EVALUATION OF MECHANICAL PROPERTIES OF MALAYSIA LOCAL SOURCE WOOD FOR ELECTRIC CRUISER BOARD APPLICATIONS

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ABSTRACT

This research project revolves around the idea to reduce the carbon emission in mitigating the issue of climate change. An idea to introduce the electrical cruiser board by Muhammad Fiqkri Ismail from Universiti Kuala Lumpur with his idea to promote carbon less form of multimodal transportation for users in urban city of Greater Kuala Lumpur leads this research to study the elastic properties of local source woods in Malaysia that could be proposed for this application. The wood is used for the construction of the deck of cruiser board which designed three layers with the cross-ply laminate. Three types of wood were selected for this research project. It is consisting of Bakau, Merawan, and Laran which all of them had gone through an experimental to evaluate their elastic properties in Forest Research Institute Malaysia (FRIM). The elastic properties as in the form of multilayer were predicted by using laminate composite theory. The result of elastic properties predicted proves that Bakau is the best candidate to be proposed for development of electric cruiser board due to higher elastic properties especially in flexural modulus. The three layers of laminate exhibits significantly higher flexural modulus in longitudinal direction. The additional lamina into seven layers improved significantly of flexural modulus in perpendicular direction and slightly diminished modulus in longitudinal direction.

ABSTRAK

Projek penyelidikan ini berkisarkan mengenai idea untuk mengurangkan isu pelepasan karbon yang menjurus kepada perubahan iklim. Muhammad Fiqkri Ismail dari Universiti Kuala Lumpur telah memperkenalkan idea untuk mencipta "electrical cruiser board" sebagai kenderaan yang bebas karbon boleh digunakan bagi tujuan pengankutan dari satu platform ke platform yang lain serta ia bersesuaian untuk digunakan di kawasan Lembah Klang. Idea ini telah membawa penyelidikan ini untuk menganalisa sifat elastik kayu-kayu tempatan bagi tujuan mengenal pasti kayu yang bersesuaian yang boleh dicadangkan untuk membuat dek kepada cruiser board tersebut. Dek tersebut telah direka menggunakan tiga lapisan kayu berorientasikan "cross-ply". Tiga pilihan kayu adalah seperti Bakau, Merawan, dan Laran. Kayu-kayu terebut telah diuji bagi mengenal pasti sifat elastik. Ujian tersebut telah dijalankan di makmal Forest Research Institute Malaysia (FRIM). Sifat elastik kayu lapisan tersebut telah diramal dengan menggunakan konsep komposit laminat teori. Daripada keputusan tersebut, ia dapat dibuktikan bahawa Bakau merupakan kayu yang sesuai untuk dicadangkan bagi membangunkan "electrical cruiser board" berikutan ia mempunyai modulus lenturan yang lebih tinggi di arah memanjang. Laminat yang menggunakan tiga lapisan kayu telah menujukkan modulus lenturan yang jauh lebih di arah yang memanjang manakala penambahan lapisan kayu kepada tujuh lapisan telah meningkatkan modulus lenturan jauh lebih tinggi di arah melintang dengan mengurangkan sedikit kadar modulus di arah memanjang.

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LIST OF SYMBOLS AND ABBREVIATIONS

For examples:

IPCC	:	Intergovernmental Panel on Climate Change
FRIM	:	Forest Research Institute Malaysia
CO_2	:	Carbon dioxide
O_2	:	Oxygen
G&S	:	Gordon and Smith
DIC	:	Digital Image Correlation
ASTM	:	American Society for Testing and Materials
FEA	:	Finite Element Analysis
BS373	:	British standard 373

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background

The issue of climate change that had been discovered from documentary Before the Flood gives foundations for this research to get a better sense of the existential dimensions of the climate challenge. Since 1880, global temperature has increases 1.4˚F which reported by Nasa and Intergovernmental Panel on Climate Change (IPCC). The CO_2 level has been reported reaches to 400.71 parts per billion which impacted from deforestation activities as wide as 1.5 million square km in year 2000 and 2015. Moreover, the reduction of ice land has been reported as much as 287 billion metric ton per year which led to rise of sea level every year at the rate of 3.2 mm and every decade has been reported 13.3% loss of arctic ice (Sivaramanan, 2015).

Since in the middle of the 20th century, the IPCC had been acknowledging and observing the climate changes were unprecedented and claimed that an anthropogenic greenhouse emissions as the highest in history (Pachauri & Mayer, 2015). Moreover, the fossil fuels combustion produces around 21.3 billion tons of CO_2 per year whereby the natural processes only capable to absorbs about half of the volumes and remaining net 10.65 billion tons of atmospheric CO_2 would be increased every in year (Kazulis, Muizniece, Zihare, & Blumberga, 2017).

This research has taken these issues as an area of concern and leads to catalyze an idea to make a comprehensive study about local source wood for development of the green personal commute (electric cruiser board) as multimodal transportation for user in urban city of Greater Kuala Lumpur.

The term of multimodal is refers to the planning concepts that considers various modes of transports such as taxi, two-wheeler, personal car, train, bus, and walking that are integrated among other modes at the transfer points in order to reach destination with time and cost saving, and the most important, it helps in mitigating amount of greenhouse gases released into the atmosphere.

Basically, multimodal transportation also means to serves as an alternative of the car or motorcycles where it gives flexible mobility to citizens with the ease of mind to reach the desired destinations. In addition, it is also provides environmental friendly along the journeys, which helps to reduce carbon emission and noise nuisance towards environment (Kumar, Parida, & Swami, 2013). The green personal commute (electric cruiser board) that has been proposed by Muhammad Fiqkri Ismail from Universiti Kuala Lumpur with his idea to promote carbon less form of multimodal transportation leads this research to study the local source wood that might best suited for his development.

The tree plays as significant roles to absorb and reducing carbon dioxide (CO_2) from environment and atmosphere, storing the carbon in the wood and releasing oxygen (O_2) for the human breath as they are growing up. However, the mature tree absorbs less CO_2 as compared to young trees. The mature trees which are left alone has potential to die by lightning strike, wind damage, or burned that will lead stored carbon released. The wood that is used to make things such as furniture is able to store carbon in a lifetime and definitely would mitigate the issues of climate change.

Based on several studies, the cruiser boards that are sold in the market typically made by four session wood such as Canadian Maple wood, China Maple wood, North America Maple wood, and etc to sustain a certain general and mechanical properties.

Typical design of the deck usually made by 7-ply construction in which veneers layered alternatingly on top of one another then interlaid with water based epoxy glue (epoxy resin) and pressed together under high pressure to become a laminate. In some cases, board laminate is made of 6 to 9 layers of pressed plywood. Malaysia has a lot of type of woods that might be competent to be suggested for this development. The local source woods have become a question about it competency that would like to study.

1.2 Objective

This research has been focused to investigate the elastic properties of commercial local source wood in Malaysia that could be proposed for development of the green personal commute (electric cruiser board) for multimodal transportation. To this end, the following objectives are proposed:

a) To investigate the elastic properties of Bakau, Merawan, and Laran woods.
b) To predict the elastic properties of multilayer wood composites for electric cruiser board using laminate composite theory.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter will discuss in-depth grasp of an overall subjects with respect to present study. Reviewed from the scholarly sources relevant, this gives a guidance and insight for this research to lay theoretical foundation by identifying, discussing, and critically analyzing the existing scholarly related. This literature review will begin with introduction of multimodal transportation, and finally dives into engineering study in order to propose suitable materials from local sources wood for development of electric cruiser board.

2.2 Multimodal transportation

The whole idea of this research is to promote utilization of the cruiser board as a part of multimodal transportation in urban area such Kuala Lumpur. Although western and others developed country has been norms with this mode of transportation in daily routines, Malaysia unfortunately seems unaware with this emergence. Until these days, this cruiser board has been associated with the extreme sport which not being categorized as a one of the transport. As congestion significantly impacts to the ground level ozone in Malaysia, the realization of this mode shall not be ignored.

In 2009, Malaysia had made a commitment during the United Nations Climate Change Conference in Copenhagen to reduce 40 percent of carbon emission by year 2020 (Shokoohi & Nikitas, 2017). Economic growth has accompanied with rapidly rising car ownership with the ratio of 361 cars per 1000 peoples in 2010 (Yazid, Ismail, & Atiq, 2011). An increasing cars ownership in Malaysia has leads to significant impact of carbon dioxide (CO_2) emission rises. The authorities had launched several initiative policies to promote sustainable mobility as well as its economic benefit.

Studies showed that even travel mode of two-wheeler such as cycling has remained as a challenge to stimulate in the car dependent city although it is closely associated to the ideas of reducing traffic congestion and car emissions besides promoting healthier lifestyles among citizen of Kuala Lumpur. Moreover, despite with the safety issues are concerned, the mindset to change cycling as a normal means of transport has turned into big challenges (Shokoohi & Nikitas, 2017). The main reason of this could be related to the expansion of two domestic manufacturing car industries in Malaysia which eventually leads to represent superior socio-economic status.

Moreover, as a solution towards these issues, government has undertaken large-scale road projects and construction of expressways that were eventually led to increase of the high speed driving and car volumes. In addition, subsidized price of fuels also allows affordability which made the private cars as a main of transport besides other modes (Mustapa & Bekhet, 2014). The term of multimodal transportation is referring to an alternative way implemented to shift the use of private vehicles to public transports by enabling transit features with several of modes integrated throughout the urban travels. Particularly, this concept has been adopted in the urban area especially in Kuala Lumpur. Typically, the factors that influencing citizen to shift from private vehicles to public transport that is because of travel time and travel cost, distance from home to public transport and distance from home to work (Almselati, Rahmat, & Jaafar, 2011).

2.3 Evolution of skateboard

The skateboard has various deck designs (see Figure 2.1) as available in the market that serves certain purposes, tricks, and activities. Historically, skateboard had been emerged during 1963 where the construction of the potential skateboard described by the assemblies the pieces of wood with the mounted roller.

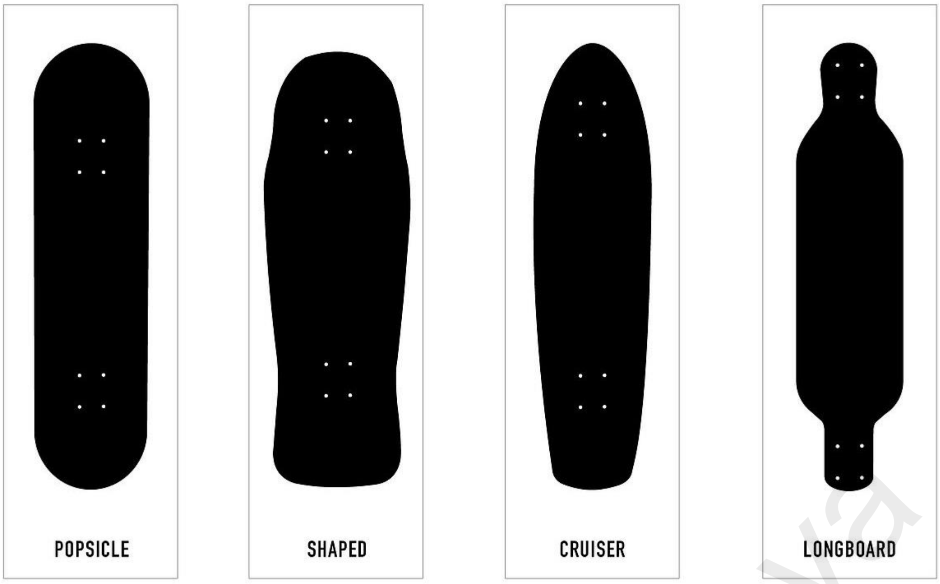

Figure 2.1 The various deck types (Gentsch, 2018)

Larry Stevenson was the first to develop the skateboard with the model named Makaha Phil Edwards model (see Figure 2.2). The name of this model gives in conjunction of prominent surfer which was from Phil Edwards. Most of the riders had preferred the Makaha skateboard which introduced by Larry Stevenson and where it was founded in Venice beach (Borden, 2019).

