with a commercial liquid PF resin by hand with a brush applicator. The resin quantity applied was calculated to be 210.3 g/m^2 (based on 100% solid content). This works out to approximately 2.7% of the total mass of the panel (particleboard, mats, and resin) not including the resin used in the production of the particleboard itself based on 100% solid content.

The mats where then placed on the faces of a bamboo particleboard (16 mm, a common thickness for particleboard used in furniture and industrial applications) and hot-pressed at 150°C for 3:00 minutes, at approximately 200 psi press pressure.

Testing was then performed on the panels overlaid with the woven bamboo mats. Testing was also performed on extra identical bamboo particleboard panels to allow for an analysis of the role played by the bamboo mats in improving panel bending performance (Table 25).

Table 25: Results of Bamboo Particleboard Overlaid with Woven Bamboo Mats

	Average Density (kg/m^3)	Bending MOR (MPa)	Bending MOE (MPa)
bamboo particleboard panel	827.3	18.8	3142
bamboo particleboard panel overlaid with bamboo mats	919.4	28.4	4117
increase in performance over bamboo particleboard panel	11.1%	51.1%	31.0%
[1] R-1		17.2	3100
[1] O-1 (//) (⊥)		23.4 9.6	4500 1300
[1] O-2 (//) (⊥)		29.0 12.4	5500 1500

[1] Canadian standard O437– 93 (CSA, 1993)

As Table 25 shows, the bamboo mats had a significant role in increasing bending performance. However, the bending MOE with the mats does not meet the higher requirements of either the O-1 or O-2 standard, and the requirements for the R-1 standard were met with the particleboard before transformation with the mats.

IB tests were not performed due to the limited supply of raw material. However, because there was low press pressure and temperature, the application of mats to the surfaces should not affect the particleboard core, which is the site of most IB failures. For that reason, IB performance should not be changed by the application of mats onto the bamboo particleboard surfaces.

In order to meet higher product standards (such as O-1 and O-2) adjustments could be made to the bamboo particleboard substrate to enhance the stiffness of the product, but this might reduce the internal bond of the particleboard. Alternatively, panel use could be based on construction codes for applications that require bending strength, but are not as stringent in terms of bending stiffness. For example, low-cost housing is unlikely to have plaster or wallboard that would crack with excessive deflections, and therefore panel stiffness is not as critical as panel strength.

7.3 Picada Panels

7.3.1 Background

The third strategy for producing high-strength panels was to use opened bamboo sections with very little processing. By avoiding the planing stage common in plybamboo, laminated bamboo lumber, etc. production steps are reduced, and therefore production costs in commercial applications will be reduced.

The bamboo used was opened *Guadua angustifolia* that were purchased at a construction material retailer (or "deposit") in Ecuador, and shipped to Canada for testing. Opened culms of bamboo are commonly used as low-cost construction sheathing in low-income housing, and are commonly called *bambu picada* (Figure 65).

Figure 65: Preparation of Bamboo Picada

Shortly after harvest, the culms are opened by hand using a machete. Normally the machete is also used to remove large parts of the interior nodal material, but much still remains. It is commonly available at construction material deposits in Latin America.

Due to increasing demand for bamboo in Ecuador, much of the bamboo supplied is being cut prematurely to take advantage of current marketing opportunities. Most of the *Guadua angustifolia* used in this study was younger than the ideal recommended for structural applications. Through consultation with local bamboo experts, it was estimated that the average age of the bamboo was approximately 1-2 years.

7.3.2 Testing Program and Results

The opened bamboo sections were lightly sanded using a belt sander or a fibreglass grinding disk in order to remove excessive interior node material, and to roughen the exterior surface. All samples still retained the exterior layer, and the nodal areas remained as protrusions above the adjacent internodal walls (i.e. the amount of processing was very limited).

A commercially available PF plywood resin was applied by hand with a brush applicator. The amount of resin applied was measured, and found to average 320 g/m^2 (based on 100% solid content). Although this is high compared with plywood resin coverage spreads, it worked out to approximately 3.9% resin content (based on 100% solids, as a percentage of total panel mass). This low amount of resin required is due to the thickness of the bamboo used.

With wood plywood and plybamboo products, the veneer layers (or bamboo splits) are much thinner, thereby requiring more gluelines to achieve the same final panel thickness. It is expected that future work could reduce the resin coverage spread closer to levels commonly found in laminated wood products (i.e. approximately 100 g/m^2 based on 100% solid content).

An exception to the resin spread mentioned above was an initial test panel (three layer-parallel) that is included in Table 26 to demonstrate the impact of high resin content, high density and high resin spread on panel performance. Clearly, as with particleboards, there is a balance that must be struck between manufacturing parameters and the desired panel properties.

The bamboo samples were hand laid into mats with an effort made to stagger the location of nodes in order to reduce density fluctuations. Several orientations were produced, and varying number of layers were used in order to test thin panels for simple sheathing applications, and thicker panels which could possibly be cut in order to serve as lumber equivalents in place of wood used for structural framing. In all cases the bamboo on the two exterior faces was placed with the silica surface towards the external face of the panel to reduce the silica surface in the glueline.

The panel thicknesses were not predetermined, or produced with spacers. Therefore, the thickness of the bamboo pieces, the number of layers, and the press pressure were the determining factors of panel thickness.

Some panels were produced with all layers of bamboo oriented in the same direction (for example 2 layer "parallel" panels). Other panels were made with bamboo in adjacent layers orthogonal to one another (e.g. 2 layer "perpendicular" panels). This label of product structure is not related to the testing orientation.

The picada panels produced (Figure 66) showed excellent bending properties as shown in Table 26.

Table 26: Average Performance Values of Picada Panels

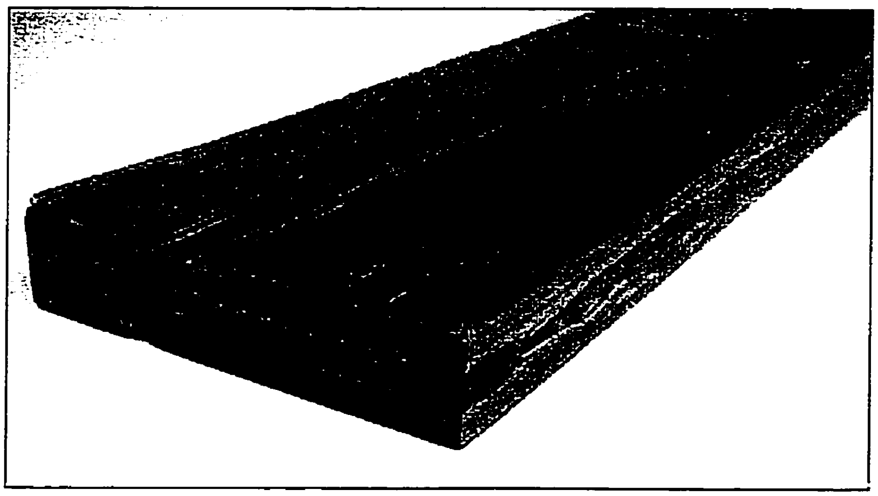
Product	Testing Orientation [1]	Resin Spread Rate (g/m2)	Resin % Based on Sample Mass	Density (kg/m3)	Panel Thickness (mm)	MOR (MPa)	MOE (MPa)
2 layer (parallel)[2]	//	306	3.5%	626	14.1	70.5	9,175
2 layer (perpendicular)[2]	// ⊥	373 373	4.1% 4.2%	765 793	11.6	33.5 37.7	1,822 2,618
3 layer (parallel)[2]	//	528	7.1%	854.2	17.5	127.6	13,337
3 layer (perpendicular)[2]	// ⊥	373 373	4.5% 4.6%	771 770	17.6	54.5 19.1	11,651 1,023

