The Suitability of *Dendrocalamus asper* Backer for Oriented Strand Lumber

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Pannipa Malanit

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Professor Dr. Jörg Ganzhorn
Leiter des Departments Biologie

fhs Fachhochschule Salzburg

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Marc Haller
Verbindungsstraße 2
5020 Salzburg
Österreich

LETTER OF CONFIRMATION

I, Marc H Haller being a full-time student at the Salzburg University of Applied Sciences located in Kuchl, confirm that I have assisted Pannipa Malanit with her doctor thesis on the production of Oriented Strand Lumber from bamboo.

Having resided in South Africa for a period exceeding twenty years I hereby confirm that I am a native english speaker having completed my entire schooling in english. My assistance involved in correcting her written text or suggesting possible text changes. In total I was able to review chapters one to six including the abstract, introduction and conclusion.

Marc H. Haller

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Pannipa MALANIT

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Contents

List of Abbreviations

ABES	Automated Bonding Evaluation System
FAO	Food and agriculture Organization
HDF	High Density Fiberboard
IB	Internal bond strength (MPa)
LSL	Laminated Strand Lumber
LVL	Laminated Veneer Lumber
MF	Melamine formaldehyde resin
MOE	Modulus of elasticity in bending (MPa)
MOR	Modulus of rupture in bending (MPa)
MUF	Melamine urea formaldehyde resin
MUPF	Melamine urea phenol formaldehyde resin
OSB	Oriented Strand Board
OSL	Oriented Strand Lumber
PB	Particleboard
PF	Phenol formaldehyde resin
pH	Potential of hydrogen
pMDI	Diphenylmethane di-isocyanate resin
PSL	Parallel Strand Lumber
SCL	Structural Composite Lumber
SG	Specific gravity
TS	Thickness swelling after water soaking at 20°C for 24 hrs (%)
WA	Water absorption after water soaking at 20°C for 24 hrs (%)
WU	Water uptake after water soaking at 20°C for 24 hrs (%)

List of Publications

Publication I

Malanit, P., Barbu, M. C., Liese, W. and Frühwald, A. 2008. Macroscopic aspects and physical properties of *Dendrocalamus asper* Backer for composite panels. Journal of Bamboo and Rattan *(In Press).*

Publiaton II

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Malanit, P., Barbu, M. C. and Frühwald, A. 2009. The Gluability and Bonding Strength of *Dendrocalamus asper* Backer for Exterior Structural Applications. In: the 8th World Bamboo Conference. 16-18th September 2009, Bangkok, Thailand *(In Press).*

Publication VI

Barbu, M. C., Malanit, P. and Frühwald, A. 2009. Development of Oriented Strand Lumber made from *Dendrocalamus asper* Backer. In: the 8th World Bamboo Conference. 16-18th September 2009, Bangkok, Thailand *(In Press).*

Publication VII

Malanit, P., Barbu, M. C. and Frühwald, A. 2009. On the Suitability of an Asian Bamboo for Structural Composite Boards. In: FAO, XIII World Forestry Congress. 18-23rd October 2009, Buenos Aires, Argentina *(In Press).*

Abstract

The Suitability of *Dendrocalamus asper* Backer for Oriented Strand Lumber

The aim of this research was to determine the basic properties of *Dendrocalamus asper* Backer and its suitability to be promoted as a raw material for the manufacture of Oriented Strand Lumber (OSL).

The results show that the macroscopic characteristics of *D. asper* change along the culm. Outer internode diameter and wall thickness gradually decrease with the culm height. The internode length increases from the bottom to the middle part and further decreases towards the top. All physical properties vary with the culm height. The specific gravity (SG) increases with culm height. The dimensional stability lengthwise is more stable than crosswise. The dimensional stability in the radial direction and water uptake are highly related to the SG of *D. asper* which shows high strengths. The mechanical properties including modulus of rupture (MOR), modulus of elasticity (MOE) and compression strength perpendicular to grain vary with the position in the culm and significantly depend on SG. On the other hand, shear strength parallel to grain are not depend on SG. The value slightly differs along the culm length.

The average pH value and acid-buffering capacity is 5.4 and 0.53 milliequivalents, respectively. There are no differences in the values taken from the different locations in the culm. The bonding quality of the bamboo strands was evaluated for three adhesives using a special device called an Automated Bonding Evaluation System (ABES). This experiment proposed three essential parameters, i.e., three types of adhesives; Melamine Formaldehyde (MF), Melamine Urea Phenol Formaldehyde (MUPF), and Phenol Formaldehyde (PF), and four pressing temperatures (150, 170, 190 and 210°C) and different pressing times (20 to 300 seconds). In accordance with this study, bond quality was improved by increasing the pressing time and temperature. The best adhesive to bond bamboo strands following the ABES was found to be MF.

In the course of the study, prototype bamboo-based OSL were produced in accordance with two manufacturing parameters, i.e., four resin types (MF, MUPF, PF and pMDI) and three levels of resin content (7, 10 and 13%). The results indicate that bamboo-based OSL exhibit superior strength properties compared to that of Structural Composite Lumber (SCL) made from wood species. The resin type has a significant effect on board properties. Moreover, all properties of the board improve generally by increasing the resin content. With regard to the internal bond, bamboo-based OSL shows less strength than that of the wood-based OSB. The best results were obtained by using 13% pMDI content at 750 kg/m³ density.

As the main result, it is concluded that *D. asper* is suitable as a raw material for OSL, although some properties are not preferable. Nevertheless, the process improvements within the facility of the present's wood based panel industry may solve this problem, so that bamboo turns out to be a competitive alternative raw material for high performance composite board and lumber.

Zusammenfassung

Die Eignung von *Dendrocalamus asper* Backer für die Herstellung von Furnierstreifenplatten (OSL)

Ziel der vorliegenden Arbeit war die Bestimmung der grundlegenden Eigenschaften von einer asiatischen Bambusart, *Dendrocalamus asper* Backer, sowie ihrer Eignung, als Rohstoff zur Herstellung von Furnierstreifenplatten (Oriented Strand Lumber - OSL) Verwendung zu finden.

Die Ergebnisse zeigen, dass sich die makroskopischen Eigenschaften von *D. asper* in Abhängigkeit von der Halmhöhe ändern. Der äußere Internodiumsdurchmesser und die Wanddicke nehmen graduell mit der Höhe des Halmes ab. Die Länge der Internodien steigt zunächst vom unteren bis zum mittleren Teil des Halmes an und fällt im oberen Bereich ab. Die physikalischen Eigenschaften verändern sich ebenfalls in Abhängigkeit zur Höhe des Halmes, wobei die Rohdichte mit zunehmender Halmhöhe ansteigt. Die Dimensionsstabilität in longitudinaler Richtung ist größer als im Querschnitt. Die Dimensionsstabilität in radialer Richtung wie auch die Wasseraufnahme hängen in hohem Maße von der Rohdichte ab. Die Bambussart, *D. asper*, besitzt hohe Festigkeiten. Es zeigt sich, dass die mechanischen Eigenschaften wie Bruchmodul, Elastizitätsmodul und Druckfestigkeit senkrecht zur Faserrichtung veränderlich mit der Position im Halm sind und signifikant von der Rohdichte abhängen. Demgegenüber ist die Scherfestigkeit parallel zur Faser nicht von der Rohdichte abhängig und die Werte unterliegen nur geringen Schwankungen längs der Halmachse.

Der durchschnittliche pH-Wert und die Pufferkapazität betragen 5,4 bzw. 0,53 Milliäquivalente. Es wurden keine Unterschiede zwischen Proben aus verschiedenen Bereichen des Halmes festgestellt. Die Verklebungsgüte von Bambusstreifen (Strands) wurde mit Hilfe der Automated Bonding Evaluation System (ABES) Methode für drei verschiedene Bindemittel untersucht. In diesem Experiment kamen folgende drei Gruppen von Parameter zur Anwendung: Melamin-Formaldehydharz (MF), Melamin-Harnstoff-Phenol-Formaldehydharz (MUPF) und Phenol-Formaldehydharz (PF), vier verschiedene Presstemperaturen (150/170/190/210°C) und unterschiedliche Presszeiten (20 bis 300 Sekunden). Dabei zeigte sich, dass die Güte der Verklebung durch verlängerte Presszeiten und erhöhte Presstemperaturen verbessert wurde. Die besten Ergebnisse wurden mit MF Leim erzielt.

Im Verlauf der Arbeit konnten erste OSL-Laborplatten aus Bambusstrands mit zwei Parameternreihen produziert werden. Es kamen vier verschiedene Bindemitteltypen zum Einsatz (MF, MUPF, PF und pMDI) sowie drei unterschiedliche Leimgehalte (7, 10 und 13%). Die Ergebnisse zeigen, dass OSL auf Bambusbasis deutlich bessere Festigkeiten besitzt als Holzwerkstoff für tragende Zwecke (Structural Composite Lumber; SCL). Die Art des Bindemittels hat einen signifikanten Einfluss auf die Platteneigenschaften. Ferner verbessern sich generell alle Platteneigenschaften mit zunehmendem Bindemittelgehalt. OSL aus Bambus zeigt eine geringere Querzugfestigkeit als OSB aus Holzstrands. Die höchsten Festigkeiten wurden mit einem Gehalt von 13% pMDI bei einer Rohdichte von 750 kg/m^3 erzielt.

Als Hauptergebnis stellt sich heraus, dass *D. asper* als Rohstoff für OSL verwendbar ist, trotzdem ein paar der Eigenschaften nicht wünschenswert sind. Nichtsdestotrotz sollten Verbesserungen der Herstellungsprozesse in den Werken der gegenwärtigen Holzwerkstoffindustrie dieses Problem lösen können, so dass sich Bambus als ein äußerst wettbewerbsfähiger Rohstoff für platten- und balkenförmige Holzwerkstoffe herausstellt.

1 Introduction

In recent years, the demand for high quality wood for construction has increased because the world population has been rising and the available quantity and quality of wood from natural forest has been declining. In Southeast Asia, the solid-sawn lumbers, and most of the wood-based products, have been either banned or discouraged from European markets, as well as other parts of the world. End-users of wood-based products have realized the serious danger to the environment if certain natural forests are diminished. Consequently, the search for alternative or substitute materials in place of wood has come into focus. A suitable substitute should be inexpensive, fast-growing, permanently available, having comparable physical and mechanical properties, environmental friendly and it should be compatible to existing processing technologies. Non-wood or agricultural-material has been receiving considerable attention as the raw material for this situation.

Bamboo is a naturally occurring composite material which abundantly grows in most of the tropical countries. It is considered a composite material because it consists of cellulose fibers imbedded in a lignin matrix. Bamboo has a very long history with the humankind since it has been widely used since thousands of years as a material for construction, furniture manufacture and daily household uses. The main advantages of bamboo are its fast growing nature, high productivity, quick maturity and better mechanical properties when compared to other wood species. In recent years, it has been widely used as a raw material for wood products manufactured in some Asian factories, such as for pulp and paper, plywood, Medium Density Fiberboard (MDF), Particleboard (PB) and Oriented Strand Board (OSB), owing to its high strength and properties.

As already known, bamboo is a woody grass distributed in tropical, subtropical and mild temperate zones in the world. Now, it becomes to be a major non-wood forest product and wood substitute. It is used for housing, crafts, pulp and paper products, wood-composite products, textiles and energy. In addition, it is also used as vegetable.

In Thailand, bamboo is one of the most socio-economically important species. They can rapidly invade into any landscape, including degraded areas, and are frequently found in open areas of land throughout the country, although they are normally found in mixed-deciduous forests. Bamboos are multipurpose species with many uses for basic living including food, household construction, supporting poles, baskets, handicraft making, firewood and paper pulping, etc. There are 13 genera and 60 species of bamboos recorded in Thailand and most of them are "sympodial type".

Dendrocalamus asper, commonly recognized as a giant bamboo, is one of the most popular bamboo species of Thailand planted in more than 60 provinces [Pungbun, 2000]. The utilization of *D. asper* can be divided into two fields, i.e. young bamboo shoots and bamboo culms. The young shoots are sweet and delicious known locally as sweet bamboo. They are widely consumed as a vegetable. Young shoots are harvested during the rainy season (in Thailand from May to June, in Java from November to May). A properly managed plantation may produce 10-11 tons young shoots per ha per year. The culms that have developed after three years of growth have thick walls; they are very strong and durable and are used as building material for houses and bridges, also in furniture, musical instruments, chopsticks, household utensils and handicrafts. Culms are preferably harvested in the dry season [Dransfield and Widijaja, 1995; Rao *et al*, 1998]. In Thailand, a plantation can produce 16 tons culms per ha per year [Pungbun, 2000]. As the interest for the ultilization of *D. asper* has increased, several researches were carried out on its fundamental characteristics. This specie has been used as raw material for particleboard, fiberboard, pulp and paper [Kamthai, 2003; Laemsak and Kungsuwan, 2000; Pakhkeree, 1997; Sutnaun *et al*, 2005].

There are several differences between bamboo and wood. Bamboo culm is straight, cylindric and hollow tube. The culm is covered by hard epidermis and inner wax layer. It also lacks ray cell, as radial pathways, and knots. Bamboo's culm diameter, culm-wall thickness, and internodal length are the macroscopically graded structures while the fiber distribution exhibits a microscopically graded architecture [Liese, 1998]. Even though the main chemical composition of bamboo is similar to that of wood, some minor chemical compositions differ from wood and also vary according the part of the culm [Liese, 1985]. For this reason, the methods, technology and equipment for wood processing cannot be applied indiscriminately in bamboo utilization. Thus, the information on bamboo properties used is necessary for assessing its suitability for wood composite manufacture.

In addition, the potential of wood composite products require adhesive to bond wood elements together. Since adhesive is a significant factor of production, being about 20% of total production cost ,and is typically not in abundant supply in the regions of the world where bamboo is currently available. Future development of bamboo-based composites will require a thorough analysis of bamboo gluability and of the bonding quality of its strands.

1 Introduction

The overall objective of this study is to evaluate the suitability of *D. asper* as an alternative raw material for structural composite lumbers. The study consists of the following specific objectives:

1. To determine the variation of the macroscopic characters, physical properties, which influence the specific gravity, shrinkage and swelling and water uptake, and mechanical properties, which influence the static bending, compressive strength perpendicular to grain and shear strength parallel to grain, were analyzed along the culm length,
2. To measure and compare the mean pH value and buffer capacity in predetermined location of culms,
3. To investigate the strength development characteristics and bonding quality between bamboo strands using different adhesives for exterior application by using the ABES equipment,
4. To fabricate bamboo-based Oriented Strand Lumber and evaluate its physical and mechanical properties of products and compare with standard requirements and for commercial products like OSB.

2 State of Knowledge

Over the last two decades, bamboo has received increasing attention for its economic and environmental benefits. It is one of the oldest building materials used by mankind in tropical and subtropical regions. The bamboo culm has been processed into an extended diversity of products ranging from domestic household products to industrial applications, especially as an alternative substitute for wood in producing pulp, paper and composite boards. In order to promote the development of technologies for bamboo industrialization, the advance technique and approximated methods are needed to make bamboo products more durable and usable in terms of building materials. Many studies have been done on the basic properties and processing of bamboo into various kinds of composite products. More studies are needed to promote and support its applications.

2.1 Situation of Bamboo in the World, Asia and Thailand

It has been postulated that the basic data about bamboo situation in the world, Asia and Thailand are important in formulating effective bamboo resource policies and its utilization.

2.1.1 Distribution Bamboo Forests

Bamboo is a perennial grass with woody stem or culm belonging to the family Poaceae, subfamily Bambusoideae and encompasses about 1,200 species within 50 genera in the world [Chapman, 1996; Qisheng *et a*l., 2002].

It is naturally distributed in the tropical and subtropical zone at latitudes from approximately 46° North to 47° South latitude and from sea level to 3,000 m elevation where has a warm climate, abundant moisture, and productive soil. It is also suitable on well drained sandy to clay loom or from underlying rocks with pH of 5.0 to 6.5 [Lobovikov *et al.*, 2007; Abd.Latif and Abd.Razak, 1991].

Lobovikov *et al.* (2007) reported that bamboo is mostly distributed in Asia, Africa and Central and South American, covering an area of over 36 million hectares. Asia is the richest continent with about 65% of total world bamboo resources. In Asia, India is the major bamboo producing country, possessing about 145 species; the area of bamboo growth exceeds 11.4 million ha or one third of the world surface covered by bamboo and 17% of the country's total forest area. Another major bamboo-producing country is China having highest bamboo biodiversity in Asia, with over 500 species, covering 5.4 million ha or about 3% of its total forested area. Other nations with significant bamboo production and utilization include Indonesia, Lao People's Democratic Republic and Thailand. The extent of bamboo forests shows an upward trend, mainly by Asia. Over the last 15 years, the bamboo area in Asia has increased by 10%, primarily as a result of large-scale bamboo planting in China and India. Interestingly, the five of the six countries, where are the largest extent of bamboo forests, are in Asia. In Latin America and Africa, bamboos occupy 10.4 respectively 2.8 million hectares or 28.4% and 7.3% of the total bamboo area, respectively. There are few indigenous bamboo species in North America, no naturally distributed bamboo plants in Europe. In recent years bamboo plants are introduced into North America and Europe [Qisheng *et al.*, 2002].

Thailand is located in the central part of the Indochina Peninsula, between latitudes of 5°37 North and 20°27 North and longitudes of 97°22 and 105°37 East. The total area of the country is 514,000 km^2. The local climate is tropical and influenced by Southwest monsoon during the wet season (May-October) and the Northeast monsoon during the dry season (November-April). The distribution of wet months ranges from 2 to 7 months yearly, with about 1,000-4,000 mm of annual rainfall. In northeast region, the day temperature may reach 42°C during the dry season, during March and April, and may drop to 0-10°C in the cool-dry season, from December to January. However, an average temperature of the whole country all the year ranges from 24 to 34° C.

In Thailand, bamboo is one of the most important species. From the report of FAO (2001), it is normally found in deciduous forests and tropical evergreen forests with total area of 260,000 hectares or about 1.8% of the total forested area. There are 13 genera and 60 species of bamboos and most of them are "sympodial type". They are mainly found in northern and western parts of the country. The important species of bamboo in Thailand may be divided into three groups according to their utilization [Pattanavibool, 2000];

(1) Bamboos for shoot production (for food) such as; *Dendrocalamus asper*, *D. brandisii*, *D. strictus*, *Bambusa blumeana*, *Thyrsostachys siamensis*, *T. oliverii* and *Gigantochloa albociliata*.
(2) Bamboos for stem production (for construction) such as; *B. bambos*, *B. blumeana, B. nana*, *D. asper, D. strictus, D. membranaceus*, *T. oliverii* and *G. hasskarliana*.

(3) Bamboos for stem production (for basketry and handicraft) such as; *B. blumeana, B. nana, T. siamensis, T. oliverii, G. hasskarliana, Schizostachyum humilis* and *Cephalostachyum virgatum*.

2.1.2 Ownership and Characteristics of Bamboo Forest and Plantation

Lobovikov *et al.* (2007) reported that over 80 % of Asian forests including bamboo forest are public areas, which are under the formal jurisdiction of governments and forest management is mostly a governmental issue, while approximately 30% of forests in the Africa are public lands. From 1990-2000, the total bamboo resources in Asia increased approximately 7% but the public ownership of bamboo resources decreased from 81 to 73 %. It can be explained by a greater rate of private ownership bamboo resource increased, especially in China where one-third of the bamboo forests were private ownership and promotes bamboo as a new material for industrial uses. Interestingly, the new ownership structure in China cooperated between the government and farmers. The farmers could rent the public land for up to 50 years and planted bamboo belonging to farmers. This system has enhanced production opportunities and market of bamboo.

In Thailand, most forest lands are the property of the state. They are classified as public land. Most of bamboo resource in Thailand grows naturally in state forests, but some areas are privately owned by local communities which have not reported total area due to their inaccessibility [FAO, 2001; Soriano, 2008]. However, Thailand reported bamboo plantation for *Dendrocalamus asper* which is one of the most popular bamboo species and wildly plants of Thailand. Tanurak (1996) revealed that now the total area of *D. asper* plantations is 68,000 hectares or 26% of total bamboo area in Thailand.

2.1.3 Commercial Products

Bamboo utilization may be divided up into following broad categories:

(1) <u>Construction</u> – bamboo is a major building material in many countries, particularly in Asia, Africa and South America, because of its strong characteristics, light weight and flexible properties. It can be used for almost all parts of houses, including posts, roofs, walls, floors, beams and trusses.

(2) Household products - these include agricultural instruments, fishing tools, handicrafts, musical instruments, furniture, crafts and woven mats, which are traditional products worldwide known in China, India, Malaysia, the Philippines and Thailand.

(3) Pulp and paper – because bamboo fibers are relatively long [Grosser and Liese, 1971], thus it can be used for paper production. Bamboo paper has practically the same quality as paper made from wood. Its brightness and optical properties remain stable, while those of paper made from wood may deteriorate over time. The morphological characteristics of bamboo fiber yield paper with a high tear index, similar to that of hardwood paper. The tensile stiffness is somewhat lower compared with softwood paper. The strain strength is between that of hardwood and softwood papers.

(4) Boards – bamboo can be processed into modern products that may successfully compete with wood products in price and performance. The use of bamboo in composite boards overcomes differences in quality related to the culms and allows the production of homogeneous products. The panels are widely used in modern construction as structural elements or as forms for concrete moldings. They are also used for flooring, roofing, partitions, doors and window frames. Bamboo panels have some advantages over wooden boards due to their rigidity and durability. Various types of bamboo veneers, boards can be broadly classified as follows: multilayer parquet, plywood, fiberboards, particleboards and oriented strand board combinations of these, and combinations of these with wood and other ligno-cellulosic materials and inorganic substances.

(5) Food – about 200 species of bamboo, a well-known feature of Chinese and other Asian cuisine, can provide suitable shoots for eating. Fresh bamboo shoots are delicious and healthy, with high fiber content.

(6) Charcoal and active carbon- bamboo charcoal is traditionally used as a substitute for wood charcoal or mineral coal. It can serve as a fuel, for cleaning drinking water, cooking, bathing, improving soil, regulating room humidity, preserving freshness of vegetables, fruits and flowers, deodorizing, for conducting electricity, etc. The calorific value of bamboo charcoal is almost half that of oil of the same weight. Activated bamboo charcoal can be used for cleaning the environment, absorbing excess moisture and producing medicines. The absorption capacity of bamboo charcoal is six times that of wood charcoal of the same weight [Qisheng *et al.*, 2002].

2.2 Introduction to Bamboo

2.2.1 Taxonomy

Bamboo belongs to the subfamily of Bambusoideae, family of Poaceae, order of Graminales, class of Monocotyledons, subphylum of Angiosperms and phylum of Spermayophyta [Chapman, 1996].

2.2.2 Morphology

Qisheng *et al.* (2002) explained the morphological characteristic that the bamboo is divided into 2 major parts, the rhizome and the stem. The rhizome is the underground part and tuber of bamboo. It is one piece of the modified branch of a bamboo plant. It serves for the uptake, transport and storage of nutrients, which function of parenchyma and conduction tissue, as well as for the vegetative production by growing into the new shoots or bamboo culms at their nodes.

The stem, called the culm, is the upper ground part of bamboo that contains most of the woody material. The culm is complimented by a branching system, sheath, foliage leaves, flowering, fruits and seedlings. The culm is straight, hollow and cylinder-formed with nodes and internode which is the parts between nodes. There is a wooden partition between two neighboring internodes, which strengthens the culm. The length of inter-nodes, the number and form of nodes, culm diameter and culm-wall thickness varies greatly in accordance with different bamboo species.

The internodes are hollow inside, which forms bamboo cavities. Internode length increases from the base to the middle part and decreases toward the top part. Bamboo culm diameter tapers from bottom to top with the reduction of culm wall thickness, whereby the outer tissue which will remain at the loss of the inner more parenchymatous tissue. Sometimes there are solid bamboo stems. The cross section of bamboo stem is circular. Both sides of the wall are covered by a special tissue. Its outer part, the cortex, as a water-tight seal prevents any moisture loss of the living culm. The outer part has a hard smooth outer skin due to the presence of silica. At the inner side is mostly found the parenchyma cells.

At the internode, the cells are axially oriented, whereas at the nodes, cells are transversely inter-connected. Being a monocotyledon, the bamboo culm lacks the secondary growth, and further not possessing radial cell elements like wood. The horizontal distribution divert through the partition wall, called the diaphragm, as presented in Figure 2.1.

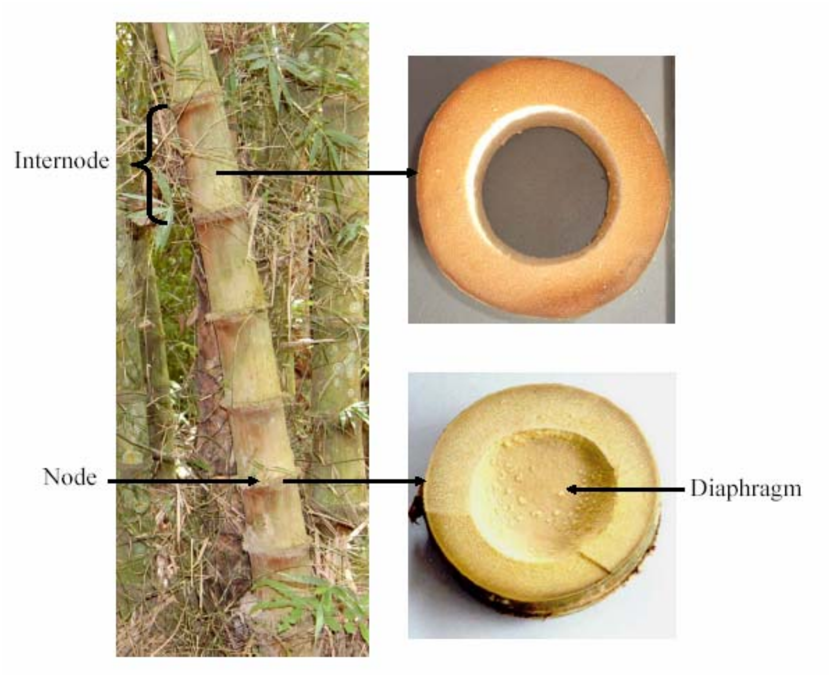

Figure 2.1 Culm morphological characteristic of *D. asper*

2.2.3 Bamboo Growth

Bamboo is a fast growing species and a high yield renewable resource. Bamboo growth depends on species, but generally all bamboo matures quickly. The fast growth characteristic of bamboo is an important incentive for its utilization. Because of bamboo utilization in the wood-composite industry, the growth and development of bamboo culm are viewed with great interest.

Unlike trees, bamboos grow to full height and girth in a single growing season. Qisheng *et al.* (2002) described that the height growth of bamboo culm is realized by the internodes growth. The cell division varies with the difference internode location. The speed of growth is also different in internodes. After the end of height growth, the height, thickness and volume of bamboo stems do not change. Consequently, the maturity process begins. In this duration, cell wall thickens and specific gravity increases, moisture content decreases and physical and mechanical properties increase.

Aminuddin and Abd. Latif (1991) demonstrated that bamboo can reach its maximum height in 4 to 6 months with a daily increment of 15 to 18 cm. They also stated that bamboo might have 40 to 50 stems in one clump, which adds 10 to 20 culms yearly. In addition, Wong (1995) stated that culms take 2 to 6 years to mature, which depends on the species. It is suggested that with a good management of the bamboo resource, the cutting cycle is normally 3 years. According to Lee *et al.* (1994), bamboo mature in about 3 to 5 years, which means its growth, is more rapid than any other plant of this size on the planet.

Dransfield and Widjaja (1995) reported that during rainy season *D. asper* can develop to their full height in less than a year. Growth of culms is good at the beginning of monsoon (June to October) A culm becomes mature in 3-4 years. A mature clump may reach a diameter of 3 m and contain about 60 culms.

2.2.4 Anatomical Structure

The structure of a bamboo culm transverse section is characterized by numerous vascular bundles embedded in the parenchymatous ground tissue, as presented in Figure 2.2 [Grosser and Liese, 1971].

Liese (1998) explained that the total culm tissue consists of 50% parenchyma, 40% fibers and 10% conducting cells. The percentage distribution shows a specific pattern within the culm, both horizontally and vertically. The parenchyma and conducting cells are more frequent in the inner third of the wall, while the percentage of fiber is higher in the outer part. In the vertical direction, the fiber amount increases from bottom to top with the decreasing parenchyma content.

The parenchyma cells are mostly thin-walled and connected to each other by numerous simple pits on the longitudinal walls. The horizontal walls are scarcely pitted. The size of the vascular bundle is large in the inner and middle layer but smaller and denser in the outer layer as shown in Figure 2.3.

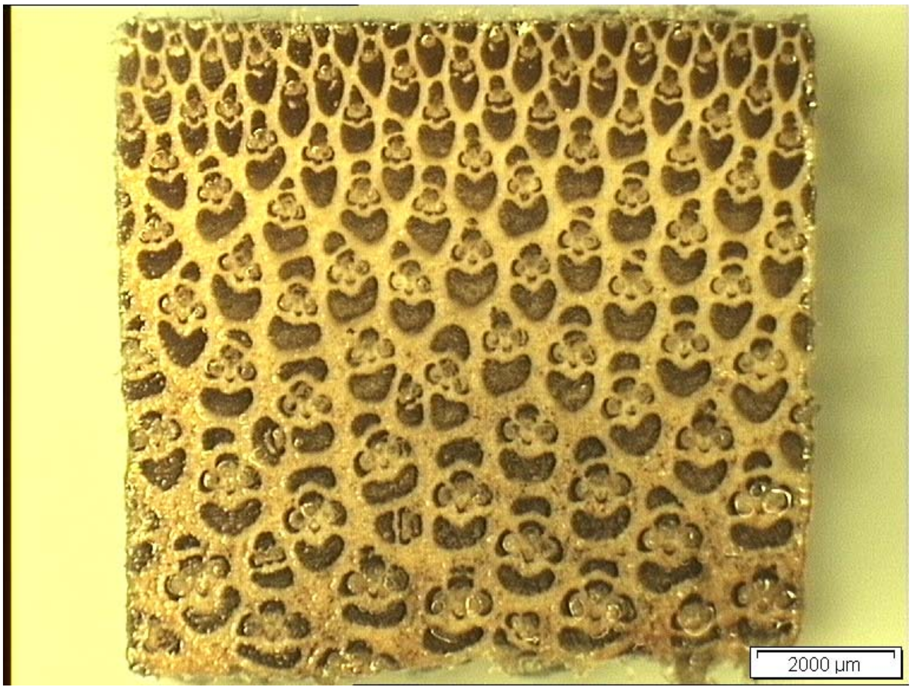

Figure 2.2 Cross section of *D. asper* culm

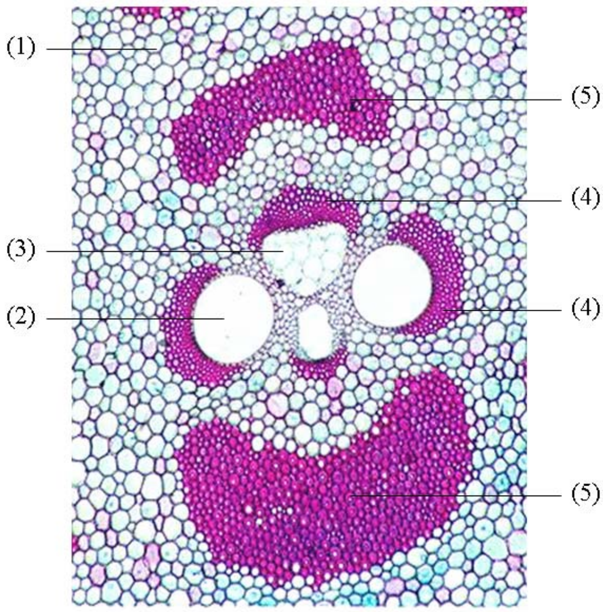

Figure 2.3 *D. asper* vascular bundle; (1) parenchyma cells, (2) metaxylem vessel, (3) phloem, (4) sclerenchyma sheath and (5) fiber strand.

The vascular bundle in the bamboo culm consists of two large metaxylem vessels and phloem (sieve tubes with companion cells), as shown in Figure 2.3. The vessels are larger at the inner part of the culm and become small toward the outer part. The vessels and phloem are surrounded by sclerenchyma cells.

Grosser and Liese (1971) explained that the vascular bundles shape, size, arrangement and number in transverse section of internode part can be used to classify the bamboo anatomical structure. Since the vascular bundles contrast the parenchymatous ground tissue, which is much lighter in color. The presence and location of fiber strands on the cross-section can be used to distinguish four different types of vascular bundles:

- Type I consists of the central vascular strand supporting tissue only as sclerenchyma.
- Type II consists of the central vascular strand supporting tissue only as sclerenchyma sheaths but the ones at the intercellular space strikingly larger than the other three types.
- Type III consists of the central vascular strand with sclerenchyma sheaths and one isolated fiber bundle.
- Type IV consists of the central vascular strand with small sclerenchyma sheaths and two isolated fiber bundles on the opposite sides.

The metaxylem consists of two large vessels and provides the water transport within the culm. They are considerable bigger at the inner culm part and smaller towards the outside, as shown in Figure 2.3.

The fibers are sclerenchymatous tissue with thicker wall, long and tapered at their ends. The ratio of length to width varies between 150:1 and 250:1. They occur in the internodes as caps of the vascular bundles and sheaths around the vessels. They contribute 40-50% of the total culm tissue. The amount of fibers, as sheaths or additional bundles, is closely related to the specific gravity, which increases within the culm from base to top and influence consequently the strength properties. Fiber percentage is higher in the outer one third of the wall and in the upper part of the culm, contributing to its superior slenderness.

Many studies have been published on the anatomical features of bamboo which directly affect the physical and mechanical properties. It is expected that these features may affect the final application of bamboo. Abd.Latif *et al.* (1990) concluded that vascular bundle size (radial/tangential ratio) and fiber length correlated positively with modulus of elasticity (MOE) and stress at proportional limit. They explained that the increase in the size (mature stage), and fiber length could be accompanied by an increase in strength properties. In addition, they mentioned that bamboo having longer fiber might be stiffer, if it has a greater vascular bundle size. The correlation between fiber length and shear strength was negative. The fiber wall thickness correlates positively with compression strength and MOE, but negatively with modulus of rupture (MOR). There was also a correlation between lumen diameter and the mechanical properties, except compression strength. Abd.Latif *et al.* (1993) found that the frequency of vascular bundles does not significantly vary with age and height of the culm. The high density of vascular bundles at the top was due to the decrease in culm wall thickness [Grosser and Liese, 1971]. The size of vascular bundles was not significantly different with height and age. There was no correlation of vascular bundles with age, but there was a significant decrease with height of the culm. They explained that the reason for the higher ratio of vascular bundle size near the basal location was due to the presence of mature tissues. The radial size decreases faster than the longitudinal size of the vascular bundles within the height of the culm. The fiber length of the species of bamboo studied did not significantly differ with age and culm height. Fiber wall thickness is not significant by age or height of the culm. They observed that there is a decrease of lumen diameter with the increase of age and height of the culm.

2.3 *Dendrocalamus asper* – the Main Species in Thailand

D. asper is one of the most popular bamboo species of Thailand planted in more than 60 provinces. It was brought from China to the farmers in Prachinburi province, which is located in Eastern part of Thailand, nearly 100 years ago [Pungbun, 2000]. From the report of Tanurak (1996), the area of *D. asper* plantations increased vary rapidly during 1990 to 1994. Now, it has been planted in 67 provinces of Thailand with total area of 68,000 hectares.

D. asper is commonly recognized as Giant bamboo. Local names for this species are bambu betung, awi bitung, buluh batung, buloh beting, buloh betong, buloh panching, bukawe, botong, butong, rebong china, hok, phai-tong, manh tong [Dransfield and Widjaja, 1995].

The origin of *D. asper* is unidentified, but it is assumed to be somewhere in South-East Asia. It is commonly planted in South-East Asia (i.e. Thailand, Vietnam, Malaysia, Indonesia and the Philippines). It has also been introduced to India, Madagascar and Sri Lanka for commercial purposes. Additionally, it has been found in botanical, experimental or private gardens in the New World and Australia.

Generally, *D. asper* can thrive in any type of soil, but it grows better in rich and heavy soils of the humid regions from the low altitudes up to 1,500 m altitude. However, it flourishes best at 400-500 m above sea-level with an annual rain fall of about 2,400 mm, but it also grows well in semi-dry areas in Thailand having sandy and rather acidic soils [Dransfield and Widjaja, 1995; Rao *et al.*, 1998].

2.3.1 Micro and Macroscopic Characteristics

In accordance with Grosser and Liese (1971), *D. asper* shares the typical anatomical characteristics of bamboo, featuring the presence of vascular bundles and parenchyma, as presented in Figure 2.3. It is classified under anatomical group D for having type IV vascular bundles. Several researches reported the fiber characteristics of *D. asper*, as illustrated in Table 2.1.

Table 2.1 Fiber characteristics of *Dendrocalamus asper*

Fiber characteristics	Unit	Sources				
		1	2	3	4	5
Fiber length	mm	3.8	2.3	3.0	4.3	3.1
Fiber diameter	µm	19.0	17.1	19.5	19.5	18.0
Fiber wall thickness	µm	6	-	14.5	6	7
Lumen width	µm	7	-	1.8	6	4

Sources: 1/ Dransfield and Widjaja (1995)
2/ Liese and Grosser (1971)
3/ Abasolo *et al.* (2005)
4/ Othman *et al.* (1995)
5/ Kamthai (2003)

Compared to some wood species [Fengel and Wegener, 1984], the dimensions of *D. asper* fiber are quit similar to those of softwood tracheids. It has long fibers, which is longer than that of hardwood species approximately 2 to 3 times. Therefore, it can be used as an alternative raw material for pulp and paper industries.