Figure 2.2 The Makaha skateboards (Rompella, 2007)

The first assembly was included a wooden deck such a miniature of the surfboard, Chicago trucks, and clay wheels (Prentiss, Skelton, Eldredge, & Quinn, 2011). In Southern California, the surfers used this rolling boards for coasting the smooth new streetscapes, and riding the slopes of dry swimming pools and drainage canals (Borden, 2001). Alternative materials had been introduced by the other manufactures with the most famous of which were the Gordon and Smith Fibreflex (see Figure 2.3) for an initially short period. This skateboard had been designed with fiberglass, epoxy, and a thin maple wood core. Due to concern for the safety, the significant popularity of the skateboard reduced. Aside, it had been assumed that it just a poor level of technology (Prentiss et al., 2011).

Figure 2.3 The G&S Fibreflex (Marcus & Griggi, 2011)

In 1969, Larry Stevenson introduced and patented the Kicktail board which had been designed with turned-up ends with better tail leverage. This design allows the riders to lever their boards, riding slopes and walls as well as for doing tricks such 360 spin, which has begun to gain popularity (Prentiss et al., 2011). Furthermore, the changes of the wheel materials form clay wheels to solid rubber had enhanced the features of skateboards and yet more comfortable to ride (Caine, 2012).

Moreover, the invention of urethane wheel by Frank Nasworthy in 1972 (see Figure 2.4) had significantly increased again the popularity and associated commercial sales of the skateboards and well accepted among the skaters in southern California. The urethane wheel, hence permitted the rider to maneuver faster in control and safer manner as it does not happen sudden stop upon blocked by the stones or any obstacles although in a vary terrain. Basically, the softer urethane wheel was used for the street racing purposes whereas the hard wheels used for wall riding contrarily (Prentiss et al., 2011).

Figure 2.4 The urethane wheel (Snyder, 2015)

Despite skateboards, there are a wide range of application had adopted this urethane wheel such as scooters, trolleys, and many more as it offers smoother ride, better grip with pavement and improved abrasion resistance compared to previous wheel materials (Thomas, Martinez, & Hadfield, 2012).

The emergence of the new so-called high performance trucks took place in 1973 by Ron Bennett (see Figure 2.5) which offered greater height between board and the ground thus far greater degree of maneuverability compared to old Chicago trucks which initially designed for roller skate (Prentiss et al., 2011).

Figure 2.5 High performance trucks by Ron Bennett (Nelson, 2017)

From these upgrading, skateboarding had turned onto new directions of the sports. In Southern California, skateboarders taken the chances from delayed development of housing tracts in hilly La Costa to enjoy with downhill and slalom racing as freshly paved roads and sidewalks developed. Furthermore, some of the skateboarders also searched for the more challenging places which had lead them to drain out the swimming pools, played on drainage ditches and the spillways to experience nearly endless array of terrain especially during regional drought season stated in 1975 and 1976. Technically, there were four leisure pursuits which presented by the skateboarders such as downhill, slalom, freestyle, and bowl or wall riding. As a result, each of these distinctive required specially designed board to perform (Prentiss et al., 2011).

Basically, downhill often required long boards which greater than 36 inches in length without Kicktails in order to experience maximum speed and stability. Unlike slalom, the skateboards had been designed without Kicktail, and shorter than type of downhill as slalom required speed and maneuverability to perform. The narrow-end design permitted the skateboarders to make a sharp turn as the wheels would not touch or rubbing the bottom deck. In the midst of 1970, many riders and manufactures delve onto slalom design. One of the recognition had been credited to Tuner Summer Ski as he does not only board shaper but also he introduced cambered design (see Figure 2.6) which permitted maximum flex for pumping through slalom courses (Prentiss et al., 2011).

Figure 2.6 Cambered design (Prentiss et al., 2011)

In the mid of 1970s, the bowl or wall riding technique had been emerged which led the manufacturers attention to commercialize this type of skateboards. Particularly, the Kicktails and rocker shape had been innovated by Zephyr and Z-Flex in 1973 (see Figure 2.7) to improve the ability of skaters to perform on steep terrain where later, the Gordon and Smith (G&S) had enhanced the design and eventually introduced the Warptail. The emergence of the Warptail was introducing new trend and design of board which constructed by using maple laminate thus reduced the weight of the board together maintaining some limited flex. Generally, the width of the bowl rider boards ranged in width up to 8 inch but was not last for very long (Prentiss et al., 2011).

Figure 2.7 Early Z-flex design (Nelson, 2017)

The first board that offers 10 plus inches of width had been introduced in 1978 by skaters and manufactures from Santa Monica, California. The board named as the Pig board. This board gave maximum stability and better foothold especially during vertical wall riding particularly in empty pools and skate parks (Prentiss et al., 2011).

The boards that were designed for doing tricks on the other hands, does not significantly change from design used in 1970s. Many skateboarders preferred a smallish board as well as double Kicktails (see Figure 2.8) which were very useful while to conduct trick movement like Walk the dog, Casper Disaster, and 360s. There were also some minor changes such as development of wider nose, double Kicktails, and the use of maple laminate materials in manufacturing (Prentiss et al., 2011).

Figure 2.8 Double Kicktails (Prentiss et al., 2011)

The emergence of Popsicle stick board (see Figure 2.9) in 1990 until 1995 had introduced significant development designs consists with the stubby shape where the length somewhat 30 to 34 in. and 7 to 8 in. width. Furthermore, with concave and double Kicktails designed, the Popsicle stick board allows the riders to perform tricks with working less especially on vertical terrain of the street facilities (Prentiss et al., 2011).

Figure 2.9 The Popsicle skateboard (Ruben, 2019)

In 1995, the longboard once again became popular since the manufacturers had included the variety of design such as slalom board shapes, Kicktails, concave, and certainly double Kicktails instead. Finally, on the next following years, it was reported that the manufactures reissued many classic designs such as z-flex skateboard to reflect nostalgia design to riders (Prentiss et al., 2011).

This research has taken the cruiser shapes design with flat surface as the board would serve for commuting for the short distance to promote the multimodal transportation in urban area of Kuala Lumpur. Generally, the cruiser board meant to just rolling around and being able to carry around comfortably without much effort as the weight much lighter and taller than others types which allows for quick acceleration (Ruben, 2019).

2.4 Mechanical properties of wood

Wood is described as an orthotropic material in which there are three mutually independent directions of axes (see Figure 2.10) at the micro scale (Jeong & Park, 2016). Basically the wood has been cut in the direction of tangent to the growth of rings and denoted as a tangential direction. The longitudinal axis is parallel to the grain whereby the radial axis that is perpendicular to the grain along the growth (Laboratory, 2013).

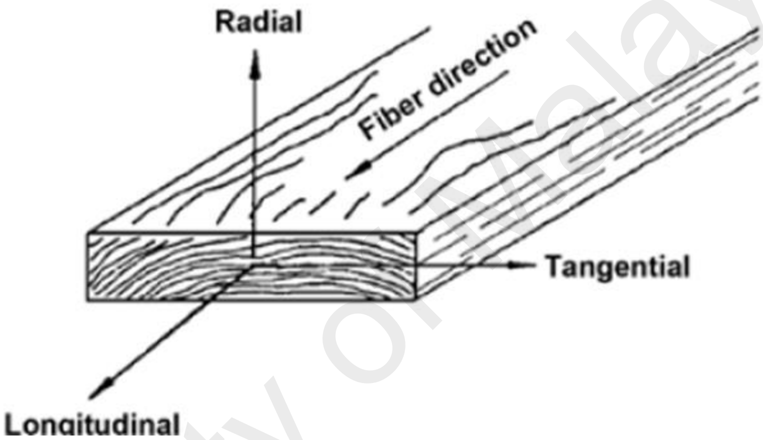

Figure 2.10 Tangent cut with three principal axes (Laboratory, 2013)

Understanding mechanical properties of the wood would be an essential part for this research to discuss. The mechanical properties of the wood could be simply explained as the ability of the wood to withstand or resist any external forces without deformed in any manner. This ability would determine the uses of the woods as its stiffness would explain the elasticity of the materials as well as the limit. Basically, there are there types of the external forces which commonly known as tensile, compressive, and shearing. Generally, the external stress which is acting at the edge of its end or simply imagine as a direct pull away from its end is defined as tensile stress. The tensile stress would cause the material elongate and a strain value is defined (Record, 2012).

On the hand, if it is the external stresses are being pushed toward the end, it is simply to be understand as compressive stress and it would cause the materials shorten as its strain value. Moreover, when the stresses are applied to an adjacent of one portion that causes slide upon another because of this action would be determined as shear stress (Record, 2012).

2.4.1 Compound stress

In a flexural bending, these three stresses are acting together which eventually produced compound stress. In the archery games, the bow which made by wood will bend accordingly when the stress is applied with the compression stress acting inside the concave side compressed all of the fibers and elongated simultaneously as on the outer or convex side. Besides that, the fibers are also believes that they may have a tendency to slide past one another in longitudinal direction while flexural is applied (Record, 2012).

This could be realized if the bow were made by two or more separate layers with equal length and it could be seen that slipping may occurred along the layers and that eventually the edge would no longer even. The layer can fix by the glue in order to avoid the slipping to occur but it is still having tendency to do so. In other cases, it was also found that these layers which have not applied the glue would be harder to bend and thus defined the stiffness possessed (Record, 2012). Similarly, in order to identify the elastic constants of the wood for the skateboard application, it is suggested that the wood should be experimented by flexural or static bending test (Munshi & Walame, 2017). In addition, due to nature of the test procedure, the strength of the wood which would need to characterize in direction of across the grain has been suggested that to use the static bending test (Naylor, Hackney, & Perera, 2012).

2.4.2 Stiffness and elasticity of the wood

Stiffness is defined as an ability of the materials to resists deformation, bending, maintain its original size, and shape when the external loads are applied. Otherwise, the material which is easily to bent would be determined as flexible and it is not corresponding to the characteristic of stiffness. The stress or load which below than elastic limit applied to the materials would not be able to change it shape upon release from the stress and thus, the body behavior is known as elastic. The stress which is applied beyond than elastic limit would hinder the recovery process and eventually it turns to permanent alteration in shapes where the elastic limit shall be noted as the limit which is impossible to carry. As the stress exceeded, the changes amount from an original and after geometrical distortion is known as permanent set (Record, 2012).

The elastic limits which particularly important to be understood as it could be determined from the ratio values of the stress at which deformation has started to occur. The relationship between stress and strain has been manifested in the stress-strain diagram in which the elastic limit is the point in the line where the diagram begins perceptibly to curve (Record, 2012).

2.4.3 Resilience

The area below the stress-strain curve (see Figure 2.11) of the elastic limit represents the amount of work done or the potential energy stored in material upon being released from a state of stress. This elastic resilience dictates the amount of work can be applied repeatedly and this would be essential information especially when designing the wood material by taking to account the toughness as the wood working quality.

As the stress is increases above than elastic limit, the deformation would turn to permanent set. The wood can be described as the near plastic property materials same goes to others like moist clay and lead. Perfectly plastic property materials can be explained when the material has no elasticity substance and requires smallest force to cause the permanent change. In order to increase the plasticity of the wood, certain processes such as wetting, heating, and even more complex by steaming and boiling (Record, 2012).