[1] refers to the direction of the lower face picada direction with respect to the long dimension of the bending sample

[2] "parallel" refers to all panel in which all layers of bamboo are aligned parallel to one another, whereas "perpendicular" refers to panels in which adjacent layers are placed perpendicular to one another

All panels had uneven surfaces due to the unique nature of each picada piece used in the layup (Figure 66). The surface quality and varying panel thickness was expected in the testing. It is assumed that this will limit the commercial acceptability of the panels in traditional markets. However, it is likely that in low-cost housing applications the enhanced performance and low production cost will offset the uneven surface, and differences in thickness between panels (and across the same panel).

Figure 66: Three Layer Perpendicular Picada Panel



Density variations were expected due to the limited number of tests, and the complex interaction between bamboo thickness, number of layers, press pressure and panel thickness.

It was noted that the 2 layer perpendicular lay-up suffered from warping due to the stresses caused by the unbalanced nature of the lay-up, a limitation often seen in bamboo flooring and other laminates of poor quality. Also of interest, is that the 2 layer perpendicular panels had lower bending MOR and MOE in the parallel direction of testing than in the perpendicular direction of testing. This occurred because the gaps that existed between bamboo pieces formed a crease at which the bamboo bent when tested in parallel (i.e. the gaps were perpendicular to the long dimension of the bending sample, and were located under the testing head). The potential benefit of a strong solid bottom layer parallel to the direction of the long dimension of the bending sample was not realised due to the gap characteristics of the bamboo in the adjacent layer. For these reasons two layer perpendicular picada panels are not likely to be useful in housing applications.

The two layer parallel panels have excellent properties as shown in Table 26. However, in some cases the gaps between bamboo pieces in the upper and lower layers were aligned, and the panel broke at that point. Careful placement of the bamboo is required to ensure that gaps do not overlap in adjacent layers.

The three layer panels have excellent properties. The parallel set-up had excellent properties in the tested (parallel) direction, but as with the two layer parallel set-up, in some samples gaps in adjacent layers were overlapping creating an obvious weak point. Depending on the application, this may be a serious detriment to successful utilisation.

The three layer panels with perpendicular set-up had excellent properties in the parallel testing orientation. Due to the reasons mentioned with the two layer perpendicular panel, when the upper layer bamboo of the bending test sample is oriented perpendicular to the long dimension of the bending sample, the existing gaps between bamboo pieces allow for a crease which led to extremely large deflections which are represented as relatively low MOE values in Table 26 for the 3 layer perpendicular panel tested in the "perpendicular" orientation.

This is essentially the same failure mode as described with the 2 layer perpendicular when tested in the "parallel" direction. It is important to note that the testing orientation was defined with respect to the bottom layer of the bending sample.

The simplicity of the picada panel resin application, lay-up, pressing, the low resin content, and excellent mechanical properties make it a highly valuable product for low-cost housing. The most promising products seem to be the two layer "parallel" (which requires attention regarding the placement of gaps), and the three layer perpendicular lay-up. Due to addition of another glueline in the three layer panel compared with a two layer panel, and the increased thickness (which requires a longer press time to cure the resin close to the centre of the panel), the three layer panel is expected to have much higher manufacturing costs.

7.4 Conclusions

The results of the bamboo waferboard and the picada panels show that the use of larger pieces of bamboo is beneficial in retaining the excellent macroscopic properties of bamboo, while maintaining relatively low resin contents. These panels show tremendous promise for low-cost housing application, although the potential for failure of the waferboard due to external silica wafers require that more attention be directed at removing the silica, or improving the waferizing process.

The use of woven bamboo mats bonded to the surface of bamboo particleboard was found to have an large impact on improving bending performance of the particleboard. However, given the target performance standards, the overlaid bamboo particleboard panel does not improve panel performance dramatically (i.e. the resulting panels did not meet a higher performance standard based on MOE results). Due to the enhanced appearance, and bending strength improvements, it is expected that this use of a low-cost substrate such as bamboo particleboard will continue to be of interest.

Another approach is to investigate the statistical occurrence of silica-related failure, and establish production models that take into account the likelihood of this failure mode. For example, a higher average MOR and MOE may be required of bamboo waferboard, with alterations made regarding variability of results in product standards. The CSA O437.0-93 standard requires that no sample panel (of the five tested) may have any property (e.g. MOR, MOE, etc.) 20% or more below the stated average for that property (Appendix A).

In addition to inferior wafer quality when compared to wood in terms of consistency of thickness, wafer dimensions, etc., the bamboo wafers were very curved which made forming difficult. This may be a limitation in commercial application, or in the very least something that would require additional plant engineering concerns above those addressed in conventional wood-waferboard production facilities.

The picada panels have excellent bending properties, and warrant further investigation. Specifically, efforts should be directed towards fastening systems. As with plybamboos, the longitudinal alignment of fibres leaves the panels susceptible to splitting when nailed. Likely, pre-drilling holes will provide substantial protection from splitting, but a testing program that covers a variety of applications under various conditions is necessary.

All three approaches taken in this chapter have demonstrated that products made from relatively large pieces of bamboo can have excellent bending properties for use in applications which require high performance panels.

The three products are very different, and require special attention in their application. For example, bamboo waferboard may be more suited to large-scale commercial production, and picada panels more suited to labour-intense production with smaller capital investment in equipment. These issues, as well as other environmental and economic concerns, will be discussed in Chapter 8.

8.0 Environmental, Economic and Social Impacts of the Commercialisation of Composite Bamboo Products

8.1 Introduction

This thesis has demonstrated the need for alternative building materials for low-cost housing, and has developed several specific bamboo-based products that have been identified as potentially economically feasible based on key manufacturing parameters such as resin content, product density and press time.

In this chapter the role of bamboo-based building materials will be discussed with respect to environmental, economic and social concerns. These points have been raised earlier (e.g. the choice of PF resins over other resins, the drive for low resin contents and short press times, the desirable properties of low-cost housing approaches for Ecuador, etc.).

Specifically, this chapter will demonstrate:

- why bamboo should be used in low-cost housing
- the economic feasibility of bamboo panels (presented with reference to international market prices for building materials)
- the positive social role of bamboo composite production in developing rural communities

8.2 Sustainable Development

"Sustainable development" is a term that many attribute to The World Commission on Environment and Development that was chaired by Gro Harlem Bruntland (and therefore often called the Bruntland commission). Their findings were published in the book "Our Common Future" (WCED, 1987) which includes much of the basis for the discussion and efforts towards reinterpreting development on a global scale.