According to Dransfield and Widjaja (1995) and Rao *et al.* (1998), *D. asper* is the densely tufted, sympodial bamboo. The colour of standing culm is dark green. They described that *D. asper* culm is up to about 20-30 m in height; lower nodes are covered with a circle of rootlets; internode length of 20-45 cm with a diameter of 8-20 cm and with relatively thick walls (11-20 mm), sometimes almost solid at base, when young it is covered with fine, golden-brown hairs, giving the overall appearance of velvet.

More information of *D. asper* macroscopic characteristics were also reported by Rao *et al.* (1998), Othman *et al.* (1995) and Sutnaun *et al.* (2005), as shown in Table 2.2.

Table 2.2 Macroscopic characteristics of *Dendrocalamus asper*

Macroscopic characteristics	Unit	Sources		
		1	2	3
Culm length	m	20-30	18-23	-
Internode length	cm	20-45	35	14-45
Internode diameter	cm	8-20	9-13	1.2-9.3
Culm wall thickness	mm	11-20	10-14	4-30

Sources: 1/ Rao *et al.* (1998)
2/ Othman *et al.* (1995)
3/ Sutnaun *et al.* (2005)

2.3.2 Physical and Mechanical Properties

Physical and mechanical properties of bamboo depend on the species, site/soil and climatic condition, silvicultural treatment, harvesting technique, age, density, moisture content, position in the culm, nodes or internodes and bio-degradation [Lee *et al.*, 1994].

Several researches reported the physical properties of *D. asper*, as shown in Table 2.3.

Table 2.3 The physical and mechanical properties of *D. asper*

Properties	Unit	Sources		
		1	2	3
Physical properties				
Moisture content green state	%	55	66.5	46
Specific gravity		0.70	0.67	0.77
Shrinkage				
- Radial	%	5	6.5	1.3
- Tangential	%	4.5	8.5	2.5
- Longitudinal	%	-	-	0.2
Mechanical properties				
Modulus of rupture (MOR)	MPa	92.5	85.65	135
Modulus of elasticity (MOE)	MPa	-	63,000	13,115
Tension parallel to grain	MPa	-	-	314
Compression parallel to grain	MPa	27.1	31.45	72
Shear parallel to grain	MPa	7.15	5.35	14

Sources: 1/ Dransfield and Widjaja (1995)
2/ Othman *et al.* (1995)
3/ Pakhkeree (1997)

The bamboo moisture content varies from bottom to the top parts and from the outer layer to the inner layer. The specific gravity of *D. asper* is high compared to those of softwood and hardwood species used for panels manufacturing such as Douglas-fir, Red Pine, Yellow poplar and American Aspen [USDA Forest Service, 1999]. Regard to anisotropic shrinkage, bamboo is similar to wood. The longitudinal shrinkage in *D. asper* is very small, at approximately 0.2%. The radial and tangential shrinkage ranges from 1.3 to 6.5% and 2.5 to 8.5%, respectively. Interestingly, the greatest shrinkage occurs in the tangential direction which is about 1.3 times as great as shrinkage in radial direction. Compared to the softwood and hardwood, the tangential shrinkage is approximately 2 times greater than the radial direction.

The mechanical properties of *D. asper* from several studies are also presented in Table 2.3. The MOR and MOE range from 92.5 to 135 MPa and 13,115 to 63,000 MPa, respectively. The compression perpendicular to grain is in the range of 27.1 to 72 MPa. Notable, the tensile strength parallel to grain of bamboo is presented only with one source, because the specimen preparation was difficult. Moreover, the specimen will fail by shear stress parallel to grain before its full tensile stress is developed between the testing. Compared to the other species [USDA Forest Service, 1999], *D. asper* is stronger than wood in bending, tension parallel to grain and compression perpendicular to grain, and is similar in shear parallel to grain.

2.3.3 Chemical Properties

The chemical composition of bamboo for the utilization of wood-composite products should be considered. The chemical composition amount of each bamboo varies with age, height and layer. Moreover, it influences its physical and mechanical properties.

Table 2.4 The chemical composition of *Dendrocalamus asper*

Chemical compositions (%)	Sources		
	1	2	3
Holocellulose	53	74	65.8
Lignin	25	28.5	30.4
Ash	3	1.5	2.3
Cold-water solubility	4.5	6.4	-
Hot-water solubility	6	9.2	-
1% NaOH solubility	22	24.7	-
Alcohol-benzene solubility	1	5.5	3.2

Sources: 1/ Dransfield and Widjaja (1995)
2/ Kamthai (2003)
3/ Laemsak and Kungsuwan (2000)

As presented in Table 2.4, the main chemical constitute of *D. asper* culms are cellulose, hemicellulose and lignin, which amount to over 90% of the total mass. The minor constituents of bamboo amount to 10%, which are composed of resins, tannins, waxes and inorganic salts [Tomalang *et al.*, 1980]. Compared to the other wood species [Fengel and Wegener, 1984], the chemical compositions of *D. asper* are similar to those of hardwoods, except for the higher ash content.

The ash of bamboo is composed of inorganic minerals, primarily silica, calcium, and potassium. Manganese and magnesium are two other common minerals [Fengel and Wegener, 1984]. Silica content is the highest in the epidermis, with very little in the nodes and is absent in the internodes. Higher ash content in some bamboo species can adversely affect the processing machinery [Abd. Latif, 1993]. Additionally, bamboo contains other organic components in addition to cellulose and lignin. It contains starch, deoxidized saccharide, fat and protein. The carbohydrate content of bamboo plays an important role in its durability and service life. Durability of bamboo against mold, fungal and borers attack is strongly associated with the chemical composition.

Kamthai (2003) investigated the chemical composition at difference location along the culm length of three year old of *D. asper*. The results indicated that the chemical compositions show relatively small differences among different location of bamboo culm. The holocellulose, α-cellulose lignin, hot-and cold-water solubility and 1% NaOH solubility are slightly constant with the different location. The ash is highest in the top part and lowest in the bottom part. Alcohol-benzene solubility increases significantly with the different location. Moreover, the node of bamboo has significantly higher lignin, ash and 1% NaOH ad the internode, while the internode shows higher hot-and cold-water solubility than the node.

2.3.4 Utilizations

The utilizations of *D. asper* can be divided into two fields:

(1) Bamboo Culms

Owing to the thick wall, which is very strong and durable, the culm of *D. asper* is mainly used for building and structural industries. It is also used in making furniture, musical instruments, chopsticks, containers, household utensils and handicrafts. From the reports of Dransfield and Widijaja (1995), culms are preferably harvested in the dry season. Since *D. asper* has recently been planted commercially for young shoots in Thailand, the culm is only used for local consumption. Thence, some economic and production data has been reported. A plantation can produce 16 tons culms per ha per year which produced an output up to 1 million ton of culms in 1994 [Tanurak, 1996].

(2) Young Bamboo Shoots

The young shoots are wildly consumed as a vegetable. They are sweet and delicious known as sweet bamboo in Thailand. Young shoots are harvested during the rainy season (in Thailand from May to June, in Java from November to May). A properly managed plantation may produce 10-11 tons young shoots per ha per year, [Dransfield and Widijaja, 1995; Rao *et al*, 1998]. In Thailand, the total young shoots produced were more than 300,000 tons of shoots and total value of shoot export was over 21 million Euro in 1994 [Tanurak, 1996].

2.4 Adhesives

Wood adhesives are polymeric materials that are capable to interact physically or chemically, or both, with the surface of wood in such a manner that stresses are transferred between bonded members, hopefully without rupture of the cured adhesive or detachment of the adhesive from the wood [Blomquist *et al.*, 1985].

Many types of glues have been used to bond wood together, but prior to the Second World War, essentially the main part of the glues were of natural origins. Adhesives based on synthetic polymers were introduced just before WWII and now represents 99% of the glues for wood bonding. These synthetic adhesives are used in situations which are far too demanding for the natural originated glues to satisfy moisture, durability, and strength requirements that were unthinkable a few years ago.

Now, most of adhesives are synthetic adhesives produced by the controlled polymerization of various organic molecules. This adhesive can be further divided into thermosetting (most common for wood adhesive) and thermoplastic types. In this part, only major wood adhesives used for the exterior application are presented.

2.4.1 Adhesives for Exterior Applications

The adhesive for gluing wood exterior application is a resin which can resist long exposure to moisture or contact to water. This adhesive can create a resistant bond between adherents. The resulting products can be used in the exterior applications. Blomquist *et al.*, (1985), Paventi (1999) and Pizzi (1994) proposed five major adhesives used for bonding wood used in exterior applications.

(1) Melamine Formaldehyde resin (MF)

MF is a thermosetting resin made from melamine and formaldehyde by polymerization. It is more resistant to high relative humidity conditions than UF resins. Unlike phenol-formaldehyde resin, it is colourless. Therefore, it can be used for plywood, end-jointing and edge-gluing of structural lumber, and scarf joining wood that can be used in protected exterior exposure. In addition, these resins are used for bonding low- and high-pressure laminates and overlays. However, melamine is four times more expensive than UF.

Thence, it is used for the wood based panels manufacturing upgrading to improve the weathering resistance [Blomquist *et al.*, 1985; Pizzi, 1994].

(2) Melamine Urea Phenol Formaldehyde resin (MUPF)

MUPF is a thermosetting resin which composition comprises as least 25 weight percent of melamine and at least 10 weight percent of phenol with urea and formaldehyde. This resin is commonly used for PB and OSB for exterior and bearing application. The main objective is the novel resin innovation showing some advantages, such as the resin can be prepared in a single container and will remain stable at room temperature for over 1 month. It is clear, water miscible and has low viscosity until ready to use. A cuing catalyst is added into the resin to achieve rapid gelling and curing once it ready to use. The resulting cured resin exhibits valuable properties of strength, toughness, water resistance and low formaldehyde emission [Paventi, 1999].

(3) Phenol Formaldehyde resin (PF)

PF is the major adhesives used for bonding wood panels for the use in exterior applications. A major utilization for PF resin is the wood based panel manufacturing for high quality plywood, Laminated Veneer Lumber (LVL), Oriented Strand Board (OSB), technical and decorative laminates etc. This resin is approximately three times more expensive than UF.

Novalac resin is produced by using an acid catalyst and an excess phenol at formaldehyde/phenol ration of less than 1. This resin has a low molecular weight and linear structure. It is unable further react without the addition of more formaldehyde due to lack of free methylol groups. For this reason, it is often referred as two-stage resins. This curing process transforms the thermoplastic resin into a thermosetting form [Blomquist *et al.*, 1985; Pizzi, 1994].

Resole resin is produced under alkaline condition using an excess of formaldehyde. Typical resole resin contains a molar ratio of formaldehyde: phenol approximately 2:1, with a resin solids content of about 35-50%. It has a high molecular weight and a highly branched structure. Because of the excess formaldehyde in the reaction mixture, resole resin has hydroxymethyl end groups which are not stable and/but continually react at room temperature. When used as a wood adhesive, resole resin is generally aqueous solution, which is cured by heat and pressure [Blomquist *et al.*, 1985; Pizzi, 1994].

(4) Isocyanate as diphenylmethane di-isocyanate resin (pMDI)

Isocyanate has become an important adhesive in the wood products industry, especially for OSB.

pMDI derives from the reactivity of the isocyanate groups. These groups react with compounds having active hydrogen, such as water, alcohols, and amines. The reaction rate can be accelerated with a high temperature. As well as reacting with the moisture in wood to form poly-urea, it is theoretically possible that covalent bonds between hydroxyl groups in the wood (e.g., on the cellulose) and the isocyanate. These covalent bonds, to the extent that they form, act to anchor the polyurea to the wood and help bridge the gap between wood.

As an adhesive, PMDI has several reported advantages to that of pMDI, namely it can be used with wood which has a higher moisture content than that generally used with other adhesives. Therefore, it can reduce the energy needed to dry the wood element before gluing. It can be cured at a lower temperature, due to it’s greater reactivity. There is no formaldehyde emissions associated with the adhesive.

There are also some disadvantages associated with the use of PMDI as an adhesive. The price of Isocyanate resin is twice as expensive to that of PF resin. As well, it can excellently bond with the metals. Thus, MDI-bonded boards (e.g., Particleboard, Oriented Standard Board) tend to adhere to the caul plates or press belts. This problem is resolved by using a releasing agent [Blomquist *et al.*, 1985; Pizzi, 1994].

(5) Resorcinol and Phenol-Resorcinol Formaldehyde resin

These glues are more expensive than the straight phenol-formaldehyde resins and are used primarily as special purpose adhesives. They are dark reddish in color and are generally supplied in liquid form. A filled liquid or powdered hardener is added to the liquid prior to use. Curing temperatures range from 70° to 150° C. Because of their cost, resorcinol based adhesives are not widely used for plywood manufacture; rather, they are used as assembly glues in solid wood products which must resist exposure to the weathering such as Glued Laminated Timber (GLT) and I-joists. They have been of particular value in a few unique exacting applications such as the manufacture of wood aircraft [Blomquist *et al.*, 1985].

2.4.2 pH and Buffer Capacity

The gluability of wood is influenced by its surface properties, such as roughness, pH, buffering capacity etc.

The pH is a measure of the concentration of H-ions (or OH-ions, respectively) in solutions, and is used for the determination of their acidic, neutral or alkaline behaviors. Numerical values greater than 7 describe basic conditions, while those less than 7 describe acidic conditions (Fengel and Wegener, 1984, Blomquist *et al.* 1985). The acidity of most wood species is caused by free acids and acidic groups which are present in extractives and noncellulosic polysaccharides and are easy to split off. The pH values of common wood species are on the acidic side. Temperate woods have pH levels in the range of 3.3-6.4, while tropical woods have pH levels in the range of 3.7-8.2 (Fengel and Wegener, 1984). The pH of wood is highly important for various ranges of its utilization, especially in wood composite products.

The buffer capacity is the resistance of wood to change in its pH level when the acid or base is added. Maloney (1993) suggested that the wood which requires a larger amount of acid catalyst to decrease the pH to the level required for optimum adhesive cure is considered as a high buffering capacity species.

To obtain high bonding strength, the pressing parameters must be adjusted for the pH conditions encountered. If this parameter is not taken care into consideration, the glue-line will be either uncured or over-cured and the result will reflect in a poor bonding strength. Thus, the pH and buffering capacity measurement of raw materials is fundamental to determine the optimum pressing parameters (the pressing time and temperature) for panel manufacturing. Understanding these properties is important when discussing the compatibility of bamboo as a raw material for OSL or OSB manufacturing.

2.4.3 Bonding Characteristic Development between Bamboo and Adhesive

On average, all wood-composite products are produced using a thermosetting resin which bonds the basic wood elements (e.g., the fibers, particles, strands, flakes, veneer, etc.) together. The bonding strength of thermosetting resin occurs during the curing process, performed in a hot-press under pressure and temperature. The pressure and pressing temperature are related to the wood furnish and resin properties, while the pressing time is influenced by several factors (e.g., pressing temperature, board thickness, thermal conductivity of the material and initial moisture content). These parameters are the key for the development of adequate bond strength in wood-composite products. They should be monitored and adjusted for a sufficient adhesive bond strength. This has led to the developing of a faster quantitative screening test for wood bonding.

The Automated Bonding Evaluation System (ABES) is designed to determine the strength development characteristics of adhesives during hot pressing process. The system enables the effects of pressing temperature and time on the strength development rate of adhesives applied on wood strips as they cure. This equipment allows accurate control of pressure, platen temperature and pressing time by lab-shear wood samples [Humphrey, 1993 and 2006]. The samples could then be removed from the ABES while still intact, equilibrated in a controlled environment, and finally tested dry or wet using a standard tensile testing machine, which is designed to provide absolute strength values.

2.5 Oriented Strand Lumber

In recent years, manufacturers of wood products are facing a challenge: the available resource is declining in size and quality, the prices increase due to the new biomass energy generation policy, while the demand for higher quality structural wood products is developing. This situation has leaded to an interest in structural composite lumber used in building and construction.

Structural Composite Lumber (SCL) is a family of reconstituted products that can help to solve the situation. It has extremely high and uniform strengths and stiffness properties and is almost warp free. The desired length and width of composite lumber can be economically produced regardless of the size and quality of the trees available.

In 1960, SCL was firstly promoted in the wood-composite market. It was used as members in airplanes during World Wall II due to its high strength-to weight ratio [Nelson, 1997].

2.5.1 Definition and Classification

SCL is a family of engineered wood composite products which are produced from veneer, strands or other small wood elements glued with the exterior adhesives to form lumber-like structural products (i.e., Laminated Veneer Lumber, Parallel Strand Lumber, Laminated Strand Lumber and Oriented Strand Lumber). These can be used for the same structural application as the traditional sawn lumber, for which they substitute, such as girders, beams, headers, joists, studs and columns [Nelson, 1997]. He also described that the important character of SCL products is that the grain of wood elements is aligned parallel with the product's length to provide its structural properties.

SCL can be considered from wood elements in products. Additionally, the orientation of wood elements must also be parallel-oriented. Thence, they are classified into two categories:

(1) SCL Product made from Veneer Sheets

Sheets of veneer are laminated and bonded with adhesive to build up member depth, such as Laminated Veneer Lumber (LVL).

LVL is an engineered wood product consisting of multiply layers of veneers (2.5- to 3.2 mm thickness) laminated together with the grain aligned primarily in the one direction. This contrasts with plywood, in which the grain orientation of adjacent layers is alternatively perpendicular. All veneer are bonded with the exterior structural adhesive, such as PF, pMDI, RF or MUF. The resulting product is a billet of lumber that may be up to 125 mm thick, 1.2 m wide, and 24.4 m long. The billets are then sawn to the desired dimension depending on the construction application.

LVL offers several advantages over typical milled lumber: it is approximately 40% stronger than stress-graded timber, straighter, and more uniform and flexible size. It is much less likely to warp, twist, bow, or shrink than that of conventional lumber due to its composite nature. It allows users to reduce the onsite labour. It is typically used for headers, beams, hip, valley rafters, scaffold planking, rimboard, edge-forming material and flange material for prefabricated wood I-joists [Nelson, 1997].

(2) SCL Product made from Strands

These products are made from longer or shorter strand oriented in the parallel formation and bonded with the exterior structural adhesive. These products comprise a group of:

(2.1) Parallel Strand Lumber (PSL)

PSL is a high-strength structural composite marketed under the trade name Parallam®. It is manufactured from long strands made from veneer sheets cut into strips with the width of 13 mm and length up to 2.4 m). The strands are also produced from the specialized machine generating thin strands from small logs. Dried strand are blended with liquid PF resin and laid in parallel formation to form the finished structural section. The mat is then pressed with a continuous press for greater densification of billet with the dimension of 0.29 x 0.48 x 21 m.

PSL is uniformly high strength and dimensionally stable, stronger and stiffer than timber and LVL. It is used for beam and header applications where high bending strength is needed. PSL is also frequently used as load-bearing columns or can be bonded together into T-beams and other structurally-efficient shapes in secondary gluing operation [Nelson, 1997].

(2.2) Laminated Strand Lumber (LSL)

LSL is engineered composite lumber marketed under the trade name TimberStrand® in North America and Intrallam™ in Europe. It is made from small strands with the dimension of 0.9 mm thick, 30 mm width and up to 300 mm long. These strands are processed through the rotating knives of a stranding machine and then screened before they are blended with a waterproof adhesive and bonded under pressure to form a single, solid piece of material. The result product is a large billet that can be cut into a range sizes for any number of use, such as rim boards, headers, beams, columns, studs, sill plates, and stair stringers [Nelson, 1997].

(2.3) Oriented Strand Lumber (OSL)

OSL is a wood-strand based composite with primarily orientation along the length of the member. The thickness of the strand should not exceed 0.635 mm and the average length should be between 75 and 150 times that of the least dimension. Combined with an exterior adhesive, the strands are formed into a large mat or billet and pressed.

Over the past decade, Weyerhaeuser has been producing OSL for the furniture markets. Strength properties make OSL a highly competitive engineered alternative to traditional lumber and will become an important SCL in construction. Now, several OSB plants in North America are adding a capability to produce OSL [ICBO, 2002; Nelson, 1997].

2.5.2 Manufacturing Process

Nelson (1997) explained that OSL can be manufactured using a similar process and technology of Oriented Strand Board (OSB). Hence, it can be manufactured by some OSB manufacturers which prepare the strands to be appropriate to produce both of OSB and OSL [Maloney, 1996].

Barker *et al.* (2007) illustrated several steps of the OSL manufacturing process include log grading based on their diameters, species and density. The sorted logs are size into strands through a strander with target length of 115 mm, thickness of 0.76 mm and width of 20 mm. These strands are then dried to a target moisture content of about 3% to 6%. The dried strands are then screened according to various strand properties, such as length, width, thickness or density. The screened dried strands are kept in storage under environmentally controlled conditions to maintain the moisture content–within the range of 3 to 6% by weight. The waterproof adhesive, such as 4,4'-diphenylmethane-diisocyanate (MDI), Melamine-urea-phenol-formaldehyde (MUPF), Melamine-urea-formaldehyde (MUF) or Phenol-formaldehyde (PF) is applied on the strands with additional compounds and additives, such as wax, fire retardant and preservative. The resinated strands are aligned one direction into a long and continuous mat, which is formed into a billet in a continuous press. The mat is then heat-pressed to desirable thickness and the appropriate compaction ratio. The maximum pressure, pressing temperature and time are employed following the suggestion of the glue supplier and one test sample. The resulting product can then go through the finishing process, such as trimming, cutting, stamping, sanding, edge treating and packaging. Figure 2.3 illustrates the manufacturing process of OSL.

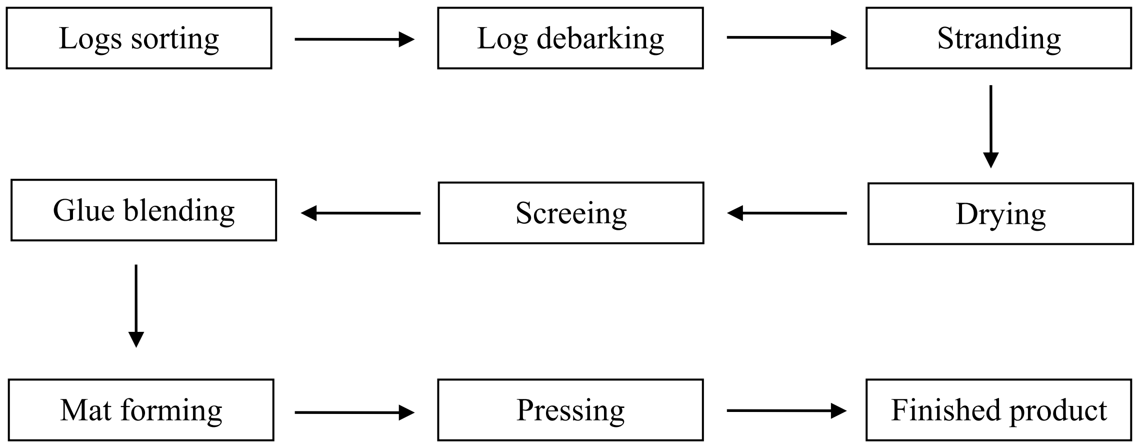

Figure 2.3 The Oriented Strand Lumber manufacturing process

2.5.3 Applications

SCL was developed in response to the increasing demand for high quality lumber at the time when it was becoming difficult to obtain this lumber type from the forest resource. As a result it has grown part of the engineered wood products industry. All types of SCL products can be substituted for sawn lumber products in many applications.

As well, OSL was developed for use in construction. It can be used as a replacement for lumber in various applications as structural members including studs, beams, columns and millwork components. In addition, it can be used in the manufacture of other engineered wood products, such as wood I-joists. Moreover, it is also used in a number of nonstructural applications, such as the manufacture of windows and doors because of its low weight and guaranteed pre-engineered properties

Although OSL is the newest product of the SCL family and markets are still under development, strength properties make it a highly competitive alternative to traditional lumber and will become an important forest based product in the future (Bowyer *et al.*, 2003).

2.5.4 Standard Testing Method

In view of the application, OSL is expected to be used in building and construction sector. It must be evaluated in order to provide safety and reliability. The US standard ASTM D 5456-99 was developed providing procedures to analyze design properties and quality assurance during production for SCL.

This standard is presented to combinable use with other standard procedures, evaluates the physical and mechanical properties, the response of the product to the end-use environment, and establishes and conforms to the quality according to the standard performance specification.

Mechanical tests suggested by ASTM D5456 are bending, tension parallel to grain, compression parallel to grain, compression perpendicular to grain and longitudinal shear, while physical properties (e.g., water absorption, thickness swelling, linear expansion and the accelerated aging test) are carried out in accordance to ASTM D 1037-97.

In contrast with sawn lumber, no standard grades or design stresses have been established for SCL. Each manufacturer may have unique design properties and procedures. Thus, the designer should consult information provided by the manufacturer.

2.5.5 Advantages and Disadvantages in Use

Nelson (1997) and Haygreen and Bowyer (1996) exposed that OSL has many potential advantages as following:

- The raw material for OSL is not limited. It can be manufactured from a wide range of fast growing species and from relatively small diameter trees.
- The production process uses a maximum amount of wood fibre from each tree that is harvested. The production process is highly automated which results in a very high yield of finished product per tree.
- The preservative and fire retardant treatment can be attained in-process by treating the strands prior to hot pressing.
- The product can be used with fastener-holding power and mechanical connector performance.
- Compared to the solid wood, OSL has the higher strength properties and more the uniform strength properties than the solid wood. Additionally, it also shows more straightness than the solid wood.

Nelson (1997) also exposed that OSL shows some disadvantages as following:

- The dimensional stability of OSL, especially thickness swelling, is not as well as that of solid wood and other SCL, because of the greater densification of wood in final product.
- OSL is heavier than the same size (cross section) sawn lumber.
- Because of the complex manufacturing process, OSL production line require a large capital investment (more than a classical OSB or PB line)

3 Methods

Since the properties of bamboo vary in location in accordance with the height, this has an effect on the bamboo-based OSL performances which also correlates with the manufacturing parameters. Therefore, the methodology and analysis were divided into two parts, e.g. the analysis of the bamboo properties at different culm height and their influences on the OSL manufacturing process and property testing.

3.1 The Fundamental Properties of *Dendrocalamus asper* Backer

The fundamental properties of *D. asper*, such as physical and mechanical properties, gluability, bonding strength between bamboo and adhesive are important in determining its utilization.

3.1.1 Macroscopic Characteristic Measurement (Publication I)

Three *D. asper* culms were cut and marked from the bottom to the top part, as shown in Figure 1 in Publication I. The macroscopic characteristics investigated were culm length, number of internodes per culm, internode length, the outer internode diameter and the culm wall thickness from the bottom towards the top.

3.1.2 Physical Properties Testing (Publication I)

To investigate the variation of physical properties of *D. asper* along the culm length, the internodes were selected from three culms. Since the specimen shape changes along the culm height, the specimen preparation and testing method were performed with some modification of the ASTM standard D 143-94, as detailed on Page no. 63 in Publication I.

From each internode, three specimens were randomly selected and cut into size to the requirement of each standard. Altogether, 81 specimens were prepared for the various tests. The air-dried specimens, (MC 50-60%), were placed for 8 weeks in a conditioning chamber, at a temperature of 20°C and relative air humidity of 65% until the MC reached 12%, before the determination of the physical properties composed of specific gravity, moisture content, dimensional stability and water uptake.

3.1.3 Mechanical Properties Testing (Publication II) [1]

Three *D. asper* culms were investigated to determine the variation of the mechanical properties along the culm length, as well as physical property analysis of the shape changes along the culm height. Hence, the specimen the preparation of the specimens and testing method were performed with some modification of the ASTM standard D 143-94, as described on Page no. 75-76 in Publication II.

Three specimens were randomly selected and cut into the size requested by each standard. Altogether, 84 specimens were cut from each culm and prepared for the various tests. The air-dried specimens, (MC 50-60%), were placed for 8 weeks in a conditioning chamber, at a temperature of 20°C and relative air humidity of 65% until the MC reached 12%, before the determination of the mechanical properties composing of static bending, compression perpendicular to grain and shear parallel to grain.

3.1.4 pH and Buffer Capacity Analysis (Publication III)

Three culms of three year old of *D. asper* were used for the pH and buffer capacity analysis. The specimens of each culm for the measurement of pH and buffer capacity were obtained from three locations which related to the height position in the culm showed in Figure 1 in Publication III. Each specimen was processed into the fine particle following the material preparation method on Page no. 86 in Publication III.

The pH measurement procedure was adapted from the measurement of hydrogen ion concentration (pH) of paper extracts by cold extraction method (TAPPI T 509 om-83). The method was presented on Page no. 87 in Publication III.

The buffer capacity measurement procedure, which was also detailed on Page no. 87 in Publication III, was adapted from the method used by Maloney and Borden Chemical Inc. (Maloney, 1993).

Each test was conducted using three replications. Analysis of the variance was performed and Duncan's Multiple Range Test was used for the comparison procedure.

[1] The manuscript has been registered as KFRI/JBR/277 and confirmed for Journal of Bamboo and Rattan.

3.1.5 Bonding Characteristic Development using ABES (Publication III)

The development of the bond strength between bamboo and adhesive was investigated with the Automated Bonding Evaluation System (ABES) technique. The ABES system is designed to determine the strength development characteristics of cured adhesives. The system enables the effects of pressing temperature and time on the strength development rate of thermosetting adhesives to be characterized. This device is composed of a small press and test module and a computer control system with testing-software program which are shown in Figure 2 in Publication III.

D. asper veneer sample of 0.8 mm thick and 20 by 120 mm were prepared, as illustrated in Figure 3.1. All veneers had been placed in a conditioning chamber, at a temperature of 20°C and relative humidity of 65% to a final average MC of 12% at the time of glue spreading.

Three adhesives for exterior uses were investigated: MF, MUPF and PF. All adhesives were blended according to the specification of their suppliers and applied onto one side of the veneer at an application rate of 200 g/m². Afterwards, the resinated veneers were then hot-pressed under controlled parameters of temperature, time and pressure, which are given in Table 2 in Publication III. The procedure was described on Page no. 86-87 in Publication III.

Figure 3.1 *D. asper* veneers for ABES bonding

3.2 The Bamboo-based Oriented Strand Lumber

The previous issues present the standard method for investigation of pH value, buffer capacity, macroscopic characteristics, physical and mechanical properties of bamboo along the culm length. In addition, the bonding characteristic analysis between bamboo and adhesive is also presented. The following issue will explore the physical and mechanical properties of bamboo-based OSL manufactured in the lab varying different parameters. It might establish a better understanding of the effect of resin type and content on the physical and mechanical properties of bamboo-based OSL.

3.2.1 The Bamboo-based Oriented Strand Lumber Production (Publication IV)

Thirty bamboo culms were used as the raw material for the bamboo-based OSL. These bamboo properties are shown on Page no. 98 in Publication IV. Four adhesives for exterior application were used in this research: melamine-formaldehyde (MF), melamine urea phenol formaldehyde (MUPF), phenol formaldehyde (PF) and isocyanate (pMDI). The MF resin (13H560) was supplied by Dynea. The MUPF resin (KML 534) was obtained from BASF. The PF resin (Bakelite 1279 HW) was supplied by Hexion Specialty Chemicals. The pMDI resin (Suprasec® 5025) was provided by Huntsman. The properties of bamboo culms and all adhesives are presented in Table 1 in Publication IV.

Strands were made from bamboo culms in the green state. The culms were crosscut into 140 mm long segments and subsequently sliced into half. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. Target strand dimensions were 140 mm long, 0.7 mm thick, and 12.5-20 mm wide. Strands were then screened via a Gilson Screen (Model TM-4) on a 12.5 mm screen-opening size. Strands that passed through the 12.5 mm screen-opening size in the classifier and remained in the pan were considered as fine fractions. All the strands were then dried to a moisture content of less than 2%. The strand preparation process is presented in Figure 1 in Publication IV.

Bamboo-based OSL with a target density of 750 kg/m^3 were manufactured using laboratory equipment regarded to four resin types (MF, MUPF, PF and pMDI) and three levels of resin content (7, 10 and 13%). The glued strands were spread into a forming-box with the dimension of 800 × 300 mm and oriented parallel in the board length. The mats were then pressed into boards at a nominal thickness of 16 mm using a single-opening hydraulic lab hot press (60 x 80 cm Siempelkamp press). Each board was pressed at the pressing temperature and time following the suggestion of glue supplier, as detailed in Table 2 in Publication IV.

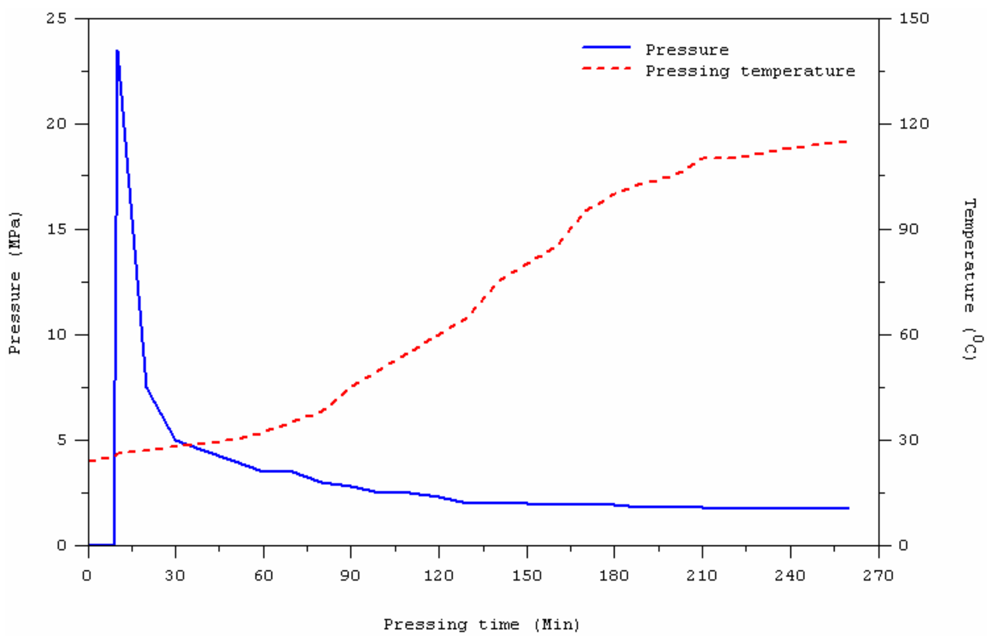

Figure 3.2 Sample of pressing diagram for bamboo-based OSL bonded with MUPF resin

The pressing diagram is illustrated in Figure 3.2. Pressing was done on a basic process. The initial pressure was applied to achieve a thickness of 16 mm. The maximum pressure was 23 MPa before it dropped off quickly and was constant to approximately 1.7 MPa. Thirty-six boards were produced and the finished boards were stacked to cool down.

3.2.2 Physical and Mechanical Properties of Bamboo-based Oriented Strand Lumber (Publication IV)

All bamboo-based OSL were cut into test specimens and placed in a conditioning room maintained at 65% RH and 20°C for 4 weeks until the constant weight was attained before they were tested. Figure 3.3 shows the specimens for thickness swelling marked A, water absorption marked B, static bending marked C and internal bond marked D.

Thirty-six specimens for each parameter-combination were tested. Thickness swelling (TS) and water absorption (WA) were carried out in accordance with EN 300: 1997 and

ASTM D 1037-97, respectively. Three-point static bending tests for modulus of rupture (MOR) and modulus of elasticity (MOE) were performed in accordance with ASTM D 5456-99 and Internal bond (IB) was measured in accordance with EN 300: 1997. All procedures are presented on Page no. 100 in Publication IV.

Figure 3.3 Bamboo-based OSL specimens for the physical and mechanical testing properties.

Effects of resin type and resin content on the properties of the boards were evaluated by analysis of variance at the 0.01 level of significance. The Duncan's Range tests were conducted to determine significant differences between mean values.

4 Results

In the previous chapter, *D. asper* was tested for some important properties (i.e., macroscopic characteristics, physical and mechanical properties, gluability and bonding characteristics between bamboo and adhesive). These results are compared to other wood species to evaluate the technical suitability for *D. asper* usage in OSL manufacturing, which are reported in this chapter, as presented in Topic 4.7. This evaluation is intended to further the understanding in order to design and decide on the important manufacturing parameters for the bamboo-based OSL.

Consequently, the bamboo-based OSL was manufactured in the laboratory using two categories of manufacturing parameters, i.e., four resin types (MF, MUPF, PF and pMDI) and three levels of resin content (7, 10 and 13%). Afterwards the physical and mechanical properties of the bamboo-based OSL were determined as follows: modulus of rupture in bending (MOR), modulus of elasticity bending (MOE), internal bond, thickness swelling and water absorption after 24 h immersion in water. The results could reveal the effect of manufacturing parameters on its property variation and demonstrate the suitability of *D. asper* for OSL manufacturing, are also presented in Topic 4.7.

4.1 The Effect of Bamboo Macroscopic Characteristic Variation on Strand Preparation for the Oriented Strand Lumber Manufacture (Publication I)

One factor contributing to the suitability of bamboo as the raw material for OSL is its macroscopic characteristics having an effect on the strand preparation, quality and output.

Most bamboo culm, including *D. asper*, is straight, cylindric and hollow. It is divided into sections, the internodes, by diaphragms or nodes [Liese, 1998], as shown in Figure 1 in Publication I. In the internodes, the cells are strongly oriented axially. No radial cell elements exist and therefore, the transversal interconnection is provided only by the nodes with their solid cross wall, called diaphragm as illustrated in Figure 2.1 in Chapter 2. The values of macroscopic characteristics of the three culms are listed in Table 1 in Publication I.

The results demonstrate that the internode length, wall diameter and thickness vary along the culm length. The internode length of the culm increases from the base to the middle part and decreases toward the top part. The maximum internode length is located in the 1st third of the culm. The culm diameter varies from 12.2 cm at the bottom to 1.6 cm at the top.