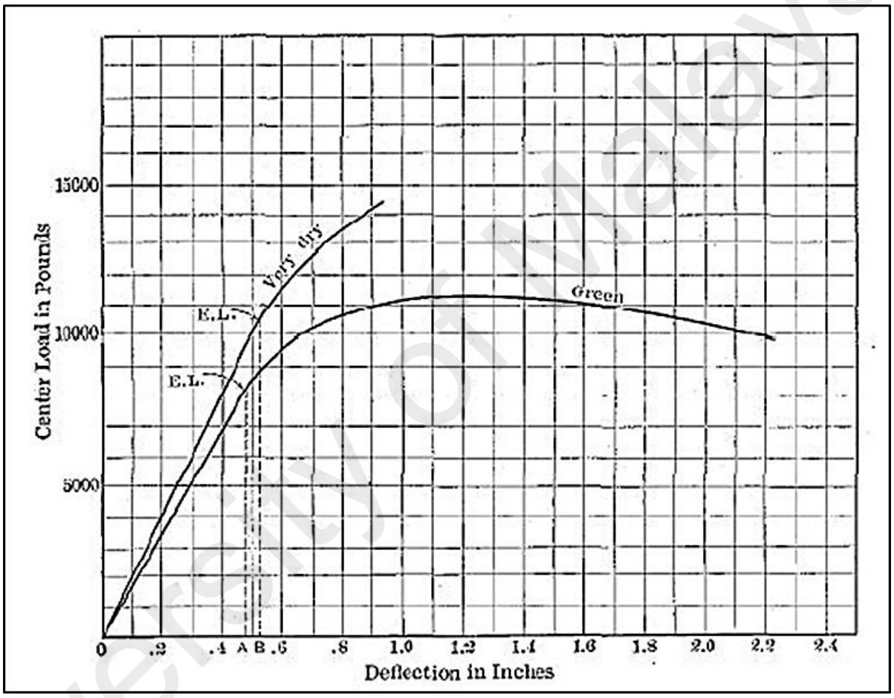

Figure 2.11 The stress strain curve (Record, 2012)

The wood which has plasticity substance able to undergo a little change in shape without ruptured. Chalk and glass has the same things in common. The wood also has been described as brash material due to their condition breaks with a clean instead of splintery without any warning thus cannot sustain with the sudden and shock load applications. Generally, the modulus of elasticity is used to determine the number indicative of the stiffness of the materials (Record, 2012).

The modulus of elasticity or coefficient of elasticity is the ratio of the stress per unit of area value divided by the stiffness or deformation per unit of length. The stiffness would not define the strength of the material. The values of modulus elasticity derived whether from tension or compression test are considered nearly the same and qualified to use in any of applications (Record, 2012). However some of the studies have showed that the magnitude of the strength property is ten times significantly higher by conducted with compression test rather compared to tensile (Naylor et al., 2012).

The large of the modulus of elasticity would determine stiffer the materials. Furthermore, in other cases, the value modulus of elasticity is different with every type of the wood especially in the green condition or in the dry condition. Such as examples, the values of stiffness obtained from static bending test for arborvitae in green condition is 643000 pounds per square inch, 1662000 pounds for longleaf pine, and 1769000 pounds for pignut hickory. On the other hand, the values found significantly greater in the dry condition in which approaching 3000000 pounds for some woods. Regardless all values of the modulus elasticity, they are still lower if it is compared to the steel (see Table 2.1) where some steel possess 30,000,000 pound per square inch for values of modulus of elasticity (Record, 2012).

Table 2.1 Comparative strength of iron, steel, and wood (Record, 2012)

Material	Sp. gr., dry	Modulus of elasticity Lbs. per. sq. in.	Tensile strength Lbs. per. sq. in.	Crushing strength Lbs. per. sq. in.	Modulus of rupture Lbs. per. sq. in.
Cast iron, cold blast (Hodgkinston)	7.l	17,270,000	16,700	106,000	38,500

Bessenger steel, high grade (Fairbain)	7.8	29,215,000	88,400	225,600	
Longleaf pine, 3.5% moisture (U.S.)	0.63	2,800,000		13,000	21,000
Redspruce, 3.5% moisture (U.S.)	0.41	1,800,000		8,800	14,500
Pignut hickory, 3.5% moisture (U.S.)	0.86	2,370,000		11,130	24,000

2.4.4 Tensile strength

Tensile test is the test use the external force exerts a pull the opposite ends of the specimen in which resulting an elongation or stretching towards direction of the force applied.

However, if the force is applied in the opposite direction, it is considered as a compression. In the wood perspective, the tensile test is the most difficult test to be applied as the wood possesses a greatest strength especially when the force exerts a pull parallel to its grain. Due to this constraint, there is very uncommon to practice the tensile test against the wood as the opposite ends of the specimen would not be able to be fastening secure enough and prone to fail around the edges as the longitudinal shear has taken place. In contrast, this will be different if compared to metal where the application of tensile strength is always needed and wood would not always prefer in the application where tensile strength is required (Record, 2012).

The wood such that, will be suitable and always be applied in the structure such as sills, beam, joists, posts, flooring, and even previous decade wood practically used to build wooden truss bridge but the steels rod has to be support as a tension member. The fiber which oriented along the axial direction would determine the greatest tensile strength of the wood. The nature and dimension of the wood are the most elements which impacts the strength of the fiber despite of their arrangement. The greatest strength of the wood exhibited in the direction of straight-grained specimen with the thick-walled fibers (see Table 2.2). The right angle direction would diminish strength of it because small fraction of strength only can be obtained from this direction as compared to parallel to the grain direction (Record, 2012).

Table 2.2 Ratio of strength of wood in tension and compression (Record, 2012)

Kind of wood	Ratio: tensile/compressive	A stick 1 square inch in cross section. Weight required to	
		Pull apart	Crush endwise
Hickory	3.7	32,000	8,500
Elm	3.8	29,000	7,500
Longleaf Pine	2.2	17,300	7,400

Practically, the flexural test will be adopted in order to determine failure of the wood in tension parallel to the grain especially for dry specimen. The fibers fails or torn in oblique pattern in flexural test besides in spiral direction as usual happened when the piece were pulled apart in lengthwise (Record, 2012).

The location of the fracture after performed flexural test exhibits the near the same tension portion as pulled in the lengthwise. Regardless of the thickness, the flexural test which applied to the wood practically would not pull apart the fibers and there is no separation of the fibers occurs along the walls. The nature of tension failure of the specimen would not be much affected by the moisture condition as compared to other strength values (Record, 2012). The tensile test for the wood which set up by the Digital Image Correlation (DIC) (see Figure 2.12) was found to be one of the most reliable methods to define the modulus of elasticity as well as poisson ratio (Jeong & Park, 2016).

Figure 2.12 DIC testing for tensile (Jeong & Park, 2016)

As the orientation of the applied stress changes to the right angle direction which commonly call as direction of perpendicular to the grain, similarly the action would be associated closely to cleavability. When the wood fails in the right angles, the thin walls fiber had been exhibited the torn of the fiber along the lengthwise whereas the thick-walled fibers would be pulled apart along the primary wall (Record, 2012).

2.4.5 Compressive or crushing strength of the wood

Compression in direction of across the grain can be associated with hardness and transverse shear. When the force is given on the across direction, the fibers would be compressed as the load gradually exerts and dictated irregularly increases when the density is higher. In other cases, flat surface of the wood would be given a different result due to the load applied affects to only small portion of the specimen upper area where the bearing plate will indent the wood, and the fibers will be crushing without touching the lower part. When the load increases in such extend eventually the specimen will split horizontally. In the microscopic view, the fiber collapses a few at a time which leads to irregular load applied and it begin with the thinnest fiber. As the load projected to an ends, it would lead to higher force needed since the strength of the material has been increased which likely same as the beam action (Record, 2012).

Nowadays, there are many applications which adopting wood to serve the purpose such as examples used for columns, props, posts, spokes, and etc. where it would may desirable to exert the load on the endwise direction. Due to that, the load applied on the endwise sides eventually would tend to shorten the material where it is well-known as the endwise compression or compression parallel to the grain. The long columns are the one of the examples such that the load applied gives the flexural bending as the length play very essential role compared to their diameter and the failure resulted on sidewise instead of crushing. One of the instant examples could be imagining is a walking-stick when the force exerted on the upper end when the hand placed as it is being used. As the force applied over than their definite amount, the flexural would take place (see Figure 2.13). A little force given after this extent will exhibit a large deflection in the middle that would represent a very large leverage which eventually can cause a rupture (Record, 2012).

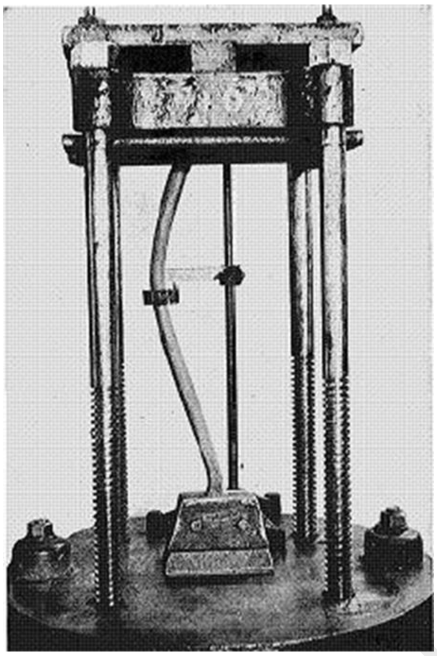

Figure 2.13 Testing a buggy spoke in endwise compression and failure by sidewise bending (Record, 2012)

As in lateral bending of the wood, the column would experience not just flexural but compression. The concave direction would determine the maximum compression stress values especially on the higher peak of deflection while convex direction experiencing tension stress. The deflection most likely tends to deflect in direction of less stiff. In the case of small block of column, bending unlikely behaves like ordinary beam. The stress distribution along the beam is uniformly distributed in which flexural is prevented and the worst case it might experiences failure in the form of splitting or crushing. The deflection of column can be prevented by adding compression members of trusses such as bracing, studding, and props (Record, 2012).

The elastic moduli were reported can be obtained by compression test especially in longitudinal direction (Kollmann, 1967). Generally, in order to achieve the act of uniformly distributed force during the test, the length shall be ensured would not exceeded that four diameters and square faced design should be designed on endwise.

Therefore the force which would apply will acts uniformly over the square inch of area and the result will gives the value of crushing strength (Record, 2012). The values of modulus of elasticity and the strength of the wood had been reported higher in direction of along the grain compared to across the grain and the strength also reported significantly higher as much as ten times greater compared by using tensile test. Same studies were found that the elastic modulus by using compression test in longitudinal direction is eight times higher compared to radial direction (Reiterer & Stanzl-Tschegg, 2001).

2.5 The elastic properties of the skateboard

The elastic properties of the skateboard as developed by the other researchers would be an essential data for this research to give understanding about the elastic modulus of the deck. The strips which had been designed by bamboo composite shows that the flexural modulus as for 50% fiber fraction were 10.821 GPa on E_x direction and 0.5 GPa on E_y direction. The flexural test (see Figure 2.14) was conducted and compiled with the standard of American Society for Testing and Materials (ASTM) D790 (Munshi & Walame, 2017).

Figure 2.14 The flexural test setup (Munshi & Walame, 2017)

In other research shows that, the recycling materials from discarded wood decks where most of them are made from plywood laminate of Sugar Maples. Furthermore, it appears to be competent materials to be recycled into a new sustainable material. Moreover, the stiffness of this recycle skateboards were tested in direction of the face and edge wise. The test had been setup in the third point bending and the result shows the average stiffness of the face and edge wise direction was 0.026 GPa and 0.033 GPa relatively (Willard & Loferski, 2018).

In addition, the mechanical properties of the wood which explained in CES software are around 6 GPa to 20 GPa and it seems to be ideal material and therefore used as a common material for skateboard deck construction (Liu, Coote, Aiolos, & Charlie, 2018).