The most often quoted passage includes the definition of sustainable development as meeting "the needs of the present without compromising the ability of future generations to meet their own needs." This concept is sometimes taken out of context to suggest that human beings must return to entirely benign activities as the planet already shows signs of being close to its ultimate limits of natural resource survival.

But in fact the Commission continues on to say that sustainable development "does imply limits - not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities." They go on to correctly point out that "technology and social organization can be both managed and improved to make way for a new era of economic growth."

This imperative of "economic growth for nations in which the majority are poor" is linked with "an assurance that those poor get their fair share of the resources required to sustain that growth."

This is a critical concept that many fail to accept: economic growth is not simply for the continued benefit of already rich countries and companies. It is a mechanism that will assist in alleviating poverty, distributing wealth, and help fulfil the goal of sustainable development in "meeting the basic needs of all and extending to all the opportunity to fulfil their aspirations for a better life."

Industrialisation which leads to equitable economic growth is therefore a positive aspect of development.

Of course, many will cite past examples to demonstrate that industrialisation specifically does not encourage the "equitable" distribution of wealth. Due to the economic reality of the cost of capital, required return on investment, ownership, and distribution of profits, manufacturing entities, for example, are not always established with the benefit of local communities as a first priority. But the failure to do so in the past should not be taken as an imperative that changes to social, market, and political systems will not endorse such aspirations, and the actions needed for these goals to become a reality.

"Deep ecologists" would suggest that the needs of the environment are paramount, and the need for improved standards of living for the world's population should not be of consideration, especially as this improvement in standards leads to further environmental disruption. This argument is a moral one. The United Nations Development Program, for example, has poverty eradication as a main objective. This is clearly and appropriately anthropocentric, yet does not imply an abuse of the planet's environment as deep ecologists would contend. The common global development perspective is that the needs of people in poverty is paramount. "The Habitat Agenda" (Chapter I - Preamble) states that "human beings are at the centre of concerns for sustainable development, including adequate shelter for all and sustainable human settlements, and they are entitled to a healthy and productive life in harmony with nature."

With these points in mind, sustainable development is a concept that is desirable. It means in a practical sense that long-term awareness of our natural resources is essential. But it also promotes the idea that economic growth will help alleviate poverty, and improve the lives of the world's citizens.

This chapter will first examine if traditional bamboo use fits the definition of sustainable development, and then discuss the economic aspects of bamboo panel development.

8.3 Small is Beautiful

There are many supporters of bamboo who feel that bamboo should primarily be used in its most natural forms. By growing small stands of bamboo in their yards, rural people can take advantage of the numerous beneficial uses of bamboo. This is usually accomplished with sustainable harvests (as the people are stewards of their own resource) and simple conversion techniques to transform the natural resource into useful forms. These products are usually free of industrial chemicals, are produced by the users, and are biodegradable after the useful lifetime has expired. There are many publications in which the many traditional uses of bamboo (Farrelly, 1984) and the important role of bamboo in the lives and economies of much of the world's population are presented (INBAR, 1997).

Through small-scale growth, management and utilisation, bamboo benefits billions of people throughout the world. There is no doubt bamboo is a wonderful material of nature.

8.4 Choices Between Materials

But this small-scale use of bamboo does not happen simply by chance. People use bamboo out of necessity. People need housing, implements, tools, baskets, food, etc. and bamboo fulfils these many needs.

If bamboo were not available people would search for other materials that could meet their needs. As people gain wealth, often they change to other materials out of practical or social concerns. Bamboo is often referred to as "the poor man's timber" and is commonly not considered a desirable building material. But when it is available, inexpensive, and the best choice (in terms of price, ease of use, durability, aesthetics, etc.) it will be used.

However, when other materials (usually processed materials such as concrete, steel, plastic) are cheaper in cost, easier to use, more durable or improve performance, people have a choice in the materials that they use.

The sight of plastic litter in many developing countries is a symptom of these changes. Where banana leaves were used as fresh food containers in markets, often plastic is now used, and the use of the container remains the same - it is discarded when not needed. The non-biodegradable plastics are now seen where once natural fibre materials, such as banana leaves, were left to decay.

Clearly, if people have an option of other competitively priced products that out-perform traditional materials, changes in consumption patterns will take place. The effects of these choices are multiplied when considered on a global scale. How does bamboo compare with other common materials?

Instead of trying to discuss a broad range of materials and their uses throughout the world, this chapter will focus on materials used for housing since the United Nations recognises "the right of everyone to an adequate standard of living for himself and his family, including adequate food, clothing and housing, and to the continuous improvement of living condition". In addition, the issues of low-cost housing are the predominant motivation behind this thesis.

Housing is an essential aspect in development as the home provides shelter, a social base for the family, geographic stability, a possible location for micro-enterprise commercial activity, etc. Yet, large portions of the world's population lives in sub-standard housing and there is a shortage of housing throughout the world. Housing is therefore a priority of the United Nations, and most developing countries around the world.

The construction of the required number of basic shelters will have tremendous ecological aspects. The negative impact of this construction can be decreased through careful selection of the materials and building practices used.

Numerous social interest housing projects aimed at the economically poor sectors of the population exist across the world. They are generally government supported housing projects for low-income families. Priorities of quality, size, social services, infrastructure, etc. vary greatly between projects.

8.5 Concrete, Wood and Steel

Concrete, wood and steel are most often used in housing construction projects throughout the world as they lend themselves to engineered design. Through knowledge of material performance, and established practices of design and construction, engineers can design and build structures with a degree of certainty regarding performance and safety.

In addition, in much of the world concrete houses have increased social prestige, and are therefore preferred over local traditional materials often in spite of their unsuitability to local conditions which include high temperatures and large amounts of solar radiation.

Concrete and steel have tremendous impacts on the environment due to the acquisition of raw materials, processing, and the recyclability and transformation of the structure at the end of it's life. To discuss the environmental sustainability of these materials in construction, it is important to consider these associated environmental impacts.

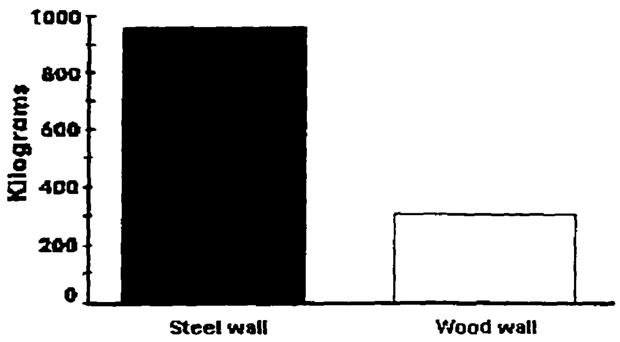
Concrete and steel are manufactured materials. This allows for careful control of physical and mechanical properties, further enhancing the reliability of engineered designs. As design reliability is improved, costly over-design is reduced. The safety and ease of design using steel and concrete (combined with durability and other benefits) make these materials obvious choices by engineers and architects in large-scale housing projects.