Bamboo culms taper towards the top with a gradual decrease in diameter. The culm wall thickness significantly decreases with height from 2.7 at bottom to 0.5 cm at the top. The variation of macroscopic characteristics along the culm height is presented in Figure 2 in Publication I.

Due to the thick wall and long culm, bamboo can be processed into many forms of wood particles, such as flour, fibers, flakes, chips, excelsior, strips, strands and veneer. In accordance with Lowood (1997), the minimum width of strand use in OSL manufacture is 12.5 mm. For bamboo, the width of strand depends on the culm wall thickness which significantly decreases from the bottom to the top part, as shown in Figure 2c in Publication I. Therefore, bamboo strands might only be produced from one in third of the lower half of the culm, because the culm wall thickness is more than 12.5 mm. Moreover, bamboo has a long straight grain which can compensate the potential shortcoming. It can easily be cut into thin pieces in radial direction using a strand disc-flaker.

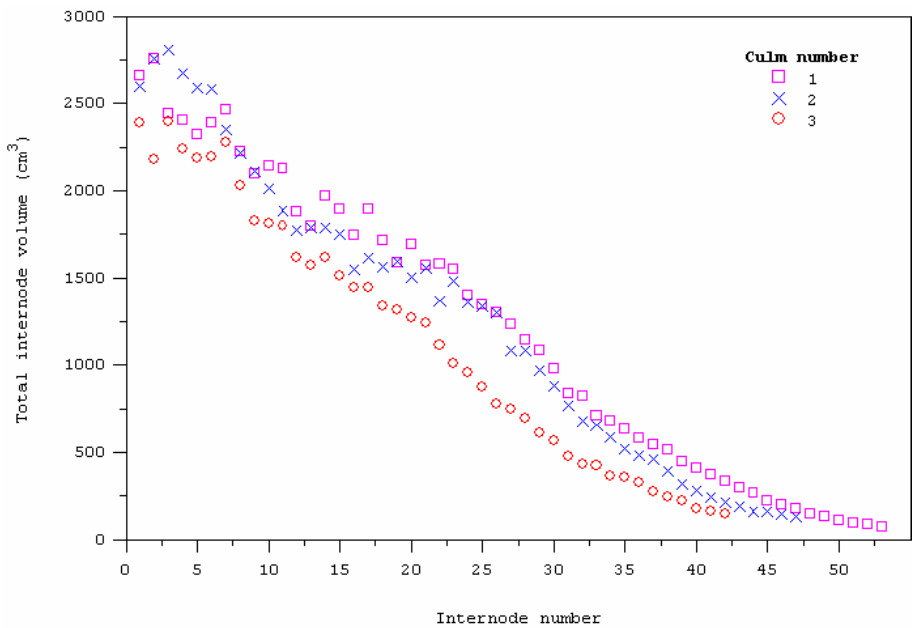

Figure 4.1 Decreasing of the internode volume of each internode along culm length of *D. asper*.

Figure 4.1 presents the total volume of each internode that might be obtained or theoretical calculated for each culm at different positions along the culm length. The total internode volume (implicitly the wall volume of each internode) decreases from the bottom to the top part from 2,800 to 70 cm^3 due to the decreasing culm diameter and wall thickness, as shown in Figure 2b and 2c in Publication I. Additionally, the strand output for each bamboo culm can be calculated to determine the effect of bamboo macroscopic characteristic variation on strand as well. According to this view, the percent value of strand output for each culm is in the range of 50-60%.

4.2 The Physical Properties of *Dendrocalamus asper* Backer (Publication I)

The suitability of *D. asper* for OSL will be dependent upon its physical properties. They were investigated as follow: specific gravity, dimensional stability and water uptake.

The specific gravity (SG) of *D. asper* at 12% MC is in the range of 0.55 to 0.90. The result indicates that the location along the bamboo culm has a significant effect on SG. The value slightly increases from the bottom to the top of the culm, as shown in Figure 4 in Publication I.

The average shrinkage of *D. asper* is different depending on directions: 1.8% in radial, 2.5% in tangential and 0.2% in longitudinal direction, as illustrated in Figure 5 in Publication I. The tangential shrinkage is about one-half as much in radial, and much less along the longitudinal direction. Additionally, the radial shrinkage shows a strong relationship with the specific gravity. The shrinkage value decreases, when the specific gravity value increases as illustrated in Figure 6 in Publication I.

The mean-swelling value of the three *D. asper* culms is 5.8% radial, 4.7% tangential and 0.4% longitudinal, as illustrated in Figure 7 in Publication I. Radial and tangential swellings differ slightly from one another, but the longitudinal swelling is distinctly lower than in the other two directions. Similarly, the swelling behavior varies in the growth direction in the same ratio like the shrinkage.

The water uptake was measured after soaking the specimens (with an initial 12% MC) in water at 20^0C for a period of 24 hrs. The values are in the range of 20-55%. Water uptake is slightly different in each position (Figure 8 in Publication I) and strongly related to specific gravity (Figure 9 in Publication I). In accordance to the specific gravity increase, the water uptake value slightly decreases from the bottom to the top. This is mainly due to the variation in the amount of parenchyma cells, which corresponds to water holding capacity.

4.3 The Mechanical Properties of *Dendrocalamus asper* Backer (Publication II) [1]

The suitability of *D. asper* for OSL manufacture will be dependent on its mechanical properties. They were investigated as follow: static bending, compression perpendicular to grain and shear parallel to grain, as presented in Publication II.

Figure 1 in Publication II shows the variation of modulus of rupture (MOR) along the culm height. The values are in the range of 127.52 to 253.45 MPa, and the average specific gravity for bamboo specimens at 10.97% moisture content is 0.766. The result demonstrates that MOR appreciably varies in the relation to culm height location but the variant pattern from the bottom to the top of the culm is not clear. Notably, the 3rd culm has an average value lower (approximately 25% less) than the other two culms because of its lower specific gravity, as mentioned below. The result further reveals that MOR is strongly related to specific gravity, as presented in Figure 2 in Publication II. The MOR increases, when specific gravity increases. Interestingly, bending failure of bamboo often occurs by horizontal shear due to the low shear strength of bamboo as mentioned below.

The modulus of elasticity (MOE) for the three culms of *D. asper* along the length is presented in Figure 3 in Publication II. The values are in the range of 8,465-25,255 MPa at an average moisture content of 10.97% and specific gravity of 0.766. It is evident that MOE slightly varies with the position in the culm. It could be the variation of bamboo specific gravity is mainly due to the variability of anatomical structures of bamboo along the culm. Hence, some deviations of MOE could be explained by the variation of the specific gravity from the bottom to the top of the culms, as presented in Figure 4 in Publication II.

The compression strength perpendicular to grain of the three culms of *D. asper* is illustrated in Figure 5 in Publication II. The values vary extremely from 4.57 to 28.30 MPa at an average moisture content of 8.25% and specific gravity of 0.767, respectively. The result indicates that the location along the bamboo culm also has a significant effect on this property. The value slightly increases from the bottom to the top of the culm. The 3rd culm also has the lower compression strength than the other culms due to its lower specific gravity. In accordance to the specific gravity increase, the value gradually increases due to the variation of microstructure in the bamboo culm, as presented in Figure 6 in Publication II.

[1] The manuscript has been registered as KFRI/JBR/277 and confirmed for Journal of Bamboo and Rattan.

The shear strength parallel to the grain of *D. asper* varies in the range of 8.05-15.36 MPa, presented in Figure 7 in Publication II, at an average moisture content of 9.92% and specific gravity of 0.746. In contrast to other properties, shear strength parallel to grain is constant along the culm location and also does not depend on specific gravity, as shown in Figure 8 in Publication II.

4.4 Analysis of the pH and Buffer Capacity of *Dendrocalamus asper* Backer and its Variation along the Culm (Publication III)

Table 3 in Publication III presents the pH value data obtained from three locations of three culms which show an average value of 5.36, 5.45 and 5.38 for bottom, middle and top of the culm, respectively. As a result, the pH values vary slightly depending on the location in the culm. No significant differences in pH value between the bamboo culm locations were detected (F-value = 0.23).

The acid-buffering capacity of *D. asper* at three different locations in the culm is also illustrated in Table 3 in Publication III. The average value for bottom, middle and top parts of the culm are 0.58, 0.54 and 0.48 milliequivalents, respectively. Although there are no significant differences between the locations (F-value = 0.27), the value gradually decrease from bottom to the top of the culm.

According to Sauter (1996), the acid-buffering capacity of *D. asper* is high. It is highly resistant to changes in the pH and weakly responds to the acid addition, as illustrated in Figure 4 in Publication III. A high amount of acid must be added to achieve a pH of 3.5. Hence, it would be considered to be the high buffer capacity specie.

The pH and buffer capacity of the raw material is very important for the various ranges of its utilization in wood composite industry. The cross-linking rate of most thermosetting adhesives used in wood composite manufacturing depends on the pH levels. Thence, the acidity of furnish particles and the catalyst which is added into the adhesive play a very important role in providing the optimum condition during resin curing.

Although the differences in buffer capacity seem small until the statistical analysis cannot find significantly differences between the three locations. It varies along the culm location. Thus, it should require some special consideration in regard to catalyst addition and resin cure for wood composite industry using this species as raw material.

4.5 Comparative Study of the Bonding Strength Development between Bamboos by ABES (Publication III)

The adhesive bond strength was observed in terms of the shear strength with the Automated Bonding Evaluation System (ABES) as a function of pressing time and temperature. The shear strength of the adhesive bond for bamboo strands, which were glued with MF, MUPF and PF are presented. This is related to pressing times (from 20 to 300 seconds) and pressing temperatures (150, 170, 190 and 210^{0}C). The results are illustrated on Page no. 91-92 in Publication III.

The results show that bonding strength of the glue-line varies significantly with different pressing temperatures. With the higher pressing temperature, the shear strength increases. It could be explained that the temperature levels influence the rate at which adhesive bonds develop. The initial shear strength rapidly increases with the higher temperature. The results also indicate that the bonding quality varies significantly with different pressing times (Figure 5-7 in Publication III). Notably, the effect of pressing time on shear strength developments is similar to the polynomial curve, as presented in Figure 5-7 in Publication III. By increasing the pressing time, the shear strength increases too due to the occurrence of the adhesive poly-condensation. The shear strength will still increase until the maximum value with the further pressing time is reached. With the prolonged pressing time, the strength will decrease because the failure of bonding in the glue line as illustrated at 190 and 210°C for MF (Figure 5) and MUPF resin (Figure 6) and 210°C for PF resin (Figure 7) in Publication III.

Moreover, the adhesive type has a significant effect on the shear strength. MF resin shows the highest shear strength value (8.54 N/mm^2, Figure 5 in Publication III), while the maximum shear strength value for MUPF (7.23 N/mm^2, Figure 6 in Publication III) is quite similar to that of PF (7.29 N/mm^2, Figure 7 in Publication III). It is important to note that the adhesive types vary significantly in the bonding conditions for which they are designed in use, especially with regards to pressing temperature and time. The results from this study clearly shows, that MF and MUPF can harden and bond properly at lower temperature (170^{0}C) as shown in Figure 5 and 6 in Publication III, while PF requires higher temperature (190^{0}C) as shown in Figure 7 in Publication III.

4.6 The Properties of Oriented Strand Lumber made from *Dendrocalamus asper* Backer (Publication IV)

The average values of the physical and mechanical properties of the bamboo-based OSL are summarized in Table 3 in Publication IV. The analysis of variance result and Dancan's Range comparison for the physical and mechanical data of bamboo-based OSL is illustrated in Table 4 in Publication IV.

The target specific gravity of the bamboo made OSL board was 0.75, while an average board specific gravity is 0.72 at 6.64% moisture content. Notable, the average board specific gravity is lower than the target board specific gravity because the springback phenomenon occurs after pressing (approximately 9.5%). Board-to-board specific gravity variation is minimal; therefore, the values are not determined by statistical analysis

OSL dimensional stability was evaluated by thickness swelling (TS) after a 24 hours water-soaking at 20°C. The values range from 2.28-26.40% (Table 3 and Figure 2 in Publication IV). Bamboo-based OSL produced with higher resin content shows better dimensional stability characteristics. In addition, pMDI resin appears to have an impressive improvement of dimensional stability over all resins. These results are further confirmed with the statistical analysis, as presented in Table 4 in Publication IV showing that the different resin type and resin content have a significant effect on TS value. Notable, the bamboo OSL made with MUPF resin shows a significant higher TS value than those of others.

The water resistance was evaluated by water absorption (WA) after 24 hours of water-soaking. The WA value of bamboo-based OSL is shown in Table 3 in Publication IV. The value ranges from 16.9 to 40.5% (Table 3 and Figure 3 in Publication IV). This property is also significantly dependant on resin type and resin content. The results suggest that OSL made with 10% pMDI resin shows the significant lowest WA (approximately 18.4%) This can be explained by the bonding strength of pMDI resin. Furthermore, the WA significantly decreases with an increasing amount of resin content due to the higher particle contact areas.

In Table 3 in Publication IV, the MOR and MOE values of bamboo-based OSL at the average SG of 0.720 are in the range of 29.1 to 65.2 MPa and 3,280 to 11,109 MPa, respectively (Figure 4 and 5 in Publication IV). The results show that resin type and resin content has a significant~~ly~~ influence on both the MOR and MOE, as presented in Table 4.6. The MOR value of pMDI-bonded board is the highest, while those of MF, MUPF and PF-bonded boards are similar. Additionally, the resin content is found to be the major factor contributing to the improvement of stiffness of board. Notable, 7% MUPF-bonded OSL shows the lowest value of MOR. This might be due to its lower specific gravity. The maximum value of MOE is 11,109 MPa for MF at 13% resin content, while the minimum value is 3,290 MPa for MUPF at 7% resin content. MF and pMDI bonded boards show quit similar MOE and approximately 35% higher value than MUPF and PF board at the same level of resin content. Similar to MOR, the MOE value increases with increasing resin content.

The value of internal bond strength (IB) for samples made with two parameters is in the range from 0.06 to 0.67 MPa (Table 3 and Figure 6 in Publication IV). The result shows that the resin type and resin content significantly influences the internal bond. The values could be discussed in accordance with the resin content because it strongly depends on the amount of resin applied. Then, the value increases with the increase of the resin content. For pMDI resin, internal bond is greater than other types because the high strength of covalent bonds between strands in the board.

4.7 The Suitability of *Dendrocalamus asper* Backer as a Raw Material for the Manufacture of Wood-composite Products

Numerous experiments have been carried out to further the understanding of the properties of *D. asper*. These results, which are presented in Publication I to III, were evaluated to determine the suitability of *D. asper* as raw material for wood composite product manufacture which is discussed in this topic.

The specific gravity of *D.asper* is one factor which could illustrate the suitability of its utilization as a raw material for wood composite products. Compared to the softwoods and hardwoods normally used in composites panels manufacturing, the specific gravity of *D. asper* is relatively high (> 0.60) [Maloney, 1993]. Based on this property, *D. asper* would not be a desirable raw material because of the low compaction rate for light panels like particleboards. For this reason, it could be used as the raw material for the high-density composite. Moreover, its specific gravity varies along the culm length. Thus, it should be considered as a supplementary variability factor in the production of composite products.

Dimensional stability is also one important property for the consideration of *D. asper*. The dimensional stability of *D. asper* in lengthwise direction is less than crosswise. This behavior is the same as in softwoods and hardwoods. The dimensional change in wood is greater in the tangential direction, while the shrinkage and swelling of *D. asper* are similar in the radial and tangential direction due to a different anatomical structure compared to wood with no radial cells [Liese, 1998]. The dimensional stability in the radial direction is affected by the position along the culm, while the dimensional stability in tangential direction has no variation along the culm length. As a result, *D. asper* shows the small shrinkage and swelling values compared to wood species, with mean values of 8% tangential shrinkage, 4% radial shrinkage and 0.1% longitudinal shrinkage from the green to oven-dried condition [Skarr, 1988]. The dimensional stability is the favorable property for the use of *D. asper* as a raw material in composite products.

The water uptake behavior of bamboo could reveal a permeability property. It will be analyzed for further processing, especially coating and gluing. The result shows that the water uptake varies along the culm length because the variation of *D. asper* anatomical structure in the radial and longitudinal directions. The adhesive penetrate deeper into bamboo strands produced from the bottom internodes of the culm. Therefore, it will present the sufficient bonding strength and generate a high quality composite. In the radial direction, the value varies within the same piece of strand because of the specific gravity variation of inner and outer side of culm. Thus, if the composite panels from *D. asper* are produced, the variation of this property should be considered.

A comparison of the mechanical properties of *D. asper* to those of other wood species which are used as raw material for wood composite manufacture is presented in Table 1 in Publication II. Overall, the strength and stiffness of *D. asper* is higher than those of all species. Interestingly, *D. asper* shows quite similar shear strength parallel to Rubberwood and slightly higher than that of others. From a practical point of view, the strength of *D. asper* in grain direction is very high, especially MOR and MOE. It could be considered as the raw material for products bearing unidirectional load such as Glue Laminated Timber (GLT), Parallel Strand Lumber (PSL) and OSL. Additionally, its low shear strength parallel to grain might support easy strand preparation. Nevertheless, the strong variation of mechanical properties of *D. asper* along the culm length is a disadvantage to take in consideration. Generally, the raw material for composite products should be considered based on their strength to weight ratio. As a result, *D. asper* has a low strength to weight ratio, it is not desirable for some applications because of the high specific gravity. However, its strength (i.e., bending strength) and availability may compensate this disadvantage.

The pH value of *D. asper* is not different from common wood species, which is shown in Table 4 in Publication III. Moreover, *D. asper* has no variation in the pH value at the different locations in the culm. It could be concluded that the same technology and practices might be applied to this bamboo specie when being used as raw material in composites manufacture. On the other hand, the acid-buffering capacity of *D. asper* is high, when compared with those of wood species [Sauter, 1996]. It would be considered to be the high buffer capacity specie and will require a higher amount of acid catalyst to reduce the pH to the optimum level required for a resin cure. This may cause problems for their use as raw material in wood composite with conventional commercial resin. Some strategies, such as the use of special glue or adjusted hot-pressing parameters, might be applied to improve resin curing and hence improve product properties. Furthermore, the acid-buffer capacity of *D. asper* varies along the culm location. Thus, it should require some special consideration in regard to catalyst addition and resin cure.

The bonding strength between *D. asper* and three adhesive as a function of pressing time and temperature was investigated using ABES. Similar to Jost and Sernek (2009), the strength is improved by increasing the hot pressing time and temperature. Notably, *D. asper* needs a longer pressing time to achieve the maximum shear strength compared to that of beech (*Fagus sylvatica)* bonded with PF, although the pressing temperature is higher. As previous mention, *D. asper* is considered as the high buffering capacity specie which would affect the curing characteristics of PF resin. Moreover, its maximum shear strength is less than that of beech due to the variation of specific gravity along the culm-wall thickness. As mention above, these aspects should require some special consideration in regard to catalyst addition, resin cure and resin distribution.

Afterwards, the prototype bamboo-based OSL was produced in the laboratory to demonstrate the suitability of *D. asper* as a result of its physical and mechanical properties testing. The results, which are reported in section 4.6, show that the average specific gravity of the board is less than the target specific gravity due to the spring back of the bamboo strand. The dimensional stability of bamboo-based OSL is preferable except that of the MUPF-bonded OSL shows a higher value than that of EN-300 requirement for OSB/3. Therefore, it requires additional treatments such as the wax addition, strands chemical pretreatments or peeling of epidermal layer to improve the bonding and the dimensional stability of bamboo-based OSL glued with MUPF resin.

The comparison of some important OSL properties (such as the specific gravity and bending strength), solid bamboo and solid lumber, used in construction, are shown in Table 5 in Publication IV. The MOR and MOE values of *D. asper*-based OSL are lower than those of solid bamboo, while the average specific gravity of bamboo-based OSL is quit similar to that of solid bamboo. This difference may be explained by shear stress associated with bending. During the test, the shear stress developing in the horizontal interfaces between strands and resin reduces the bending strength of OSL. Compared to spruce solid lumber (*Picea abies)*, the bending strength of bamboo-based OSL is superior.

The result suggests that the OSL made from *D. asper* shows low internal bond strength. It could be explained by the specific gravity variation along bamboo culm and low compaction ration. Additionally, *D. asper* shows high buffer capacity which is reported in Publication III. Then, the high amount of catalyst or the special resin should be used for *D. asper* composite boards.

5 Further Researches

The properties *of D. asper* and their variation within the culm significantly influence it's utilization potential uses and the potential product properties. In this chapter, these properties are discussed and recommended for the further researches for *D. asper* based product development, the property improvement and the enhancement of knowledge regarding the bamboo as a raw material for structural products.

In general, bamboo is an abundant natural source, especially in South-east Asia and Latin America. *D. asper* is the most widely used bamboo in Thailand, although it is not a indigenous specie of Thailand. The Royal Forest Department (RFD) of Thailand has given it's support to re-cultivate this species and continued to support farmers in different provinces. Thus, the study about the ownership structure, tenure system, plantation area and annual production as a raw material for wood industries are important to formulate it's efficiency and policies.

Almost all of the properties of *D. asper* are comparable to those of wood species which are commonly used for composite products. The dimensional stability of *D. asper* is desirable due to its small shrinkage and swelling. It shows high water absorption which is an advantage for certain types of gluing. Consequently, *D. asper* is suitable as the alternative raw material for various types of structural composite products.

Since *D. asper* has thick walls, long culm and straight grain, it can be cut into short strands (approximately 140 mm in length), which are used for OSL and OSB manufacture. It may also be processed into long strands used for PSL and LSL manufacture. But high efficient methods and equipment for stranding are needed and recommended. Although only the bottom part of the culm can be used for high quality strand production, the remains can be processed into a range of particles, such as flour, paper fiber, fiber bundle, particle, flake, chip and excelsior. At this point, *D. asper* can be used with some modifications as the raw material for various types of wood composite products.

Some specific characteristics of bamboo lead to negative influences on processing and its utilization. The bamboo culm is divided into sections of the internodes, by nodes. Since nodes show the low significantly properties [Liese, 1985], it could be intended that nodes cause damage or rapid wear of equipments/tools and lower product properties. Although nodes are not desirable in bamboo utilization, especially for bamboo-composite products, they can not be separated from internodes. Thence, the properties of nodes, such as gluablitly, physical and mechanical properties should be investigated. The data will permit the knowledge and consideration to find the suitable utilization of nodes. Additionally, the outer part of culm is covered with a wax layer of poor affinity for water and adhesives (strongly repellant). Thus, it should be considered too.

The specific gravity of *D. asper* is relatively high compared to that of soft wood. It should be used for the high-density composite products. Thence, the study of appropriate specific gravity of product is suggested. However, the greater weight and machining property of dense product should be considered. On the other hand, it could be suitable to generate the fibers for High Density Fiberboard (HDF).

Compared to common wood species, the pH value of *D. asper* is quit similar, while its acid-buffering capacity is relative high. This may cause problems for its use as raw material in wood composite with conventional commercial resin. Hence, a special glue or adjusted hot-pressing parameter should be considered. Moreover, the additional research about *D. asper* for the wood composite manufacture should be considered, such as the alkali buffer capacity, the relation buffer capacity and its chemical composition, the resin gel time and the effect of *D. asper* on resin gel time.

Compared to wood species, bamboo contains more starch which attracts insects and fungi. This creates serious challenges for the storage of the raw material, the quality and durability properties of finished products. Thus, an efficiency process reducing the starch content or increasing the resistance to the insect and fungi should be investigated.

In the basic process of wood composite manufacture, *D. asper* culms were processed into particles, chips or strand. The large percentage of ash content, including of inorganic minerals, primarily silica, calcium and potassium, of *D. asper* in comparison to common wood species can adversely affect tools wear during machining. Therefore, the effect of bamboo-based products on tool wear should be determined.

The bamboo-based OSL produced in the laboratory exhibits superior properties compared to the commercial products made from wood for the building sector. The study could be extended in the future to the further parameters that influence physical and mechanical properties of the product, such as bamboo-strand geometry, specific gravity and advanced pressing parameters. These parameters may be manipulated to improve product performance. All together, the concern about possible health effects from formaldehyde emitted from bamboo-based OSL manufactured with formaldehyde-based resin should be considered, because it's usage constitutes a large proportion of building components and furniture fitments in domestic and public buildings. Furthermore, the economic feasibility of using bamboo, as a structural composite material should also be investigated with regards to the raw material price and finished product compared to that of composite lumber.

Finally, the study of other bamboo species is recommended, because bamboo offers a broad range of properties which is related to its utilization. This may extend the applications of bamboo for composite products.

6 Summary

In recent years, the availability of large size solid-sawn lumber for construction has been declining, because of the rapid development of the global economy and the increase in population growth, especially in Asia and Latin America. At the same time, the overall demand for wood and wood-composite products for construction has been rising. Consequently, alternative or substitute materials, such as Structural Composite Lumber, in place of solid-sawn lumber became of interest for the building and construction industry.

Structural Composite Lumber (SCL) are engineered wood composite products manufactured from small wood elements glued with adhesives for exterior (also interior) applications to form lumber-like structural products (i.e., Laminated Veneer Lumber, Parallel Strand Lumber, Laminated Strand Lumber and Oriented Strand Lumber). They show very high and uniform strengths and stiffness and can be used for the same structural application, such as girders, beams, headers, joists, studs and columns, but with reduced cross sections (material volume) of the elements.

Oriented Strand Lumber (OSL) is a wood-strand based composite with the main orientation being along the length axes of product. The thickness of the strand should not exceed 0.635 mm and the average length should be between 75 and 150 times that of the least dimension. OSL was developed in the 1991 at by MacMillan Bloedel Ltd. Now Weyerhaeuser in the USA is attempting to produce strands which can be used to manufacture a wide range of OSB and OSL. Firstly, Weyerhaeuser produced OSL for the furniture markets. Because of the superior strength and more the uniform properties, OSL becomes a highly competitive engineered alternative to traditional lumber in construction. It is primarily used as structural members including beams and columns. Additionally, OSL can be manufactured from a wide range of fast growing species with relatively small tree diameters. An additional process, such as preservative or fire retardant treatment can be attained in-process by treating the strands prior to hot pressing. The finished product can be joined with fastener-holding power and mechanical connector performance. However, OSL is the newest product of the SCL family and its market is still under development. Many researches are needed to improve product properties and technologies in order to become a competitive forest based product in the future.

6 Summary

Bamboo (*Bambusoideae* sp.) is a perennial, giant, woody grass belonging to family Poaceae which covers more than 1,200 species in 50 genera in the world. The total area of the bamboo forest in the world amounts to 14 million ha distributed mainly in the most of the tropical countries of Asia, South and Central America and Africa. Asia is the richest continent with about 65 % of total world bamboo resources. In Thailand, bamboo is one of the most important species. From the report of FAO (2001), it is distributed in deciduous and tropical evergreen forests with total area of 2.6 million hectares or about 1.8% of the total forested area. Thailand has 13 genera and 60 species of bamboos.

Dendrocalumus asper is the most popular bamboo species of Thailand. The area of *D. asper* plantations have increased rapidly between 1990 to 1994. Now, it has been planted in 67 provinces with total area of 68,000 hectares [Tanurak, 1996]. The utilization of *D. asper* can be divided into two fields, i.e. young bamboo shoots and bamboo culms. The young shoots are widely consumed as a vegetable. The culms after 3 years of growth are very strong and durable and used as building material for houses and bridges, also in furniture, musical instruments, chopsticks, household utensils and handicrafts.

Adhesive is one of the most important factors in the efficient utilization, development and use of the wood composite products, especially for those manufactured in a dry-process, which require the resin to bond the wood elements together. Utilization of non-wood resources (e.g., bamboo, cereals straw, sugar cane) by conversion to structural composite products, need a highly durable synthetic resin. In addition, the outer layer of the bamboo culm is covered by a heavily cutinized shine cuticle which itself is overlaid with a layer of waxy cutin to prevent loss of water from the culm. It has been agreed upon that waxy outer layer cuticle is very difficult to bond. In the future, the adhesives for structural exterior applications will continue to be a major factor for the efficient utilization of bamboo as a valuable source of raw material for the manufacture of composite materials. Efficiency in converting bamboo to OSL will help to ensure the continual conservation of forest resources.

During recent years, bamboo has received an increase in attention as the alternative raw material for the use in the manufacture of wood based composites owing to it's many advantages, such as easy propagation, fast growth, quick maturity, high productivity and better mechanical properties when compared to other wood species. Hence, it could be the substitute material in place of wood because of the global shortage of forest resources. Recently, several researches have contributed to further the understanding of the properties of

bamboo and improve processing technologies for a wider use. Numerous researches have evaluated the properties of bamboo-based composites, especially engineering composite products, regarding the effective use of bamboo for various products such as plywood, OSB, waferboard, zephyr board and laminated bamboo lumber. They showed that bamboo is able to produce high quality engineering composite products. Therefore, bamboo could be proposed as an alternative material for the manufacture of OSL.

Although bamboo shows only a slight difference in the anatomical structure and chemical composition compared to that of wood species, its morphology, macroscopic characteristics, physical and mechanical properties differ from those of wood. Moreover, the properties of bamboo depended on many factors, such as the age, culm height, growth location etc. For this reason, information on the macroscopic characteristics, physical and mechanical properties and gluability of bamboo are necessary for assessing its suitability for OSL and to decide the approximately methods, technology and equipment suitable for bamboo processing.

For future development of the bamboo-based composite products, an intensive research about bamboo properties and the interaction between bamboo and adhesive for exterior structural applications will be required. The relationship between the basic properties of *D. asper* and the culm height location, the macroscopic characteristics, physical properties, mechanical properties, pH value and buffer capacity are necessary. As well, the bonding mechanisms between *D. asper* strands and adhesives should be analyzed. Thereafter, the physical and mechanical properties of the bamboo-based OSL produced in an laboratory should also be determined. Such information forms the basis of a probability study for bamboo-based composite product industrial development.

6.1 Conclusion

All the culm characteristics vary with the culm height location. The utilization of *D. asper* for OSL will be affected by the culm wall thickness, because the width of strands used in OSL manufacture depend on the culm-wall thickness of bamboo which significantly decreases from the bottom to the top part.

The SG of *D. asper* is relatively high compared to wood species that normally used in composites panels manufacturing. For this reason, it is ideal for high-density composite products. In addition, the SG slightly increases from the bottom to the top of the culm. Thus, the products made from *D. asper* should be considered for a potential higher specific gravity variation than wood.

The dimensional stability of *D. asper* in lengthwise direction is less than crosswise, while the dimensional stability in radial direction slightly differs from the tangential one. This behavior is different compared to wood species because of the different anatomical structure of bamboo compared to that of wood. Additionally, the dimensional stability in the radial direction is affected by the position along the culm and the SG. Both shrinkage and swelling of *D. asper* is lower compared to that of normal wood species. The dimensional stability is a favorable property for the use of *D. asper* as a raw material in composite products.

The water uptake of *D. asper* slightly increases from the bottom to the top part of the culm and is strongly related to SG. The water uptake behavior of bamboo could reveal certain permeability analyzed for coating and gluing processes. The permeability greatly influences the adhesive penetration. The ability of the adhesive to penetrate deeper will create the sufficient bonding strength and produce high quality composite products. Because the water uptake varies along the radial and longitudinal directions of the bamboo culm, the adhesive penetration varies along the two growth directions of bamboo culm as well. Thus, if composite panels from *D. asper* are produced, the variation of this property should be considered.

The mechanical property investigation of *D. asper* for OSL manufacture includes the testing of the static bending, compression perpendicular to grain and shear parallel to grain. In general, *D. asper* shows higher strength and stiffness compared to that of wood species used as raw material for wood composite manufacture. All properties, except the shear strength parallel to the grain, vary with the culm height location and are strongly related to specific gravity. The strength in grain direction of *D. asper* is relative high, especially MOR and MOE. It could be considered as an appropriate raw material for SCL with bearing unidirectional load. Additionally, its low shear strength parallel to the grain might support an easy strand production.

The average pH value of *D. asper* is very close to that of common wood species, particularly that of softwoods, while the acid-buffer capacity is higher (approximately 5 times) than that of common wood species. They don't vary along the location of the culm.

Consequently, *D. asper* should require some special consideration in regard to catalyst addition and resin cure when being used as raw material in composites manufacture.

The adhesive bond strength was characterized in terms of the shear strength using the ABES testing method as a function of pressing time, temperature and glue. This is related to pressing times (from 20 to 300 seconds) and pressing temperatures (150, 170, 190 and 210°C). The shear strength of the adhesive bond for bamboo strands were tested with MF, MUPF and PF resins. The results show that bonding strength of glue-line vary significantly with different pressing times and temperatures. Also, the bonding strength differs depending on the adhesive type. MF resin shows the highest shear strength value (8.54 N/mm^2), while the maximum shear strength value for MUPF (7.23 N/mm^2) is quite similar to that of PF (7.29 N/mm^2).

The bamboo-based OSL were manufactured in the laboratory using two categories of manufacturing parameters, i.e., four resin types (MF, MUPF, PF and pMDI) and three levels of resin content (7, 10 and 13%). Then, their physical and mechanical properties were determined and statistical analyzed. The results could reveal that the average specific gravity of the board is less than the target specific gravity due to the spring back of the bamboo strand. With the same specific gravity, the properties of bamboo-based OSL show improved properties with different resin types and the resin contents. The bamboo-based OSL resinated with 13% pMDI show the highest properties. Bamboo-based OSL shows comparable physical and mechanical properties with that of the wood based commercial products. However, the board resinated with MUPF adhesive is not satisfactory. Wax should be added to improve the dimensional stability. The internal bond strength is lower than the minimal standard requirement. Special glue or approximate pressing parameters are recommended.

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Curriculum Vitae

Name	Pannipa Malanit
Date of Birth	20 April 1977
Place of birth	Chumporn, Thailand
Nationality	Thai
Gender	Female
Family status	Single
Address (Home)	70/3 M.7 Bangson, Pathiv, Chumporn, 86160, Thailand
Address (Actual)	Room no. 315, Billwiese 22, Hamburg, 21033, Germany
E-mail Address	p.malanit@holz.uni-hamburg.de, mpannipa@wu.ac.th,

Education

1995 - 1999	B.Sc. (Forestry), Department of Forest Product, Faculty of Forestry Kasetsart University, Bangkok, Thailand
1999 - 2003	M.Sc. (Forestry), Department of Forest Product, Faculty of Forestry Kasetsart University, Bangkok, Thailand

Experience

2003 - 2004	Research Assistant, Wood Science and Engineering Research Unit, Walailak University, Nakhorn, Sri Thammarat, Thailand
2004 - Present	Lecturer, Institute of Engineering and Resources Walailak University, Nakhorn, Sri Thammarat, Thailand
2006 – Present	DAAD Scholarship holder, Department of Wood Science University of Hamburg, Hamburg, Germany

Declaration

I hereby declare that this thesis is my own work and to the best of my knowledge and belief original. It contains neither material previously published or written by any person, nor material to a substantial extent has been awarded for any degree of a university or institute of higher education. Where other sources of information have been used, they have been acknowledged.

Pannipa Malanit

Hamburg, July 2009.

Publication I

Macroscopic aspects and physical properties of *Dendrocalamus asper* Backer for composite panels

Pannipa Malanit[1*], **Marius C. Barbu**[1,2], **Walter Liese**[1] and **Arno Frühwald**[1]

[1] *Department of Wood Science, University of Hamburg, Germany*
[2] *Faculty for Wood Industry, "Transilvania" University Brasov, Romania*

Abstract: The aim of this research was to determine the basic properties of *Dendrocalamus asper* and its suitability as raw material for manufacture of composite panels. For this purpose, macroscopic characteristics and physical properties such as specific gravity, shrinkage and swelling, and water uptake were studied.

The results show that some of the macroscopic characteristics change at different positions along the bamboo culm. Outer internode diameter and wall thickness gradually decrease with the culm height. The internode length increases from the bottom to the middle part and further decreases toward the top. The tissue volume of internodes decreases from the bottom to the top. All physical properties, like specific gravity, shrinkage, swelling and water uptake vary with the culm height. The specific gravity increases with culm height. The dimensional stability in the radial direction and water uptake are highly related to specific gravity. The dimensional stability lengthwise is more stable than crosswise. The study shows that *D. asper* has superior physical properties, which are comparable to those of some softwood and hardwood species. It should therefore be promoted as a substitute for wood in the manufacturing of structural composite lumber like Oriented Strand Board or Oriented Strand Lumber.

Key words: *Dendrocalamus asper,* macroscopic characteristics, physical properties, structural composite lumber.

INTRODUCTION

With the rapid development of the global economy and constant increase in population, the overall demand for wood and wood-based products will continue to rise. The available wood supply will decrease due to the global energy demands. Consequently, the search for alternative or substitute materials in place of wood has come into focus. A suitable substitute should be inexpensive, fast-growing, easily available raw material having comparable physical and mechanical properties, and also it should be compatible to the existing processing technologies. Bamboo could be such a non-wood substitution material for the tropical and subtropical regions.

Bamboo belongs to the large woody grasses (Family Poaceae, Subfamily Bambusoideae) and encompasses about 1,200 species within 50 genera in the world (Chapman, 1996; Qisheng *et al*., 2002). It is mostly distributed in the tropical and subtropical regions, covering an area of over 36.8 million hectares. In Latin America and Africa, bamboos occupy 10.4 and 2.8 million hectares respectively (Lobovikov *et al.*, 2007). Thailand is one of the richest areas of bamboo in Asia. There are 13 genera and 60 species, mainly of the sympodial type with denser clumps and with long, strong, and flexible culms which lend themselves to be used as a construction material.

E-mail: p.malanit@holz.uni-hamburg.de, mpannipa@wu.ac.th

Dendrocalamus asper, commonly recognized as a giant bamboo, has 20-30 m tall culms, 20-40 cm long indernodes, a diameter of 8-20 cm with a relatively thick culm wall of 10 to 20 mm (Rao *et al.*, 1998). It has been planted regularly or growing throughout tropical South-East Asia. This bamboo species is commercially important in Eastern parts of India and has been widely introduced elsewhere in tropical and subtropical botanic gardens (Dransfield and Widjaja, 1995). It is one of the most popular bamboo species of Thailand and has been planted in more than 60 provinces. It was brought from China to the farmers in Prachinburi province, which is located in Eastern part of Thailand, nearly 100 years ago (Pungbun, 2000).