2.5.1 Orientation of the laminate

The same research which evaluated the Bamboo as a composite laminate used a thickness of the 6 plies where each of them are 2 mm with the stacking sequence of [0, 45, -45]s. The result which obtained from Finite Element Analysis (FEA) showed that the highest stress of 22.22 MPa occurred at the plies of 0˚ after 1420 N or 145 kg load had been applied in z-direction. Furthermore, for the ply of 45˚ and -45˚ the maximum stresses obtained was 14.23 MPa and 7.85 MPa respectively (Munshi & Walame, 2017).

As stated in United States patent, the construction of the skateboard deck typically consist of seven layers of Maple plies in which each of them has 1/16 in. thick and the total has 7/16 in. with two plies being cross plies (Patent & Office, 2001).

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this stage, the methods that will be used to conduct this research are discussed. The method that would be suitable to realize the first research objective is by conducting mechanical test in order to obtain the values of elastic and shear modulus that would be essential uses to evaluate mechanical properties of lamina and laminate in stiffness matrix calculation. This theoretical calculation will be used to compare with the actual laminate in order to verify their competency and that will be the answer for the method of second research objective.

3.2 Primary data

There are three type of wood plank which had been given by department of sawmills (see Figure 3.1) from Forest Research Institute Malaysia (FRIM) in order to carry out this research. There are Bakau, Merawan, and Laran.

Figure 3.1 Sawmills department, FRIM

There are three types of wood which would be used for the experiment as well as the appropriate samples such recommended by the laboratory Forest Research Institute Malaysia (FRIM) (see Table 3.1).

Table 3.1 Type of wood and number of samples

Type of wood	Samples (Pieces) for bending/shear
Bakau	10
Merawan	10
Laran	10

3.3 Design of the laminate

The alternating layers of sliced wood ply will be glued together (see Figure 3.2) with the water based epoxy glue – epoxy resin. In this case, the way by which diverse angular layers of the lamina arranged would determines the laminate mechanical properties.

Figure 3.2 Glued plies laminate

This laminate is designed to use three stack of lamina with the orientation of $[0, \overline{90}]_s$ (see Figure 3.3) that shall be consists of Face, and Cross-band of plies.

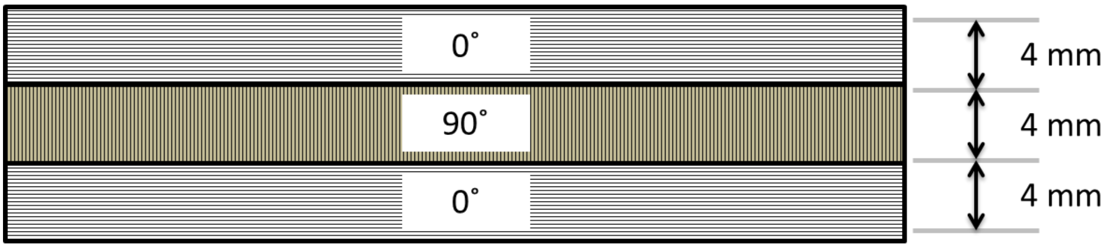

Figure 3.3 Designed laminate with the respective angular

The dimension of the laminate of the cruiser board has been decided as 70 cm for length and 20 cm for width (see Figure 3.4). Typically, the most important aspects that should be considered while constructing cruiser boards are focused on strength which able to withstand with high flexural stress in order to support the weight of the skateboarders. Therefore, the comprehensive data such of the maximum stress, strain, modulus of elasticity, shear strength would be a parameter that has to be defined before it can be proposed to use for cruiser board. The actual product of laminate also will be testing and compared with the mechanic's calculation to justify the actual capabilities such as mentioned before.

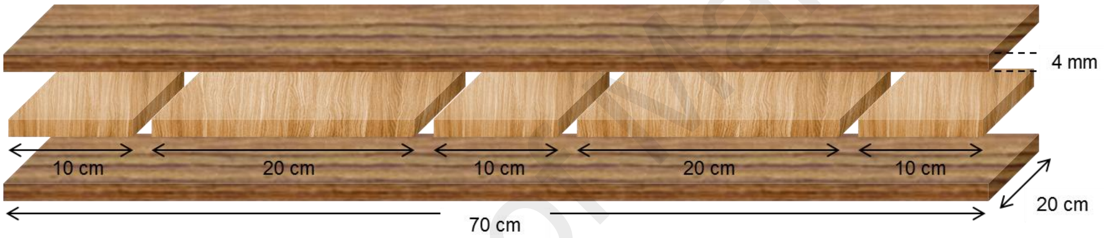

Figure 3.4 Dimensional laminate designed for cruiser board

The elastic properties of the laminate by taking the same design as available in the market also will be predicted. Typically, the construction of the maple laminate as regularly available in the market consisting of 7 plies (see Figure 3.5) in which each of them has 1/16 in. thick made from veneer with the cross ply orientation – $[0,90,0,\overline{90}]_s$.

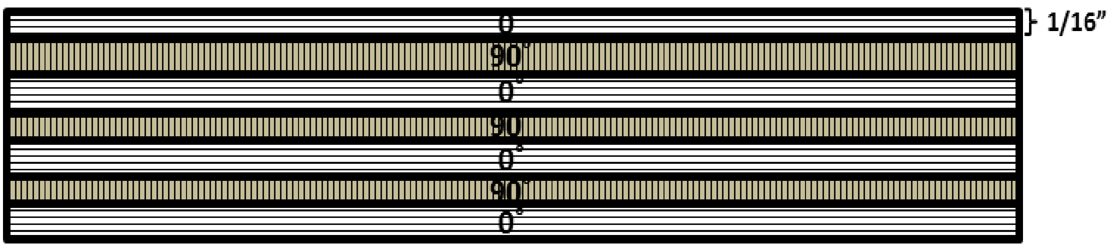

Figure 3.5 The construction of the 7 plies laminate

3.4 British Standard BS373

This research has taken the British Standard 373 (BS373) in order to perform the testing for the quantitative data. There are only two testing required which are elastic and shear modulus for primary data in order to be used for calculating of stiffness matrix.

3.4.1 Modulus of elasticity

As for the modulus of elasticity, there are two types of directions that would be required to test in the central loading method.

Therefore E_1, the static bending test shall be orientated in direction of parallel to the grain and the dimension (see Table 3.2) will be followed as stated in BS373. The span for this test shall be designed parallel to the grain and the distance between the points of support of the test piece shall be 28 cm. The standard stated for the loading head shall be setting constantly at 0.26 in. /min. The modulus of elasticity would be calculated without the necessity of allowing shear deflection as its length in a considerable proportion while subjected to uniform bending moment.

Moreover, for E_2, the static bending shall be tested in direction of the span perpendicular to the grain. However there is none of the standard been given in BS373 for this direction and the dimension (see Table 3.2) had been decided by following the basic principal discussed with FRIM members.

Table 3.2 Dimension for bending test

Testing	**Quantity (pcs)**	**Dimension (cm)**
E_1	10	2 x 2 x 30
E_2	10	12.7 x 12.7 x 2

3.4.2 Shear modulus

The shear stress test is a vital to obtain the shear modulus, G_{12}. The dimension (see Table 3.3) has been followed as stated in BS373 standard. This cube size of 2 cm shall be load and applied with the loading rate at 0.025 in. /min.

Table 3.3 Dimension for shear test

Testing	Quantity (pcs)	Dimension (cm)
G_{12}	10	2 x 2 x 2

3.5 Secondary data

This research would be taken the sources of information and data from the literature especially from journal, book, report, website and etc to support the justification which will be given later.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction

The tests carried out by following the methodology designed in the chapter 3 for three types of wood in order to obtain the values of modulus of elasticity, E_1 and E_2, and shear modulus, G_{12}. The woods there are Bakau, Merawan, and Laran had been tested and complied with the British standard 373 (BS373) gave a vital result which will be used for further evaluations. The laminate has been designed to use $[0, \overline{90}]_s$ orientation.

4.1.1 Static bending test

The three types of wood were cut according to static bending test standard stated in BS373. As for the static bending test on the direction of parallel to the grain E_1 (see Figure 4.1), those three types of wood were used the dimension of 2 cm by 2 cm by 30 cm for central loading where each of them tested with 10 samples.

Figure 4.1 Static bending in longitudinal direction

On the other hand, the static bending for transverse direction E_2 has no given standard such direction of E_1. Regardless of this matter, the dimension of this direction were agreed to use as 12.7 cm by 12.7 cm by 2 cm with the 10 samples from each type of wood. Same goes to E_1, the central loading method (see Figure 4.2) had been used to obtain the Young's modulus.

Figure 4.2 Static bending in transverse direction

4.1.2 Shear parallel to the grain test

The shear test (see Figure 4.3) conducted with the dimension of 2 cm by 2 cm by 2 cm. This cube size was cut and loaded into the machine with the testing speed of 0.025 in. /min.

Figure 4.3 Shear test parallel to the grain

4.2 Engineering elastic constants

Since the poisson ratio of ν_{12}, has been assumed as 0.3 and therefore the value of poisson ratio of ν_{21} can be obtained by using reciprocal formula (see Equation 1). It is applied to all types of woods.

$$\nu_{21} = \left(\frac{\nu_{12}}{E_1}\right)(E_2) \tag{1}$$

$$\nu_{21,\text{Bakau}} = \left(\frac{0.3}{19204.29}\right)(256.82)$$

$$= 4.0119 \times 10^{-3}$$

$$\nu_{21,\mathrm{Merawan}} = \left(\frac{0.3}{9798.20}\right)(585.26)$$

$$= 0.0179$$

$$\nu_{21,\mathrm{Laran}} = \left(\frac{0.3}{10971.55}\right)(50.54)$$

$$= 1.3819 \times 10^{-3}$$

The result obtained from tests were compiled in the in the check sheet which attached in the appendix page. These engineering elastic constants results obtained (see Table 4.1) had been averaged and would be used for further calculation.

Table 4.1 Result from the mechanical properties test

Type of wood	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ν_{21}
Bakau	19.204	0.257	0.533	0.30	0.0040119
Merawan	9.798	0.585	0.242	0.30	0.0179
Laran	10.972	0.051	0.203	0.30	0.0013819

4.3 The coordinate system

Initial analysis started by determined the coordinate system of the laminates (see Figure 4.4). As understood that the unidirectional lamina has a low stiffness and strength properties especially in transverse direction, therefore the laminates should be consisted and designed with multiple directions of an angle lamina and so it does in this study. Basically, the x-y coordinates system representing the global-axes, whereas the 1-2 coordinates system representing local-axes or the off-axes. The angle between the two axes is denoted by θ.

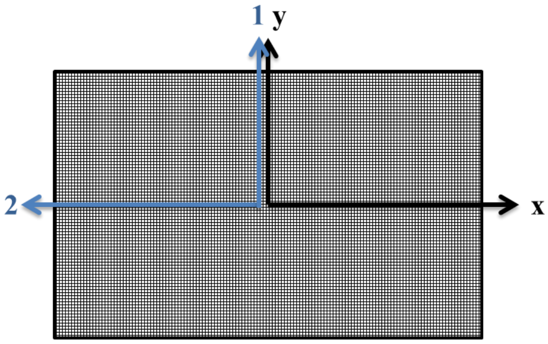

Figure 4.4 The coordinate system for designed laminate

4.4 Reduced stiffness matrix

These engineering elastic constants were used to calculate the reduced stiffness matrix (see Equation 2). As for an orthotropic plane stress problem, the stress-strain relationship can be simplified from three to two dimensional stress-strain equations with the four independent stiffness elements in the matrix (see Equation 3, 4, 5, 6).