Unfortunately, the extraction of raw materials and the processing of steel and cement have large negative environmental impacts.

Binkley (1993) noted that cement production is the second largest source of CO_2 emissions in Canada after fossil fuel consumption. Koch (1992) noted that to replace wood studs in construction by steel requires 9 times as much energy, and to replace a wooden flooring system with concrete requires 21 times as much energy.

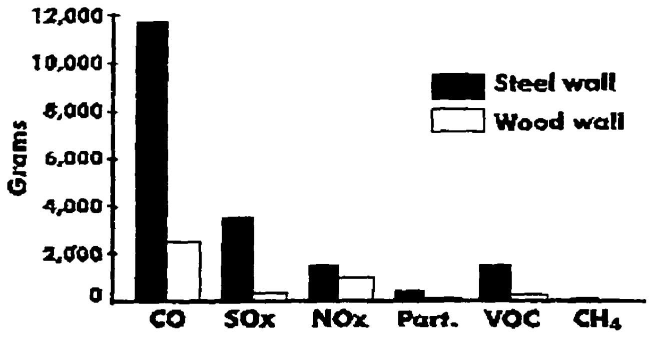
Meil (1993) provided estimates of the impacts of two construction systems (2" by 4" wood stud construction, and 20 gauge non-structural steel). His group modelled the materials needed to construct a non structural wall, arbitrarily designed to be 3 metres high, and 30 metres long. Using criteria such as energy use, water demand and a variety of air emissions, wood construction had significantly less environmental impact than steel construction. Figure 67 through Figure 71 show Meil's estimation of manufacturing effluents and environmental impact for the steel and wood walls.

Figure 67: Comparative Carbon Dioxide Emissions



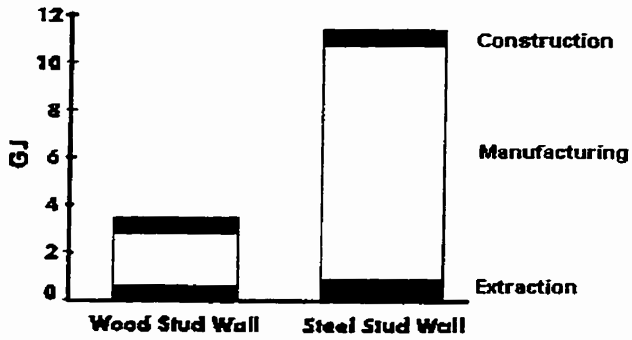
Source: Meil (1993)

Figure 68: Other Air Emissions



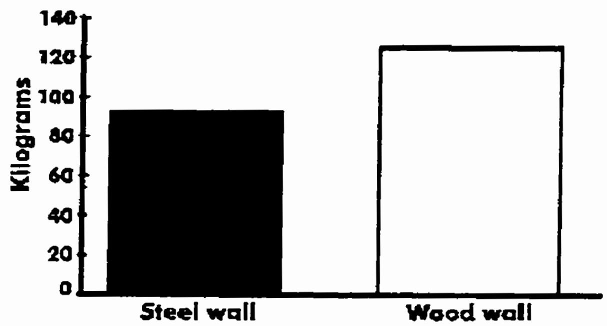
Source: Meil (1993)

Figure 69: Comparative Energy Use



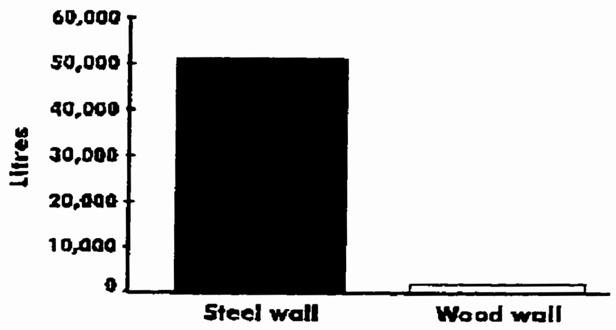
Source: Meil (1993)

Figure 70: Comparative Solid Wastes



Source: Meil (1993)

Figure 71 : Water Demand



Source: Meil (1993)

The only category in which wood construction performed poorly was in comparative solid wastes generated during manufacturing and construction. This is largely due to the use of the slag by-products resulting from the manufacture of steel, and due to the more efficient use of steel on the construction site.

This study, done by an economist within the wood industry, was intended to "encourage the wider use of all materials in any particular building design such that together they minimise the building's environmental impact" recognising that wood, steel and concrete all offer benefits and costs in terms of environmental impact, performance, and applicability in construction.

Constructions built from steel and concrete are also difficult to recycle. This is in contrast to the marketing information of the modern steel organisations in which advertisements mention that steel is environmentally beneficial because it is often recycled (e.g. cars, etc.). In addition, the impact of mining, quarrying, and refinement of raw materials has significant negative environmental implications, and due to the finite amount of minerals that exist is unsustainable by definition.

8.6 The Use of Wood

Given the environmental costs of using concrete and steel in construction, the increased use of natural fibres, such as tree-wood and bamboo, is a positively contrasting alternative.

Traditional uses of wood include lumber and timber members which require only small amounts of processing. In spite of rigorous testing of material properties, the natural variability within wood samples (even within the same species) leads to larger factors of safety in construction design. This uncertainty and requirement of safety factors leads to non-optimal wood utilisation, thereby increasing costs.

Recent advancements in the utilisation of wood have largely been based on manufactured products. Through a controlled manufacturing process, the producers can largely "engineer" the properties of the final product (hence the name "engineered composite products"). The control of product properties is considered the most important advantage of composites. In addition to dictating the size and thickness of products, the actual physical mechanical properties themselves can be largely controlled. Plywood, particleboard, and oriented strandboard are examples of engineered composite materials.

Engineered composites allow for the use of a wider range of raw materials. Wood species that suffer from too much variation in physical mechanical properties might produce suitable composite products, given proper controls in the manufacturing process.

To produce composite products, the refined raw material can be quite small (e.g. particles, fibres, etc.) which leads to less waste of the original roundwood tree. This minimisation of waste in the wood products industry is now at exceptional levels, and almost all parts of harvested trees are used in some way (see Table 27).

Table 27: Roundwood Yield Efficiency for Wood Products

Product	Yield Efficiency from Roundwood
Lumber	30 % - 70 %
Veneer	approx. 50 %
Particleboard	75 % - 90 %

The controlled manufacturing of lumber and wood products has allowed for the introduction of standards for product performance and for specific product applications. This is an essential component for the wide use of wood in construction, especially in technologically advanced countries that aim to protect public safety through safe engineering design practices.

In summary, "engineered wood products represent one of the best options to extend our fiber basket, providing for the efficient use of a wide variety of wood fiber and species sources" (Bykhovsky, 1993).

Hart noted (1997) that there are three ways of stabilising or reducing the global population's "environmental burden", namely decreasing population, lowering levels of affluence (and therefore consumption), or "changing fundamentally the technology used to create wealth".