D. asper young shoots are sweet and delicious known locally as sweet bamboo. They are widely consumed as vegetable. Young shoots are harvested during the rainy season (in Thailand from May to June). A properly managed plantation may produce 10-11 t young shoots per ha per year. The culms developed after three years of growth have thick walls; they are very strong and durable and are used as building material for houses and bridges, also in furniture, musical instruments, chopsticks, household utensils and handicrafts. Culms are preferably harvested in the dry season (Dransfield and Widijaja, 1995; Rao *et al.*, 1998). In Thailand, a plantation can produce 16 t culms per ha per year (Pungbun, 2000).

The macroscopic characteristics and physical properties of bamboo have significant differences to wood species. The properties of bamboo vary in vertical and horizontal directions in the culm. They are important factors to determine its utilization. The increased research during recent years has contributed to understand bamboo properties as well as to improve processing technologies for wider uses (Nugroho and Ando, 2000; Sumardi *et al.*, 2007). In Thailand, several researches were carried out on the fundamental characteristics of *D. asper* and have been used as raw material for particleboard, fiberboard, pulp and paper (Kamthai, 2003; Laemsak and Kungsuwan, 2000; Pakhkeree, 1997; Sutnaun *et al.*, 2005). However, none of these studies researched bamboo as raw material for the structural composite lumber. The objective of this study was to analyze the suitability of *D. asper* as a raw material for structural composite lumber. Therefore, the variation of the macroscopic characters and physical properties, which influence the specific gravity, shrinkage, swelling and water uptake, were analyzed along the culm length.

MATERIALS AND METHODES

Some of the investigations were done at Wood Science and Engineering Research Unit, Walailak University in Nakhon Sri Thammarat, South of Thailand and further in the Department of Wood Science, University of Hamburg, Germany.

Materials

Three *D. asper* culms were harvested in April, 2007 from a private plantation, located in Nakhon Sri Thammarat province, South of Thailand. The terrain is mostly rugged hilly forest area with an elevation of about 600 m a.s.l., 217 mm mean annual rainfall, and 27^{o}C mean temperature. The culms were three years old as confirmed by macroscopic features.

Macroscopic characteristics

The culms were cut and marked from the bottom to the top part as shown in Figure 1. The macroscopic characteristics investigated were culm length, number of internodes per culm, internode length, the outer internode diameter and the culm wall thickness from the bottom towards the top.

Physical properties

Each culm was then cut into each internode along its length. From the following internode, three specimens were randomly selected and cut into size to the requirement of each standard (ASTM D 143-94). Altogether, 81 specimens were cut from each culm and analyzed for the various tests. The air-dried specimens (MC 50-60%) were placed for 8 weeks in a conditioning chamber, at a temperature of 20°C and relative air humidity of 65 percent until the MC reached 12 percent, before determination of the physical properties.

Specific gravity, shrinkage and swelling and water uptake

For the determination of the specific gravity, specimens were made from each internode. The testing method was performed with some modification to the ASTM standard D 143-94, because the specimen shape changes along the culm height. To evaluate the dimensional stability, further specimens were taken from each internode. The bamboo skin was removed (about 1 mm) before the specimens were cut into rectangular dimensions of 2 cm long and 1 cm width with variable wall thickness. The shrinkage and swelling of each internode sample in the radial, tangential and longitudinal directions were measured following the procedure of ASTM D 143-94. Shrinkage of the specimens was measured from 12 percent MC (after conditioning at T = 20^{o}C, RH = 65%) to the oven-dried condition (0% MC). The swelling was measured starting with the oven-dried condition and after soaking the specimens in distilled water at 20^{o}C for 24 h.

Specimens for the water uptake measurement were also taken from each internode along the culm length (2 cm × 1 cm × culm wall thickness). The water uptake was determined at 12 per cent MC (after conditioning at T = 20^{o}C, RH = 65%) and after soaking at 20°C for 24 h.

RESULTS AND DISCUSSION

Macroscopic characteristics

Culm, the above ground portion of bamboo that contains most of the “woody” material is straight, cylindric and hollow (Figure 1). The culm skin is green in color at the younger stage. Liese (1998) described the morphological characteristics of a bamboo culm divided into sections, the internodes, by diaphragms or nodes. In the internodes, the cells are strongly oriented axially. No radial cell elements exist and therefore, the transversal interconnection is provided only by the nodes with their solid cross wall, called diaphragm. The values of macroscopic characteristics of the three culms investigated are listed in Table 1.

Figure 1. Culm aspects of *Dendrocalamus asper*

Table 1. Culm characteristics of *D. asper*

Macroscopic characters	Culm number		
	1	2	3
Culm height (m)	20.90	19.50	17.50
Number of internodes per culm	53	47	42
Internode length (cm)	25-50	28-50	26-48
Diameter along the culm from bottom to top (cm)	12.2-1.59	11.64-2.44	10.74-2.17
Wall thickness along the culm from bottom to top (cm)	2.67-0.55	2.54-0.58	2.72-0.63

The Figure 2 shows the variation of macroscopic characteristics along the culm height. It demonstrates that the internode length, wall diameter and thickness changes in accordance to the culm position. The internode length of the culm increases from the base to the middle part (from about 26 to 50 cm) and decreases toward the top part (from about 50 to 25 cm). The maximum internode length is located in the 1st third of the culm (approximately 10 m above ground level). The culm diameter varies from 12.2 cm at the bottom to 1.6 cm at the top. Bamboo culms taper towards the top with a gradual decrease in diameter. The culm wall thickness significantly decreases with height from 2.7 at bottom to 0.5 cm at the top.

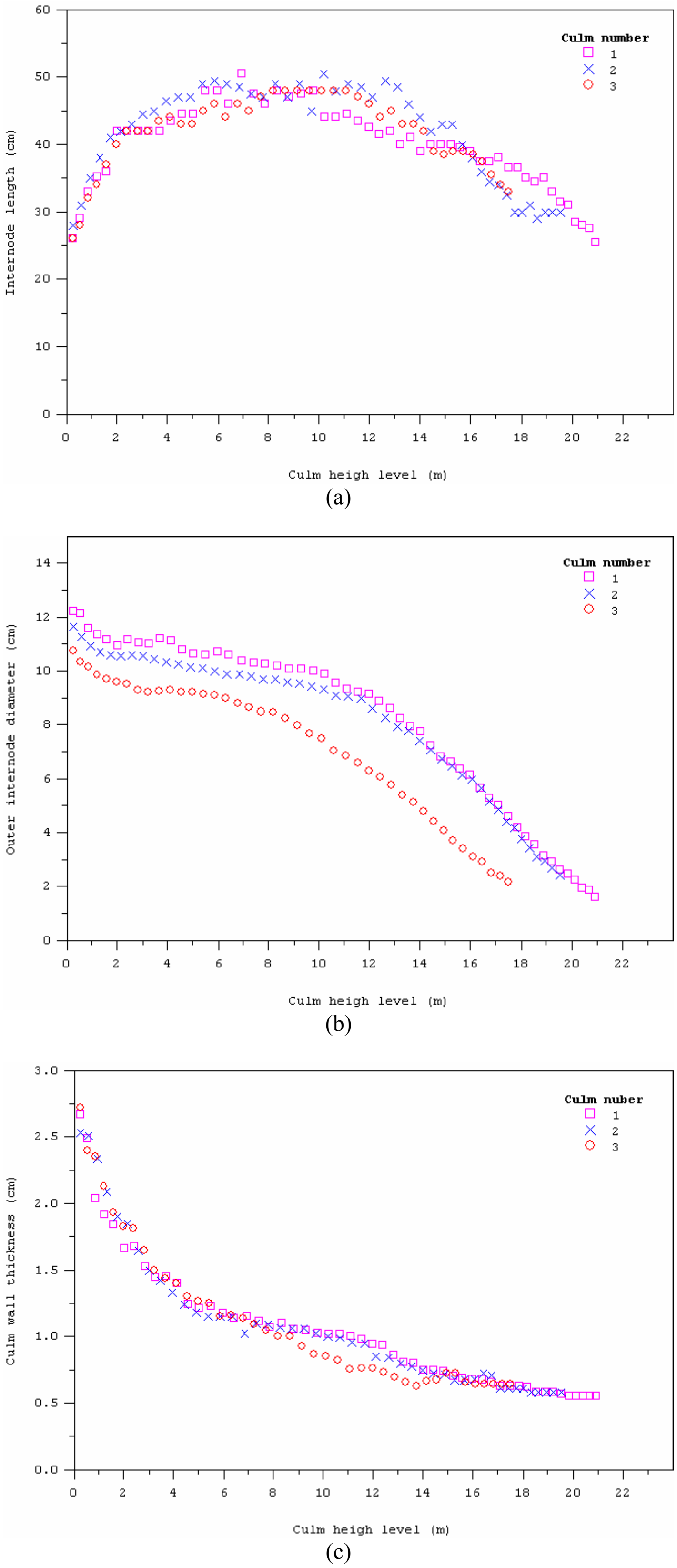


Figure 2. Variation of macroscopic characteristics along the height of *D. asper* (a) internode length, (b) outer internode diameter, (and) (c) culm wall thickness

Culm almost reaches its maximum growth within the first year. This implies that the main culm characteristics, such as culm length, length of internodes, and culm wall thickness show no further increment in the following years**.** It confirms results on the relation between culm characteristics and age of *Bambusa vulgaris* and *Gigantochloa scortechinii* (Abd. Latif and Liese, 2002). Figure 3 presents the tissue volume of internodes that might be obtained or calculated for each culm at different internode position along the culm length. The volume decreases from the bottom to the top part from 2,800 to 70 cm^3 due to the decreasing culm diameter and wall thickness.

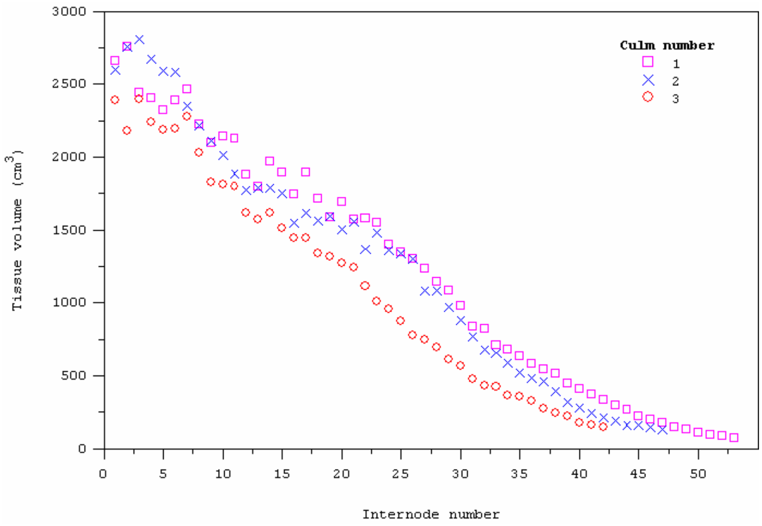


Figure 3. Decrease of the tissue volume of each internode along culm length of *D. asper*

Utilization *D. asper* as raw material for structural composite lumber would be affected by culm wall thickness. The width of strands used in Oriental Standard Lumber (OSL) manufacture shall not be less than 12.5 mm (Lowwood, 1997). For bamboo, this mainly depends on the culm wall thickness, which significantly decreases from the bottom to the top part. Therefore, bamboo strands might be only produced from the lower half of the culm, because the culm wall thickness is more than 12.5 mm. However, bamboo has a long straight grain which can compensate the potential shortcoming. It can easily be cut into thin pieces in radial direction using a strand disc-flaker.

Physical properties

Specific gravity

The suitability of *D. asper* for OSL will be dependent upon its physical properties. The specific gravity of *D. asper* at 12 percent MC is in the range of 0.55 to 0.90, as presented in Figure 4. The result indicates that the location along the bamboo culm is significant for the specific gravity value. The value slightly increases from the bottom to the top of the culm.

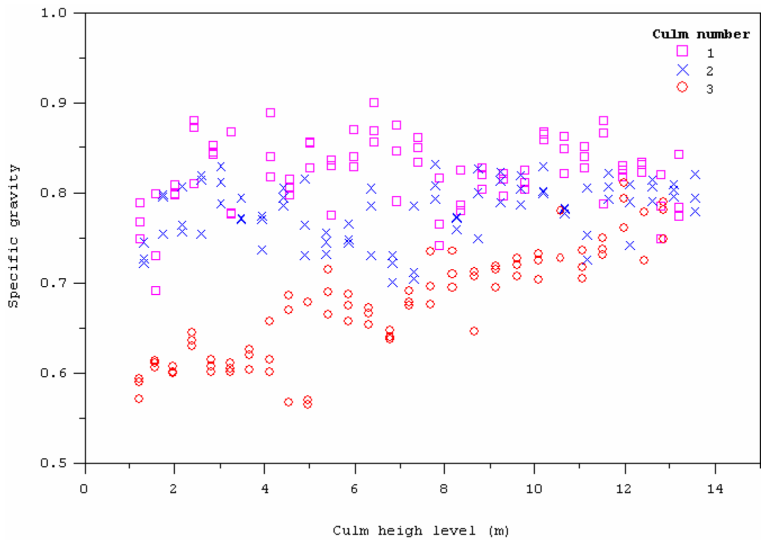


Figure 4. Variation of specific gravity along the culm of *D. asper* (12% MC)

Several studies (Abd. Latif *et al.,* 1993; Abd. Latif and Liese, 2002; Liese, 1998) have shown that the specific gravity increases along the culm from bottom to the top due to the higher fiber density at the culm periphery. The amount of these fibers strongly increases from the bottom to the top. The increment of specific gravity during the first year depends on the fiber cell wall thickening with ageing (Liese and Weiner, 1996; Abd. Latif and Liese, 2002).

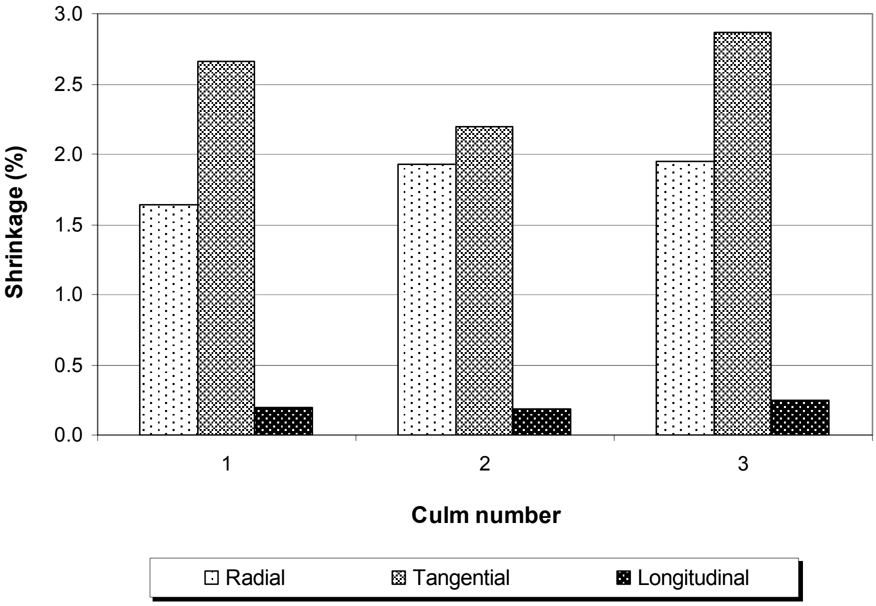
When compared to the hardwoods or heavy tropical timber species which are normally used in composites panels manufacturing, the specific gravity of *D. asper* is relatively high (> 0.60) (Blomquist *et al.,* 1983). On the other hand, specific gravity of *D. asper* would be affected by its position along the culm. Thus, if the composites are made from *D. asper*, a potential higher specific gravity variation should be considered.

Shrinkage and swelling

The dimensional shrinkage of *D. asper* in different directions, following the three orthotropic directions, is illustrated in Figure 5. The average shrinkage is 1.8 percent radial, 2.5 percent tangential and 0.2 percent longitudinal directions. The tangential shrinkage is about one-half as much in radial, and much less along the longitudinal direction. When compared to the wood species, shrinkage property shown by *D. asper* occurs as well as in others. Moreover, it shrinks less than some softwood and hardwood species, which mean value are 8 percent tangential shrinkage, 4 percent radial shrinkage, and 0.1 percent longitudinal shrinkage from the green to oven-dried condition (Skaar, 1988).

The regression equations with the coefficient of determinations (R^2) are plotted in Figure 6 to perform the relation between specific gravity and radial shrinkage. The results indicate a strong relationship between radial shrinkage and specific gravity. The shrinkage value decreases, when specific gravity value increases. When position and specific gravity are considered, radial shrinkage shows significant difference from another. Some sources explained that in bamboo, the tangential shrinkage is higher in the outer part of the wall than in the inner part. The shrinkage of the whole wall appears to be governed by shrinkage of the outermost portion, which possesses also the highest specific gravity due to the higher fiber content. Mature culms shrink less than younger ones.

Figure 7 shows the different directional swelling of the three *D. asper* culms. The mean-swelling value is 5.8 percent radial, 4.7 percent tangential and 0.4 percent longitudinal. Radial and tangential shrinkage are slightly different from one another, but the longitudinal shrinkage is distinctly lower than in the other two directions. Similarly, the swelling behavior varies in the growth direction in the same ratio like the shrinkage.



Culm No.	1			2			3		
Direction	R	T	L	R	T	L	R	T	L
Minimum (%)	0.42	0.59	0.00	1.14	0.79	0.00	0.80	1.12	0.00
Maximum (%)	3.16	4.91	0.71	3.13	4.22	0.64	3.85	4.34	0.60
Average (%)	1.64	2.66	0.20	1.93	2.19	0.19	1.94	2.86	0.25
SD (%)	0.58	0.96	0.18	0.45	0.80	0.17	0.63	0.80	0.97

Figure 5. Variation of shrinkage in different growth directions of *D. asper* (12% MC to oven-dried condition)

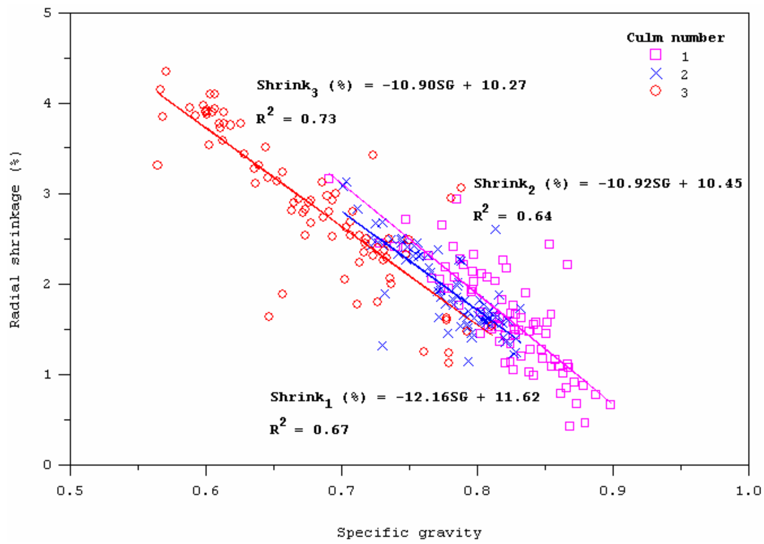
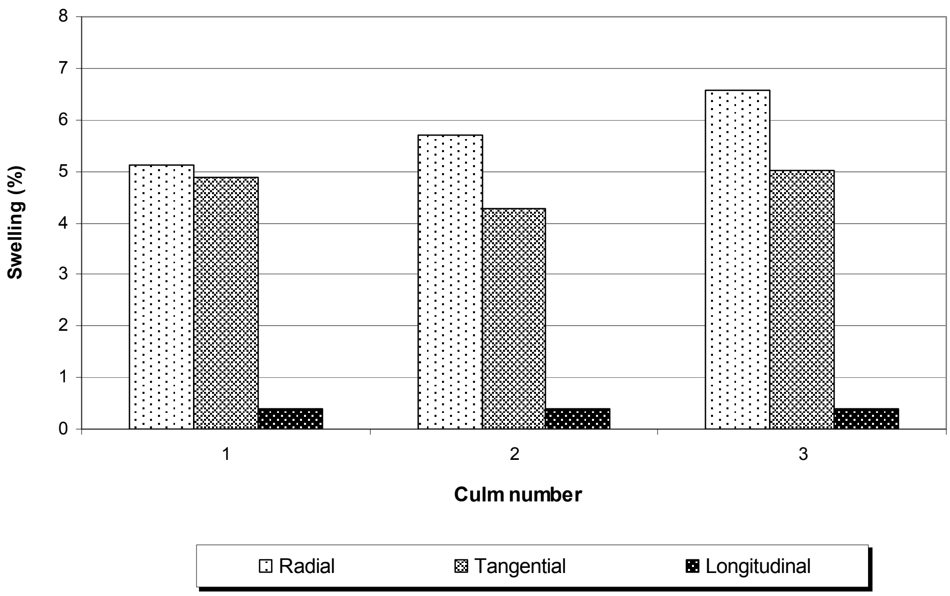


Figure 6. The relation between radial shrinkage and specific gravity of *D. asper*



Culm no.	1			2			3		
Direction	R	T	L	R	T	L	R	T	L
Minimum (%)	3.28	1.21	0.03	3.92	2.59	0.10	5.19	1.70	0.03
Maximum (%)	6.49	7.60	1.18	7.33	6.82	1.00	7.95	9.78	0.81
Average (%)	5.12	4.89	0.39	5.71	4.27	0.40	6.56	5.03	0.40
SD (%)	0.74	1.32	0.27	0.74	1.02	0.21	0.64	1.69	0.18

Figure 7. Variation of swelling for *D. asper* (from oven-dried condition till after 24 hrs soaking in water at 20°C)

The study reveals that the dimensional stability of *D. asper* in lengthwise direction is less than crosswise. This behavior is the same as in softwoods and hardwoods. In these wood species, most of the microfibrils orientations are aligned nearly parallel to the longitudinal axis. The explanation can be also applied to bamboo. Moreover, the shrinkage and swelling are slightly different between radial and tangential directions. This is in contrast to wood species which have greater dimensional stability in the tangential direction. The explanation is that bamboos have a different anatomical structure compared to wood with no radial cells and no growth rings (Liese, 1998). Thus, the dimensional movement is similar in the two directions.

Although the dimensional stability in the radial direction is affected by the position along the culm, the dimensional stability in all directions of *D. asper* is more favorable compared to that of wood. Moreover, the dimensional stability in tangential direction has no variation along the culm length. These are the favorable properties for the use of *D. asper* as a raw material in composite panels. Thus, *D. asper* has higher dimensional stability than those of wood.

Water uptake

The water uptake was measured after soaking the specimens (with an initial 12% MC) in water at 20°C for a period of 24 h. The value is in the range of 20-55 percent, presented in Figure 8. Moreover, the third culm has an average value higher (approximately 15% more) than the other culms because of its lower specific gravity. Water uptake is slightly different in each position and strongly related to specific gravity, as shown in Figure 9. In accordance to the specific gravity increase, the water uptake value slightly decreases from the bottom to the top. This is mainly due to the variation in the amount of parenchyma cells, which corresponds to water holding capacity.

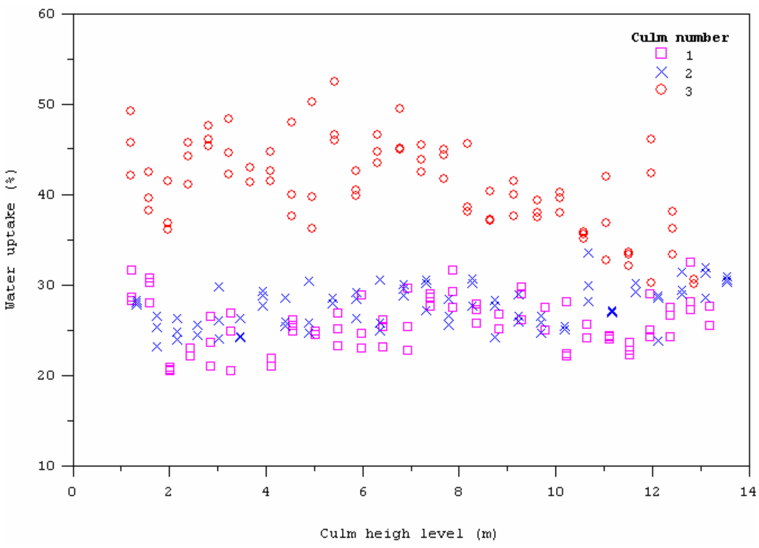


Figure 8. Variation of water uptake along the culm of *D. asper* (start at 12 per cent MC after 24 hrs soaking in water at 20°C).

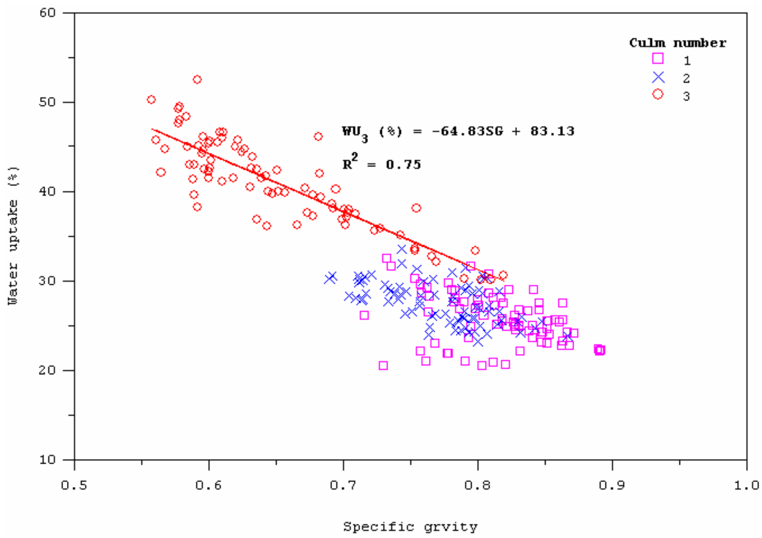


Figure 9. The relation between water uptake and specific gravity of *D. asper*. (start at 12% MC after 24 hrs soaking in water at 20^{o}C)

As a result, water uptake is influenced by position in culm which has different cell types and amounts. The tissue of a culm consists of parenchyma cells and the vascular bundles, which are composed of vessels, sieve tubes with companion cells, and fibers. The percentage distribution of cells shows a defined pattern within the culm, both horizontally and vertically. Parenchyma and conducting cells are more frequent in the inner third of the wall, whereas in the outer third the percentage of fibers is distinctly higher. In the vertical direction, the amount of fibers increases from bottom to top, whereas that of parenchyma decreases (Liese, 1998).

Compared to wood, the water uptake behavior of bamboo could reveal certain permeability. This property will be analyzed for further processing, especially coating and gluing. The permeability of the pore structure in wood greatly influences the adhesive penetration. From an appropriate point of view, the variation of *D. asper* anatomical structure causes differences in water uptake in the radial and longitudinal directions. In strands originating from the bottom internodes of bamboo, composed of more parenchyma cells with lower specific gravity, the adhesive can more deeply penetrate, it will perform the sufficient bonding strength and can produce a high quality composite. In radial direction, the water uptake varies within the same piece of strand because of the specific gravity variation of inner and outer side of culm. Thus, if the composite panels from *D. asper* are to be produced, the variation of this property should be considered.

The information generated will be used to assess the suitability of this bamboo species for composite applications. The results demonstrate some typical properties like a higher specific gravity of *D. asper* compared to wood, which will limit its use only for higher specific gravity composites products. The dimensional stability is an important property due to the small shrinkage and swelling value. However, further research, such as mechanical properties and gluability, are needed to optimize the board properties made from this bamboo species.

CONCLUSIONS

Culm macroscopic characteristics and some physical properties of *D. asper* were analyzed. The following conclusions can be drawn from this study:

All the culm characteristics differ within each internode along the culm; its outer diameter and wall thickness gradually decrease with the height; internode length increases from the bottom to the middle part and decreases towards the top.

The tissue volume of each internode also decreases from bottom to the top. The decrease is strongly related to the macroscopic characteristics of the culm.

Specific gravity significantly increases from bottom to the top of the culm.

Longitudinal shrinkage and swelling are small. Dimensional stability in radial direction is not significantly different from the tangential direction.

Water uptake decreases with increased specific gravity.

ACKNOWLEDGEMENTS

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Publication II

Mechanical Properties of Sweet Bamboo (*Dendrocalamus asper* Backer) [1]

Pannipa Malanit[1, 2, *], Marius C. Barbu[1, 3], Arno Frühwald[1]

[1] *Department of Wood Science, University of Hamburg, Germany*
[2] *School of Engineering and Resources, Walailak University, Thailand*
[3] *Faculty for Wood Industry, "Transilvania" University Brasov, Romania*

Abstract: The aim of this research was to determine the basic properties of *Dendrocalamus asper* Backer and its suitability as a raw material for manufacture of composite panels. For this purpose some aspects, such as macroscopic characteristics, physical and mechanical properties, pH value, buffer capacity and bonding quality using different types of glue were studied. This research presents the mechanical properties in relation to the position along bamboo culm, for each internode and in three culms.

The results demonstrate that *D. asper* shows high strengths. The mean values of the modulus of rupture (MOR), modulus of elasticity (MOE), compression strength perpendicular to grain and shear strength parallel to grain are 198.52 MPa, 15,363 MPa, 14.39 MPa and 11.91, respectively. They vary with the position in the culm and significantly depend on the specific gravity. On the other hand, shear strength parallel to grain are not depend on the specific gravity. The value slightly differs along the culm length.

As result, it is concluded that *D. asper* has superior mechanical properties, which are comparable to some softwood and hardwood species. It should therefore be promoted as a substitute for wood in the manufacturing of structural composite lumber like Oriented Strand Board or Oriented Strand Lumber.

Key words: Dendrocalamus asper Backer, Mechanical properties, Oriented Strand Lumber, Oriented Strand Board

INTRODUCTION

Bamboo is a perennial, giant, woody grass belonging to family Poaceae which covers more than 1,200 species in 50 genera in the world (Chapman, 1996; Qisheng *et al*., 2002). The total area of bamboo forest in the world amounts to 14 million ha distributed mainly in the most of the tropical countries of Asia, South and Central America and Africa. However, Asia is the richest continent with about 65 % of total world bamboo resources (Lobovikov *et al.,* 2007). Bamboo is considered as a composite material because it consists of cellulose fibers imbedded in a lignin matrix. Cellulose fibers are aligned in the length of the bamboo providing high strength and rigidity in that direction (Liese, 1998). Bamboo has been used for a very long period by humans. It has received increasing attention owing to its easy propagation, vigorous regeneration, fast growth, high productivity and quick maturity. Furthermore, it is an efficient user of land, and produces more biomass per unit area than most wood species. Hence, bamboo products have been found increasing uses in various applications such as: flooring, handicrafts, sports equipment, musical instruments and other building materials.

E-mail: p.malanit@holz.uni-hamburg.de, mpannipa@wu.ac.th

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Additionally, bamboo as raw material is used for pulp, paper, veneer, decorative boards and panels. Bamboo could be an excellent raw material to replace traditional wood in the industries since there is only a slight difference in the anatomical structure and even in the chemical composition (Abd. Razak *et al.,* 1995; Liese, 2004). Recently, bamboo has been regarded as a raw material for structural composite products such as: Oriented Strand Lumber (OSL) and Oriented Strand Board (OSB). Since its morphology, micro- and macroscopic characteristics, physical and mechanical properties differ from those of wood, methods, technology and equipment for wood processing cannot be applied indiscriminately for bamboo utilization. According to Abd. Latif and Liese (2002), the bamboo properties, which affect on its utilization, are depended on many factors, such as the age, culm height, growth location etc. For this reason, information on macroscopic characteristics, physical and mechanical properties and gluability of bamboo are necessary for assessing its suitability for end products.

The suitability of bamboo for structural composite products is proven by its mechanical properties. Analysis of mechanical properties is the study of behavior of the materials under different loading conditions. Information about the deformation behavior, stress and the failure behavior of bamboo in different forms is important data for the effective use of bamboo as an alternative raw material for OSL and OSB. Therefore, the variation of the mechanical properties, influenced by the specific gravity and position in the culm, was analyzed.

MATERIALS AND METHODS

Some of the investigations were done at Wood Science and Engineering Research Unit, Walailak University in Nakhon Sri Thammarat, South of Thailand and further in the Department of Wood Science, University of Hamburg, Germany.

Materials

Three *D. asper* culms were harvested in April, 2007 from a private plantation, located in Nakhon Sri Thammarat province, South of Thailand. The terrain is mostly rugged hilly forest area with an elevation of about 600 m above sea level, 217 mm mean annual rainfall, and 27^0C mean temperature. The culms were three years old as confirmed by macroscopic features.

The culms were cut into each internode along their length. From following internode, three specimens were randomly selected and cut into size requested by each standard (ASTM D 143-94). Altogether, 84 specimens were cut from each culm and analyzed for the various tests. The air-dried specimens, (MC 50-60%), were placed for 8 weeks in a conditioning chamber, at a temperature of 20°C and relative air humidity of 65% until the MC reached 12%, before determination of the mechanical properties.

Methods

Following mechanical properties were tested**:**

Static Bending

The static bending test method was performed with some modification to the ASTM standard D 143-94, because the specimen shape changes along the culm height. The specimen width depended on the culm-wall thickness, while the thickness was kept equal to the width. The specimen length, which was parallel to grains, varied depending on the thickness of the specimen. The span was established in order to maintain a minimum span-to-depth ratio of 14. The test was carried out in the 50 kN Karl Frank Universal Testing Machine. Load was applied at mid-span of the specimen culm-wall thickness with a constant speed of the movable crosshead of 2.5 mm/min until specimen failure occurred. The maximum load at failure was recorded for Modulus of Rupture (MOR) calculation, while the resulting load and the deflection at the proportional limit were measured for Modulus of Elasticity (MOE) calculation. The specimens were cut near the point of failure in the length of 25 mm for specific gravity and moisture content determinations.

Compression Perpendicular to Grain

Specimens for the compression strength perpendicular to grain test were also taken from each internode along the culm length (6 cm length × 1 cm × culm wall thickness). The testing method was performed with some modification to the ASTM standard D 143-94, since the specimen width varied depending on the culm-wall thickness. The trials on the specimens were done using a universal testing machine (LLOYD 150 kN) equipped with a computerized data acquisition system. The load was applied through a metal bearing plate 50 mm in width, which was placed cross the upper surface of the culm-wall thickness and at the right angles to the length. This was applied continuously throughout the test at a constant speed of the movable crosshead of 0.305 mm / min. The compression stress perpendicular to grain was calculated at fiber stress at proportional limit ($\sigma_{P.L.}$). The specific gravity and moisture content was determined for each specimen.

Shear Parallel to Grain

For the determination of shear strength parallel to grain, specimens were also taken from each internode. The testing method was performed with some modification to the ASTM standard D 143-94, because the specimen shape changes along the culm height. All specimens were cut parallel to grains with the size of 2 cm × 1 cm × culm wall thickness. The specimens were tested on 50 kN Karl Frank Universal Testing Machine. The load was applied continuously throughout the test at constant speed of the movable crosshead of 0.6 mm / min. Only the maximum load was recorded for shear strength calculation. The specific gravity and moisture content was determined for each specimen.

RESULTS AND DISCUSSION

The suitability of *D. asper* for OSL manufacture will be dependent upon it's mechanical properties. They were investigated as static bending, compression perpendicular to grain and shear parallel to grain.

Static Bending

Figure 1 shows the variation of modulus of rupture (MOR) along the culm height. The values are in the range of 127.52 to 253.45 MPa, and the average specific gravity for bamboo specimens at 10.97% moisture content is 0.766. The result demonstrates that MOR appreciably varies in the relation to culm height location but the variant pattern from the bottom to the top of the culm is not clear. According to the study of Royal Forest Department (2003) observed the mechanical properties of *D. asper* in Thailand and reported that MOR value varies from 92-100 MPa and that it slightly differs between locations of the culm. This result also agrees with some findings of other researchers including Gnanaharan *et al*. (1995) and Li and Li (1983). Notable, the 3rd culm has an average value lower (approximately 25% less) than the other two culms because of its lower specific gravity, as mentioned below.