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{2}$$

$$Q_{11} = \frac{E_1}{1 - \nu_{21}\nu_{12}} \tag{3}$$

$$Q_{11,Bakau} = \frac{19204.29}{1 - (4.0119 \times 10^{-3})(0.3)}$$

$$= 1.9227 \times 10^{10}\,\text{Pa}$$

$$Q_{11,Merawan} = \frac{9798.20}{1 - (0.0179)(0.3)}$$

$$= 9.8512 \times 10^{9}\ \text{Pa}$$

$$Q_{11,\text{Laran}} = \frac{10971.55}{1 - (1.3819 \times 10^{-3})(0.3)}$$

$$= 1.0976 \times 10^{10} \text{ Pa}$$

$$Q_{12} = \frac{\nu_{12} E_2}{1 - \nu_{21}\nu_{12}} \quad (4)$$

$$= \frac{(0.3)(256.82)}{1 - (4.0119 \times 10^{-3})(0.3)}$$

$$= 7.7139 \times 10^{7} \text{Pa}$$

$$Q_{12,\text{Merawan}} = \frac{(0.3)(585.26)}{1 - (0.0179)(0.3)}$$

$$= 1.7653 \times 10^{8} \text{ Pa}$$

$$Q_{12,\text{Laran}} = \frac{(0.3)(50.54)}{1 - (1.3819 \times 10^{-3})(0.3)}$$

$$= 1.5168 \times 10^{7} \text{Pa}$$

$$Q_{22} = \frac{E_2}{1 - \nu_{21}\nu_{12}} \quad (5)$$

$$Q_{22,\text{Bakau}} = \frac{256.82}{1 - (4.0119 \times 10^{-3})(0.3)}$$

$$= 2.5713 \times 10^{8} \text{Pa}$$

$$Q_{22,\text{Merawan}} = \frac{585.26}{1-(0.0179)(0.3)}$$

$$= 5.8842 \times 10^{8}\ \text{Pa}$$

$$Q_{22,\text{Laran}} = \frac{50.54}{1-(1.3819 \times 10^{-3})(0.3)}$$

$$= 5.0561 \times 10^{7}\ \text{Pa}$$

$$Q_{66} = G_{12} \tag{6}$$

$$Q_{66,\text{Bakau}} = 5.334 \times 10^{8}\ \text{Pa}$$

$$Q_{66,\text{Merawan}} = 2.4236 \times 10^{8}\ \text{Pa}$$

$$Q_{66,\text{Laran}} = 2.0333 \times 10^{8}\ \text{Pa}$$

$$[Q]_{\text{Bakau}} = \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix} \text{Pa}$$

$$[Q]_{\text{Merawan}} = \begin{bmatrix} 9.8512 \times 10^{9} & 1.7653 \times 10^{8} & 0 \\ 1.7653 \times 10^{8} & 5.8842 \times 10^{8} & 0 \\ 0 & 0 & 2.4236 \times 10^{8} \end{bmatrix} \text{Pa}$$

$$[Q]_{\text{Laran}} = \begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 5.0561 \times 10^{7} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix} \text{Pa}$$

4.5 The transformed reduced stiffness matrix 90˚

Instead of global axes, by using the four independent stiffness elements such Q_{11}, Q_{12}, Q_{22}, and Q_{66} where that was defined before, then the calculation can be furthered to calculate for local axes of second lamina by using the transformed reduced stiffness matrix (see Equation 7, 10, 11, 12, 13, 14, 15). In this case local axes are using 90˚ angle where the cos and sin (see Equation 8, 9) functions were used.

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} = \begin{bmatrix}\overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16}\\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26}\\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \tag{7}$$

$$c = \cos(\theta) \tag{8}$$

$$= \cos(90)$$

$$= 0$$

$$s = \sin(\theta) \tag{9}$$

$$= \sin(90)$$

$$= 1$$

$$\overline{Q}_{11} = Q_{11}c^4 + Q_{22}s^4 + 2(Q_{12} + 2Q_{66})s^2c^2 \tag{10}$$

$$\overline{Q}_{11,\mathrm{Bakau}} = (1.9227 \times 10^{10})(0)^4 + (2.5713 \times 10^{8})(1)^4 + 2[(7.7139 \times 10^{7}) + 2(5.334 \times 10^{8})](1)^2(0)^2$$

$$= 2.5713 \times 10^{8}\ \mathrm{Pa}$$

$$\overline{Q}_{11,\text{Merawan}} = (9.8512 \times 10^{9})(0)^4 + (5.8842 \times 10^{8})(1)^4 + 2[(1.7653 \times 10^{8}) + 2(2.4236 \times 10^{8})](1)^2(0)^2$$

$$= 5.8842 \times 10^{8} \text{ Pa}$$

$$\overline{Q}_{11,\text{Laran}} = (1.0976 \times 10^{10})(0)^4 + (5.0561 \times 10^{7})(1)^4 + 2[(1.5168 \times 10^{7}) + 2(2.0333 \times 10^{8})](1)^2(0)^2$$

$$= 5.0561 \times 10^{7} \text{ Pa}$$

$$\overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + Q_{12}(c^4 + s^2) \quad (11)$$

$$\overline{Q}_{12,\text{Bakau}} = [(1.9227 \times 10^{10}) + (2.5713 \times 10^{8}) - 4(5.334 \times 10^{8})](1)^2(0)^2 + (7.7139 \times 10^{7})[(0)^4 + (1)^2]$$

$$= 7.7139 \times 10^{7} \text{ Pa}$$

$$\overline{Q}_{12,\text{Merawan}} = [(9.8512 \times 10^{9}) + (5.8842 \times 10^{8}) - 4(2.4236 \times 10^{8})](1)^2(0)^2 + (1.7653 \times 10^{8})[(0)^4 + (1)^2]$$

$$= 1.7653 \times 10^{8} \text{ Pa}$$

$$\overline{Q}_{12,\text{Laran}} = [(1.0976 \times 10^{10}) + (5.0561 * 10^{7}) - 4(2.0333 \times 10^{8})](1)^2(0)^2 + (1.5168 \times 10^{7})[(0)^4 + (1)^2]$$

$$= 1.5168 \times 10^{7} \text{ Pa}$$

$$\overline{Q}_{22} = (Q_{11})s^4 + (Q_{22})c^4 + 2[Q_{12} + 2(Q_{66})]s^2c^2 \tag{12}$$

$$\overline{Q}_{22,\text{Bakau}} = (1.9227 \times 10^{10})(1)^4 + (2.5713 \times 10^8)(0)^4 + 2[(7.7139 \times 10^7) + 2(5.334 \times 10^8)](1)^2(0)^2$$

$$= 1.9227 \times 10^{10} \text{ Pa}$$

$$\overline{Q}_{22,\text{Merawan}} = (9.8512 \times 10^9)(1)^4 + (5.8842 \times 10^8)(0)^4 + 2[(1.7653 \times 10^8) + 2(2.4236 * 10^8)](1)^2(0)^2$$

$$= 9.8512 \times 10^9 \text{ Pa}$$

$$\overline{Q}_{22,\text{Laran}} = (1.0976 \times 10^{10})(1)^4 + (5.0561 \times 10^7)(0)^4 + 2[(1.5168 \times 10^7) + 2(2.0333 \times 10^8)](1)^2(0)^2$$

$$= 1.0976 \times 10^{10} \text{ Pa}$$

$$\overline{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})c^3s - [Q_{22} - Q_{12} - 2(Q_{66})]s^3c \tag{13}$$

$$\overline{Q}_{16,\text{Bakau}} = [(1.9227 \times 10^{10}) - (7.7139 \times 10^7) - 2(5.334 \times 10^8)](0^3)(1) - [(2.5713 \times 10^8) - (7.7139 \times 10^7) - 2(5.334 \times 10^8)](1)^3(0)$$

$$= 0 \text{ Pa}$$

$$\bar{Q}_{16,Merawan} = [(9.8512 \times 10^9) - (1.7653 \times 10^8) - 2(2.4236 \times 10^8)](0^3)(1) - [(5.8842 \times 10^8) - (1.7653 \times 10^8) - 2(2.4236 \times 10^8)](1)^3(0)$$

$$=0 \text{ Pa}$$

$$\bar{Q}_{16,Laran} = [(1.0976 \times 10^{10}) - (1.5168 \times 10^7) - 2(2.0333 \times 10^8)](0^3)(1) - [(5.0561 \times 10^7) - (1.5168 \times 10^7) - 2(2.0333 \times 10^8)](1)^3(0)$$

$$=0 \text{ Pa}$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})cs^3 - (Q_{22} - Q_{12} - 2Q_{66})c^3s \quad (14)$$

$$\bar{Q}_{26,Bakau} = [(1.9227 \times 10^{10}) - (7.7139 \times 10^7) - (2)(5.334 \times 10^8)](0)(1)^3 - [(2.5713 \times 10^8) - (7.7139 \times 10^7) - 2(5.334 \times 10^8)](0)^3(1)$$

$$= 0 \text{ Pa}$$

$$\bar{Q}_{26,Merawan} = [(9.8512 \times 10^9) - (1.7653 \times 10^8) - (2)(2.4236 \times 10^8)](0)(1)^3 - [(5.8842 \times 10^8) - (1.7653 \times 10^8) - 2(2.4236 \times 10^8)](0)^3(1)$$

$$= 0 \text{ Pa}$$

$$\bar{Q}_{26,\text{Laran}} = [(1.0976 \times 10^{10}) - (1.5168 \times 10^{7}) - (2)(2.0333 \times 10^{8})](0)(1)^{3} - [(5.0561 \times 10^{7}) - (1.5168 \times 10^{7}) - 2(2.0333 \times 10^{8})](0)^{3}(1)$$

$$= 0 \text{ Pa}$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})s^{2}c^{2} + Q_{66}(s^{4} + c^{4}) \quad (15)$$

$$\bar{Q}_{66,\text{Bakau}} = [(1.9227 \times 10^{10}) + (2.5713 \times 10^{8}) - 2(7.7139 \times 10^{7}) - 2(5.334 \times 10^{8})](1)^{2}(0)^{2} + (5.334 \times 10^{8})[(1)^{4} + (0)^{4}]$$

$$= 5.334 \times 10^{8} \text{ Pa}$$

$$\bar{Q}_{66,\text{Merawan}} = [(9.8512 \times 10^{9}) + (5.8842 \times 10^{8}) - 2(1.7653 \times 10^{8}) - 2(2.4236 \times 10^{8})](1)^{2}(0)^{2} + (2.4236 \times 10^{8})[(1)^{4} + (0)^{4}]$$

$$= 2.4236 \times 10^{8} \text{ Pa}$$

$$\bar{Q}_{66,\text{Laran}} = [(1.0976 \times 10^{10}) + (5.0561 \times 10^{7}) - 2(1.5168 \times 10^{7}) - 2(2.0333 \times 10^{8})](1)^{2}(0)^{2} + (2.0333 \times 10^{8})[(1)^{4} + (0)^{4}]$$

$$= 2.0333 \times 10^{8} \text{ Pa}$$

$$[\bar{Q}]_{90,\text{Bakau}} = \begin{bmatrix} 2.5713 \times 10^{8} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 1.9227 \times 10^{10} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix} \text{Pa}$$

$$[\bar{Q}]_{90,\text{Merawan}} = \begin{bmatrix} 5.8842 \times 10^{8} & 1.7653 \times 10^{8} & 0 \\ 1.7653 \times 10^{8} & 9.8512 \times 10^{9} & 0 \\ 0 & 0 & 2.4236 \times 10^{8} \end{bmatrix} \text{Pa}$$

$$[\bar{Q}]_{90,\text{Laran}} = \begin{bmatrix} 5.0561 \times 10^{7} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix} \text{Pa}$$