The last point involves transformations (or "advances") of technology in many sectors of society. Most of our current technological advances are due to commercial effort, or through research and development that has commercial application of technologies as its goal. As Hart notes "technology is the business of business." Perhaps the large scale industrialisation which takes advantage of economies of scale is the bridge for commercial interests to move away from unsustainable industrial activity and concentrate on sustainable practices and products using natural fibre sources.

Alternative fibre sources such as bamboo, hemp and agricultural wastes can offer an alternative supply of natural fibre for the production of construction material composites, bio-energy production and to meet pulp and paper fibre demands.

8.7 Natural Fibre Sources

Natural fibre based products are clearly in common use throughout the world in many forms. As growing population and wealth increase the demand for construction materials, energy, and paper, natural fibre sources can offer a sustainable source of raw material.

The supply of wood is in question. Sutton (1993) noted that "there appears to be a limited scope globally to increase wood harvest levels from traditional sources. Wood harvest levels from natural forests might even decline significantly if other forest values (like biodiversity, protection of endangered species) are considered by society to be more important and to be incompatible with wood harvesting." RISI (1993) stated "the question is not whether timber supply conditions will get worse but how fast and to what degree". Plantations of fast-growing species are thought to be one solution.

With increased wealth there is generally increased demand for wood products (Sutton, 1993). Given current population growth, and the increasing levels of development, pressures on existing material supplies, including timber supplies, will increase.

8.8 The Demand for Wood Products

The Food and Agriculture Organization (FAO) of the United Nations (FAO, 1993) stated that the global production for particleboard was 40.2 million m^3 in 1980, and 49.5 million m^3 in 1991 - an increase of 23%. In the North and Central American region, production was 7.0 million m^3 and 9.9 million m^3 for 1980 and 1991 respectively (an increase of 42%). South American production of particleboard rose 27% during the same time period, from a volume of approximately 1.0 million m^3 in 1980 to approximately 1.3 million m^3.

The Food and Agriculture Organization of the United Nations (FAO, 1997) noted that global demand for wood-based panels in 1994 was 127 million m^3, of which 36 million m^3 (or 27%) were produced in developing countries. Apparent consumption of wood-based panels per thousand people in 1994 was 78.36 m^3 in developed countries, yet only 10.01 m^3 in developing countries. As with many trends associated with development, the consumption of wood-based panels can be expected to grow in developing regions, and therefore the source of fibre for composite production will become an important issue.

The United Nations Economic Commission for Europe noted that the apparent consumption of particleboard (including non-wood particleboard and waferboard) in North America was expected to rise from 20.4 million m^3 in 1995 to 22.7 million m^3 in 1997 (United Nations, 1996 a). The Commission estimated that in 1997 a total of 5.0 million m^3 of particleboard would be imported into the USA alone.

The market data also demonstrates the trend of North American users to proportionately increase their use of composite panels as shown in Table 28 (United Nations, 1996 b) as the availability of mature trees for veneer production decrease.

Table 28: Apparent Consumption of Wood-based Panels (excluding veneer sheets) in North America, 1991 to 1995

	Volume (million m^3)					Percent of Total	
Product	1991	1992	1993	1994	1995	1991	1995
Particleboard[1]	14.37	16.82	18.1	19.05	20.31	37.7	44.9
Plywood	18.38	18.81	18.86	19.19	18.89	48.3	41.7
Fibreboard	5.32	5.50	5.65	5.91	6.06	14.0	13.4
Total	38.07	41.13	42.61	44.15	45.26	100.0	100.0

Source: United Nations, 1996 b)

[1] particleboard refers to particleboard and strandboard

The trends of increased composite panel use are expected to continue. RISI (1998) projects that particleboard consumption will grow from 9.5 million m^3 in 2000 to 12.6 million m^3 in 2010 (see Table 29) in the USA alone.

In addition, wholesale market prices are expected to increase throughout that time period, after a lull in the late 1990's due to increases of medium density fibreboard production from new plants coming on-line.

Table 29: Particleboard Market Projections in USA

Year	Industrial Particleboard Prices (USD/m^3, ¾")		Particleboard Consumption (million m^3)
	South (East) region	West (Coast) region	USA
2000	$ 148	$147	9.494
2005	$ 173	$170	11.368
2010	$ 189	$181	12.625

Source : RISI, 1998

Similarly, wholesale OSB prices are expected to increase as OSB continues to be substituted for plywood in construction applications (Table 30) in USA markets.

Table 30 : OSB Market Projections in USA

Year	Industrial OSB Prices (USD/m^3)		OSB Consumption	
	South region	West region	million m^3	% of structural panel market
2000	$ 192	$202	7.76	81%
2005	$ 198	$212	11.72	88%
2010	$ 213	$227	13.24	90%

Source : RISI, 1998

In summary, wood composite panels are a well known product throughout the world, and as large trees decrease in availability, composite panels will continue to take larger market shares. And with ever-increasing demands for wood in all forms, the wholesale prices for panel products are expected to increase.

8.9 Production Costs

In Chapters 5-7 technical work on bamboo particleboards, waferboards, overlaid bamboo particleboard and picada panels were presented. Throughout this work efforts were made to keep resin contents and densities low, and press times short in an effort to reduce production costs.

A production cost model was developed (based in large-part on detailed information from the wood products industry) that allows for the estimate of composite panel production costs. The model allows for the input of values for various expenses (such as fibre costs, resin costs, power costs, labour costs, the number of workers required, etc.) and production configurations (press size, operating days per year, etc.). The major production properties of the desired product (press time, resin content, panel density, etc.) are also entered.

This model was verified as accurate using financial data from the wood industry. It was subsequently used to estimate the costs of bamboo particleboard and bamboo waferboard production. The results are presented in Table 31.

Table 31: Estimated Production Costs (USD/m^3)

	Wood PB[1]	Bamboo PB[2]	Wood OSB[3]	Bamboo Waferboard[4]
Fibre	$ 33	$ 23	$ 53.73	$ 23
Resin	$ 26	$ 24	$ 19.14	$ 24
Wax	$ 2	$ 3	$ 2.83	$ 3
Labour	$ 21	$ 2	$ 17.76	$ 4
Electricity	$ 8	$ 8	$ 11.69	$ 16
Overhead (15%)	$ 13.50	$ 9	$ 15.77	$ 10.50
Total	$103.50	$ 69	$120.92	$ 80.50

[1] Source: RISI, 1998 (1999 projected average variable costs for southern USA UF-bonded wood particleboard)
[2] Assumes *Guadua angustifolia* particleboard (16 mm thick, 750 kg/m^3, 4% resin content)
[3] Source: RISI, 1998 (1999 projected average variable costs for southern USA OSB)
[4] Assumes *Bambusa vulgaris* waferboard (11.1 mm thick, 740 kg/m^3, 2.5% resin content)

The bamboo particleboard production cost estimates for industrial production were based on the following assumptions: fibre $25 per oven-dry (OD) tonne; resin $0.65/kg PF resin (based on 100% solids); $0.05 per kWh; labour $15/shift; and wax $0.35/kg.