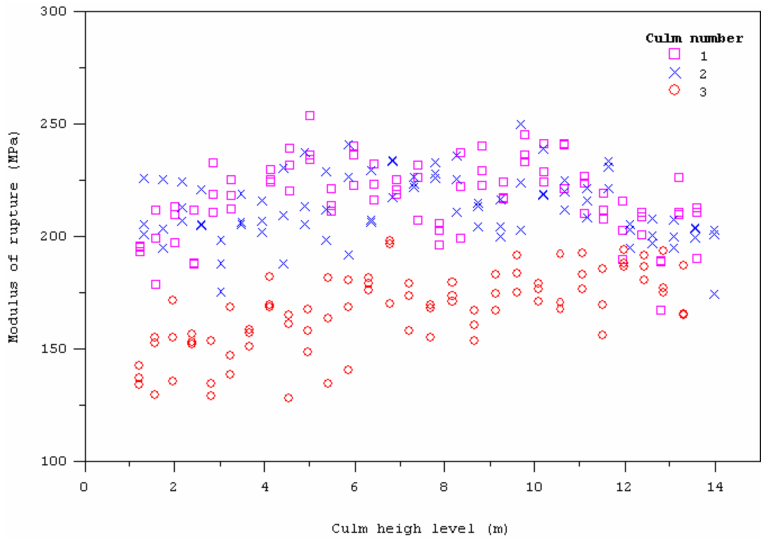

Figure 1. Variation of modulus of rupture along the culm of *D. asper*

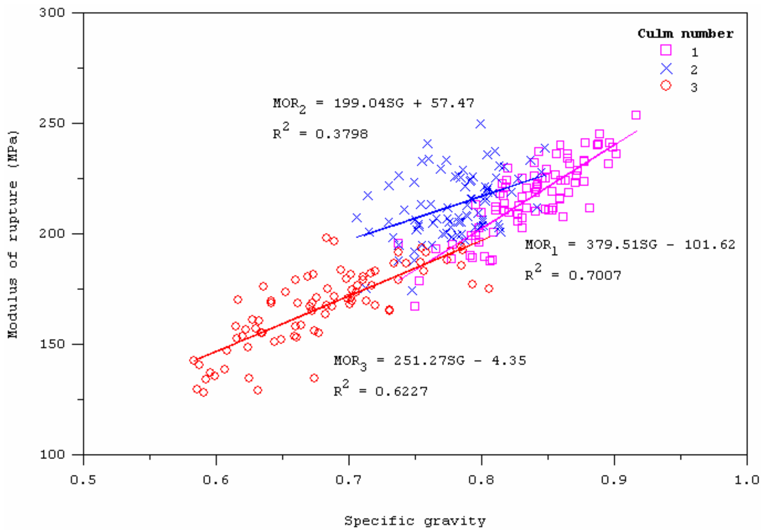

Figure 2. Correlation of specific gravity on modulus of rupture and of *D. asper*

The result further reveals that MOR is strongly related to specific gravity, as shown in Figure 2. The regression equations with the coefficient of determinations (R^2) are plotted to perform the strong relation between MOR and specific gravity. The MOR increases, when specific gravity increases. This observation is consistent with Anwar *et al*. (2005) and Yu *et al*. (2008) who found that the strengths of bamboo (i.e., MOR, MOE, compressive strength parallel to grain and tensile strength) depend on its specific gravity. Abd. Razak *et al.* (1995) explained that the bamboo specific gravity is closely related to the relative proportions of vascular bundles and ground tissues; especially as the proportion of thick-walled sclerenchyma cells within the culm.

Interestingly, bending failure of bamboo often occurs by horizontal shear. Along with low shear strength, as mentioned below, bamboo has low strength to splitting.

The modulus of elasticity (MOE) for the three culms of *D. asper* along the length is presented in Figure 3. The values are in the range of 8,465-25,255 MPa at an average moisture content of 10.97% and an average specific gravity of 0.766. It is evident that MOE slightly varies with the position in the culm, although the variant pattern from the bottom to the top of the culm is also not clear. Furthermore, the MOE values vary significantly in the relation to bamboo specific gravity which is presented in Figure 6. The linear regression equation and coefficient of determination (R^2) indicate a small relationship between the two properties.

This result is confirmed by the findings of Abd. Latif *et al*. (1990 & 1994). They found that the mechanical properties of bamboos vary significantly with culm height. Additionally, the mechanical properties of bamboo are also correlated to anatomical features, such as vascular bundle size and distribution and fiber dimensions. It is generally accepted that the variation of bamboo specific gravity is mainly due to the variability of anatomical structures of bamboo along the culm. Hence, some deviations of MOE could be explained by the variation of the specific gravity from the bottom to the top of the culms.

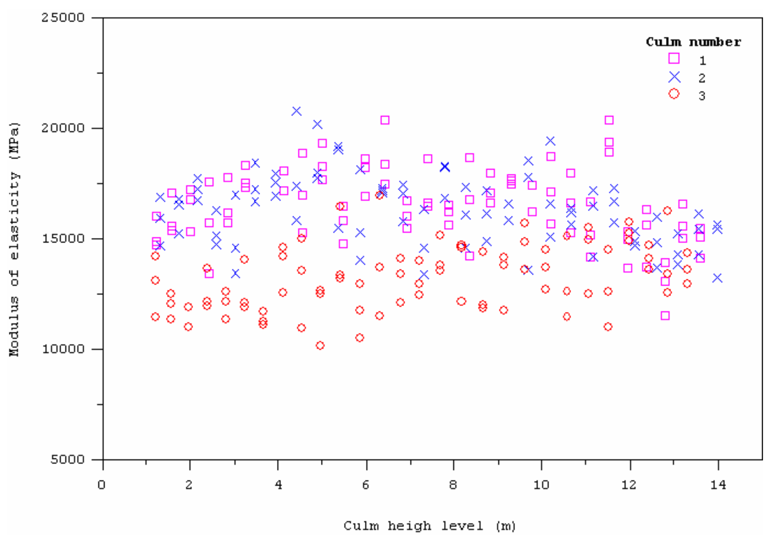

Figure 3. Variation of modulus of elasticity along the culm of *D. asper*

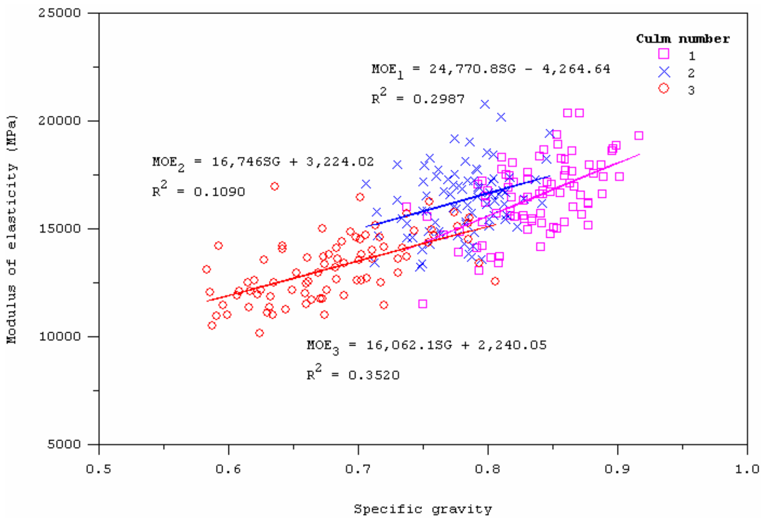

Figure 4. Correlation of specific gravity on modulus of elasticity of *D. asper*

Compression Perpendicular to Grain

The compression strength perpendicular to grain of the three culms of *D. asper* is illustrated in Figure 5. The values vary extremely from 4.57 to 28.30 MPa at an average moisture content and specific gravity of 8.25% and 0.767, respectively. The result indicates that the location along the bamboo culm is also significant for this property. For the effect of the height, the compression strength slightly increases from the bottom to the top of the culm. The 3rd culm also has the lower compression strength than the other culms. It could be explained by its lower specific gravity. In accordance to the specific gravity increase, the strength value gradually increases, as illustrated in Figure 6. This is mainly due to the variation of microstructure in the bamboo culm, as mentioned above.

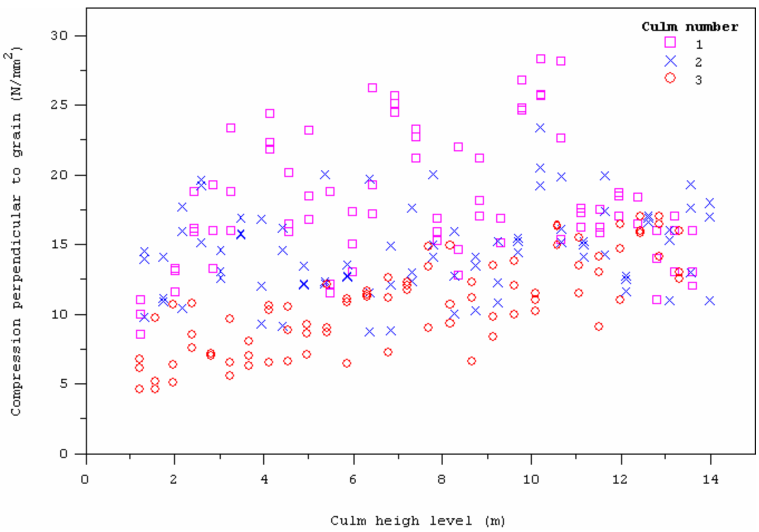

Figure 5. Variation of compression strength perpendicular to grain along the culm of *D. asper*

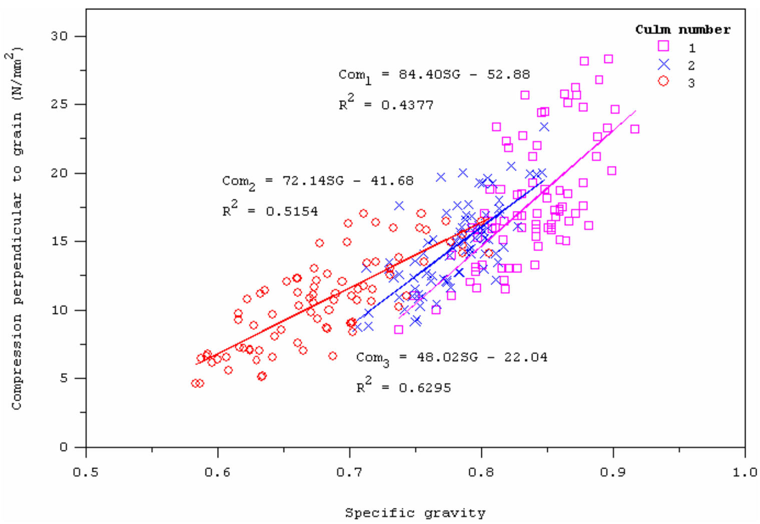

Figure 6. Correlation of specific gravity on compression strength perpendicular to grain of *D. asper*

Shear Parallel to Grain

The shear strength parallel to grain of *D. asper* varies in the range of 8.05-15.36 MPa, presented in Figure 7, at an average moisture content of 9.92% and an average specific gravity of 0.746. This result agrees with some part of the report of the Royal Forest Department (2003) which studied the shear strength parallel to grain of *D. asper* in Thailand and found that the value varies from 8.4-10.0 MPa. In contrast to findings of other properties, shear strength parallel to grain is constant along the culm location and also does not depends on specific gravity, as presented in Figure 8.

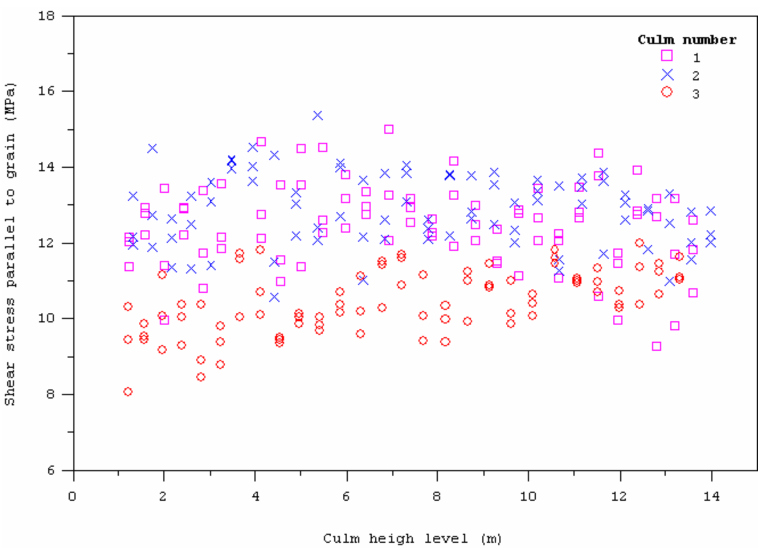

Figure 7. Variation of shear strength parallel to grain along the culm of *D. asper*

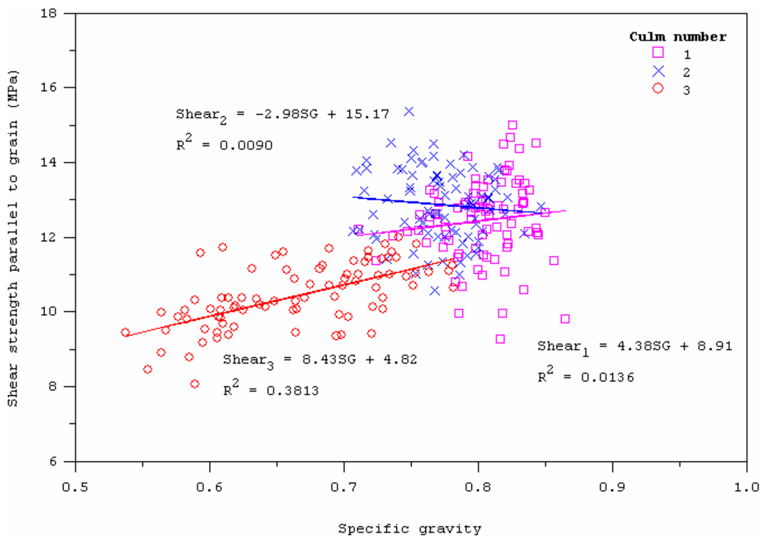

Figure 8. Correlation of specific gravity on shear strength parallel of *D. asper*

A comparison of the mechanical properties of *D. asper* to those of other wood species which are used as raw material for wood composite manufacture is presented in Table 1. In general, the strength and stiffness of bamboo is higher than that of wood. The mean MOR of *D. asper* is approximately 2 to 3 times higher than softwood and hardwood species, while the mean MOE is slightly higher compared to other wood species. As well, its compression strength perpendicular to grain is higher than wood species approximately 2 to 3 times. Interestingly, *D. asper* shows quite similar shear strength parallel to Rubberwood and a slightly higher strength than another species. However, all of the above mentioned wood species have lower specific gravity by 15 to 50%.

Table 1. Comparison of the average values for physical and mechanical properties of *D. asper* and used wood species for panels manufacturing.

Species	SG	MOR (MPa)	MOE (GPa)	Com ⊥ (MPa)	Shear // (MPa)
Dendrocalamus asper	0.75	199	15	14.4	11.9
Douglas-fir (*Pseudotsuga menziesii*) [1]	0.48	85	13	5.5	7.8
Red Pine (*Pinus resinosa*) [1]	0.46	76	11	4.1	8.4
Yellow poplar (*Liriodendron tulipifera*) [1]	0.42	70	11	3.4	8.2
American Aspen (*Populus tremuloides*) [1]	0.38	58	8	2.6	5.9
Rubberwood (*Hevea brasilliensis*) [2]	0.65	87	9	9.2	11.8

Source: [1] USDA Forest Service (1999)
[2] Hong and Sim (1994)

From a practical point of view, the strength of *D. asper* in grain direction is extremely high, especially MOR and MOE. It might be suitable as the raw material for such products as oriented structural boards which bears unidirectional load. Additionally, its low shear strength parallel to grain might encourage easy strand preparation. Nevertheless, the strong variation of material properties is a disadvantage to take in consideration. The results show that the mechanical properties of *D. asper* vary along the culm length. Furthermore, its strength is more variable than that of wood. According to the mechanical properties, the raw material for composite products should be considered based on their strength to weight ratio. As a result, *D. asper* has a low strength to weight ratio, it is not desirable for some applications because of it's high specific gravity. All these complex features must be taken into concern for the bamboo utilization in the wood composite manufacture. However, its strength (i.e., bending strength) and availability may outweigh this disadvantage.

CONCLUSIONS

Some properties of *D. asper* have been analyzed. The following conclusions can be drawn from this study:

1. The mechanical properties of *D. asper*, except for shear strength parallel to grain, vary in the relation to culm height location. Generally, the top of the culm shows the highest mechanical properties.
2. The mechanical properties of *D. asper*, except for shear strength parallel to grain, also are strongly related to specific gravity. The properties will increase, when specific gravity value increases.
3. The bending strength (i.e., MOR and MOE) of *D. asper* are approximately 2 to 3 times higher than those of traditional wood species used for panel manufacturing.
4. The variability of some mechanical properties from the third culm to the other is higher than between wood logs and significantly depends on microstructure and specific gravity variations of bamboo.

ACKNOWLEDGEMENTS

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THE GLUABLITLY AND BONDING QUALITY OF AN ASIAN BAMBOO (*Dendrocalamus asper* Backer) FOR THE PRODUCTION OF COMPOSITE LUMBER

P. Malanit[1,*], M. C. Barbu[1, 2] & A. Frühwald[1]

[1]Department of Wood Science, University of Hamburg, Hamburg, Germany
[2]Faculty for Wood Industry, "Transilvania" University Brasov, Romania

KEYWORDS

Bamboo, *Dendrocalamus asper* Backer, Gluability, pH, Buffer capacity, Structural Composite Lumber, Oriented Strand Lumber, Oriented Strand Board

ABSTRACT

The aim of this research was to determine the fundamental properties of *Dendrocalamus asper* Backer and its suitability to be promoted as a raw material for the manufacture of structural composite lumber. The purpose was to study certain aspects of pH value, buffer capacity and the bonding quality of bamboo strands. The pH and acid-buffering capacity were investigated in three locations along the culm length. The results indicate that the average pH value is 5.4, which is quite similar to some softwood species. An average acid-buffering capacity is 0.53 milliequivalents which is a high buffer capacity compared to that of other wood species. There are no differences in the values taken from the different locations in the culm. The bonding quality of the bamboo strands was evaluated for three adhesives using a special device called an Automated Bonding Evaluation System (ABES). This experiment proposed three essential parameters, i.e., three types of glues; Melamine Formaldehyde (MF), Melamine Urea Phenol Formaldehyde (MUPF), and Phenol Formaldehyde (PF), and four pressing temperatures (150, 170, 190 and 210°C) and different pressing time (20 to 300 seconds). In accordance with this study, bond quality was improved by increasing the hot pressing time and temperature. The best adhesive to bond bamboo strands following the ABES was found to be MF.

INTRODUCTION

In recent years, the demand for high quality wood for construction has increased because the world population has been rising especially in Asia and Latin America and the available quantity and quality of wood from natural forest has been declining. Consequently, the search for non-wood resources as an alternative to raw materials in place of the traditional use of wood has been accelerated. Bamboo is a non-wood lignocellulosic material which has been widely used since thousands of years in tropical countries as a material for construction, furniture manufacture and daily household uses. Recently, it has been widely used as a raw material for wood products manufactured in some Asian factories, such as for pulp and paper, plywood, Medium Density Fiberboard (MDF), Particleboard (PB) and Oriented Strand Board (OSB), owing to its high strength and properties.

The bamboo culms are generally cylindrical and hollow. The outer part of the culm is covered by a cutin layer with a wax coating on top, while the inner part consists of parenchyma cells and vascular bundles, which are comprised of vessels, thick-walled fibers and sieve tubes (Liese 1985 & 1998). A previous study has reported that the waxy outer layer cuticle is harder to glue than the inner layer of the culm (Lee *et al*. 1996). It is well established that the main constitutes of bamboo culms are cellulose, hemicellulose and lignin. From the study of Kamthai (2003), the average chemical composition of a three-year old *Dendrocalamus asper* comprises α-cellulose (68%) and lignin (29%). It contains about 1.5% of ash, 6% of alcohol-benzene soluble, 8% of hot-water soluble, 7% of cold-water soluble and 25% of 1% NaOH soluble materials. Compared with other wood species, the chemical composition of *Dendrocalamus asper* is similar to that of wood with cellulose, hemicellulose and lignin accounting for over 90% of the total mass. Its cellulose and lignin contents and hot-water solubility are comparable to the reported cellulose and lignin content of softwoods, which are illustrated in Table 3.

The gluability of wood is influenced by its surface properties, such as roughness, pH, buffering capacity etc. The pH values of common wood species are on the acidic side. Woods from temperate zones have pH levels in the range of 3.3-6.4, while tropical woods have pH levels in the range of 3.7-8.2 (Fengel & Wegener 1984). The pH values of several agriculture materials are higher than those of woods. The values are more than 6 in the case of wheat straw, flax and reed canary grass, and more than 7 in the case of hemp (Hague *et al.* 1998). The buffer capacity is the resistance of wood to change in its pH level. Maloney (1993) suggested that the wood which requires a larger amount of acid catalyst to decrease the pH to the level required for optimum adhesive cure is considered as a high buffering capacity species. Many previous researchers (Freeman 1959; Johns & Niazi 1980; Van Niekerk & Pizzi 1994; Zanetti & Pizzi 2003) studied the pH and buffer capacity of wood and their effects on curing time of some resins and product properties. According of these studies, the adhesive curing time and its bond strength are decreasing with the increasing of wood pH and buffer capacity. Moreover, catalyst buffering action has strong effects on curing time and the degree of networks formed in case of MUF, PF and tannin adhesives.

A change in raw material type, however, may affect the physical and mechanical properties of the wood based composite boards and require further adaptation of the processing conditions, such as the adhesive system and hot pressing parameters. Humphrey (1993) developed the Automated Bonding Evaluation System (ABES) for determining the rate of strength development of adhesives applied on wood strips as they cure (Humphrey 2006). This equipment allows accurate control of pressure, platen temperature and pressing time by lab-shear veneer samples. This technique leads to an interest in developing a faster quantitative screening for wood-based composite hot-pressing.

To obtain high bonding strength, the pressing parameters must be adjusted for the pH conditions encountered. Thus, the pH and buffering capacity measurement of raw materials is fundamental to determine the optimum pressing parameters for panel manufacturing. Understanding these properties is important when discussing the suitability of bamboo as a raw material for Oriented Strand Lumber (OSL) or Oriented Strand Board (OSB) manufacture. Therefore, the objectives of this article are to measure and compare the mean pH value and buffer capacity in each location of *Dendrocalamus asper* culms, and investigate the strength development characteristics and bonding quality between bamboo strands using different adhesives for exterior application by using the ABES equipment.

MATERIALS AND METHODS

Some of these investigations were done at the Wood Science and Engineering Research Unit, Walailak University in Nakhon Sri Thammarat, South of Thailand and further in the Department of Wood Science, University of Hamburg, Germany.

Materials

Three *Dendrocalamus asper* culms for this study were collected in April 2007 from plantations located in Nakorn Sri Thammarat, South of Thailand. Three culms of three years old were harvested and transported to Wood Science and Engineering Research Unit, Walailak University in Thailand for future investigation. These bamboos had an average culm length of 19 m. The culm diameter at the bottom was about 11.5 cm, while the top culm was about 2 cm. An average culm wall thickness was 1.6 cm. An average specific gravity at 12% MC was 0.75. Each culm was divided into three parts each of 6 m lengths. Specimens were obtained from these three locations which were related to the height position in the culm following the scheme in Figure 1.

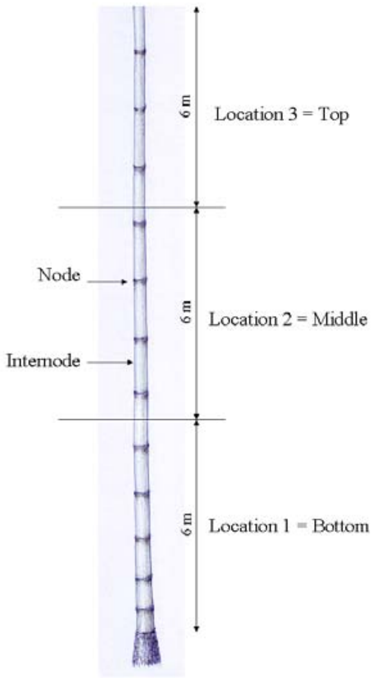


Figure 1 Sampling technique from *Dendrocalamus asper* culm.

Bamboo chips from each part were ground into particles by a Wiley machine. The samples were then placed in a shaker with sieves to pass through a 40# mesh screen (0.425 mm in diameter) and retained on a 60# mesh screen (0.250 mm in diameter). The particle remaining on the mesh screen was used for the measurement of pH value and buffer capacity.

Three adhesives were used in this research: Melamine formaldehyde resin (MF), Melamine urea phenol formaldehyde resin (MUPF) and Phenol formaldehyde resin (PF). The MF resin (Prefer13H560) was supplied by Dynea. The MUPF resin (KML 534) was obtained from BASF. The PF resin (Bakelite 1279 HW) was supplied by Hexion Specialty Chemicals GmbH. Their properties are presented in Table 1.

Table 1 Some properties of three glues

Properties	Glue types		
	MF	MUPF	PF
Appearance	Brown liquid	Pale brown	Red brown
Solids content (%)	62.5	65	48
pH at 20^0C	9.73	9.3-9.8	8.5-10.5
Viscosity at 20^0C (mPa$*$s)	100-150	150-400	650-700

pH Value Measurement

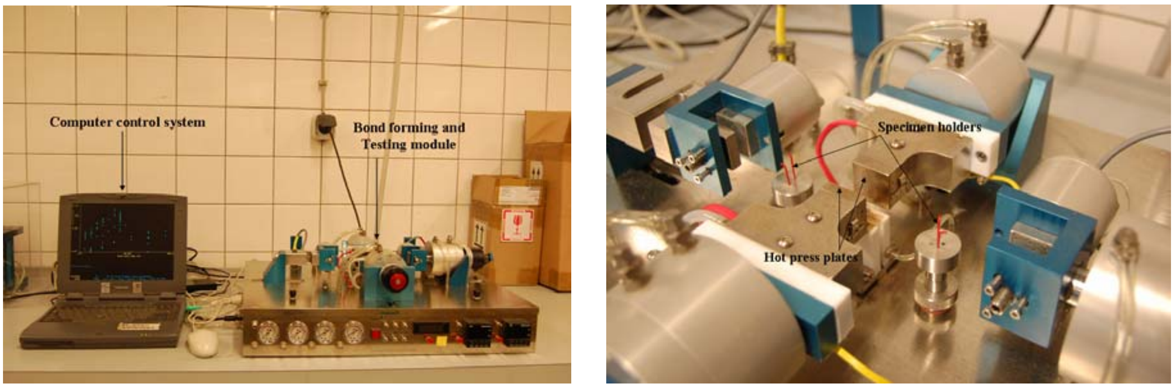
The pH measurement procedure was adapted from the measurement of hydrogen ion concentration (pH) of paper extracts by cold extraction method (TAPPI T 509 om-83). One gram of specimen was transferred into a 100-ml beaker and distilled water (pH $\approx$ 6.7) was added until the specimen was wet. More distilled water was added again to bring the total volume to 70-ml. The mixture was stirred and allowed to soak for one hour at room temperature (20^0C). A pH meter (Type WTW pH 330i) was used for the measurement. The pH value was recorded when there was no more drift in the measurement for a period of 30 seconds.

Buffer Capacity Measurement

The buffer capacity measurement procedure was adapted from the method used by Maloney and Borden Chemical Inc. (Maloney 1993). 30 grams of dry specimen were soaked in 400 g of distilled water at 20 ± 1^0C for 30 minutes. The mixture was stirred during the soaking. The liquid was then decanted into a Buchner (Coors) filter no.2 containing a Whatman filter paper no.4. The liquid was drawn though the filter paper with the aid of a vacuum and 150 g of the liquid was placed in a 400-ml beaker. The same pH meter was used for determining the pH value and the original pH value was recorded. Sulfuric acid (0.01N) was next added to the liquid in small increments (5 ml). The liquid was mixed by a magnetic stirrer and the pH was measured after each addition, until a pH of 3.5 was reached. The pH and milliequivalents (N×ml) of acid needed to change the pH to 3.5 were calculated as the buffer capacity.

Bonding Quality

The bonding quality measurement was investigated with the Automated Bonding Evaluation System (ABES). This device is composed of a small press and test module, which are present in Figure 2, and a computer control system with testing-software program.



(a) (b)

Figure 2 Details of Automated Bonding Evaluation System device, (a) An overview of the ABES system, which is composed of the bond-forming and testing module and computer control system (b) A close-up of the bond pressing zone, which is composed of the hot press plates and specimen holders.

The 0.7 mm thick bamboo strands were obtained from the bottom internodes having culm wall thicknesses thicker than 2.0 cm. The bamboo strand was cut to a size of 12 cm by 2 cm for the ABES bond quality testing. All strands had been placed in a conditioning chamber, at a temperature of 20°C and relative humidity of 65% to a final average MC of 12% at the time of glue spreading. Three adhesives for exterior uses were investigated: MF, MUPF and PF (Tabble1). All adhesives were blended according to the specification of their suppliers. The adhesive was then spread on one surface (5x10 mm) of the bamboo strand with a hand brush. Spread rate was approximately 200 g/m² of a single glue line. As suggested by working hypothesis and literature review (Lee *et al.* 1996), the outer layer of bamboo culm is harder to glue than the inner layer. Hence, two bamboo strands were placed in the bond pressing zone of ABES with both grains parallel to eachother in an outer-layer-to-inner-layer configuration. After lay up, the strands were then hot-pressed under controlled parameters of temperature, time and pressure which are given in Table 2. Immediately after each bond was cured to the required level, it was tested to destruction in shear mode according to the ASTM standard test method D-3165-07. Tensile load and gripping head movement (sample elongation) were PC-monitored during strands pulling, and shear-stress to failure was calculated. The operation manner of equipment experiment is described in Figure 3.

Table 2 Design parameters for the trials

Sample parameters	Interval
Resin types and Hardener	• MF + 3% NH_4NO_3 • MUPF + 3% NH_4NO_3 • PF + 6% K_2CO_3
Resin spread rate	200 g/m^2
Sample moisture content	12%
Pressing parameters	
Pressing temperatures	150, 170, 190 and 210^{0}C
Pressing times	20 to 300 seconds (in 20 seconds steps)
Pressure	4 N/mm^2 (constant)

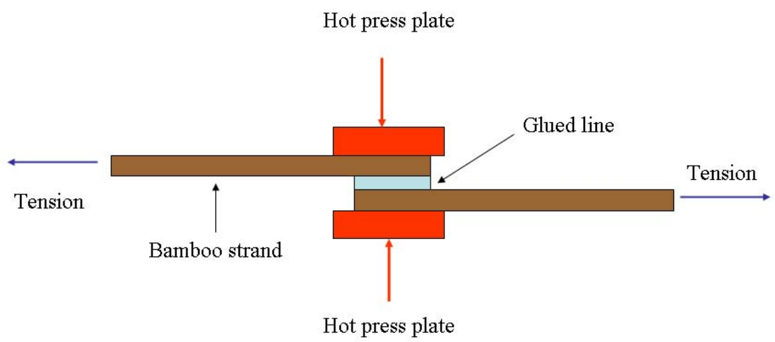


Figure 3 Schematic description of shear test by Automated Bonding Evaluation System (ABES)

RESULTS AND DISCUSSION

pH and buffer capacity are important parameters which characterizes *Dendrocalamus asper* as a substitute for wood in composite panel manufacturing. The pH can be measures the acidity of material, while buffer capacity measures the changing resistance of material to its pH level.

pH Value

Table 3 presents the pH value data, which was obtained for the pH measurement from three locations of three culms. The pH value of *Dendrocalamus asper* is on the acid side. The mean values of bottom, middle and top parts of culm are 5.36, 5.45 and 5.38, respectively. As for the results, the pH values vary slightly depending on the location in the culm. Table 4 presents the pH values of several wood species. The pH value of *Dendrocalamus asper* is quite similar to European beach.

The cross-linking rate of most thermosetting adhesives used in wood composite manufacturing depends on the pH levels. Thence, the acidity of particles and the catalyst which is added into the adhesive play a very important role in providing the optimum condition during resin curing. The higher pH level species need an added catalyst into an adhesive in order to properly cure the resin during hot pressing.

It is desirable that the pH value of *Dendrocalamus asper* is not different from common wood species. Moreover, *Dendrocalamus asper* has no variation in pH value at the different locations on the culm. The same technology and practices might be applied to this bamboo specie when being used as an alternative raw material in composites manufacture.

Table 3 The pH values and buffer capacity in each location of the culm of *Dendrocalamus asper*

Values	Replication	Culm locations		
		Bottom	Middle	Top
pH	1	5.51	5.71	5.40
	2	5.21	5.30	5.33
	3	5.37	5.33	5.41
	Mean	5.36	5.45	5.38
Buffer capacity (me.)	1	0.45	0.52	0.47
	2	0.42	0.41	0.48
	3	0.88	0.69	0.49
	Mean	0.58	0.54	0.48

Buffer Capacity

The acid-buffering capacity of *Dendrocalamus asper* at three different locations in the culm is illustrated in Table 3. The average buffer capacity of bottom, middle and top parts of the culm are 0.58, 0.54 and 0.48 milliequivalents, respectively. Notable, the bottom part of the third culm shows highest acid-buffer capacity value, which contrast to other findings of this research. One possible explanation might be rest on the variation between the culms. Each culm was cut from each clum in the three sites. Abd. Latif & Liese (2002) and Gnanaharan (1994) reported that generally, the qualities of bamboo (i.e., culm characteristics, physical and mechanical properties) are influenced by environmental site factor. These bamboo properties could affect the variation of chemical composition in bamboo culm. It is reasonable to hypothesize that the chemical properties of raw material, especially water extracts and inorganic matters, have effect on its buffer capacity. This hypothesis can be confirmed by finding of Passialis *et al.* (2008). They found out that hot-water extracts and inorganic elements, which evidently are present in the bark of wood, have significantly effect on the buffer capacity of wood.

The pH value changing of *Dendrocalamus asper* on the acid addition is presented in Figure 4.

It is evident that *Dendrocalamus asper* has extremely high resistance to changes in the pH and weakly responds to the acid addition (sulfuric acid) when compared to normal wood, as shown in Figure 4 too. *Dendrocalamus asper* needs 5 times the amount of acid which is required for wood to achieve a pH of 3.5.

The acid-buffering capacity of *Dendrocalamus asper* is high, when compared with those of wood species. It would be considered to be the high buffer capacity specie and will require a larger amount of acid catalyst to reduce the pH to the optimum level which is required for a resin cure. This may cause problems for their use as raw material in wood composite with conventional commercial resin. Some strategies, such as the use of special glue to produce boards or adjusted hot-pressing parameters, might be applied to improve resin curing and hence improve product properties too; despite the fact that the production costs will be compromised.

The buffer capacity of bamboo varies along the culm location, although the differences seem small between three locations. Thus, it should require some special consideration in regard to catalyst addition and resin cure.

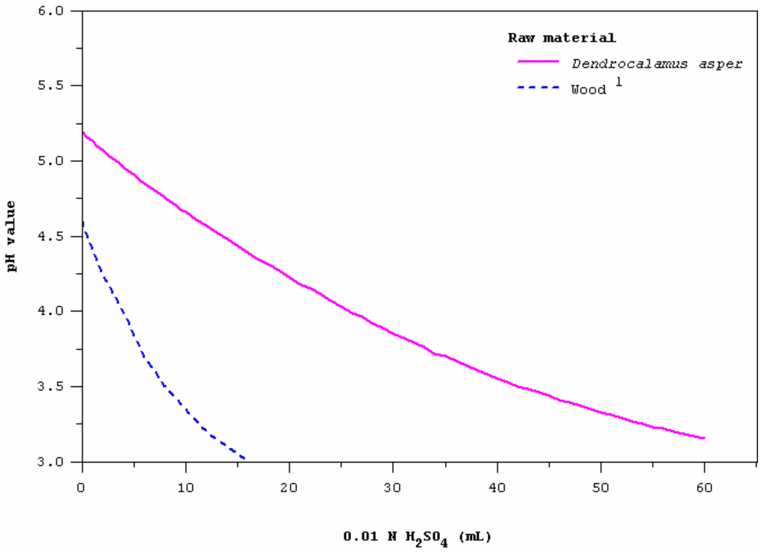


Figure 4 The pH changes of *Dendrocalamus asper* and wood during the acid addition. Data source: [1] Sauter 1996

Bonding Quality

The adhesive bond strength was observed in terms of the shear strength of each adhesive bond as a function of pressing time and temperature. Figure 5, 6 and 7 present the results of shear strength which is related to pressing times (from 20 to 300 seconds in 20 seconds step) and pressing temperatures (150, 170, 190 and 210^{0}C) for bamboo strands, which were glued with MF, MUPF and PF, respectively.

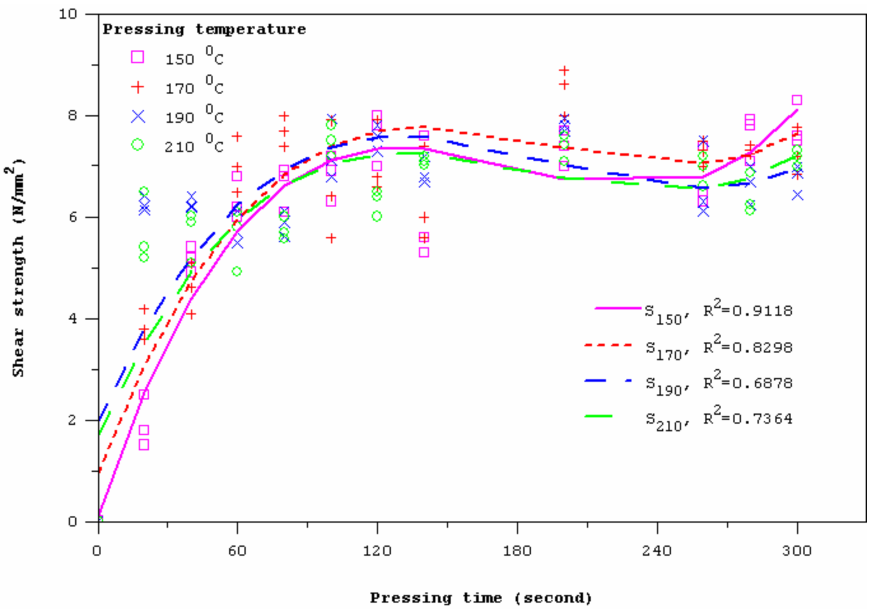


Figure 5 Shear strength developments of MF glued bamboo strands as a function of pressing times and temperatures.