4.6 The transformed reduced stiffness matrix 0°

For the third lamina therefore, it has to repeat the transformed reduced stiffness matrix again for the 0° angle.

$$c = \cos(0)$$

$$c = 1$$

$$s = \sin(0)$$

$$s = 0$$

$$\bar{Q}_{11} = Q_{11}c^4 + Q_{22}s^4 + 2(Q_{12} + 2Q_{66})s^2c^2$$

$$\bar{Q}_{11,\text{Bakau}} = (1.9227 \times 10^{10})(1^4) + (2.5713 \times 10^{8})0^4 + 2[(7.7139 \times 10^{7}) + 2(5.334 \times 10^{8})](0)^2(1)^2$$

$$= 1.9227 \times 10^{10} \text{ Pa}$$

$$\overline{Q}_{11,\text{Merawan}} = (9.8512 \times 10^9)(1^4) + (5.8842 \times 10^8)0^4 + 2[(1.7653 \times 10^8) + 2(2.4236 \times 10^8)](0)^2(1)^2$$

$$= 9.8512 \times 10^9 \text{ Pa}$$

$$\overline{Q}_{11,\text{Laran}} = (1.0976 \times 10^{10})(1^4) + (5.0561 \times 10^7)0^4 + 2[(1.5168 \times 10^7) + 2(2.0333 \times 10^8)](0)^2(1)^2$$

$$= 1.0976 \times 10^{10} \text{ Pa}$$

$$\overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + Q_{12}(c^4 + s^2)$$

$$\overline{Q}_{12,\text{Bakau}} = [(1.9227 \times 10^{10}) + (2.5713 \times 10^8) - 4(5.334 \times 10^8)](0)^2(1)^2 + (7.7139 \times 10^7)[(1)^4 + (0)^2]$$

$$= 7.7139 \times 10^7 \text{ Pa}$$

$$\overline{Q}_{12,\text{Merawan}} = [(9.8512 \times 10^9) + (5.8842 \times 10^8) - 4(2.4236 \times 10^8)](0)^2(1)^2 + (1.7653 \times 10^8)[(1)^4 + (0)^2]$$

$$= 1.7653 \times 10^8 \text{ Pa}$$

$$\overline{Q}_{12,\text{Laran}} = [(1.0976 \times 10^{10}) + (5.0561 \times 10^7) - 4(2.0333 \times 10^8)](0)^2(1)^2 + (1.5168 \times 10^7)[(1)^4 + (0)^2]$$

$$= 1.5168 \times 10^7 \text{ Pa}$$

$$\overline{Q}_{22} = (Q_{11})s^4 + (Q_{22})c^4 + 2[Q_{12} + 2(Q_{66})]s^2c^2$$

$$\overline{Q}_{22,Bakau} = (1.9227 \times 10^{10})(0)^4 + (2.5713 \times 10^8)(1)^4 + 2[7.7139 \times 10^7 + 2(5.334 \times 10^8)](0)^2(1)^2$$

$$= 2.5713 \times 10^8 \text{ Pa}$$

$$\overline{Q}_{22,Merawan} = (9.8512 \times 10^9)(0)^4 + (5.8842 \times 10^8)(1)^4 + 2[(1.7653 \times 10^8) + 2(2.4236 \times 10^8)](0)^2(1)^2$$

$$= 5.8842 \times 10^8 \text{ Pa}$$

$$\overline{Q}_{22,Laran} = (1.0976 \times 10^{10})(0)^4 + (5.0561 \times 10^7)(1)^4 + 2[(1.5168 \times 10^7) + 2(2.0333 \times 10^8)](0)^2(1)^2$$

$$= 5.0561 \times 10^7 \text{ Pa}$$

$$\overline{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})c^3s - [Q_{22} - Q_{12} - 2(Q_{66})]s^3c$$

$$\overline{Q}_{16,Bakau} = [(1.9227 \times 10^{10}) - (7.7139 \times 10^7) - 2(5.334 \times 10^8)](1)^3(0) - [(2.5713 \times 10^8) - (7.7139 \times 10^7) - 2(5.334 \times 10^8)](0)^3(1)$$

$$= 0 \text{ Pa}$$

$$\overline{Q}_{16,\text{Merawan}} = [(9.8512 \times 10^{9}) - (1.7653 \times 10^{8}) - 2(2.4236 \times 10^{8})](1)^{3}(0) - [(5.8842 \times 10^{8}) - (1.7653 \times 10^{8}) - 2(2.4236 \times 10^{8})](0)^{3}(1)$$

$$= 0 \text{ Pa}$$

$$\overline{Q}_{16,\text{Laran}} = [(1.0976 \times 10^{10}) - (1.5168 \times 10^{7}) - 2(2.0333 \times 10^{8})](1)^{3}(0) - [(5.0561 \times 10^{7}) - (1.5168 \times 10^{7}) - 2(2.0333 \times 10^{8})](0)^{3}(1)$$

$$= 0 \text{ Pa}$$

$$\overline{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})cs^{3} - (Q_{22} - Q_{12} - 2Q_{66})c^{3}s$$

$$\overline{Q}_{26,\text{Bakau}} = [(1.9227 \times 10^{10}) - (7.7139 \times 10^{7}) - (2)(5.334 \times 10^{8})](1)(0)^{3} - [(2.5713 \times 10^{8}) - (7.7139 \times 10^{7}) - 2(5.334 \times 10^{8})](1)^{3}(0)$$

$$= 0 \text{ Pa}$$

$$\overline{Q}_{26,\text{Merawan}} = [(9.8512 \times 10^{9}) - (1.7653 \times 10^{8}) - (2)(2.4236 \times 10^{8})](1)(0)^{3} - [(5.8842 \times 10^{8}) - (1.7653 \times 10^{8}) - 2(2.4236 \times 10^{8})](1)^{3}(0)$$

$$= 0 \text{ Pa}$$

$$\begin{aligned}\bar{Q}_{26,\text{Laran}} = {} & [(1.0976 \times 10^{10}) - (1.5168 \times 10^{7}) \\ & - (2)(2.0333 \times 10^{8})](1)(0)^{3} \\ & - [(5.0561 \times 10^{7}) - (1.5168 \times 10^{7}) \\ & - 2(2.0333 \times 10^{8})](1)^{3}(0)\end{aligned}$$

$$= 0 \text{ Pa}$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})s^{2}c^{2} + Q_{66}(s^{4} + c^{4})$$

$$\begin{aligned}\bar{Q}_{66,\text{Bakau}} = {} & [(1.9227 \times 10^{10}) + (2.5713 \times 10^{8}) \\ & - 2(7.7139 \times 10^{7}) - 2(5.334 \times 10^{8})](0)^{2}(1)^{2} \\ & + (5.334 \times 10^{8})[(0)^{4} + (1)^{4}]\end{aligned}$$

$$= 5.334 \times 10^{8} \text{ Pa}$$

$$\begin{aligned}\bar{Q}_{66,\text{Merawan}} = {} & [(9.8512 \times 10^{9}) + (5.8842 \times 10^{8}) \\ & - 2(1.7653 \times 10^{8}) - 2(2.4236 \times 10^{8})](0)^{2}(1)^{2} \\ & + (2.4236 \times 10^{8})[(0)^{4} + (1)^{4}]\end{aligned}$$

$$= 2.4236 \times 10^{8} \text{ Pa}$$

$$\begin{aligned}\bar{Q}_{66,\text{Laran}} = {} & [(1.0976 \times 10^{10}) + (5.0561 \times 10^{7}) \\ & - 2(1.5168 \times 10^{7}) - 2(2.0333 \times 10^{8})](0)^{2}(1)^{2} \\ & + (2.0333 \times 10^{8})[(0)^{4} + (1)^{4}]\end{aligned}$$

$$= 2.0333 \times 10^{8} \text{ Pa}$$

$$[\bar{Q}]_{0,\text{Bakau}} = \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix} \text{Pa}$$

$$[\bar{Q}]_{0,Merawan} = \begin{bmatrix} 9.8512 \times 10^9 & 1.7653 \times 10^8 & 0 \\ 1.7653 \times 10^8 & 5.8842 \times 10^8 & 0 \\ 0 & 0 & 2.4236 \times 10^8 \end{bmatrix} \text{Pa}$$

$$[\bar{Q}]_{0,Laran} = \begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^7 & 0 \\ 1.5168 \times 10^7 & 5.0561 \times 10^7 & 0 \\ 0 & 0 & 2.0333 \times 10^8 \end{bmatrix} \text{Pa}$$

4.7 Extensional of the stiffness matrix of 3-plies laminate

As the values of transformed stiffness matrix for 0˚ and 90˚ obtained, the calculation further to obtain values of stiffness matrix as in the laminates or composite form since it has been designed to use 3 layers with the laminate code $[0, \overline{90}]_s$. This can be realized by using the extensional compliance matrix [A] formula (see Equation 16).

$$A_{ij} = \sum_{k=1}^{n} \left[(\bar{Q}_{ij})\right]_k (h_k - h_{k-1}) \quad (16)$$

The plies will be divided into coordinate locations (see Figure 4.5) where h representing the thickness of the laminate and t_k is the thickness of ply.

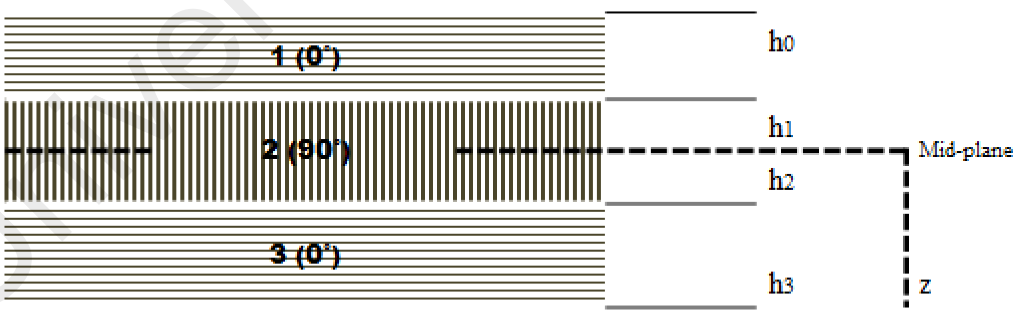

Figure 4.5 Coordinate locations of plies in a laminate

The coordinate location of the mid-plane is the value of h/2 that is from top surface h_0 to the center of laminate as well as from bottom surface h_3 to center (see Equation 17, 20).