The bamboo waferboard production assumptions were identical, except for resin which was estimated to cost $1.00/kg. The assumptions used to estimate bamboo panel production costs were deemed conservative for countries, such as Ecuador, where future bamboo development is likely.

In spite of the fact that the bamboo cost used in the model was higher than the expected $8.00/tonne mentioned in Section 2.3.4.2 (done to conservatively estimate buying bamboo from private landholders), the bamboo products are cheaper to produce than the comparable wood products because of lower fibre and labour costs. The low fibre cost was especially pronounced in comparison with wood OSB which requires raw material of a higher quality than that required for wood particleboard.

It should be noted that the cost estimates for the bamboo products are very low, but not unheard of in composite production in the world. For example, in Canada (a source of very low-cost raw material) wood particleboard 1999 variable production cost (RISI, 1998) is $105 CDN and wood OSB variable production cost is $131 CDN, or (assuming current exchange rates of $1 CDN = 0.68 USD) $71.40 USD/m^3 for wood particleboard and $89.08 USD/m^3 for wood OSB. All estimates were for production in eastern Canada.

Finally, if the bamboo products were exposed to excessive insect and weathering attack, the use of preservatives, such as borates, added to the panels during production would greatly enhance their durability. Trials were successfully performed with borates in bamboo particleboard, although it is not presented in this thesis. The addition of borates would increase expected variable manufacturing costs by approximately $\$20/m^3$.

Table 31 shows that the estimated production costs for the bamboo particleboard presented in Chapter 5 is $ 69 USD/m^3. To demonstrate the role of critical production parameters (press time, resin content and panel density), the estimated production cost using the production parameters for the commercially available bamboo particleboard in China were determined assuming a product density of 950 kg/m^3, a press time of 10 minutes, and a resin content of 10% liquid PF resin, and keeping all production cost estimates as stated above. In that case the production costs are estimated to be $145 USD/$m^3$. Note that this estimate is lower than actual production costs in China (Section 4.3.3.1) due to very high prices for bamboo in China.

Of course, one of the largest impacts that press time has on economic analysis is that it decreases the total number of panels produced per year, thereby increasing the unit break-even price (which includes the cost of overhead, capital financing, administration, maintenance, etc as well as the per unit production costs). For example, assuming the raw material and input costs above for a particleboard (density 750 kg/m^3 and a resin content of 4%), a 3 minute press time leads to production costs of approximately $\$69/m^3$ and break-even costs of $\$83/m^3$ (assuming approximate overhead, administration and maintenance costs for a representative commercial operation). A 10 minute press time only increases production costs to approximately $\$77/m^3$, but the break-even costs rise dramatically to $\$118/m^3$. Note that these examples do not include capital financing.

8.10 Large-Scale Benefits of Bamboo

From a broader perspective, sustainable bamboo cultivation promotes soil erosion control, carbon sequestration, stability in hydrological cycles, oxygen production, and many other benefits of natural plant growth. While some of these benefits (e.g. soil erosion control) might be known to the user, they are largely benefits for the overall ecosystem.

As mentioned in Chapter 3, bamboo yields are high per unit area. Due to the rapid growth of bamboo, plantations and forests absorb large amounts of CO_2, and are therefore useful carbon sinks that can help reduce global pollution produced by the burning of fossil fuels.

Economically bamboo plantations have excellent potential. Firstly, the yield of bamboo is high per unit area, so smaller bamboo plantations can produce the same amount of fibre as larger tree-wood plantations meaning that a smaller investment in land resources is required for bamboo.

Bamboo harvesting costs are also practical, as shown in Chapter 2. Based on the studies presented, and field investigations in Ecuador, it is estimated that the harvest cost for bamboo is approximately $8.00 USD per OD tonne, with the bamboo extracted in 6 m culms for construction use (i.e. not damaged). For composites production, the chipping of the bamboo could occur in the field, further reducing the handling and transportation components of harvesting costs.

For a small composites factory which produces 10 panels per pressing cycle (annual production of 60,000 m^3 per year at full capacity), it is estimated that the necessary plantation would employ approximately 300 people full-time to manually harvest the bamboo. An additional 95 people would be employed in the particleboard factory directly.

It is interesting to note that STCP (1993) conducted a survey of the wood industry in Ecuador, and found that the total harvest costs (not including administration) was $16.39/$m^3$, or assuming a density of 600 kg/m^3 (likely a high estimate), $27.20 USD/ OD tonne.

Including administration, transportation, government harvest taxes, payment to the land-owner, wood raw material costs for small sawmills were approximately $97 USD/$m^3$, for large sawmills $78 USD/$m^3$, and for plywood production $134 USD/$m^3$. Due to past deforestation, the transportation distances between standing wood and the mills is now substantial.

Although there is no large-scale global trade in bamboo fibre, the Ecuadorian example provides an interesting benchmark. Over 30% of houses in Guayaquil, Ecuador's largest city, were made of bamboo according to a 1982 census (INEC, 1983), and it is commonly used in housing construction. Garcia-Rios (1992) noted that 52% of houses in squatter settlements have walls made from bamboo (split open and used as wall sheathing), and 40% made from bamboo and wood, with the remaining 8% of walls made from concrete block.

Although no absolute quantity of new squatter construction using bamboo was given, the squatter settlements form a significant part of the city, and since the bamboo is sold through privately owned construction material deposits these free market prices for bamboo coming from private lands are likely an accurate estimate of true bamboo harvesting costs. These costs are very competitive with large scale, industrial tree-wood harvesting costs.

8.11 Is Bamboo Industrialisation Sustainable?

Bamboo industrialisation projects can create hundreds of new jobs. These jobs include conventional agricultural jobs common in developing regions, and higher skilled jobs required to process the bamboo raw material into value-added products such as furniture.

As noted by Fundación Ecuador (1996), there is a close relationship between the percentage of exports of a country which are manufactured and the quality of life. Currently less than 5% of exports in Ecuador are manufactured, or are value-added products made from the existing natural resources. Equitable global development depends on countries transforming natural resources, not simply supplying raw materials for further processing abroad.

Bamboo plantations, due to their high yield per unit area, allow for companies to economically grow their own fibre for processing. Because these companies are stewards of their own resource, they are more likely to pursue sustainable management of the bamboo. Due to the unique nature of bamboo, selective harvesting programs are also rewarded with increased yields (Liese, 1985).

8.12 Technologies Substituting Bamboo for Wood

Let us consider what the potential global role of bamboo could be. If we consider bamboo as a fibre source, we can compare it directly with the global supply and demand of wood and wood products. But is that a valid comparison?

There has been recent work in the development of viable bamboo products throughout Asia. The Chinese Academy of Forestry (Zhu et. al., 1994) provides a comprehensive view of bamboo substitution for wood in China. Unfortunately, cost issues are not discussed.

The bamboo panels commercially produced internationally often have properties superior to the properties of similar wood products. However, as shown throughout this thesis, these existing bamboo products have inefficient production variables (resin content, panel density and press time). In addition, products such as plybamboo and bamboo matboard require significantly more labour during production. These concerns make existing bamboo products costly and unable to compete directly with wood products, unless there are unique economic considerations such as those in China.