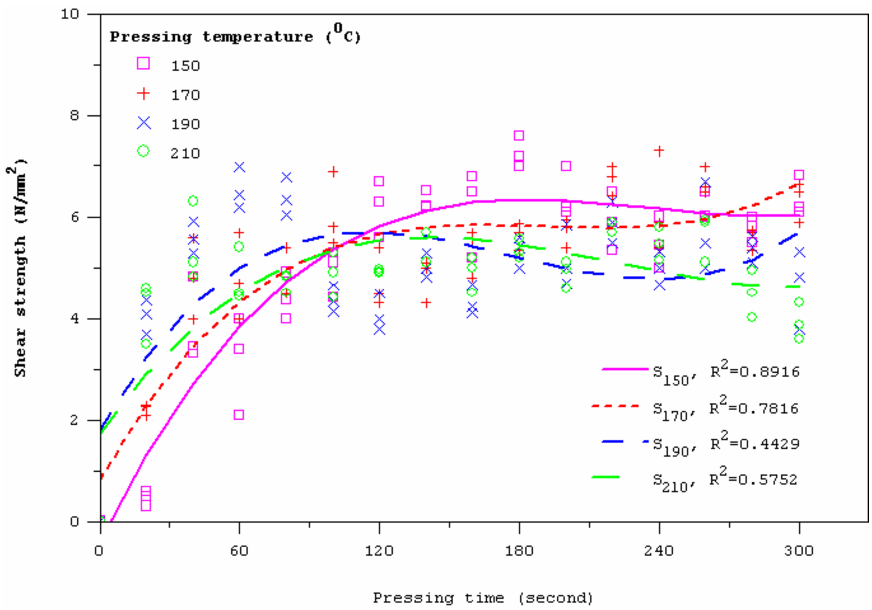


Figure 6 Shear strength developments of MUPF glued bamboo strands as a function of pressing time and temperature.

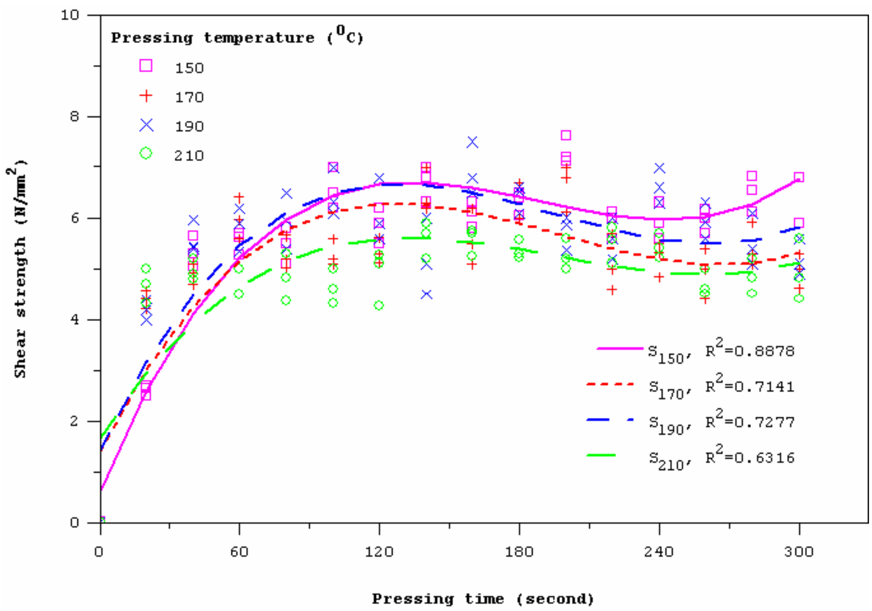


Figure 7 Shear strength developments of PF glued bamboo strands as a function of pressing time and temperatures.

Influence of Pressing Temperature and Time

The results of ABES test indicate that bonding strength of glue-line vary significantly with different pressing temperatures and time. The maximum value of shear strength is 8.90 N/mm^2 for MF resin at 170°C and 200 seconds (as shown in Figure 5), while the minimum value of shear strength is 0.30 N/mm^2 for MUPF resin followed at 150°C and 20 seconds (as shown in Figure 6).

The effect of the higher pressing temperature is mainly related to an increase in shear strength in the glueline. The temperature levels influence the rate at which adhesive bonds develop which can be suggested by the rapidly increasing initial shear strength with the higher temperature. As usual, heat is used during the pressing for faster bonding development. The resin can cure (as quickly as possible) quicker when the temperature increases. At low pressing temperatures, the bonding strength is limited because the resin can not completely cure, but an excess temperature can reduce or eliminate the bonding strength in glueline as illustrates at 190 and 210°C for MF and MUPF resin (Figure 5 and 6, respectively) and 210°C for PF resin (Figure 7).

The results also indicate that bonding quality vary significantly with different pressing times. Notably, most of the shear strength developments related to pressing time present as the polynomial expressions which can be demonstrated by correlation (R^2) and graphs in Figure 5-7. This graph could be separated into 3 phases, where each phase can be explained the observed relation. In the first phase, the bonding strength shows that the shear strength is zero at the beginning of pressing, where the pressing time is zero, because the poly-condensation reaction of adhesive doesn't occur. After prolonged pressing time, the bonding strength occurs and increases very rapidly as linear. It shows that increasing the pressing time, the bonding strength increases because of the propagation of polycondensation reaction and the growth of polymer chains. In the second phase, the bonding strength will increase until the maximum shear strength value is reached. Then, the strength value is slightly constant. During this phase, strong adhesions between the molecules of bamboo and adhesive take place. With the additional pressing time, the strength will decrease, which can be presented as the third phase, which can distinctly be observed only higher pressing temperature conditions. It can be mentioned that a longer pressing time would attack the completed bond which already occurs in the glueline. Noteworthy, the bonding strength developments, which were taken place at the excess temperatures (190 and 210°C for MF and MUPF resin and 210°C for PF resin), behave differently. They show lower shear strength value than those of other. In accordance with Blomquist *et al.* (1983), PF resin requires high press temperatures for condensation reaction. Actually, this is the basic results in the laboratory scale. Further study is requested in order to explore this in an accurate parameter on an industrial scale.

Furthermore, the press temperature has a greater influence than the pressing time. At lower temperature, a longer pressing time is needed to reach the maximum bonding strength, whereas the shorter pressing time is used with a higher temperature, as distinctly illustrated in Figure 5. At 150°C, the maximum shear strength is 7.84 N/mm^2 at 300 seconds pressing time, while the maximum shear strength for 170°C is 8.57 N/mm^2 at 200 seconds pressing time. In theory but not in industrial practice, a long pressing time at a lower temperature is more preferable than a short pressing time at a higher temperature (Maloney 1993). However, economical aspects decrease pressing time and still maintain a good board quality.

Influence of Resin Types

The three adhesives, which were evaluated in this study, show different maximum shear strength. MF resin shows a highest shear strength value (8.54 N/mm^2) as shown in Figure 5, while the maximum shear strength value form MUPF (7.23 N/mm^2) is quite similar to that of PF (7.29 N/mm^2) as shown in Figure 6 and 7, respectively. All of them appear to have no different behaviors related to pressing time. Thence, almost all of the relations are parabola graphs. Furthermore, all of them are thermosetting resins. Their cross linking reactions take place in the bond under applied pressure and heat, but their network bonding can be attacked by excess temperature. It is important to note that the adhesive types vary significantly in the bonding conditions for which they are require in use, especially with regard to temperature and time. MF and MUPF can harden and bond properly at lower temperature (170^{0}C), while PF requires higher temperature (190^{0}C).

Compared to a previous study (Jost & Sernek 2009), the bonding strength of PF resins increased with the increasing pressing time. Similar results of shear strength development in relation to of pressing time have been obtained. These results certainly suggest that the maximum shear strength of *Dendrocalamus asper* bonded with PF resin is reached 7.0 N/mm^2 at 170°C and 140 seconds (as shown in Figure 5), while the maximum shear strength value of beech (*Fagus sylvatica)* bonded with PF resin is 8.0 N/mm^2 at 160°C and 50 seconds. It is evident that *Dendrocalamus asper* needs 3 times the pressing time which is required for beech to achieve the maximum shear strength, although the pressing temperature is higher. This finding of this research reinforces this hypothesis. As previous mention, *Dendrocalamus asper* is considered as the high buffering capacity specie which would affect the curing characteristics of PF resin. It should be noticed that the difference between the results of this research and previous studies could be due to the specific characteristics of adhesive and wood species when compared to bamboo.

CONCLUSIONS

The pH value, buffer capacity and bonding quality of *Dendrocalamus asper* strands have been analyzed. The following conclusions can be drawn from this part of the study:

1. *Dendrocalamus asper* has a comparable pH value to other wood species, particularly softwood. The pH value does not vary along the location of the culm.
2. Buffering capacity of the *Dendrocalamus asper* strands is shown to be higher than those of other wood species. The value slightly varies along the culm location.
3. The bond strength between bamboo strands and adhesive curing is improved according to ABES tests by increasing the hot pressing time and temperature. Several adhesives exhibited satisfactory bond quality for gluelines in bamboo strands bonding. The best adhesive to bond bamboo strands was found by the ABES method to be MF for its glueline strength.

RECOMMENDATIONS

The following recommendations for further research using *Dendrocalamus asper* as raw material in wood composite manufacture in the topic of gluability should determine:

1. the alkali buffer capacity of *Dendrocalamus asper*
2. the relation buffer capacity and chemical composition of *Dendrocalamus asper*
3. the resin gel time and the effect of *Dendrocalamus asper* on resin gel time of each glue

ACKNOWLEDGEMENTS

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Table 4 Chemical composition and pH value for some bamboo, softwood and hardwood species

Scientific Name	Common Name	Chemical Compositions (%)						pH Value
		Holocellulose	Cellulose	Lignin	Alcohol-Benzene Solubility	Hot-Water Solubility	Ash	
Bamboos								
Bambusa vulgaris [1]	-	66.5	-	26.9	4.1	5.1	2.4	-
Dendrocalamus asper Backer [2]	Sweet bamboo	76.3	68.1	28.7	5.9	8	1.5	-
Gigantochloa levis [1]	-	62.9	-	24.2	3.2	4.4	5.3	-
Softwoods [3]								
Picea abies Karst.	European spruce	80.9	46	27.3	2	2	-	5.3
Pinus strobus L.	Yellow pine	-	61.6	29.6	10.2	7.7	0.2	4.9
Pseudotsuga menziesii Mirb.	Douglas fir	67	50.4	27.2	4.4	5.6	0.2	3.3
Hardwoods (Temperate zone) [3]								
Acer saccharum Marsh.	Sugar maple	-	-	22.7	-	-	0.3	5.1
Fagus sylvatica L.	European beech	85.6	49.1	23.8	0.8	-	0.3	5.4
Populus spp.	Aspen	78.4	-	20.9	3.3	4.3	-	5.8
Hardwoods (Tropical zone) [3]								
Millettia laurentii De	Wenge, Awong	-	38.8	31.5	6.7	3.0	0.2	4.3
Ochroma lagopus Sw.	Balsa	-	52	24.5	2.6	2.8	1.6	6.7
Tectona grandis L.	Teak	-	39.1	29.3	13	1.8	0.7	5.1

Sources:
[1] Liese 1985
[2] Kamthai 2003
[3] Fengel & Wegener 1984

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Publication IV

Physical and Mechanical Properties of Oriented Strand Lumber made from an Asian Bamboo (*Dendrocalamus asper* Backer)

Pannipa Malanit[1,*], Arno Frühwald[1], Marius C. Barbu[2]

[1]Department of Wood Science, University of Hamburg, Germany
[2]Faculty for Wood Industry, "Transilvania" University Brasov, Romania

Abstract

The study was conducted to determine the physical and mechanical properties as follows: modulus of rupture, modulus of elasticity, internal bond, thickness swelling and water absorption of oriented strand lumber (OSL) made from the Asian bamboo *Dendrocalamus asper* Backer. Thirty-six lab boards were produced from these bamboo strands varying into two categories of manufacturing parameters, i.e., four resin types (MF, MUPF, PF and pMDI) and three levels of resin content (7, 10 and 13%). The results indicate that OSL made from bamboo strands exhibit superior strength properties compared to the commercial products made from wood for the building sector. The resin type has a significant effect on board properties. Moreover, all properties of the board improve generally with the increasing of resin content. With regard to the internal bond, bamboo-based OSL shows less strength than that of the wood-based boards. The best results were obtained by using a 13% pMDI content at 750 kg/m³ density.

1 Introduction

Over the past decade, the demand for wood composites as building material has continuously increased. At the same time, the quantity and quality of wood resources, from the forest, as a raw material for this application have been declining. Consequently, the search for an alternative or substitute materials in place of wood has come into focus.

Bamboo (*Bambusoideae* sp.) is a non-wood lignocellulosic material that has received increasing attention as the alternative raw material for use in the manufacture of paper and wood composites in the late 20th century. The main advantages of bamboo are its fast growing nature and better mechanical properties when compared to other wood species. It has traditionally been used for housing construction, furniture manufacture and articles for daily life in Asian and Latin American countries. In recent years, bamboo has gained greater interest as the substitute material in place of wood because of the global shortage of forest resources.

During recent years, several researches have contributed to understand the bamboo properties and improve processing technologies for wider use. Numerous researches have evaluated the properties of bamboo-based composites, especially engineering composite products, and regarded the effective use of bamboo for various products such as plywood (Chen 1985), oriented strand board (OSB) (Lee et al.1996 and 1997; Sumardi *et al.* 2007 and 2008), waferboard (Zhang 2001), zephyr board (Nugroho and Ando 2000) and laminated bamboo lumber (Nugroho and Ando 2001). They showed that bamboo can be able to provide high quality engineering composite products. Therefore, bamboo could be proposed as an alternative material for the manufacture of structural composite lumber (SCL) such as oriented strand lumber (OSL).

OSL is a wood-strand based composite with primarily orientation along the length of the member. The thickness of the strand should not exceed 0.635 mm and the average length should be between 75 and 150 times that of the least dimension (ICBO 2002). OSL is a concept that utilizes similar technologies and processes to that of OSB. OSB is primarily used in panel applications, such as roofing and sheathing, while OSL is developed for use as structural members including beams and columns. It is the newest product of the SCL family, and markets are still under development. Strength properties make it a highly competitive alternative to traditional lumber and will become an important forest based product in the future (Bowyer et al. 2003).

The objective of this research was to determine the suitability of a wide spread Asian bamboo type, *Dendrocalamus asper* Backer as a raw material for the manufacture of OSL. It's physical and mechanical properties with the respect to the two processing parameters (resin type and resin content) were analyzed. The product properties were compared with standard requirements and for commercial products like OSB.

2 Materials and methods

2.1 Materials

Three-year-old bamboo culms from bamboo plantations located in Nakorn Sri Thammarat, South of Thailand, were used as the raw material for the prototype bamboo-boards. These bamboos have an average culm length of 19 m, and a culm-wall thickness in the range of 6-27 mm. The average specific gravity at 12% MC is 0.7.

Four exterior adhesives were used in this research: melamine-formaldehyde (MF), melamine urea phenol formaldehyde (MUPF), phenol formaldehyde (PF) and isocyanate (pMDI). The MF resin (13H560) was supplied by Dynea. The MUPF resin (KML 534) was obtained from BASF. The PF resin (Bakelite 1279 HW) was supplied by Hexion Specialty Chemicals. The pMDI resin (Suprasec® 5025) was provided by Huntsman. Their properties are presented in Table 1.

Table 1 Some properties of the used resins.

Properties	Resin types			
	MF (Prefere 13H560)	MUPF (Basf KML 534)	PF (Bakelite1279HW)	pMDI (Suprasec® 5025)
Appearance	Pale liquid	Pale brown liquid	Red brown liquid	Liquid brown
Solids content (%)	62.5	64±1	48	-
pH at 20°C	9.73	9.3-9.8	8.5-10.5	-
Viscosity (mPa*s)	100-150	150-400	650-700	180-240

2.2 Strand processing

Strands were made from bamboo culms in the green state with a culm-wall thickness more than 12.5 mm, as presented in Fig. 1a. The nodes were removed before stranding. No attempt was made to remove the epidermis of the bamboo culms. The culms were crosscut into 140 mm long segments and subsequently sliced into half, as presented in Fig. 1b. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. Machine conditions were set as follows: counter-knife angle of 60 degrees, knife projection of 0.736 mm and scoring-knife distance of 140 mm, respectively. Target strand dimensions were 140 mm long, 0.7 mm thick, and 12.5-20 mm wide, as presented in Fig. 1c. Strands were then screened via a Gilson Screen (Model TM-4) on a 12.5 mm screen-opening size. Strands that passed through the 12.5 mm screen-opening size in the classifier and remained in the pan were considered as fine fractions, as presented in Fig. 1d. All strands then were dried in a 70°C rotary dryer to a moisture content of less than 2%.

Fig. 1 Bamboo type *Dendrocalamus asper*: a – culm cross section, b – internodes with epidermis, c – flaked strands; d – graded and dried strands

2.3 Board manufacturing

Bamboo-based OSL with target density of 750 kg/m³ were manufactured using laboratory equipment based on four resin types and three levels of resin content. Each resin was mixed following the supplier's suggestion and spread onto the strand using an inhouse-made paddle-type blender with a drum diameter of 62 cm, 100 cm length at 45 rpm for 20 minutes. To ensure uniform glue distribution, the optimal conditions of rotation rate, retention time in the blender and the amount of furnish for one-glue application were determined by pretests. The glued strands were spread by hand into a forming-box with the dimension of 800 × 300 mm and oriented parallel in one direction. After forming, mats were transferred to a single-opening hydraulic lab hot press (60 x 80 cm Siempelkamp press) and pressed into boards at a nominal thickness of 16 mm. In this study, 36 boards were produced by employing a pressing temperature and time following the suggestion of glue supplier, as presented in Table 2

Table 2 Pressing conditions used in this study for each resin.

Resin type	Hardener	Mat moisture content (%)	Pressing temperature (^{0}C)	Pressing time (s/mm)
MF	3% Ammonium nitrate	9	210	12
MUPF	3% Ammonium nitrate	9	190	16
PF	6% Potassium carbonate	14	190	12
pMDI	-	6	220	10

2.4 Board properties testing

The lab boards were machined into test specimens and placed in a conditioning room maintained at 65% RH and 20°C for 4 weeks until constant weight was attained. Thirty-six specimens for each parameters combination were determined as follows:

- Thickness swelling (TS) and water absorption (WA) with the dimension of 50 x 50 mm were immersed in water at 20°C for 24 hours in accordance with EN 300: 1997 and ASTM D 1037-97, respectively.

- Three-point static bending tests for modulus of rupture (MOR) and modulus of elasticity (MOE) with the dimension of 50 x 322 mm were performed in accordance with ASTM D 5456-99 using a 50 kN FRANK universal testing machine ;
- Internal bond (IB) with the dimension of 50 x 50 mm was measured in accordance with EN 300: 1997.

Effects of resin type and resin content on the properties of the boards were evaluated by analysis of variance at the 0.01 level of significance. The Duncan's Range tests were conducted to determine significant differences between mean values.

3 Results and discussion

The average values of the physical and mechanical properties of the bamboo-based OSL are summarized in Table 3. The analysis of variance result and Dancan's Range comparison for the physical and mechanical data of bamboo-based OSL is illustrated in Table 4.

Table 3 The average values of the physical and mechanical properties of bamboo-based OSL

Resin type	Resin content (%)	Specific gravity	MC (%)	TS 24 h (%)	WA 24 h (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
MF	7	0.72 (0.01) [1]	7.7 (0.2)	18.8 (2.1)	39.6 (4.7)	39.9 (13.1)	7,750 (263)	0.12 (0.02)
	10	0.73 (0.01)	7.6 (0.6)	13.2 (1.8)	41.7 (2.3)	52.6 (6.4)	8,730 (229)	0.14 (0.01)
	13	0.82 (0.03)	7.8 (0.3)	16.0 (0.7)	32.3 (6.5)	61.0 (1.6)	11,109 (1,107)	0.33 (0.02)
MUPF	7	0.65 (0.02)	7.4 (0.1)	26.4 (3.1)	76.4 (4.0)	29.1 (0.6)	3,290 (829)	0.06 (0.01)
	10	0.73 (0.04)	6.7 (0.2)	17.2 (0.5)	48.8 (8.0)	53.5 (2.7)	6,274 (95)	0.19 (0.02)
	13	0.70 (0.02)	7.1 (0.4)	11.1 (4.4)	45.9 (12.7)	55.1 (7.2)	6,698 (121)	0.22 (0.02)
PF	7	0.69 (0.01)	7.7 (0.4)	12.8 (4.4)	50.9 (9.1)	35.0 (5.3)	4,855 (242)	0.09 (0.01)
	10	0.71 (0.10)	9.1 (1.1)	7.1 (0.4)	44.3 (6.8)	46.3 (4.3)	5,915 (1,438)	0.26 (0.02)
	13	0.71 (0.02)	8.6 (0.5)	5.8 (0.5)	44.1 (2.0)	58.8 (10.4)	6,682 (845)	0.39 (0.07)
pMDI	7	0.74 (0.04)	3.6 (0.3)	4.5 (1.3)	24.4 (3.0)	45.2 (3.3)	6,897 (726)	0.37 (0.02)
	10	0.76 (0.02)	2.9 (0.1)	2.3 (0.3)	18.4 (1.2)	62.5 (5.5)	10,497 (550)	0.47 (0.08)
	13	0.71 (0.04)	3.5 (0.5)	3.0 (1.8)	19.5 (2.2)	65.2 (2.9)	10,300 (1,041)	0.67 (0.13)

[1] Numbers in parentheses are standard deviations from the sample mean.

Table 4 The variance analysis for all properties of bamboo oriented strand lumber

Source of variation	F-value				
	TS (n=36)[1]	WA (n=36)	MOR (n=36)	MOE (n=36)	IB (n=36)
Resin type	84.75**	55.03**	6.52**	68.69**	87.70**
Resin content	30.80**	13.17**	41.49**	50.57**	65.37**
Interaction	6.10**	4.30**	0.86NS	3.17*	2.10NS

[1] n is the number of replications per treatment combination.
** indicates significance at the 1% level of probability.
* indicates significance at the 5% level of probability.
NS indicates not significant.

3.1 Physical properties

The physical properties of bamboo-based OSL were investigated as specific gravity, thickness swelling and water absorption. These are compared to the commercial product (OSB/3 ISO/EN). These values are graphically presented in this part. Board-to-board specific gravity variation is minimal; therefore, the values are not presented in graph and also not determined by statistical analysis.

3.1.1 Specific gravity

The target specific gravity of the bamboo made OSL board was 0.75, while an average board specific gravity is 0.72 at average moisture content level is 6.64%. The minimum value of board specific gravity was 0.65 for the trial with 7% of MUPF resin content, while the maximum value was 0.82 for the trial with 13% of MF resin content (as presented in Table 3).

These results suggest that the average board specific gravity is lower than the target board specific gravity. Additionally, 7% resin content-bonded board shows the lower specific gravity values. This result may provide an explanation as a more intensive springback phenomenon after pressing of the bamboo based board compared to the wood-based one. In the case of 7% MUPF-bonded OSL, the bonding strength cannot resist the internal stress due to excess moisture which could not escape as steam from the mat during hot pressing. Consequently, the board thickness increases and the density of the boards decrease after pressing or during conditioning. These findings are confirmed by the thickness deviation of board. The board thickness increase after pressing of bamboo-based OSL board bond with 7% MUPF and 10% MUPF are 11.92% and 6.50%, respectively.

3.1.2 Thickness swelling

OSL dimensional stability was evaluated by thickness swelling (TS) after a 24 hours water-soaking at 20°C. The TS values are presented in Table 3 and Fig. 2. The value ranges from 2.28-26.40%. Boards made with higher resin content generally result in better dimensional stability characteristics similar to the findings of previous works (Lee et al. 1996; Nugroho and Ando 2000). In addition, pMDI resin appears to have an impressive improvement of dimensional stability over all resins. These results are further confirmed with the statistical analysis, as presented in Table 4. This result shows that the different resin type and resin content have a significant effect on TS value. Furthermore, it has a positive interaction between these two parameters.

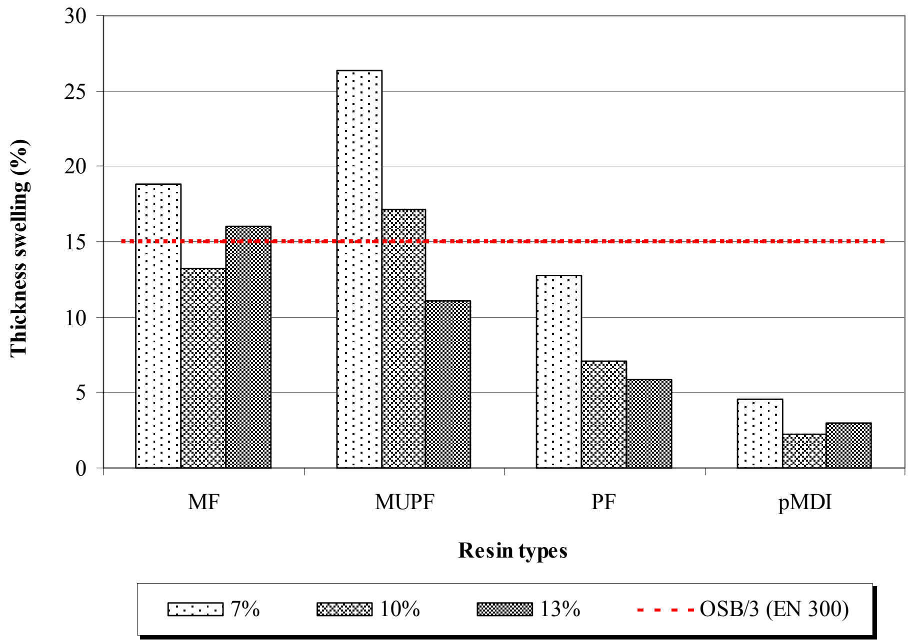

Fig. 2 Thickness swelling after 24h water soaking (20°C) of bamboo-based OSL

It has been previously known that the moisture content has a strong influence on dimensional change of wood. Wood shrinks as it loses moisture and swells again as it regains moisture. In this case, during water soaking, the swelling of bamboo strands will take place. Therefore, the alternating swelling generates stresses on the glue line between adjacent strands as well as in the strands themselves. The amount of these stresses and their possible effects on the TS depend on the ability of the glue to resist stresses. More specifically, the anatomical structure of bamboo is quite different to that of wood. These differences, such as cell type, shape, size, arrangement and number, influence on the bamboo properties. These might be the cause of excessive stresses which occur in the glue-lines between bamboo strands when samples are soaked in the water.

Notable, the bamboo OSL made with MUPF resin shows a significant higher TS value than those of others. This can be explained by the lower hydrolysis resistance of the MUPF resin. Under the influence of high moisture content, MUPF resin can be easily hydrolyzed because the bonding between the carbon of the methylene bridge and the nitrogen of urea is weak. Additionally, adhesion of water to cellulose is stronger than that of urea-formaldehyde-oligomers to cellulose. Consequently, water molecules are able to displace the hardened resin (Pizzi 1994).

It has been previously known that MF and PF resins are typically used in the manufacture of products requiring some degree of exterior exposure durability (i.e. high dimensional stability). In view of this study the MF-bonded bamboo OSL shows a higher TS value than of PF-bonded OSL and a more and more higher value than of pMDI-bonded OSL. This is quite possible due to its higher average specific gravity.

The maximum allowed TS value (after 24 hours water soaking) for OSB/3 by the requirement of EN 300: 1997 is 15%, as graphically presented in Fig. 2. Even, the TS value of MUPF bonded OSL produced from *Dendrocalamus asper* is higher (i.e. poor dimensional stability). As a result, these boards require additional treatments such as the wax addition, strands chemical pretreatments or peeling of epidermal layer to improve the dimensional stability of bamboo-based OSL manufactured with MUPF resin, which is the standard resin for high performance OSB made from wood.

3.1.3 Water absorption

The water resistance was evaluated by water absorption (WA) after 24 hours of water-soaking. The WA value of bamboo-based OSL is shown in Table 3 and Fig. 3 for different resin types and contents. The value ranges from 16.9 to 40.5%. Multifactor analysis variance based on resin type and resin content is presented in the Table 4. Similar to the thickness swelling, the water absorption is also significantly dependant on resin type and resin content. The results suggest that OSL made with 13% pMDI resin shows the significant lowest WA, as presented in Fig. 3. This can be explained by the bonding strength of pMDI resin. pMDI, having the reactivity of -NCO groups, can react with the -OH groups of the cellulose of the bamboo and form as covalent bonds in the from of urethane linkages. Thus, the bamboo is chemically bonded to the adhesive, resulting in a highly strong bond, which shows extremly hydrolytic and anti-hydrolysis stability. Furthermore, the WA significantly decreases with an increasing amount of resin content due to the higher bonding strength. This observation shows a similar trend, which was observed by Nugroho and Ando (2000). They indicated that the higher level of resin contents allows smaller value of WA. Compared to previous reports, the bamboo based OSL made from MUPF, PF and pMDI resins show smaller water absorption after 24 hours water immersion than those of other bamboo-strand based boards (Lee et al. 1996; Nugroho and Ando, 2000) and Scots pine-based OSB (Paul et al. 2006). The reason of this circumstance has not been addressed.

Notably, 7% MUPF-bonded OSL shows a higher WA value than the others. This might be due to its lower specific gravity. Then, more water can be absorbed. Moreover, MUPF resin is low hydrolysis resistance.

In contrast to the thickness swelling, the WA for PF-bonded OSL is higher than that of MF-bonded OSL. The higher WA for PF-bonded OSL can be suggested by the hydroscopic behavior of the alkali in the PF resin. Thus, a greater amount of water is absorbed without affecting the TS (Pizzi 1994).

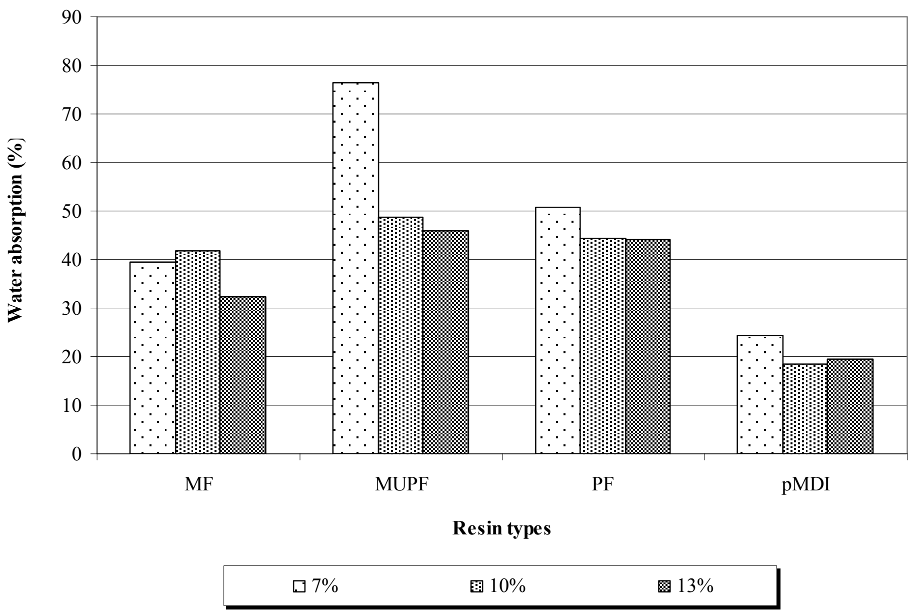

Fig. 3 Water absorption after 24h soaking of bamboo-based OSL

3.2 Mechanical properties

OSL is an engineered product with specific elasticity and strengths. Therefore, the mechanical properties of bamboo-based OSL were investigated for bending behavior and internal bond.

3.2.1 Static bending

The static bending properties of bamboo-based OSL are illustrated in Table 3, Fig. 4 and 5. The MOR and MOE values of bamboo-based OSL calculated based on linear regression equation at the average board density 720 kg/m^3 are in the range of 29.1 to 65.2 MPa and 3,280 to 11,109 MPa, respectively. The results of the analysis of variance conducted on the effect of the two factors and their interaction, as presented in Table 4, show that the resin type and resin content significantly influence on both of MOR and MOE.

Fig. 4 illustrates the effect of resin type and resin content on MOR value of the boards. Comparing the mean values of all boards, the MOR value of pMDI-bonded board is highest, as shown in Fig. 4, while those of MF, MUPF and PF-bonded boards are similar. The higher MOR of pMDI-bonded OSL is due to the high bonding strength of the cross linked polyurea network, as mentioned earlier. Additionally, the resin content is found to be the major factor contributing to the improvement of stiffness of board. This is in agreement with the result of Barnes (2000) and Post (1958) who found that increasing the resin content of composite board increases physical and mechanical properties. Notable, 7% MUPF-bonded OSL shows the lowest value of MOR. This might be due to its lower specific gravity (around 0.65 as presented in Table 2).

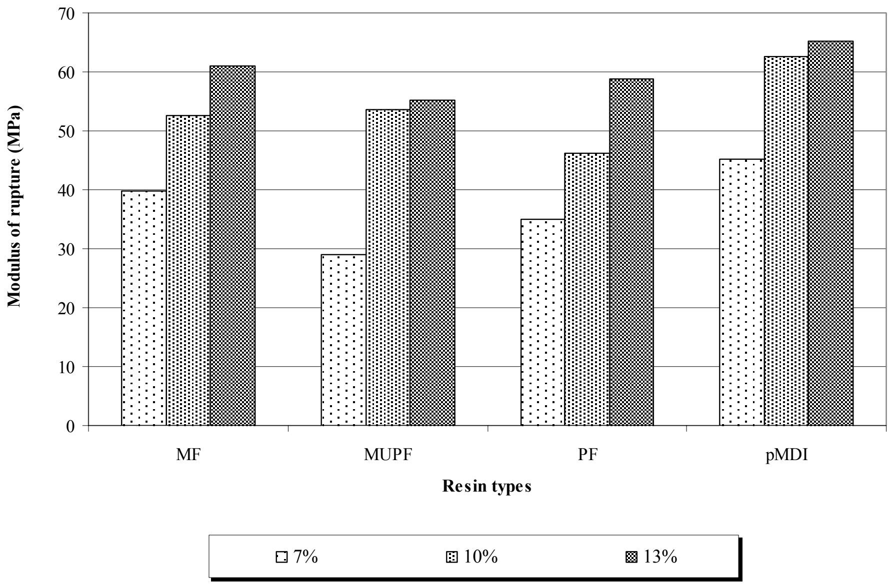

Fig. 4 Modulus of rupture of bamboo-based OSL

Relationship between two parameters (resin type and content) and MOE value of the boards is illustrated in Fig.5. The maximum value of MOE is 11,109 MPa for MF at 13% resin content, while the minimum value is 3,290 MPa for MUPF at 7% resin content. MF and pMDI bonded boards show quit similar MOE and approximately 35% higher value than MUPF and PF board at the same level of resin content. Moreover, the MOE value increases with increasing resin content. Similar tendencies are found in MOR values.

To address the known relationship between resin content and product strength, increasing the resin content, the product strength properties will increase too. As the resin is increased, there will be an increase of the intimate contact area between adjacent bamboo strands in the board. The current finding shows that increasing the resin content from 7% to 10% improves the MOR and MOE rapidly, reaching an effective maximum at 13%. Comparing the OSL resinated with 10 and 13%, the values differ slightly until the statistical analysis cannot find significantly differences. The MOR and MOE developments related to resin content present exponential expressions, especially MUPF and pMDI resins. This finding is also in agreement with Maloney (1993) and Barnes (2000).

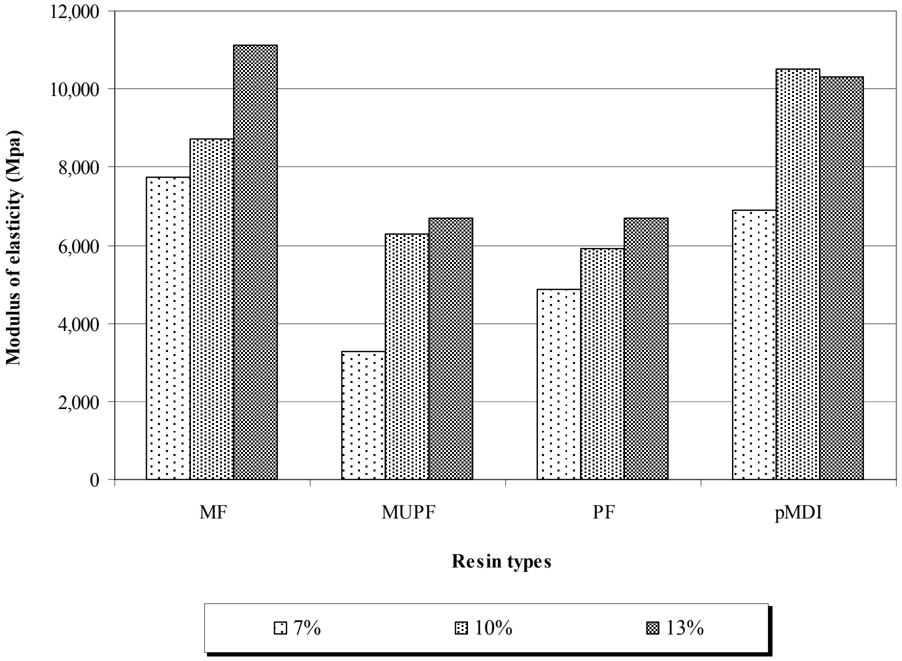

Fig. 5 Modulus of elasticity of bamboo-based OSL

The comparison of some important OSL properties (such as specific gravity and bending strength) for bamboo-based OSL, solid bamboo and solid lumber, used in construction, is shown in Table 5. For *Dendrocalamus asper* based OSL, the MOR is approximately 50% lower and the MOE 20% lower than solid bamboo, while the average specific gravity of bamboo-based OSL is quit similar to that of solid bamboo. This difference may be explained by shear stress associated with bending. During the test, shear stress developing in the horizontal interfaces between strands and resin reduces the bending strength of OSL. Compared to spruce solid lumber (*Picea abies)*, the bending strength of bamboo-based OSL is superior. It should be noted that bamboo-based OSL shows higher specific gravity than solid spruce lumber approximately 1.7 times.