The z-coordinate for both bottom surfaces h_1 and h_2 of each plies would be calculated by considering the total laminate h has 12 mm thick and the lamina t_k is 4 mm thick of each (see Equation 18, 19).

$$h_0 = -\frac{h}{2}\,(\text{top surface}) \tag{17}$$

$$= -\frac{12\text{ mm}}{2}$$

$$= -6\text{ mm}$$

$$h_1 = -\frac{h}{2} + t_1\,(\text{bottom surface}) \tag{18}$$

$$= -\frac{12\text{ mm}}{2} + 4\text{ mm}$$

$$= -2\text{ mm}$$

$$h_2 = -\frac{h}{2} + \sum_{=1}^{k} t\,(\text{bottom surface}) \tag{19}$$

$$= -\frac{12\text{ mm}}{2} + 8\text{ mm}$$

$$= 2\text{ mm}$$

$$h_3 = \frac{h}{2}\,(\text{bottom surface}) \tag{20}$$

$$= \frac{12\text{ mm}}{2}$$

$$= 6\text{ mm}$$

Therefore, the extension compliance matrix [A] can be calculated by using the transformed reduced stiffness matrices of 0˚ and 90˚ for all type of woods.

$$[A]_{Bakau} = \left[[\bar{Q}]_{0,Bakau}\right]_1 (h_1 - h_0) + \left[[\bar{Q}]_{90,Bakau}\right]_2 (h_2 - h_1) + \left[[\bar{Q}]_{0,Bakau}\right]_3 (h_3 - h_2)$$

$$= \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_1 (4 \times 10^{-3}) + \begin{bmatrix} 2.5713 \times 10^{8} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 1.9227 \times 10^{10} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_2 (4 \times 10^{-3}) + \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_3 (4 \times 10^{-3})$$

$$[A]_{Bakau} = \begin{bmatrix} 1.548 \times 10^{8} & 9.257 \times 10^{5} & 0 \\ 9.257 \times 10^{5} & 7.897 \times 10^{7} & 0 \\ 0 & 0 & 6.401 \times 10^{6} \end{bmatrix} \mathrm{Pa.m}$$

$$[A]_{Merawan} = \left[[\bar{Q}]_{0,Merawan}\right]_1 (h_1 - h_0) + \left[[\bar{Q}]_{90,Merawan}\right]_2 (h_2 - h_1) + \left[[\bar{Q}]_{0,Merawan}\right]_3 (h_3 - h_2)$$

$$= \begin{bmatrix} 9.8512 \times 10^{9} & 1.7653 \times 10^{8} & 0 \\ 1.7653 \times 10^{8} & 5.8842 \times 10^{8} & 0 \\ 0 & 0 & 2.4236 \times 10^{8} \end{bmatrix}_1 (4 \times 10^{-3}) + \begin{bmatrix} 5.8842 \times 10^{8} & 1.7653 \times 10^{8} & 0 \\ 1.7653 \times 10^{8} & 9.8512 \times 10^{9} & 0 \\ 0 & 0 & 2.4236 \times 10^{8} \end{bmatrix}_2 (4 \times 10^{-3}) + \begin{bmatrix} 9.8512 \times 10^{9} & 1.7653 \times 10^{8} & 0 \\ 1.7653 \times 10^{8} & 5.8842 \times 10^{8} & 0 \\ 0 & 0 & 2.4236 \times 10^{8} \end{bmatrix}_3 (4 \times 10^{-3})$$

$$= \begin{bmatrix} 8.116 \times 10^{7} & 2.118 \times 10^{6} & 0 \\ 2.118 \times 10^{6} & 4.411 \times 10^{7} & 0 \\ 0 & 0 & 2.908 \times 10^{6} \end{bmatrix} \mathrm{Pa.m}$$

$$[A]_{Laran} = \left[[\bar{Q}]_{0,Laran}\right]_1 (h_1 - h_0) + \left[[\bar{Q}]_{90,Laran}\right]_2 (h_2 - h_1) + \left[[\bar{Q}]_{0,Laran}\right]_3 (h_3 - h_2)$$

$$= \begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 5.0561 \times 10^{7} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_1 (4 \times 10^{-3})$$
$$+ \begin{bmatrix} 5.0561 \times 10^{7} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_2 (4 \times 10^{-3})$$
$$+ \begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 5.0561 \times 10^{7} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_3 (4 \times 10^{-3})$$

$$= \begin{bmatrix} 8.801 \times 10^{7} & 1.82 \times 10^{5} & 0 \\ 1.82 \times 10^{5} & 4.431 \times 10^{7} & 0 \\ 0 & 0 & 2.44 \times 10^{6} \end{bmatrix} \mathrm{Pa.m}$$

4.8 In-plane engineering constants of 3-plies laminate

Inverting the extensional stiffness matrix [A] which obtained before would give the extensional compliance matrix where therefore the in-plane engineering constants for all the woods can be calculated.

$$[A]_{\mathrm{Bakau}}{}^{-1} = \begin{bmatrix} 1.548 \times 10^{8} & 9.257 \times 10^{5} & 0 \\ 9.257 \times 10^{5} & 7.897 \times 10^{7} & 0 \\ 0 & 0 & 6.401 \times 10^{6} \end{bmatrix}^{-1} \mathrm{Pa.m}$$

$$= \begin{bmatrix} 6.459 \times 10^{-9} & -7.571 \times 10^{-11} & 0 \\ -7.571 \times 10^{-11} & 1.266 \times 10^{-8} & 0 \\ 0 & 0 & 1.562 \times 10^{-7} \end{bmatrix} (\mathrm{Pa.m})^{-1}$$

$$[A]_{\mathrm{Merawan}}{}^{-1} = \begin{bmatrix} 8.116 \times 10^{7} & 2.118 \times 10^{6} & 0 \\ 2.118 \times 10^{6} & 4.411 \times 10^{7} & 0 \\ 0 & 0 & 2.908 \times 10^{6} \end{bmatrix}^{-1} \mathrm{Pa.m}$$

$$= \begin{bmatrix} 1.234 \times 10^{-8} & -5.924 \times 10^{-10} & 0 \\ -5.924 \times 10^{-10} & 2.27 \times 10^{-8} & 0 \\ 0 & 0 & 3.438 * 10^{-7} \end{bmatrix} (\mathrm{Pa.m})^{-1}$$

$$[A]_{Laran}{}^{-1} = \begin{bmatrix} 8.801 \times 10^7 & 1.82 \times 10^5 & 0 \\ 1.82 \times 10^5 & 4.431 \times 10^7 & 0 \\ 0 & 0 & 2.44 \times 10^6 \end{bmatrix}^{-1} \text{Pa.m}$$

$$= \begin{bmatrix} 1.136 \times 10^{-8} & -4.668 \times 10^{-11} & 0 \\ -4.668 \times 10^{-11} & 2.257 \times 10^{-8} & 0 \\ 0 & 0 & 4.098 \times 10^{-7} \end{bmatrix} (\text{Pa.m})^{-1}$$

The engineering constant of laminate which consists of E_x (see Equation 21), E_y (see Equation 22), G_{xy} (see Equation 23), ν_{xy} (see Equation 24), and ν_{yx} (see Equation 25) for all type of the woods subjected in-plane loading can be determined as follows.

$$E_x = \frac{1}{hA_{11}} \quad (21)$$

$$E_{x,Bakau} = \frac{1}{(0.012 \text{ m})(6.459 \times 10^{-9} (\text{Pa.m})^{-1})}$$

$$= 12.902 \text{ GPa}$$

$$E_{x,Merawan} = \frac{1}{(0.012 \text{ m})(1.234 \times 10^{-8} (\text{Pa.m})^{-1})}$$

$$= 6.753 \text{ GPa}$$

$$E_{x,Laran} = \frac{1}{(0.012 \text{ m})(1.136 \times 10^{-8} (\text{Pa.m})^{-1})}$$

$$= 7.336 \text{ GPa}$$

$$E_y = \frac{1}{hA_{22}} \tag{22}$$

$$E_{y,Bakau} = \frac{1}{(0.012\ m)(1.266 \times 10^{-8}(Pa.m)^{-1})}$$

$$= 6.582\ GPa$$

$$E_{y,Merawan} = \frac{1}{(0.012\ m)(2.27 \times 10^{-8}(Pa.m)^{-1})}$$

$$= 3.671\ GPa$$

$$E_{y,Laran} = \frac{1}{(0.012\ m)(2.257 \times 10^{-8}(Pa.m)^{-1})}$$

$$= 3.692\ GPa$$

$$G_{12} = \frac{1}{hA_{66}} \tag{23}$$

$$G_{xy,Bakau} = \frac{1}{(0.012\ m)(1.562 \times 10^{-7}(Pa.m)^{-1})}$$

$$= 0.534\ GPa$$

$$G_{xy,Merawan} = \frac{1}{(0.012\ m)(3.438 \times 10^{-7}(Pa.m)^{-1})}$$

$$= 0.242\ GPa$$

$$G_{xy,Laran} = \frac{1}{(0.012\ \text{m})(4.098 \times 10^{-7}(\text{Pa.m})^{-1})}$$

$$= 0.203\ \text{GPa}$$

$$\nu_{xy} = -\frac{A_{12}}{A_{11}} \tag{24}$$

$$\nu_{xy,Bakau} = -\left[\frac{-7.571 \times 10^{-11}(\text{Pa.m})^{-1}}{6.459 \times 10^{-9}(\text{Pa.m})^{-1}}\right]$$

$$= 0.012$$

$$\nu_{xy,Merawan} = -\left[\frac{-5.924 \times 10^{-10}(\text{Pa.m})^{-1}}{1.234 \times 10^{-8}(\text{Pa.m})^{-1}}\right]$$

$$= 0.048$$

$$\nu_{xy,Laran} = -\left[\frac{-4.668 \times 10^{-11}(\text{Pa.m})^{-1}}{1.136 \times 10^{-8}(\text{Pa.m})^{-1}}\right]$$

$$= 4.109 \times 10^{-3}$$

$$\nu_{yx} = -\frac{A_{12}}{A_{22}} \tag{25}$$

$$\nu_{yx,Bakau} = -\left[\frac{-7.571 \times 10^{-11}(\text{Pa.m})^{-1}}{1.266 \times 10^{-8}(\text{Pa.m})^{-1}}\right]$$

$$= 5.98 \times 10^{-3}$$

$$\nu_{yx,Merawan} = -\left[\frac{-5.924 \times 10^{-10}(Pa.m)^{-1}}{2.27 \times 10^{-8}(Pa.m)^{-1}}\right]$$

$$= 0.026$$

$$\nu_{yx,Laran} = -\left[\frac{-4.668 \times 10^{-11}(Pa.m)^{-1}}{2.257 \times 10^{-8}(Pa.m)^{-1}}\right]$$

$$= 2.068 \times 10^{-3}$$

The results of in-plane engineering constants for three types of wood had been summarized (see Table 4.2) and it can be seen that Bakau has the highest values of the elastic properties.

Table 4.2 In-plane engineering constants result

Types of woods	**E_x (GPa)**	**E_y (GPa)**	**G_{12} (GPa)**	**ν_{xy}**	**ν_{yx}**
Bakau	12.902	6.582	0.534	0.012	0.00598
Merawan	6.753	3.671	0.242	0.048	0.026
Laran	7.336	3.692	0.203	0.004109	0.002068

4.9 Bending stiffness matrix of 3-plies laminate

Practically, the Cruiser board will be subjected the bending force from the z direction or out of plane direction. The bending stiffness matrix [D] (see Equation 26) consists of resultant bending moments to the plate curvatures. Therefore, the bending compliance matrix $[D]^{-1}$ has to be used in order to define effective flexural moduli.