Private commercial development of bamboo products is unlikely as the limited scientific knowledge of bamboos is not widely known by commercial operations which are familiar with wood-based manufacturing. In addition, the international wood industry makes use of existing supplies of well-known species. Bamboo industrialisation requires investment and the acceptance of alternative fibre sources, something that many corporate leaders are unwilling to risk.

Given the expected rate of increase of wood costs, alternative fibre sources will become more important in the future. Those companies and public organisations that begin now will have a commanding lead in the supply of low-cost fibre for a wide variety of applications. It is likely that a combination of private initiatives combined with public support for environmental protection and rural development will be required to diversify risk and provide access to capital. This consideration is important if it is expected that bamboo industrialisation begin in the near future in non-traditional bamboo areas.

8.13 Conclusions

Bamboo is a material that is currently useful to many small-scale users world-wide. Given the many attributes of this natural fibre material, bamboo should be supported and encouraged in continued traditional uses.

But if we are to take bold steps forward in global economic development, and we wish the changes to be environmentally and socially sustainable, then large-scale bamboo growth and use should be encouraged. Through modern processing techniques such as those presented in this thesis, bamboo raw material can be transformed into many products (including bamboo particleboard, bamboo waferboard, picada panels, etc. as shown in Chapters 5, 6 and 7) that can compete directly with, for example, wood products in price and performance (Section 8.9).

Environmental protection in a larger context will gain from increased use of bamboo in large-scale, sustainably managed projects, largely in part to the fact that natural fibre products are far more sustainable in the long-term than products of plastic, steel and concrete.

Bamboo plantations are efficient uses of land, and produce more fibre per unit area than most other tree species. Conventional hand-harvesting of bamboo is economical, maximises annual yields, and is a positive factor in mitigating erosion and in watershed management.

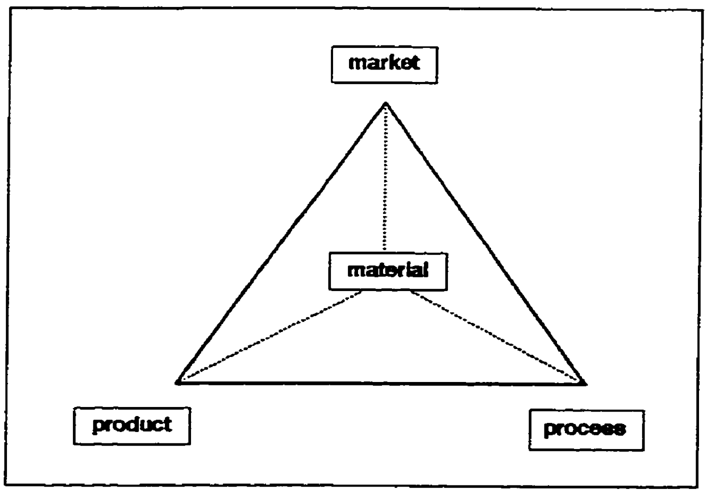
These factors, and others, make bamboo an ideal material for future sustainable growth. The bamboo supporters and international funding agencies should support large-scale bamboo industrialisation in efforts to meet the existing goals of environmental protection, rural development, creation of jobs, and low-cost housing.

9.0 Conclusions and Recommendations

9.1 Research in Perspective

As introduced in Chapter 1, the raw material utilisation model (Figure 72) illustrates the relationship between the manufacturing process, the products, and the application or market for which they are directed. Any modification or change in one of the three variables requires adaptations in the other two variables. All of these variables are considered with respect to the chosen material.

Figure 72: Raw Material Utilisation Model



The use of bamboo in this model has shown the market needs, especially for low-cost housing (as identified in Chapter 2), will be largely met with panel products. Due to the unique characteristics of bamboo, such as high density, the possible products and their associated manufacturing processed are unique, and careful attention must be given to this interplay of application (market), possible products, and the manufacturing steps required.

Due to the interrelationships of the market-product-process issues, and the lack of research addressing this comprehensive approach to bamboo in housing, a review of the situation of one country, Ecuador, was presented in Chapter 2 to provide a framework in which bamboo technology was developed.

A review of bamboo as a material, and its use in construction was presented in Chapter 4 and Chapter 5.

The technical work presented in Chapters 5, 6 and 7 is a unique contribution to the science of composite products. PF bonded bamboo particleboard manufactured with several species of bamboo with specific emphasis on low resin contents and short press times has been well researched, as has a variety of high strength bamboo panels using a variety of bamboo species as raw material.

The results show that a number of bamboo panel products meet industrial particleboard standards (i.e. suitable for value-added transformation in furniture applications), and structural panel standards are feasible both technically and economically. Chapter 8 shows the usefulness of bamboo composites in the broad context of sustainable development.

9.2 *Future Work*

As a result of this research, a number of future research topics have been identified:

1. Comparison of bamboo particleboards with bamboo from managed and well-documented plantations should be conducted. This will allow for more complete knowledge of the role of a variety of growth factors on the impact of panel performance. A range of raw material conditions (species, location, age at harvest, time of harvest, amount of fertilisation, etc.) will allow for a more detailed economic analysis of plantation management, and the impact that the range of conditions has on panel performance (and therefore what adjustments in manufacturing are required to meet desired product standards).
2. Analysis of the raw materials used to make panels in terms of fibre content, lignin content, etc. should be conducted in combination with panel testing. (This was not possible for the current study due to limited financial resources, and the high cost of these tests in Canada). These properties are known to change with varying raw material conditions.
3. Production of full-size panels, and their use in housing in field applications will provide information regarding adjustments required in panel performance for specific applications in bamboo regions, and allow for refinement of design and construction practices using bamboo panels.
4. Testing of panels for decay and insect attack in bamboo regions is an important step in further enhancing the life-span of the panels, and therefore providing for a longer term housing solution for inhabitants of bamboo panel houses.

Clearly, many of these tests would be best performed in a bamboo region where raw materials could be more easily and more cost-effectively obtained and tested. Because these factors will further enhance the performance and economics of the products, they are seen as important for commercial development.

However, the work conducted in this thesis has already shown that given a range of bamboo raw materials from a variety of growth environments bamboo composite panels suitable for low-cost housing can be produced, and therefore are suitable for commercial production.

The bamboo research efforts internationally are limited due to the lack of commercial production and support for research and development. Assuming continued difficulty in obtaining support for laboratory work, it is therefore recommended that efforts be directed towards commercialisation of these technologies in small pilot plants. Due to the closure of many small composite mills in Northern countries (either due to lack of economically available raw material or increasing labour costs), there are many small factories that could be purchased and installed in developing countries. By using local bamboo resources, or by starting bamboo plantations, bamboo panel industries could be easily established to provide composite panels for domestic low-cost housing, and for transformation to furniture for domestic and export markets.

This small industrial base could then easily carry out further development and enhancement of bamboo panel products.

Unlike the wood industry that can build on a wide range of research before making investment decisions, the potential bamboo panel production in countries with open economies must attract investment based on the relatively limited research conducted in the field of bamboo, and by demonstrating through work such as that presented in this thesis that bamboo panel production is feasible, and potentially profitable.