Table 5 Comparison of properties of bamboo-based OSL, solid bamboo and spruce lumber

Type	Specific gravity	Bending strength (MPa)	
		MOR	MOE
Bamboo-based OSL [1]	0.76	62.5	10,497
Dendrocalamus asper [2]	0.73	135	13,115
Spruce *(Picea abies)* [3]	0.44	72	8,500

Source: [1] selected processing parameter is 10% pMDI resin
[2] Pakhkeree, 1997
[3] USDA Forest Service, 1999

3.2.2 Internal bond

The value of internal bond strength for samples made with different resin types and contents is presented in Table 3 and Fig. 6. The value is in the range from 0.06 to 0.67 MPa. The result of the analysis of variance (as presented in Table 4) conducted on the effect of the different factors and their interaction shows that the resin type and resin content significantly influences the internal bond. The internal bond values should be discussed in reference to the resin content because it strongly depends on the amount of resin applied. Then, the value consequently increases with the increase of the resin content. For pMDI resin, internal bond is greater than other types because the high strength of covalent bonds between strands in the board, as mentioned above.

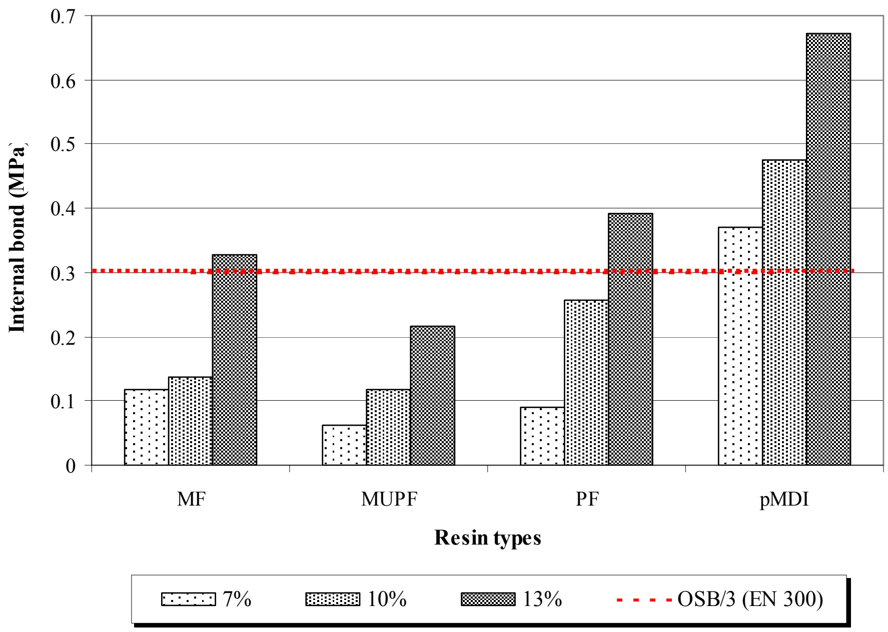

Fig. 6 Internal bond of bamboo-based OSL

According to EN 300: 1997, the minimal requirement of internal bond for OSB/3 is 0.30 MPa. The most striking result is the demonstration that the internal bond value of OSL bonded with pMDI resin are higher than that of the standard requirement, while those of MF and PF-bonded OSL with 13% resin achieve this requirement. The result suggests that the OSL made from *Dendrocalamus asper* shows low internal bond strength. Several possible reasons might explain for this circumstance. The tissue of the bamboo culm consists of fiber-like structural features known as vascular bundles and parenchyma cells. The distribution of cells shows a definite pattern, such as specific gravity, with in the culm, both horizontally and vertically. The bamboo specific gravity increases along the culm from the bottom (an average value is 0.51) to the top (an average value is 0.62). Furthermore, the outer culm has a far higher specific gravity than the inner part, decrease from 0.80 to 0.50 (Liese 1985). This variation could influence glue bonding, because the resin must be as strong as the high specific gravity zones and be able to penetrate them adequately without over-penetrating the low specific gravity zones. Furthermore, the wax layer of the epidermis (Liese 1985) may have affected the bond strength of the bamboo-based OSL. This may affect the bond strength of the bamboo-based OSL. Additionally, it has been previously known that the agricultural residues have extremely high buffer capacity when compared to normal wood. This property makes these materials unsuitable for use with some of the commercial resin used for wood based boards. Thence, internal bond is the limiting property (Hague et al. 1998; Sauter 1996).

4 Conclusions

The following conclusions can be drawn at this stage:

1. Dominant parameters controlling physical and mechanical properties are resin type, and resin content. The physical and mechanical properties of pMDI-bonded bamboo based OSL are higher than those of MF, MUPF and PF-bonded OSL. All properties improve with increasing resin content.
2. The best parameters of this study are pMDI resin at 13% resin content.
3. Compare to the commercial products, bamboo OSL shows high strength properties.

5 Recommendations

From all properties analysis, it has been found that OSL made from *Dendrocalamus asper* shows its performances. It has high bending strength and less swelling as well as less water absorption compared to wood-based board. Although, it shows low internal bond, this can be improved by manufacturing parameters, i.e. pressing time or adding hardener in glue-mixing. As well, the use of special developed resins to produce boards can minimize this problem. The following recommendations for further research using *Dendrocalamus asper* as raw material in board composite manufacture should determine:

1. The effect of other processing parameters on OSL properties such as specific gravity, strand dimension.
2. The mat forming system improvement.
3. The biological resistance, weather ability, finishing properties and fastening-holding capacity.
4. The optimal parameter for OSL based on bamboo manufacturing process by “Response surface method”. The information can be evaluated by using the statistic analysis system to compare the controlled conditions and find the optimal parameters.

6 Acknowledgements

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Publication V

The Gluability and Bonding Strength of *Dendrocalamus asper* Backer for Exterior Structural Applications

Pannipa Malanit[1, 2], Marius C. Barbu[1, 3], Arno Frühwald[1]

[1]Department of Wood Science, University of Hamburg, Germany
[2] School of Engineering and Resources, Walailak University, Thailand
[3]Faculty for Wood Industry, "Transilvania" University Brasov, Romania

Abstract

This study evaluated the effect of culm location in *Dendrocalamus asper* Backer, on the pH and acid-buffer capacity and glueline bonding strength of strands using four adhesive types. These properties were analyzed in order to prove its suitability to be promoted as a raw material for the manufacture of structural composite products like Oriented Strand Board (OSB), Oriented Strand Lumber (OSL) etc. The pH and acid-buffering capacity were investigated in three locations, which composed of bottom, middle and top parts, along the culm length. The obtained results from this study indicate that the average pH value and acid-buffer capacity of *Dendrocalamus asper* is 5.4 and 0.53 milliequivalents, respectively The different culm location has no effect on this value. The bonding strength development of bamboo strands bonded with exterior used type adhesives was investigated by using a special testing device called an Automated Bonding Evaluation System (ABES). This experiment proposed three parameters, i.e., three types of glues; Melamine Formaldehyde (MF), Melamine Urea Phenol Formaldehyde (MUPF), and Phenol Formaldehyde (PF), and four pressing temperatures (130, 150, 170 and 190°C) and different pressing time (20 to 200 seconds). It was found that bonding strength was improved by increasing the hot pressing time and temperature. The best adhesive to bond bamboo strands following the ABES was found to be MF.

Introduction

The available high quality wood from natural forest in the world has declined. Then, structural composite products for construction building has been taken placed of massive wood lumber and increase their global market share every year. In the past few decades, wood composite industry has used the forest plantation and saw mill residues as the raw material for engineered product manufacturing. At the same time, the strength harvesting regulation and pressure from environmental policy have created decreasing high quality wood supply and an increasing cost. Consequently, the search for alternative resources of fiber instead of the traditional use of wood has been focused. Non-wood or agricultural-material has been received considerable attention as an alternative raw material.

Bamboo is a non-wood lignocellulosic material which has been widely used in tropical countries as a material for construction, furniture manufacture and daily household. Recently, it has been widely used as a raw material for wood composite manufactures, such as for Medium Density Fiberboard (MDF), Particleboard (PB) and Oriented Strand Board (OSB), owing to its high strength and properties. It is known that the chemical composition of bamboo culms is similar to that of wood with cellulose, hemicellulose and lignin accounting for over 90% of the total mass. From the study of Kamthai (2003), the average chemical composition of a three-year old *Dendrocalamus asper* consists of α-cellulose (68%) and lignin (29%). It contains about 1.5% of ash, 6% of alcohol-benzene soluble, 8% of hot-water soluble, 7% of cold-water soluble and 25% of 1% NaOH soluble materials.

However, a change in raw material may affect on product properties and requires additional adjustment of some processing manufacture, such as the adhesive system. Since the adhesive is a significant cost factor in board production (about 20% of total production cost), future development of bamboo-based composites will require an analysis of bamboo gluability and the bonding strength of its strands. The cross-linking rate of most thermosetting adhesives used in wood composite manufacturing depends on the pH levels. Many previous researchers (Freeman 1959; Johns and Niazi 1980; Van Niekerk and Pizzi 1994; Zanetti and Pizzi 2003) studied the influence of pH and buffer capacity of wood on curing time of some resins and product properties. According of these studies, the adhesive curing time and its bond strength decreased with the wood increasing pH and buffer capacity. Moreover, catalyst buffering action has strong effects on curing time and the degree of networks formed of MUF, PF and tannin based adhesives. Thus, the pH and buffering capacity measurement of raw materials is fundamental to determine the optimum of pressing parameters (i.e., time and temperature) for wood-based composite manufacturing. Understanding these properties is important when discussing the suitability of bamboo as a potential raw material for structural composite products. Therefore, the objectives of this paper are to measure and compare the mean pH value and buffer capacity in each culm location of *Dendrocalamus asper* and investigate application by using the ABES equipment the strength development characteristics and bonding quality between bamboo strands using different adhesives for exterior.

Materials and Methods

Materials

In this study, the 3 years old of *Dendrocalamus asper* culms were collected from plantations located in Nakorn Sri Thammarat, Thailand. The three culms were harvested and transported to Walailak University in Thailand. These bamboos had an average culm length of 18 m. The culm diameter at the bottom was about 11.5 cm, while the top culm was about 2 cm. The average culm wall thickness was 1.6 cm. The average specific gravity at 12% MC was 0.75. Each culm was divided into three parts each of 6 m lengths. Specimens were obtained from three locations which were related to the height position in the culm.

Bamboo chips from each part were cut into fine particles. The samples were then put into a shaken screener to pass through a $40^{\#}$ mesh screen and retained on a $60^{\#}$ mesh screen. The particle remaining on the mesh screen was used for the measurement of pH value and buffer capacity.

The bamboo strands with a size of 120 mm by 20 mm and a thickness of 0.7 mm were used to prepare the two-layer lap-shear specimens for the ABES bond quality testing. All strands had been dried a final MC of 12% before gluing.

Three commercial exterior adhesives were used in this research: Melamine formaldehyde (MF), Melamine urea phenol formaldehyde (MUPF) and Phenol formaldehyde (PF). The MF resin (Prefere13H560) was supplied by Dynea. The MUPF resin (KML 534) was supplied from BASF. The PF resin (Bakelite 1279 HW) was supplied by Hexion. All adhesive mixtures were prepared following the supplier's suggestion. Their properties are presented in Table 1.

Table 1 Characteristic property of the used glues

Properties	Glue types		
	MF	MUPF	PF
Appearance	Pale liquid	Pale brown liquid	Red brown liquid
Solids content (%)	62.5	$64\underline{+}1$	48
pH at 20^0C	9.73	9.3-9.8	8.5-10.5
Viscosity at 20^0C (mPa∗s)	100-150	150-400	650-700

pH Value and Buffer Capacity Measurement

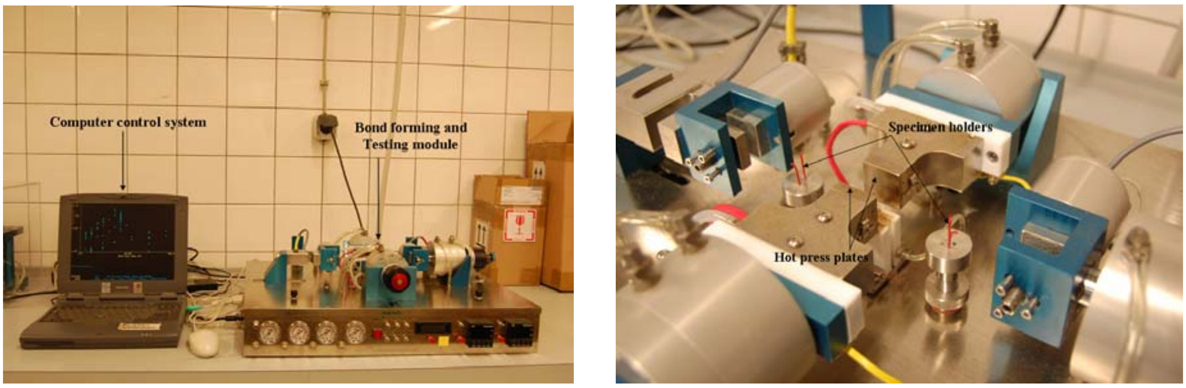
The cold extract pH was measured according to TAPPI T 509 om-83. 1 g of specimen was put into a 100 ml beaker and distilled water was added to bring the total volume to 70 ml. The mixture was stirred and allowed to soak for one hour at room temperature (20^0C). A pH meter (Type WTW pH 330i) was used for the measurement.

The buffer capacity measurement procedure was adapted from the method suggested by Maloney (1993). 30 g of dry specimen were soaked and stirred in 400 g of distilled water at 20 ± 1^0C for 30 minutes. The liquid was then poured into a Buchner (Coors) filter no.2 containing a Whatman filter paper no.4. 150 g of the liquid was transferred in a 400 ml beaker. The pH meter was used for determining the pH value. The solution was then titrated to a pH of 3.5 with nominal 0.01N Sulfuric acid solution. The liquid was mixed by a magnetic stirrer. The pH and milliequivalents (N×ml) of acid needed to change the pH to 3.5 were calculated as the buffer capacity

Bonding Quality

The bonding strength development was investigated with the Automated Bonding Evaluation System (ABES). The ABES is designed to determine the development of adhesive bonding strength between two pieces of strands. The bonding is affected by temperature, curing time or the pressure that is applied to lab-shear samples (Humphrey 1993). This device is composed of a bond-forming and test module, which are present in Figure 1, and a computer control system with testing-software program.

The adhesive was spread onto one side (5x10 mm^2 of overlapping area) of the bamboo strand with a hand brush at an application rate of 200 g/m^2. After lay up, the strands were then hot-pressed under controlled parameters of temperature and time and pressure which are given in Table 2. After each bond was cured to the required time and temperature, the pressure was released from the specimen, which was then immediately pulled in a shear mode. Tensile load and gripping head movement (sample elongation) were PC-monitored during strands pulling, and load at failure was recorded by a computer like for the determining the shear strength of the adhesive bond. At least three replications were performed for each of the condition.



(a) (b)

Figure 1 Details of Automated Bonding Evaluation System device, (a) ABES overview, which is composed of the bond-forming with testing module and computer control system (b) A close-up of the bond forming zone, which is composed of the hot press plates and specimen holders.

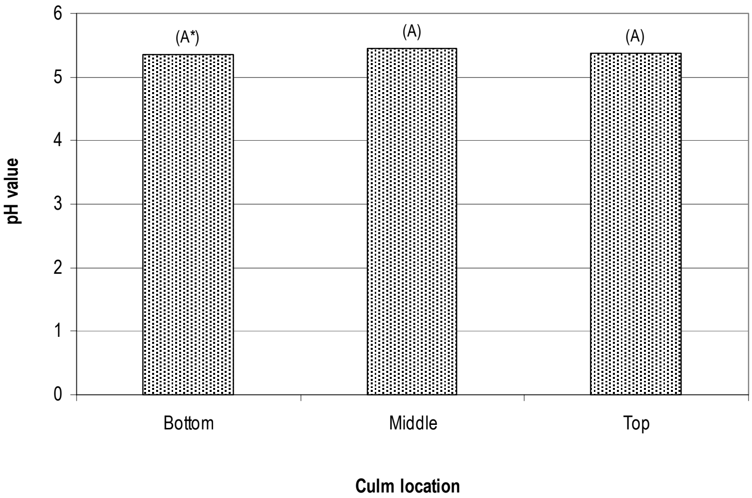
Table 2 Design parameters for the experiments

Sample parameters	Data
Resin types	• MF (Prefere 13H560) + 3% NH_4NO_3 • MUPF (KML 534) + 3% NH_4NO_3 • PF (Bakelite 1279 HW) + 6% K_2CO_3
Resin spread rate	200 g/m^2
Sample moisture content	12%
Pressing parameters	
Pressing temperatures	130, 150, 170 and 190^{0}C
Pressing times	20 to 200 seconds
Pressure	4 N/mm^2 (constant)

Results and Discussion

pH and Effect of Culm Location on Value

Figure 2 presents the pH value data, obtained for the measurement from three locations of three bamboo culms. The pH value of *Dendrocalamus asper* ranges in the acid region from 5.36 – 5.45. The highest value occurs in bottom part, while the lowest value occurs in top part of the culm. The differences of pH value between each location is not significant (F-value = 0.23). Compared to wood species, the pH value of *Dendrocalamus asper* is quite similar to some softwood and hardwood species, which have value in the range of 4-6 (Fengel and Wegener 1984).



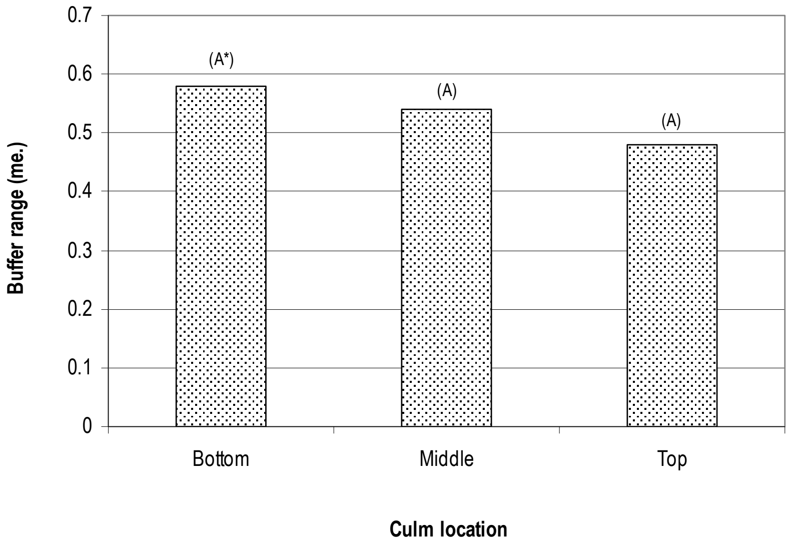
Note: * Means with the same letter for the location are not significantly different at $p<0.05$ by Duncan's Multiple Range Test

Figure 2 pH value of *Dendrocalamus asper* at different locations

Buffer Capacity and the Effect of Culm Location on Value

The acid-buffering capacity of *Dendrocalamus asper* at three different locations in the culm is illustrated in Figure 3. The average value of bottom, middle and top parts of the culm are 0.58, 0.54 and 0.48 milliequivalents, respectively. Although there are not significant differences between the location (F-value = 0.27), the value gradually decrease from bottom to the top of the culm. It is known that bamboo extractives have some variation in their vertical location. The bottom part of the culm has significantly higher extractive contents, particularly with hot-water extracts, alcohol-benzene extracts, 1%NaOH extracts and ash, than the other parts (Kamthai 2003). It is reasonable to hypothesize that the chemical composition of bamboo, especially water extracts and inorganic matters, has effect on its buffer capacity.

It is clear that *Dendrocalamus asper* has extremely high resistance to pH changes and weakly responds to the acid addition when compared to normal wood (Sauter 1996). It would be considered as the high buffer capacity specie. It requires a huge amount of acid catalyst to reduce the pH to the optimum level which is required for a resin cure. This may cause problems to use it as raw material in wood composite with conventional gluing technology. Some strategies, such as the use of special glue to produce boards or adjusted hot-pressing parameters, might be applied to improve resin curing and therefore improve product properties too. As the result, the buffer capacity would be mentioned as a key factor for consideration *Dendrocalamus asper* as the raw material in all wood composite manufacturing processes. It is also a noteworthy issue that its buffer capacity varies along the culm location, although the differences seem small until the statistical analysis cannot find. Thus, it should require some special consideration in regard to catalyst addition and resin cure.



Note: * Means with the same letter for the location are not significantly different at p<0.05 by Duncan's Multiple Range Test

Figure 3 Buffer capacity of *Dendrocalamus asper* at different culm locations

Bonding Strength Development of MF, MUPF and PF adhesives

The development of bond strength was observed in terms of the shear strength of each adhesive as a function of pressing time and temperature. A typical bond strength development of MF, MUPF and PF adhesive is shown in Figure 4, 5 and 6, respectively.

The results of ABES test indicate that bonding strength of glue-line vary significantly with different adhesive type, pressing temperatures and time. The maximum shear strength is 8.90 N/mm^2 for MF resin at 170°C and 200 seconds (Figure 4), while the minimum shear strength is 0.15 N/mm^2 for MUPF resin at 130°C and 20 seconds (Figure 5).

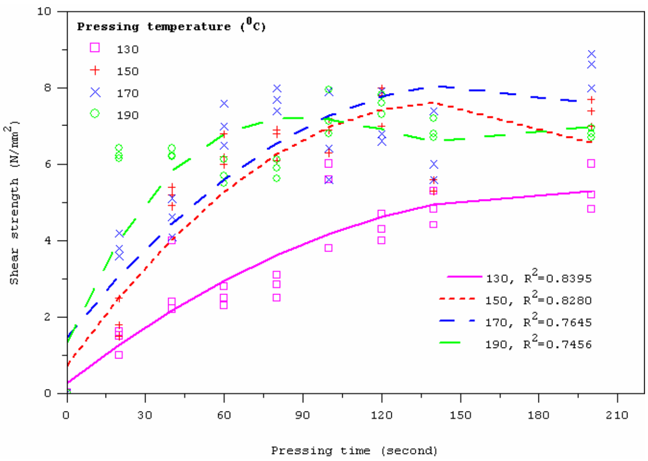


Figure 4 Development of shear strength of MF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

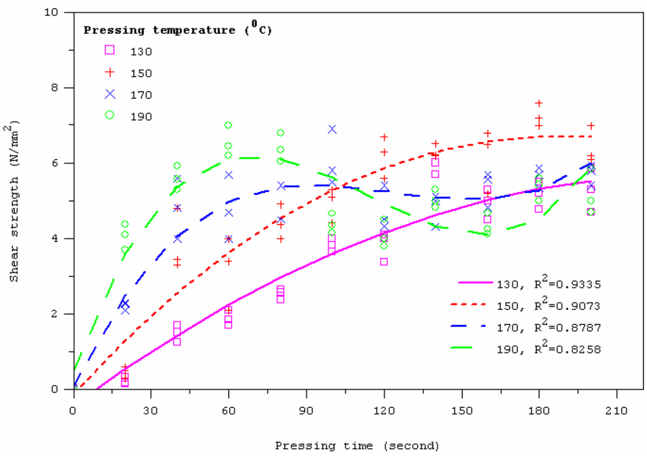


Figure 5 Development of shear strength of MUPF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

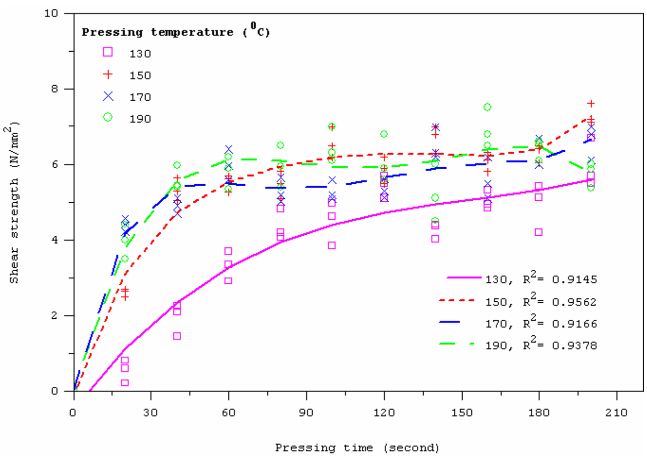


Figure 6 Development of shear strength of PF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

Influence of Pressing Temperature and Time

The results indicate that bonding quality vary significantly with different pressing times. The effect of the higher pressing temperature is mainly related to an increase in shear strength in the glueline. The temperature increase influences the rate at which adhesive bonds develop which can be suggested by the rapidly increasing of initial strength. As usual, heat is used during the pressing for faster bonding development. The resin can cure fast when the pressing temperature increases. At low temperatures, the bonding strength is limited because the resin can not completely cure, but an excess temperature can reduce or eliminate the bonding strength in glueline as illustrates at 190°C for MF and MUPF resin (Figure 4 and 5, respectively).

Notably, most of curves for shear strength development related to pressing time could be separated into two distinct phases, where each phase can be explained the observed relation. In the first phase, which can be denoted as an initial, the shear strength is low at the beginning of the hot pressing for each temperature level since the tiny bond line occurs. After 20 seconds of pressing, strong adhesion between the adhesive and bamboo start to build up, resulting in a rapid increasing of bonding strength which causes the growth as a linear fraction of the shear strength graph. The results suggest that the higher pressing temperature, the shorter the first phase, as distinctly illustrated in Figure 7. At 150°C, the end of first phase is reached at 80 seconds pressing time, while the end of first phase for 170°C is reached in 40 seconds pressing time. In the second phase, the bonding strength further increase with the increasing pressing time until the maximum value of each graph is reached, where the bonding strength value is highest. With the further pressing time, the strength is slightly constant. During the end of this phase, the shear strength slightly decreases with the longer pressing time at higher pressing temperature, as distinctly illustrated in 170°C for MF and 170, 190°C for MUPF resin (Figure 4 and 5, respectively). It can be observed that longer pressing time would deteriorate the completed bond which already occurs in the glueline.

Noteworthy, the bonding strength development, which were taken place at the excess temperatures (in the case of 190°C for MF and MUPF resin) behave differently. They are slightly constant and show small shear strength values. In accordance with Blomquist et al. (1983), PF resin requires high press temperatures for condensation reaction. Actually, this is the basic results on the laboratory scale. Further study is requested in order to explore this in an optimal parameter on an industrial scale. Furthermore, the pressing temperature has a greater influence than the pressing time. At lower temperature, a longer pressing time is needed to reach the maximum bonding strength, whereas the shorter pressing time is used at a higher temperature, as distinctly illustrated in Figure 5. At 150°C, the maximum shear strength is 7.60 N/mm^2 at 180 seconds pressing time, while the maximum shear strength for 170 and 190°C is 6.90 and 7.00 N/mm^2 at 100 and 60 seconds pressing time, respectively.

Influence of Resin Types

The three adhesives, which were evaluated in this study, show different maximum shear strength. It can be seen that MF resin shows the highest shear strength value (8.90 N/mm^2) as shown in Figure 4, while the maximum shear strength value for MUPF (7.60 N/mm^2) is quite similar to that of PF (7.90 N/mm^2) as shown in Figure 5 and 6, respectively. The results suggest that all of them appear to have a similar pattern for the bond strength development, although the times, when particular phases occurred, vary with the different adhesives. Furthermore, all of them are thermosetting resins. Their cross linking reactions take place in the bond under applied pressure and heat, but their network bonding can be effect by excess temperature. It is important to note that the adhesive types vary significantly in the bonding conditions for which they are require in use, especially with regard to pressing temperature and time. MF and MUPF can harden and bond properly at lower temperature (150-170°C), while PF requires higher temperature (190°C).

Conclusions

The pH value, buffer capacity of *Dendrocalamus asper* and its bonding strength development have been analyzed. The following conclusions can be drawn from this part of the study:

1. *Dendrocalamus asper* has an average pH value of 5.40 which is compared to other wood species, particularly softwood. The pH value does not vary along the location of the culm.
2. Buffering capacity of the *Dendrocalamus asper* strands is shown to be 5 times higher than those of other wood species. The value slightly varies along the culm location.
3. The bond strength between bamboo strands and adhesive is improved according to ABES tests by increasing the hot pressing time and temperature. Several adhesives exhibited satisfactory bond strength. The best glueline strength between bamboo strands was found by the ABES method to be MF.

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Development of Oriented Strand Lumber made from *Dendrocalamus asper* Backer

Marius C. Barbu[1, 2], Pannipa Malanit[1, 3], Arno Frühwald[1]

[1]Department of Wood Science, University of Hamburg, Germany
[2]Faculty for Wood Industry, "Transilvania" University Brasov, Romania
[3] School of Engineering and Resources, Walailak University, Thailand

Abstract

The study was conducted to evaluate the suitability of using Sweet bamboo (*Dendrocalamus asper* Backer) for Oriented Strand Lumber (OSL) manufacturing. The boards were manufactured from bamboo-strands using four resin types (MUPF, MF, PF and pMDI) and three levels of resin content (7, 10 and 13%). The physical and mechanical properties of lab manufactured OSL were evaluated by ASTM 1037, ASTM 5456 and EN 300. It was found that OSL made from bamboo strands exhibit acceptable strength properties compared to the commercial products (i.e., Oriented Strand Board) and the engineered products (i.e., zephyr and Parallel Strand Lumber) made from bamboo and wood. The resin type and content have a significant effect on its properties. Regarding the internal bond, bamboo-based OSL shows less strength than others. Further improvements in the internal bond and thickness swelling may lead to OSL industrial for structural use. The best results were obtained by using 13% pMDI content at 750 kg/m³ density.

Introduction

Wood has distinct advantages over other construction materials because it is a renewable raw materials and also friendly to the environment. Moreover, wood has unique characteristics of being superior in strength-to-weight ratio, shock absorbance, vibration, and aesthetically appealing as well as warm touchable. Then, it has been used by humans for the varied requirement, especially for constructions. The availability of timber for the production of large size solid-sawn lumber has declined, while the demand for high quality wood has increased because of the increasing of the world population and restrictive harvesting regulation from natural forest. Thus, this has led to continuous efforts to find new resources as an alternative to wood. Bamboo can be a potentially usable alternative raw material.

Bamboo is one of the promising raw materials that can be used for wood composite manufacturing, because it is a fast-growing, short-rotation life and has similar ligno-cellulosic structure. It has better mechanical properties compared to some wood species. Bamboo has been used since thousands of years for building, especially in the Asia and Pacific region. Thailand is one of the richest areas of bamboo in Asia. There are 13 genera and 60 species. *Dendrocalamus asper* is one of the most popular bamboo species of Thailand planted in more than 60 provinces (Pungbun 2000). The utilization of *Dendrocalamus asper* can be divided into two fields, i.e. young bamboo shoots and bamboo culms. The young shoots are widely consumed as a vegetable. The culms are strong and durable and used as building material and for houses and bridges, also in furniture, musical instruments, chopsticks, household utensils and handicrafts (Dransfield and Widijaja 1995; Rao et al 1998). In many countries, the interest for bamboo utilization has increased after several studies have evaluated bamboo's properties and its potential as an alternative resource for wood composites industry, and regarded the effective use of bamboo for engineered products such as plywood (Chen 1985), oriented strand board (OSB) (Lee et al 1996 and 1997; Sumardi et al 2007 and 2008), waferboard (Zhang 2001), zephyr board (Nugroho and Ando 2000) and laminated bamboo lumber (Nugroho and Ando 2001). They confirmed that bamboo is able to provide high quality engineered wood products. At the same time, several researches in Thailand were carried out to use this species as raw material for fiberboard, pulp and paper (Kamthai 2003; Laemsak and Kungsuwan 2000). However, none of these studies researched bamboo as raw material for the Oriented Strand Lumber (OSL).

The primary objective of this study was to determine the physical and mechanical properties of OSL made from *Dendrocalamus asper* with the respect to the two processing parameters (resin type and resin content), and to compared its properties to standard requirements and previous researches.

Materials and methods

Materials

Three-year-old bamboo culms, with an average culm length of 19 m, and a culm-wall thickness in the range of 6-27 mm, were collected from bamboo plantations located in Nakorn Sri Thammarat, South of Thailand. They were used as raw material for the prototype bamboo-based OSL. Four exterior used resins were used in this research: Melamine Urea Phenol Formaldehyde (MUPF), Melamine Formaldehyde (MF), Phenol Formaldehyde (PF) and Isocyanate (pMDI). The MF resin (Prefere13H560, Liquid) was supplied by Dynea. The MUPF resin (KML 534, Liquid) was obtained from BASF. The PF resin (Bakelite 1279 HW, Liquid) was supplied by Hexion. The pMDI resin (Suprasec® 5025, Liquid) was provided by Huntsman. Their properties are presented in Table 1.

Table 1 Resin properties and manufacturing parameters of bamboo-based OSL

Resin types	Resin properties			Manufacturing parameters			
	Solid content (%)	pH at 20°C	Viscosity (mPa*s)	Hardener	Mat moisture content (%)	Pressing temperature (^{0}C)	Pressing time (s/mm)
MUPF	64±1	9.3-9.8	150-400	NH_4NO_3	9	210	16
MF	62.5	9.73	100-150	NH_4NO_3	9	190	12
PF	48	8.5-10.5	650-700	K_2CO_3	14	190	12
pMDI	-	-	180-240	-	6	220	10

Preparation of strands

Bamboo strands were prepared from green-state culms, with the moisture content in the range of 80-100%, having a culm-wall thickness more than 12.5 mm. The culms were crosscut to 140 mm long pieces and spited into half. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. The average dimensions of bamboo strands were 140 mm long, 0.7 mm thick, and 12.5-20 mm wide. Strands were then graded by a Gilson Screen (Model TM-4) through meshes of 12.5 mm. Strands that passed through the 12.5 mm screen-mash and remained in the pan were considered as fine fractions. After these processes, all strands were dried with a laboratory-made rotary dryer to 2% final moisture content.

Lab manufacture of bamboo-based OSL

Uni-directional oriented strand boards with the dimension of 800 mm x 300 mm x 16 mm and 750 kg/m³ in target density were manufactured using laboratory equipment using four resin types and three levels of resin content. All commercial liquid resins were applied to strands using an inhouse-made paddle-type blender. No waxes or other additives were used. Hand-formed mats were transferred to a single-opening hydraulic lab hot press (Siempelkamp press) and pressed into boards. In this study, 36 boards were produced by using a pressing temperature and time following the suggestion of glue supplier, as presented in Table 1.

Properties evaluation of bamboo-based OSL

The lab boards were trimmed and cut into specimens for physical and mechanical properties testing. All specimens were conditioned for several weeks at 65% relative air humidity (RH) and 20°C until constant weight was attained. The property tests for Specific gravity (SG), Thickness swelling (TS), Water absorption (WA), Modulus of rupture (MOR), Modulus of elasticity (MOE) and Internal bond (IB) were conducted in accordance with the ASTM D 5456, ASTM D 1037 and EN 300. All data from the tests were statistically analyzed. A factorial analysis of variance was conducted to test level of significance in difference between factors and the test values.

Results and discussion

The results of the of resin type and resin content influence on bamboo-based OSL are graphically presented in this part. Table 2 shows the results of multifactor analysis variance for bamboo-based OSL properties based on two chosen parameters.

Table 2 Multifactor analyses of variance of resin type and resin content influence on the physical and mechanical properties of bamboo-based OSL

OSL properties	Source of variation	F-value	Significance level
Thickness swelling	Resin type	84.75	**
	Resin content	30.80	**
	Interaction	6.10	**
Water absorption	Resin type	55.03	**
	Resin content	13.17	**
	Interaction	4.30	**
Modulus of rupture	Resin type	6.52	**
	Resin content	41.49	**
	Interaction	0.86	NS
Modulus of elasticity	Resin type	68.69	**
	Resin content	50.57	**
	Interaction	3.17	*
Internal bond	Resin type	87.70	**
	Resin content	65.37	**
	Interaction	2.10	NS

Note: ** indicates significance at the 1% level of probability.
* indicates significance at the 5% level of probability.
NS indicates not significant.

Specific gravity

The target specific gravity of the bamboo-based OSL is 0.75, while an average specific gravity is 0.72 at an average moisture content level of 6.64%. This result suggests that the average board specific gravity is lower than the target one (board specific gravity). It may provide an explanation as a spring-back phenomenon of the board after pressing, since the internal board strength cannot resist the internal stress due to excess steam pressure which could not escape from the mat during hot pressing. In this case, the board thickness after pressing increases around 11.92% and 6.50% for bamboo-based OSL bonded with 7% MUPF and 10% MUPF, respectively.

Thickness swelling

The result suggests that the thickness swelling (TS) value ranges from 2.3-26.4 % which is shown in Figure 1. It can be seen that pMDI-bonded board shows less thickness change than those of other boards. Moreover, board made with higher resin content results in improved dimensional stability similar to the findings of previous works (Lee et al 1996; Nugroho and Ando 2000). These results are further confirmed with the statistical analysis, as presented in Table 2. The result shows that the different resin type and resin content have a significant effect on TS value. Notable, the MUPF-bonded OSL shows a significant higher TS value than those of others. It can be explained as a result of the higher hydrolysis sensitivity of the MUPF resin. The lack of resistance to high moisture content is attributed to the presence of hydrolysable group between carbon of the methylene linkage and nitrogen of urea (Pizzi 1994).