Concerns about fibre supply will continue to increase, and the role of fast-growing bamboo will therefore be enhanced as the benefits, the excellent properties, and the feasibility of its products are demonstrated.

It is time for those people and organisations, both public and private sector, that are concerned about housing, the environment, sustainability, and development to join in support of the commercial development of bamboo panel products.

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Appendix A: North American Particleboard and Structural Composite Product Standards

Table 32: Canadian Standard O437.0-93 (CSA, 1993)

Group 1	Limit	Units	Direction	R-1	O-1	O-2
MOR	Min	MPa	//[1] ⊥	17.2 17.2	23.4 9.6	29.0 12.4
MOE	Min	MPa	// ⊥	3100 3100	4500 1300	5500 1500
IB	Min	MPa		0.345	0.345	0.345
Bond durability-MOR after 2 h boil	Min	MPa	// ⊥	8.6 8.6	11.7 4.8	14.5 6.2
TS- 24 h soak 12.7 mm or thinner thicker than 12.7 mm	Max	%		15 10	15 10	15 10
Group 2						
linear expansion-oven dry to saturated	Max	%	// ⊥	0.40 0.40	0.35 0.50	0.35 0.50
Lateral nail resistance	Min	N	// ⊥	70t [2] 70t	70t 70t	70t 70t

Note: Requirements given are average values for a sample consisting of five panels. No individual in the five panel samples shall have any property more than 20% below (or above in the case of thickness swell and linear expansion) the listed five panel average for that property.

[1] // means parallel to the indicated direction of face alignment; ⊥ means perpendicular to the indicated direction of face alignment

[2] "t" is the nominal thickness in millimetres

Table 33: ANSI A208.1-1993 Particleboard Standard
Source: National Particleboard Association, 1993

ANSI A208.1-1993

Table A
Requirements for Grades of Particleboard [1,2]

Grade[3]	Length & Width mm (inch)	Thickness Tolerance[4]: Panel Average from Nominal mm (inch)	Thickness Tolerance[4]: Variance from Panel Average mm (inch)	Modulus of Rupture N/mm² (psi)	Modulus of Elasticity N/mm² (psi)	Internal Bond N/mm² (psi)	Hardness N (pounds)	Linear Expansion max. avg. (percent)	Screw-holding: Face N (pounds)	Screw-holding: Edge N (pounds)	Formaldehyde Maximum Emissions (ppm)
H-1	±2.0 (0.080)	±0.200 (0.008)	±0.100 (0.004)	16.5 (2393)	2400 (348100)	0.90 (130)	2225 (500)	NS[5]	1800 (405)	1325 (298)	0.30
H-2	±2.0 (0.080)	±0.200 (0.008)	±0.100 (0.004)	20.5 (2973)	2400 (348100)	0.90 (130)	4450 (1000)	NS	1900 (427)	1550 (348)	0.30
H-3	±2.0 (0.080)	±0.200 (0.008)	±0.100 (0.004)	23.5 (3408)	2750 (398900)	1.00 (145)	6675 (1500)	NS	2000 (450)	1550 (348)	0.30
M-1	±2.0 (0.080)	±0.250 (0.010)	±0.125 (0.005)	11.0 (1595)	1725 (250200)	0.40 (58)	2225 (500)	0.35	NS	NS	0.30
M-S[6]	±2.0 (0.080)	±0.250 (0.010)	±0.125 (0.005)	12.5 (1813)	1900 (275600)	0.40 (58)	2225 (500)	0.35	900 (202)	800 (180)	0.30
M-2	±2.0 (0.080)	±0.200 (0.008)	±0.100 (0.004)	14.5 (2103)	2250 (326300)	0.45 (65)	2225 (500)	0.35	1000 (225)	900 (202)	0.30
M-3	±2.0 (0.080)	±0.200 (0.008)	±0.100 (0.004)	16.5 (2393)	2750 (398900)	0.55 (80)	2225 (500)	0.35	1100 (247)	1000 (225)	0.30
LD-1	±2.0 (0.080)	+0.125 (0.005) -0.375 (0.015)	±0.125 (0.005)	3.0 (435)	550 (79800)	0.10 (15)	NS	0.35	400 (90)	NS	0.30
LD-2	±2.0 (0.080)	+0.125 (0.005) -0.375 (0.015)	±0.125 (0.005)	5.0 (725)	1025 (148700)	0.15 (22)	NS	0.35	550 (124)	NS	0.30

1) Particleboard made with phenol formaldehyde based resins do not emit significant quantities of formaldehyde. Therefore, such products and other particleboard products made with resin not containing formaldehyde are not subject to formaldehyde emission conformance testing.

2) Grades listed in this table shall also comply with the appropriate requirements listed in Section 3. Panels designated as "exterior glue" must maintain 50% MOR after ASTM D 1037 accelerated aging (paragraph 3.3.3).

3) Refer to Annex C for general use and grade information.

4) Thickness tolerance values are only for sanded panels as defined by the manufacturer. Unsanded panels shall be in accordance with the thickness tolerances specified by agreement between the manufacturer and the purchaser.

5) NS - Not Specified

6) Grade "M-S" refers to medium density, "special" grade. This grade was added to the Standard after grades M-1, M-2, and M-3 had been established. Grade "M-S" falls between M-1 and M-2 in physical properties.

Table B
Requirements for Grades of Particleboard Flooring Products [1,2]

Grade[3]	Length & Width Tolerance mm (inch)	Thickness Tolerance[4]: Panel Average from Nominal mm (inch)	Thickness Tolerance[4]: Variance from Panel Average mm (inch)	Modulus of Rupture N/mm² (psi)	Modulus of Elasticity N/mm² (psi)	Internal Bond N/mm² (psi)	Hardness N (pounds)	Linear Expansion max. avg. (percent)	Formaldehyde Maximum Emissions (ppm)
PBU	+0 (0) -4.0 (0.160)	±0.375 (0.015)	±0.250 (0.010)	11.0 (1595)	1725 (250200)	0.40 (58)	2225 (500)	0.35	0.20
D-2	±2.0 (0.080)	±0.375 (0.015)	±0.250 (0.010)	16.5 (2393)	2750 (398900)	0.55 (80)	2225 (500)	0.30	0.20
D-3	±2.0 (0.080)	±0.375 (0.015)	±0.250 (0.010)	19.5 (2828)	3100 (449600)	0.55 (80)	2225 (500)	0.30	0.20

1) Particleboard made with phenol formaldehyde based resins do not emit significant quantities of formaldehyde. Therefore, such products and other particleboard products made with resin not containing formaldehyde are not subject to formaldehyde emission conformance testing.

2) Grades listed in this table shall also comply with the appropriate requirements listed in Section 3. Panels designated as "exterior glue" must maintain 50% MOR after ASTM D 1037 accelerated aging (paragraph 3.3.3).

3) Refer to Annex C for general use and grade information.

4) Thickness tolerance values are only for sanded panels as defined by the manufacturer. Unsanded panels shall be in accordance with the thickness tolerances specified by agreement between the manufacturer and the purchaser.