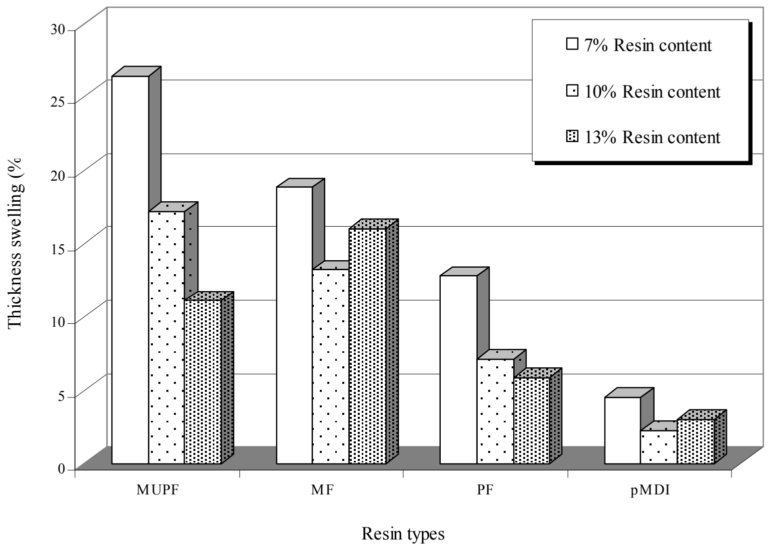

Figure 1 Effect of resin type and content on thickness swelling after 24h water soaking (20°C) of bamboo-based OSL

In accordance with the requirement of OSB/3 type by EN 300 standard, the allowed maximum TS value (24 hours water soaking) is 15%. The MUPF-bonded OSL does not achieve this requirement. It can be explained by no wax or other treatments were done. Accordingly, it requires the wax adding or additional strands pretreatments to improve the dimensional stability of bamboo-based OSL.

Water absorption

The WA of bamboo-based OSL is shown in Figure 2. The value ranges from 16.9 to 40.5%. Analysis variance based on resin type and content is presented in the Table 2. From these data, it may be concluded that the resin type and resin content have a significant effect on this property. The results suggest that OSL made with 13% pMDI resin shows the significant lowest WA, as presented in Fig. 3. A distinctly increase in hydrophobic characteristic observed for pMDI-bonded OSL can be explained by the highly strong bonds between NCO groups of resin and -OH groups of the bamboo cellulose. Furthermore, the obtained values show a slight decreasing trend along with the increase in their resin content in boards.

This result is consistent with the TS, 7% MUPF-bonded OSL shows a higher WA value than the others. This might be due to its lower specific gravity. Then, more water can be absorbed. Moreover, MUPF resin is low hydrolysis resistance. In distinct contrast to the TS, the WA for PF-bonded OSL is higher than that of MF-bonded OSL. This phenomenon can be suggested by the hydroscopic behavior of the alkali in the PF resin. Thus, a greater amount of water is absorbed without affecting the TS (Pizzi 1994).

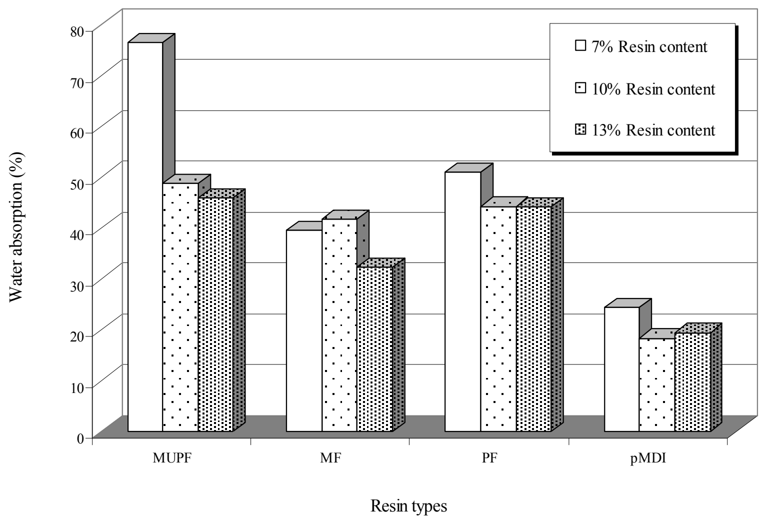

Figure 2 Effect of resin type and content on water absorption after 24h soaking of bamboo-based OSL

Compared to previous reports, the bamboo-based OSL made from pMDI resin show a quit similar WA value to that of bamboo-zephyr (Nugroho and Ando, 2000), while bamboo-based OSL bonded with MUPF and PF resins show smaller values than those of other bamboo-strand based boards (Lee et al. 1996) and Scots pine-based OSB (Paul et al. 2006). The reason of this circumstance has not been addressed.

Static bending

The static bending strengths of bamboo-based OSL are illustrated Figure 3 and 4. The MOR and MOE values are in the range of 29.1 to 65.2 MPa and 3,280 to 11,109 MPa, respectively. The analysis of variance testing conducted on the effect of the two factors and their interaction (Table 2), confirms here that the resin type and resin content significantly influence on both of MOR and MOE.

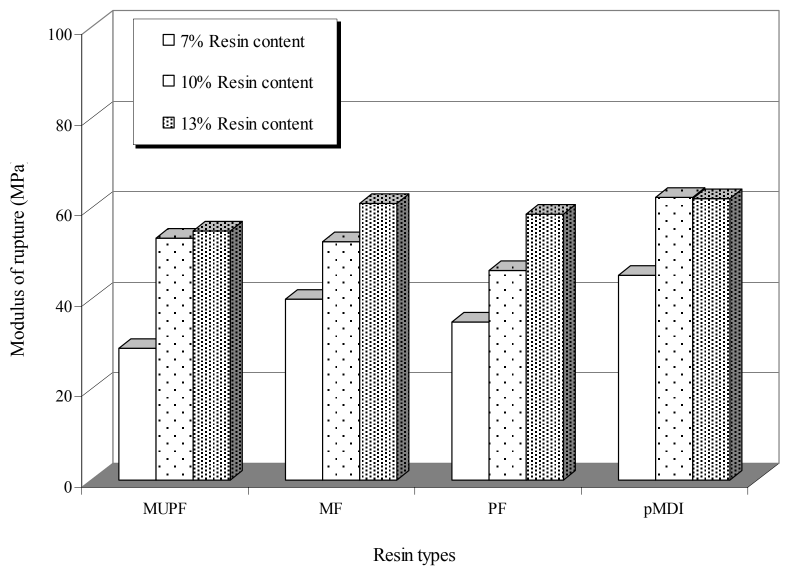

Figure 3 Effect of resin type and content on modulus of rupture of bamboo-based OSL

From Figure 3, it can be seen that the MOR value of pMDI-bonded OSL is highest, while those of MF and PF-bonded OSL are quit similar, and that of MUPF-bonded OSL is lowest. One explanation may lie in the high bonding strength of the cross linked polyurea network of pMDI resin, as mentioned earlier. As well, the resin content contributes to improve board strength and stiffness. In basic knowledge, it can be described the relationship between resin content and product strength that with the increasing of resin content, the product strength will improve by the increase of the intimate contact area between adjacent bamboo strands in the board. These results are also in agreement with the result of Barnes (2000) and Post (1958) who show that with higher resin content of composite board, the physical and mechanical properties of board increase.

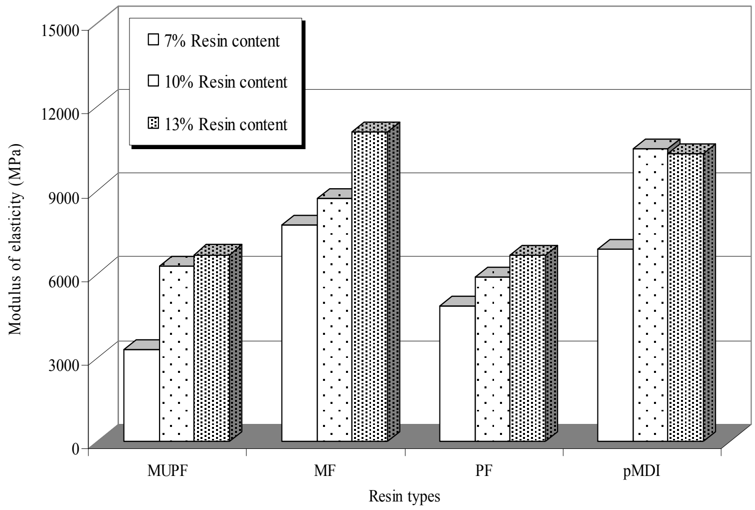

Figure 4 Effect of resin type and content on modulus of elasticity of bamboo-based OSL

From Figure 4, the result suggests that MOE of bamboo-based OSL are mainly influenced by the resin type. The strengths increase in the order MUPF, PF, pMDI and MF bonded OSL. Moreover, they also increase with the resin level. The maximum value is 11,109 MPa for MF at 13% resin content, while the minimum value is 3,290 MPa for MUPF at 7% resin content at the target density of 750 kg/m³. It is impossible to distinguish the difference between MF- and pMDI-bonded OSL and they are approximately 35% higher value than MUPF and PF bonded board at the same level of resin content.

The comparison of MOR and MOE values between bamboo-based OSL and several engineered wood products in the previous researches (Liu and Lee 2003; Malanit et al. 2005; Nugroho and Ando 2000). The average MOR of bamboo-based OSL is quit similar to bamboo-zephyr, but slightly lower than those of wood-based boards. The MOE of bamboo-based OSL is also quit similar to bamboo-zephyr, but approximately 50 to 75% lower than wood-based boards, while the average specific gravity of all products are quit similar. Although bamboo-based OSL was found to be less rigid, but it exhibits acceptable strength property, as indicated by its high MOR value.

Internal bond

The internal bond strength (IB) of bamboo-based OSL made with different resin types and content is shown in Figure 5. The minimum value is 0.06 MPa for the board made with 7% MUPF resin content which shows lower density than those of other and occurs the blisters inside the board., while the maximum value is 0.67 MPa for the board made with 13% pMDI resin content. The analysis of variance result (Table 2) conducted on the effect of two factors and their interaction shows that the resin type and resin content significantly influences the internal bond. The IB of the MF-bonded OSL is quite similar to PF-bonded OSL. Their values are approximately 35% lower than pMDI-bonded OSL because of the high strength of covalent bonds between strands, as mentioned above.

Compare to other engineered composite products (Liu and Lee 2003; Nugroho and Ando 2000; Malanit et al. 2005), PF-bonded bamboo-based OSL shows approximate 3 to 9 time smaller IB value than Rubberwood-OSL. The average IB value of bamboo-based OSL made from pMDI resin is approximate 2 times smaller than those of bamboo-zephyr and Rubberwood-OSL. A possible explanation might rest for this situation. The bamboo specific gravity varies within the horizontal and vertical of culm (Liese 1985). This variation could influence the glue penetration and bonding.

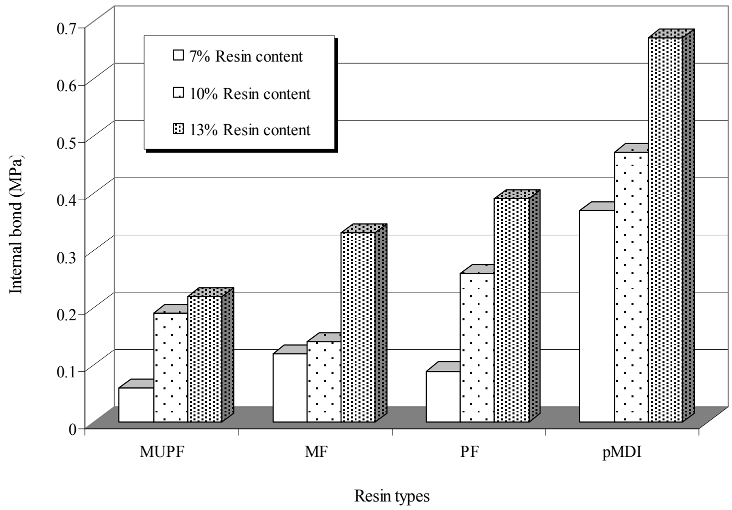

Figure 5 Effect of resin type and content on internal bond of bamboo-based OSL

The minimum IB required by the EN 300 standard for OSB/3 is 0.35 MPa. The result demonstrates that, only the IB value obtained from pMDI-bonded OSL is higher than that of the standard requirement (EN300). It seems likely that the OSL made from *Dendrocalamus asper* shows low internal bond strength. Further experiments to improve of board with special consideration in strands preparation are necessary.

Conclusions

From the results of this study on the physical and mechanical properties of OSL made from *Dendrocalamus asper* conclusions are drawn as follows:

1. Resin type and content are dominant parameters controlling physical and mechanical properties of OSL. The pMDI-bonded OSL show better physical and mechanical properties than MF, MUPF and PF-bonded one. All properties are improving with the increase of resin content.
2. The best parameters of this study are achieved for 13% pMDI resin content.
3. Compare to the commercial products and other engineered wood products, bamboo-base OSL exhibit acceptable strength properties. Then, bamboo-based OSL can be used for structural purposes.
4. *Dendrocalamus asper* can be promoted as an alternative raw material for OSL manufactures, but the special improvements like strand pretreatment and equipment adaptation/pressing optimization are necessary.

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Publication VII

On the Suitability of an Asian Bamboo for Structural Composite Boards

Pannipa Malanit [1, 2)], Marius C. Barbu [3)], Arno Frühwald [2)]

[1] Department of Wood Science, University of Hamburg, Germany
[2] School of Engineering and Resources, Walailak University, Thailand
[3] Faculty for Wood Industry, "Transilvania" University Brasov, Romania

Key words

Dendrocalamus asper Backer, Bamboo characterization, Bamboo utilization, ABES, Bamboo-based board, Oriented Strand Lumber

Abstract

Bamboo is widely distributed in Asia and Latin America. The use of bamboo for products has a long tradition on the level of craftsmanship but industrial based products still have not gained a real breakthrough. A Thailand-German-University-Project, financed through the German-Academic-Exchange-Service (DAAD), investigates the potential of *Dendrocalamus asper* Backer for the manufacture of building elements. As a lead product Oriented Structural Lumber (OSL) was selected to investigate the potential of this bamboo species.

Anatomical, chemical and physical properties of the material were tested, including the variation of properties along the axis of the culm and the circumference/culm-wall thickness. Strands were produced and their dimensions have been evaluated against strands from traditional wood species. The bonding strength of bamboo strands employing all the relevant glue types for wood based panels used for structural applications was investigated, using a special testing device called an Automated Bonding Evaluation System (ABES).

It was found that bonding strength was improved by increasing the hot pressing time and temperature. The gluing tests in general show good results but for some glue types a more clear insight is necessary to increase bond quality towards the level of "normal wood". In addition, the properties of the bamboo-based OSL produced in the laboratory are close to the requirements to the type OSB 3 according to CEN-EN 300-Standards. The resin type and content have a significant effect on its properties. Further improvements will lead to a concept to use bamboo for OSB-type building elements.

A further project will look on the combination of Bamboo and Asian tropical traditional and plantation wood species.

Introduction

Over the past decade, the demand for high quality wood for construction has increased because of the rise of world population and the decline of wood from natural forest. Consequently, the search for alternative or substitute materials instead of the traditional use of wood has been focused. A suitable substitute should be inexpensive, fast-growing, permanently available, having comparable physical and mechanical properties, environmental friendly and it should be compatible to existing processing technologies. Bamboo could be such a non-wood substitution material.

Bamboo belongs to the large woody grasses (Family Poaceae, Subfamily Bambusoideae) and encompasses about 1,200 species within 50 genera in the world (Chapman, 1996; Qisheng *et al.*, 2002). It is mostly distributed in the tropical and subtropical regions, covering an area of over 37 million hectares. In Latin America and Africa, bamboos occupy 10.4 and 2.8 million hectares respectively (Lobovikov *et al.*, 2007). Bamboo is a non-wood lignocellulosic material which has been widely used as a material for construction, furniture manufacture and daily household uses. In recent times, it has been used as a raw material for wood products manufactured in Asian factories, such as for pulp and paper, plywood, Medium Density Fiberboard (MDF), Particleboard (PB) and Oriented Strand Board (OSB), because of its high strength and properties. However, a change in raw material may affect on product properties and requires additional adjustment of some processing parameters, such as the adhesive system. Since the adhesive is a significant cost factor in board production, future development of bamboo-based board will require an analysis of the bonding strength between bamboos and adhesives.

Therefore, the objectives of this study are to investigate the bonding strength characteristic of *D. asper* bonded using different adhesives for exterior applications. Additionally, the boards made from *D. asper* were produced the lab-scale regarding to the two processing parameters (resin type and resin content) and their properties were investigated and compared to standard requirements and previous researches.

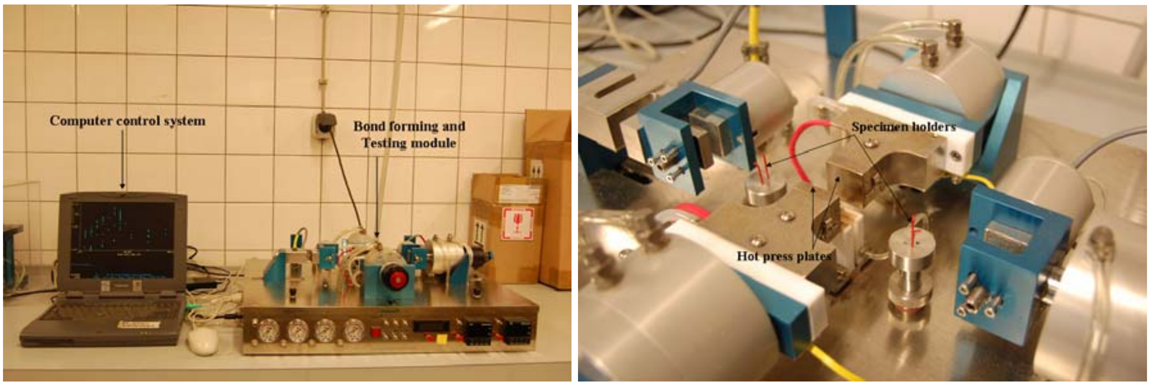
Materials and methods

Bonding strength characteristic

In this study, the three years old of *D. asper* culms were collected from plantations located in Nakorn Sri Thammarat, Thailand. These bamboos had an average culm length of 18 m. The culm diameter at the bottom was about 11.5 cm, while the top culm was about 2 cm. The average culm wall thickness was 1.6 cm. The average specific gravity at 12% MC was 0.75.

The 0.8 mm thick bamboo strands and 20 by 120 mm were prepared. All strands had been placed in a conditioning chamber, at a temperature of 20°C and relative humidity of 65%. The final average of MC was 12%.

The bonding strength was investigated with the Automated Bonding Evaluation System (ABES) determining the development of adhesive bonding strength between two bamboo strands which is affected by temperature, curing time or the pressure that is applied to lab-shear samples (Humphrey, 1993). This device is composed of a bond-forming and test module, which are present in Figure 1, and a computer control system with testing-software program.



(a) (b)

Figure 1 Features of Automated Bonding Evaluation System device, (a) The ABES system composing of the bond-forming and testing module and computer control system (b) A close-up of the bond pressing zone composed of the hot press plates and specimen holders.

Four adhesives for exterior uses were investigated: Melamine Urea Phenol Formaldehyde (MUPF), Melamine Formaldehyde (MF), Phenol Formaldehyde (PF) and Isocyanate (pMDI). Their characteristics are presented in Table 1. Each adhesive was blended in accordance with the specification of their suppliers and applied onto one side of the strand at a rate of 200 g/m². Afterwards, two resinated strands were laid up in the bond-pressing zone and then hot-pressed under controlled parameters of temperature, time and pressure, which are given in Table 2. Immediately after each bond was cured to the required level, the shear strength was tested. Tensile load and gripping head movement (sample elongation) were PC-monitored during strands pulling, and shear-stress to failure was calculated.

Table 1 Some properties of four exterior used resins.

Resin types	Resin properties				
	State	Solid content (%)	pH at 20°C	Viscosity (mPa∗s)	Hardener
MUPF (KML 534)	Liquid	64±1	9.3-9.8	150-400	NH_4NO_3
MF (Prefere13H560)	Liquid	62.5	9.73	100-150	NH_4NO_3
PF (Bakelite 1279 HW)	Liquid	48	8.5-10.5	650-700	K_2CO_3
pMDI (Suprasec® 5025)	Liquid	-	-	180-240	-

Table 2 Design parameters for the bonding strength development tested by ABES

Sample parameters	Interval
Resin types	MUPF, MF, PF and pMDI
Resin spread rate	200 g/m^2
Sample moisture content	12%
Pressing parameters	
Pressing temperatures	130, 150, 170 and 190^{0}C
Pressing times	20 to 200 seconds (in 20 seconds steps)
Pressure	4 N/mm^2 (constant)

Bamboo-based OSL

As well, the same three-year-old bamboo culms collected from plantations in surroundings of Nakhon Sri Thammarat were used as raw material for the prototype bamboo-based product. Bamboo strands were prepared from green-state culms. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. The average dimensions of bamboo strands were 140 mm long, 0.7 mm thick, and 12.5-20 mm wide. Strands were then graded by a Gilson Screen (Model TM-4) through meshes of 12.5 mm. All strands were dried with a laboratory-made rotary dryer to 2% final moisture content.

One-directional oriented strand boards with 0.75 in target specific gravity were manufactured using the same four resin types (MUPF, MF, PF and pMDI), as given in Table 1, and three levels of resination (7, 10 and 13%). All resins in liquid state were applied to strands using an inhouse-made paddle-type blender. Hand-formed mats were transferred to a single-opening hydraulic lab hot press (Siempelkamp press, 60 x 80 m^2) and pressed into 16 mm boards.

All boards were trimmed and cut into specimens for physical and mechanical properties testing. All specimens were conditioned for several weeks at 65% relative air humidity (RH) and 20°C until constant weight was attained. Following properties were tested: Specific gravity (SG), Thickness swelling (TS), Water absorption (WA), Modulus of rupture (MOR), Modulus of elasticity (MOE) and Internal bond (IB), which were conducted in accordance with the ASTM D 1037, ASTM D 5456 and EN 300.

Results and discussion

Bonding strength characteristic

A characteristic of bond strength development of MUPF, MF, PF and pMDI resins is shown in Figure 2. The results indicate that bonding strength of glue-line vary significantly with different resin type, pressing temperatures and time. The maximum value of shear strength is 8.66 N/mm^2 for pMDI resin at 170°C and 180 seconds pressing time as presented in Figure 2(d), while the minimum value of shear strength is 0.15 N/mm^2 for MUPF resin at 130°C and 20 seconds as presented in Figure 2(a).

The effect of the higher pressing temperature is mainly related to an increase in shear strength in the glueline. The temperature increase influences the rate at which adhesive bonds develop which can be suggested by the rapidly increasing of initial strength. At low temperatures, the bonding strength is low because of the incompletely resin cure, but an excess temperature can reduce or eliminate the bonding strength in glue-line as illustrates at 190°C for MUPF resin in Figure 2(a). Notably, most of graphs for shear strength development related to pressing time could be separated into two parts. In the first part indicated as an initial, the shear strength is low at the beginning of the pressing. After pressing, strong adhesion between the adhesive and bamboo strands start to rise resulting in a fast increase of bonding strength which causes the growth as a linear portion of graph. The results suggest that the higher pressing temperature, the shorter the first part as distinctly illustrated in Figure 2(a). At 150°C, the maximum shear strength is 7.60 N/mm^2 at 180 seconds pressing time, while the maximum shear strength for 170 and 190°C is 6.90 and 7.00 N/mm^2 at 100 and 60 seconds pressing time, respectively. In the second part, the bonding strength further increase with the increasing pressing time until the maximum value of each graph is reached, where the bonding strength value is highest. With the further pressing time, the strength is slightly constant. During the end of this phase, the shear strength slightly decreases with the longer pressing time at higher pressing temperature (Malanit *et al.*, 2009). It can be observed that longer pressing time would deteriorate the completed bond which already occurs in the glue-line.

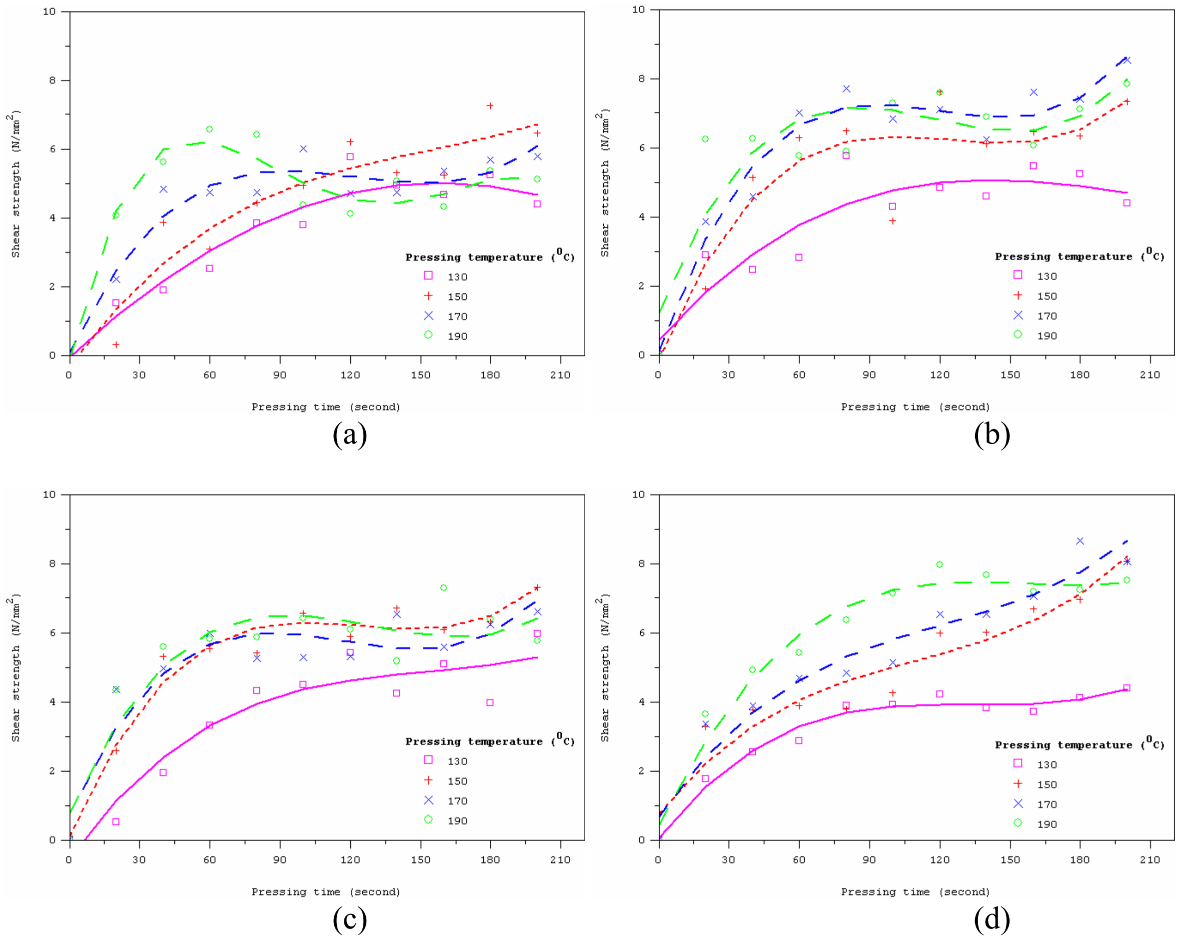


Figure 2 Shear strength development of bamboo strands glued with; (a) MUPF, (b) MF, (c) PF and (d) pMDI, as a function of pressing times and temperatures.

Compared to a previous study (Jost & Sernek 2009), similar results of shear strength development of wood strands in relation to of pressing time have been obtained. These results certainly suggest that the maximum shear strength of *D. apser* bonded with PF resin is reached 7.0 N/mm^2 at 170°C and 140 seconds as presented in Figure 2(c), while the maximum shear strength value of beech (*Fagus sylvatica*) bonded with PF resin is 8.0 N/mm^2 at 160°C and 50 seconds. It is evident that *D. asper* needs 3 times the pressing time which is required for beech to achieve the maximum shear strength, although the pressing temperature is higher. This finding of this research reinforces the previous research (Malanit *et al.*, 2009). They presented that *D. asper* shows high buffering capacity which would affect the curing characteristics of PF resin.

Bamboo-based OSL

The results after testing the properties of bamboo based OSL and the influence of the different resin type and resin content on the bamboo-based boards are presented in Table 3.

Table 3 The average values of the physical and mechanical properties of bamboo-based OSL

Resin type	Resin content (%)	SG [a]	MC [a] (%)	TS [a] 24 h (%)	WA [a] 24 h (%)	MOR [b] (MPa)	MOE [b] (MPa)	IB [a] (MPa)
MUPF	7	0.65	7.4	26.4	76.4	29.1	3,290	0.06
	10	0.73	6.7	17.2	48.8	53.5	6,274	0.19
	13	0.70	7.1	11.1	45.9	55.1	6,698	0.22
MF	7	0.72	7.7	18.8	39.6	39.9	7,750	0.12
	10	0.73	7.6	13.2	41.7	52.6	8,730	0.14
	13	0.82	7.8	16.0	32.3	61.0	11,109	0.33
PF	7	0.69	7.7	12.8	50.9	35.0	4,855	0.09
	10	0.71	9.1	7.1	44.3	46.3	5,915	0.26
	13	0.71	8.6	5.8	44.1	58.8	6,682	0.39
pMDI	7	0.74	3.6	4.5	24.4	45.2	6,897	0.37
	10	0.76	2.9	2.3	18.4	62.5	10,497	0.47
	13	0.71	3.5	3.0	19.5	65.2	10,300	0.67

Note: [a] The number of specimens for SG, MC, TS, WA and IB for each treatment is 15.
[b] The number of specimens for static bending is 6.

This result suggests that the average specific gravity of bamboo-based OSL is lower than the target specific gravity. It may be explained by a spring-back phenomenon of the board after pressing, since the internal board strength cannot resist the internal stress due to excess steam pressure which could not escape from the mat during hot pressing. In this case, the board thickness after pressing increases around 11.92% and 6.50% for bamboo-based OSL bonded with 7% MUPF and 10% MUPF, respectively.

The TS value (after 24 hours water-soaking at 20°C) ranges from 2.3-26.4 %. It can be seen that pMDI-bonded OSL shows less thickness change than those of other. Moreover, board made with higher resin content results in improved dimensional stability similar to the findings of previous works (Lee et al 1996; Nugroho & Ando 2000). Notable, the MUPF-bonded board shows a significant higher TS value than those of others. It can be explained as a result of the higher hydrolysis sensitivity of the MUPF resin. In reference to the requirement of OSB/3 type by EN 300 standard, the allowed maximum TS value (24 hours water soaking) is 15%. The MUPF-bonded OSL does not achieve this requirement. It can be explained by no wax or other treatments were done. Accordingly, it requires the wax adding or additional strands pretreatments to improve the dimensional stability of bamboo-based OSL.

The WA (24 hours water soaking) value of bamboo-based OSL ranges from 16.9 to 40.5%. The results suggest that board with 13% pMDI resin shows the significant lowest value. A distinctly increase in hydrophobic characteristic observed for pMDI-bonded OSL can be explained by the highly strong bonds between NCO groups of resin and -OH groups of the bamboo cellulose. Furthermore, the obtained values show a slight decreasing trend along with the increase in their resin content in boards. This result is consistent with the TS, 7% MUPF-bonded OSL shows a higher WA value than the others. This might be explained by its lower specific gravity. Then, more water can be absorbed. Moreover, MUPF resin is low hydrolysis resistance than pMDI.

The MOR and MOE values of bamboo-based OSL at the average specific gravity 0.72 are in the range of 29.1 to 65.2 MPa and 3,280 to 11,109 MPa, respectively. It can be seen that the MOR value of pMDI-bonded OSL is highest, while those of MF and PF-bonded OSL are quit similar, and that of MUPF-bonded OSL is lowest. One explanation may lie in the high bonding strength of the cross linked polyurea network of pMDI resin, as mentioned above. The resin content also contributes to improve board strength and stiffness. The result suggests that MOE of bamboo-based OSL are also mainly influenced by the resin type. The strengths of bamboo-based OSL increase with the resin performances in the order MUPF, PF, pMDI and MF. Moreover, they also increase with the resin level. The maximum value is 11,109 MPa for MF at 13% resin content, while the minimum value is 3,290 MPa for MUPF at 7% resin content at the target density of 750 kg/m³. It is impossible to distinguish the difference between MF- and pMDI-bonded OSL and they are approximately 35% higher value than MUPF and PF bonded board at the same level of resin content.

The minimum IB value of bamboo-based OSL is 0.06 MPa for the board made with 7% MUPF resin content which shows lower density than those of other and occurs the blisters (steam) inside the board, while the maximum IB value is 0.67 MPa for the board made with 13% pMDI resin content. The IB of the MF-bonded OSL is quite similar to PF-bonded OSL. Their values are approximately 35% lower than pMDI-bonded OSL because of the high strength of covalent bonds between strands, as mentioned above. Compare to the previous researches (Nugroho & Ando, 2000; Malanit *et al.*, 2005), bamboo-based OSL shows lower IB value than Rubberwood-OSL and bamboo-zephyr. It might be explained by three possible reasons. The specific gravity of *D. asper* varies along the culm length (Malanit *et al.*, 2008). This variation could influence the glue penetration and bonding. Additionally, it has been previously known that the *D. asper* has extremely high buffer capacity when compared to normal wood. This property makes it unsuitable for the use with some of the standard commercial resin used for wood-based boards. Moreover, the bamboo-based OSL show the huge density variation and the steam blisters inside the board. All of these causes could effect on the IB value. The minimum IB required by the EN 300 standard for OSB/3 is 0.35 MPa. The result demonstrates that, only the IB value obtained from pMDI-bonded OSL is higher than that of the standard requirement (EN300). It seems likely that the OSL made from *D. aper* shows low internal bond strength. Further experiments to improve of board with special consideration in strands preparation are requested.

Conclusions

The following conclusions can be drawn from this study:

1. The bonding strength development of *D. asper* glued with four exterior adhesives is improved according to ABES tests by increasing the hot pressing time and temperature. Several adhesives exhibited satisfactory bond strength. The best glueline strength between bamboo strands was found by the ABES method to be pMDI.
2. The physical and mechanical properties of boards made from *D. asper* are influenced by resin type and content. The pMDI-bonded board show better physical and mechanical properties than MF, MUPF and PF-bonded one. All properties are improving with the increase of resin content. The best parameters of this study are achieved for 13% pMDI resin content.

Acknowledgements

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Annex

Journal of Bamboo and Rattan

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6th July 2009

Miss. Pannipa Malanit
Department of Wood Science
University of Hamburg
Germany.

Dear Miss. Panippa,

Sub: Your Manuscript No. JBR/KFRI/270

Your MS. No. JBR/KFRI/270 entitled "Macroscopic aspects and physical properties of *Dendrocalamus asper* Backer for composite panels" is accepted for publication in Journal of Bamboo and Rattan and will appear in JBR Vol. 7 Nos. 3&4 2008. This volume of the Journal will be brought out in August 2009.

Chief Editor
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Institut Penyelidikan Perhutanan Malaysia
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Tel : 603-6279 7000 Fax : 603-6273 1314
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FRIM394/671/5/1(38) 15 April 2009

To whom it may concern,

Dear Sir/Mdm,

Re: P. Malanit

We are pleased to inform you that Miss Pannipa Malanit from the Department of Wood Science, University of Hamburg, Hamburg, Germany, is the first author for the paper 'The gluablitly and bonding quality of an Asian bamboo (*Dendrocalamus asper* backer) for the production of composite lumbers' which was submitted to the *Journal of Tropical Forest Science* (JTFS). The second and third authors are M. C. Barbu and A. Frühwald respectively.

The paper has been assigned the number 65/2008 and has been scheduled for publication in the October 21(4) 2009 issue of the JTFS.

JTFS is an international reviewed journal concerned with the development of tropical forest sciences. It is published by the Forest Research Institute Malaysia (FRIM) and is indexed in the ISI.

Thank you.

Yours sincerely,

Sarifah, K. A.
Editor
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FRIM

sarifah@frim.gov.my
Tel: 603-62797486
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Holz als Roh- und Werkstoff
Holzforschung München, Winzererstraße 45, 80797 München, Germany

Miss Pannipa Malanit
Leuschnerstr 91
Universität Hamburg
Wood Science
21031 Hamburg

Herausgeber:

Prof. Dr. G. Wegener
Prof. Dr. P. Glos

Schriftleitung:

Holzforschung München
Winzererstraße 45
80797 München
Germany

Telefon: (089) 21 80-6475
Telefax: (089) 21 80-6429
E-*mail:* metzger@wzw.tum.de

Munich, 8th July 2009

Dear Miss Malanit,

Please find enclosed the confirmation of acceptance as requested in the e-mail dated 8th July 2009.

Yours sincerely,
Ursula Metzger

Confirmation

This is to confirm the acceptance of the manuscript by Malanit P., Frühwald A., Barbu M., entitled "Physical and Mechanical Properties of Oriented Strand Lumber made from an Asian Bamboo (Dendrocalamus asper Backer)" for publication in our journal European Journal of Wood and Wood Products.

Munich, 8th[nd] July 2009

Prof. Dr. Gerd Wegener
Editor-in-Chief

VIII WORLD BAMBOO CONGRESS THAILAND 2009

June 14, 2009

Dear Pannipa Malanit -

I am very pleased to announce to you that both of your papers have been well received and accepted by the World Bamboo Congress Review Panel, headed by Dr. Walter Liese. We are happy to invite you to the 8th World Bamboo Congress in Bangkok, 16-19 September, 2009 to make an oral presentation on your work,

<< The Gluability and Bonding Strength of *Dendrocalamus asper* Backer for Exterior Structural Applications >>
and
<< Development of Oriented Strand Lumber made from Dendrocalamus asper Backer. >>

Congratulations!

Before 1 July, you will be advised of the amount of time you will be given to present this paper, on which day, and in which session. At this time, we will need to know what kind of audio/visual equipment you require, and any other specific needs from your side. Since the World Bamboo Organization is not a funding organization, you will need to seek travel sponsorship from your institution or other funding bodies. However, we can waive the Congress registration fee.

Please refer to our website for details about the event, hotel rooms, field trips, etc. If you have any questions, please feel free to contact me. I look forward to meet you in Bangkok! Congratulations on this fine work.

Best regards,

Susanne Lucas

Susanne Lucas
Chair, International Organizing Committee
8th World Bamboo Congress, Thailand

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