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}\left[\left(\overline{Q}_{ij}\right)\right]_k \left(h_k^3 - h_{k-1}^3\right) \tag{26}$$

$$D_{Bakau} = \frac{1}{3}\left[[\bar{Q}]_{0,Bakau}\right]_1 (h_1^3 - h_0^3) + \frac{1}{3}\left[[\bar{Q}]_{90,Bakau}\right]_2 (h_2^3 - h_1^3) + \frac{1}{3}\left[[\bar{Q}]_{0,Bakau}\right]_3 (h_3^3 - h_2^3)$$

$$= \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_1 (2.08\times10^{-7}) + \frac{1}{3}\begin{bmatrix} 2.5713\times10^{8} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 1.9227\times10^{10} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_2 (1.6\times10^{-8}) + \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_3 (2.08\times10^{-7})$$

$$= \begin{bmatrix} 2.668\times10^{3} & 11.108 & 0 \\ 11.108 & 138.199 & 0 \\ 0 & 0 & 76.81 \end{bmatrix} \mathrm{Pa.m^3}$$

$$D_{Merawan} = \frac{1}{3}\left[[\bar{Q}]_{0,Merawan}\right]_1 (h_1^3 - h_0^3) + \frac{1}{3}\left[[\bar{Q}]_{90,Merwan}\right]_2 (h_2^3 - h_1^3) + \frac{1}{3}\left[[\bar{Q}]_{0,Merawan}\right]_3 (h_3^3 - h_2^3)$$

$$= \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_1 (2.08\times10^{-7}) + \frac{1}{3}\begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_2 (1.6\times10^{-8}) + \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_3 (2.08\times10^{-7})$$

$$= \begin{bmatrix} 1.369\times10^{3} & 25.42 & 0 \\ 25.42 & 134.134 & 0 \\ 0 & 0 & 34.9 \end{bmatrix} \mathrm{Pa.m^3}$$

$$D_{Laran} = \frac{1}{3}\left[[\bar{Q}]_{0,Laran}\right]_1 (h_1^3 - h_0^3) + \frac{1}{3}\left[[\bar{Q}]_{90,Laran}\right]_2 (h_2^3 - h_1^3) + \frac{1}{3}\left[[\bar{Q}]_{0,Laran}\right]_3 (h_3^3 - h_2^3)$$

$$= \frac{1}{3}\begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^7 & 0 \\ 1.5168 \times 10^7 & 5.0561 \times 10^7 & 0 \\ 0 & 0 & 2.0333 \times 10^8 \end{bmatrix}_1 (2.08 \times 10^{-7}) + \frac{1}{3}\begin{bmatrix} 5.0561 \times 10^7 & 1.5168 \times 10^7 & 0 \\ 1.5168 \times 10^7 & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^8 \end{bmatrix}_2 (1.6 \times 10^{-8}) + \frac{1}{3}\begin{bmatrix} 1.0976 \times 10^{10} & 1.5168 \times 10^7 & 0 \\ 1.5168 \times 10^7 & 5.0561 \times 10^7 & 0 \\ 0 & 0 & 2.0333 \times 10^8 \end{bmatrix}_3 (2.08 \times 10^{-7})$$

$$= \begin{bmatrix} 1.522 \times 10^3 & 2.184 & 0 \\ 2.184 & 65.55 & 0 \\ 0 & 0 & 29.28 \end{bmatrix} \text{Pa.m}^3$$

4.10 Flexural engineering constants of 3-plies laminate

Similarly, by inverting bending stiffness matrix before would give bending compliance matrix that permits to calculate flexural engineering constants of a laminate.

$$D_{Bakau}{}^{-1} = \begin{bmatrix} 2.668 \times 10^3 & 11.108 & 0 \\ 11.108 & 138.199 & 0 \\ 0 & 0 & 76.81 \end{bmatrix}^{-1} \text{Pa.m}^3$$

$$= \begin{bmatrix} 3.75 \times 10^{-4} & -3.014 \times 10^{-5} & 0 \\ -3.014 \times 10^{-5} & 7.238 \times 10^{-3} & 0 \\ 0 & 0 & 0.013 \end{bmatrix}^{-1} (\text{Pa.m}^3)^{-1}$$

$$D_{Merawan}{}^{-1} = \begin{bmatrix} 1.369 \times 10^3 & 25.42 & 0 \\ 25.42 & 134.134 & 0 \\ 0 & 0 & 34.9 \end{bmatrix}^{-1} \text{Pa.m}^3$$

$$= \begin{bmatrix} 7.329 \times 10^{-4} & -1.389 \times 10^{-4} & 0 \\ -1.389 \times 10^{-4} & 7.482 \times 10^{-3} & 0 \\ 0 & 0 & 0.029 \end{bmatrix}^{-1} (\text{Pa.m}^3)^{-1}$$

$$D_{Laran}{}^{-1} = \begin{bmatrix} 1.522\times10^{3} & 2.184 & 0 \\ 2.184 & 65.55 & 0 \\ 0 & 0 & 29.28 \end{bmatrix}^{-1} \text{Pa.m}^3$$

$$= \begin{bmatrix} 6.569\times10^{-4} & -2.189\times10^{-5} & 0 \\ -2.189\times10^{-5} & 0.015 & 0 \\ 0 & 0 & 0.034 \end{bmatrix}^{-1} (\text{Pa.m}^3)^{-1}$$

By using the compliance bending matrix $[D]^{-1}$, therefore the flexural engineering constants for a laminate where consists of E_x^f (see Equation 27), E_y^f (see Equation 28), G_{xy}^f (see Equation 29), ν_{xy}^f (see Equation 30), and ν_{yx}^f (see Equation 31) would be calculated.

$$E_x^f = \frac{12}{h^3 D_{11}^{-1}} \tag{27}$$

$$E_{x,Bakau}^f = \frac{12}{(0.012\text{ m})^3(3.75\times10^{-4}\ (\text{Pa.m}^3)^{-1})}$$

$$= 18.519\text{ GPa}$$

$$E_{x,Merawan}^f = \frac{12}{(0.012\text{ m})^3(7.329\times10^{-4}\ (\text{Pa.m}^3)^{-1})}$$

$$= 9.475\text{GPa}$$

$$E_{x,Laran}^f = \frac{12}{(0.012\text{ m})^3(6.569\times10^{-4}\ (\text{Pa.m}^3)^{-1})}$$

$$= 10.572\text{ GPa}$$

$$E_y^f = \frac{12}{h^3 D_{22}^{-1}} \tag{28}$$

$$E_{y,Bakau}^f = \frac{12}{(0.012\ \text{m})^3 (7.238 \times 10^{-3}\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.959\ \text{GPa}$$

$$E_{y,Merawan}^f = \frac{12}{(0.012\ \text{m})^3 (7.482 \times 10^{-3}\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.928\ \text{GPa}$$

$$E_{y,Laran}^f = \frac{12}{(0.012\ \text{m})^3 (0.015\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.463\ \text{GPa}$$

$$G_{xy}^f = \frac{12}{h^3 D_{66}^{-1}} \tag{29}$$

$$G_{xy,Bakau}^f = \frac{12}{(0.012\ \text{m})^3 (0.013\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.534\ \text{GPa}$$

$$G_{xy,Merawan}^f = \frac{12}{(0.012\ \text{m})^3 (0.029\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.239\ \text{GPa}$$

$$G_{xy,Laran}^f = \frac{12}{(0.012\ \text{m})^3 (0.034\ (\text{Pa.m}^3)^{-1})}$$

$$= 0.204\ \text{GPa}$$

$$\nu_{xy}^{f} = -\frac{D_{12}^{-1}}{D_{11}^{-1}} \tag{30}$$

$$\nu_{xy,Bakau}^{f} = -\left[\frac{-3.014 \times 10^{-5}(Pa.m^3)^{-1}}{3.75 \times 10^{-4}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.08$$

$$\nu_{xy,Merawan}^{f} = -\left[\frac{-1.389 \times 10^{-4}\ (Pa.m^3)^{-1}}{7.329 \times 10^{-4}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.19$$

$$\nu_{xy,Laran}^{f} = -\left[\frac{-2.189 \times 10^{-5}\ (Pa.m^3)^{-1}}{6.569 \times 10^{-4}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.033$$

$$\nu_{yx}^{f} = -\frac{D_{12}^{-1}}{D_{22}^{-1}} \tag{31}$$

$$\nu_{yx,Bakau}^{f} = -\left[\frac{-3.014 \times 10^{-5}\ (Pa.m^3)^{-1}}{7.238 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 4.164 \times 10^{-3}$$

$$\nu_{yx,Merawan}^{f} = -\left[\frac{-1.389 \times 10^{-4}\ (Pa.m^3)^{-1}}{7.482 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.019$$

$$\nu^f_{yx,Laran} = -\left[\frac{-2.189 \times 10^{-5}\ (Pa.m^3)^{-1}}{0.015\ (Pa.m^3)^{-1}}\right]$$

$$= 1.459 \times 10^{-3}$$

The flexural engineering constants result of laminate (see Table 4.3) for all type of woods has been summarized as follows. Bakau is the best wood could be proposed for the development of the cruiser board and the actual laminate is the best if could be test to verify it competency.

Table 4.3 Flexural engineering constants

Type of woods	$\mathbf{E^f_x}$ **(GPa)**	$\mathbf{E^f_y}$ **(GPa)**	$\mathbf{G^f_{xy}}$ **(GPa)**	$\boldsymbol{\nu^f_{xy}}$	$\boldsymbol{\nu^f_{yx}}$
Bakau	18.519	0.959	0.534	0.08	0.0042
Merawan	9.475	0.928	0.239	0.19	0.0190
Laran	10.572	0.463	0.204	0.033	0.0015

4.11 7-plies construction of laminate

The analysis furthered by designing 7-plies of laminate with the orientation of $[0,90,0,\overline{90}]_s$ as typically available in the markets by using three types of woods as proposed in the methodology. Similarly, the laminate would be divided into the coordinate locations (see Figure 4.6).

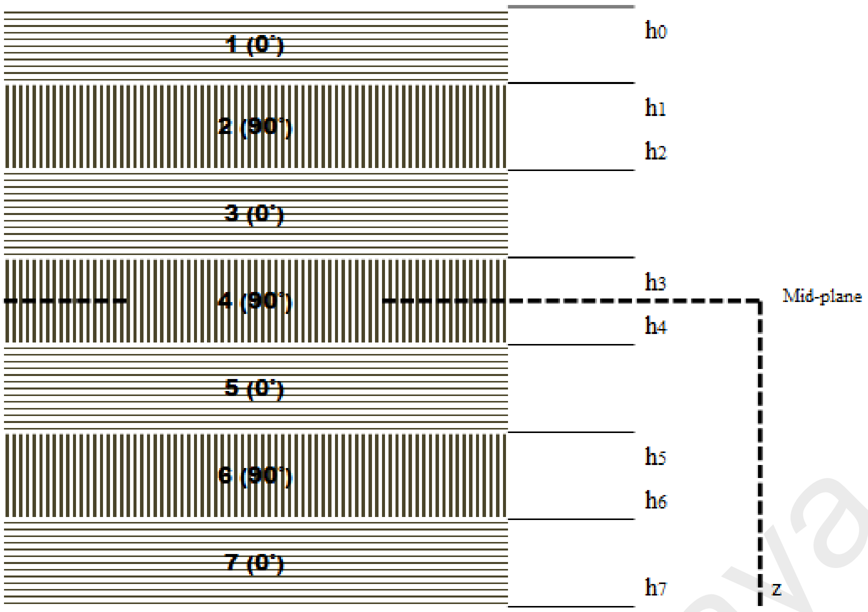

Figure 4.6 Coordinate locations of 7-Plies laminate

Each of the lamina t_k has 1/16 in. thick and total thickness of laminate h is 7/16 in. which is same as available in the markets. The z-coordinate from top and bottom surface would be defined as follows.

$$h_0 = -\frac{h}{2}\,(\text{top surface})$$

$$= -\frac{0.0111125\ \text{m}}{2}$$

$$= -5.55625 \times 10^{-3}\ \text{m}$$

$$h_1 = -\frac{h}{2} + t_1\,(\text{bottom surface})$$

$$= -0.00555625\ \text{m} + 0.0015875\ \text{m}$$

$$= -3.96875 \times 10^{-3}\ \text{m}$$

$$h_2 = -\frac{h}{2} + \sum_{=1}^{k} t \text{ (bottom surface)}$$

$$= -0.00555625 \text{ m} + 0.003175 \text{ m}$$

$$= -2.38125 \times 10^{-3} \text{ m}$$

$$h_3 = -\frac{h}{2} + \sum_{=1}^{k} t \text{ (bottom surface)}$$

$$= -0.00555625 \text{ m} + 0.0047625 \text{ m}$$

$$= -7.9375 \times 10^{-4} \text{ m}$$

$$h_4 = -\frac{h}{2} + \sum_{=1}^{k} t \text{ (bottom surface)}$$

$$= -0.00555625 \text{ m} + 0.00635 \text{ m}$$

$$7.9375 \times 10^{-4} \text{ m}$$

$$h_5 = -\frac{h}{2} + \sum_{=1}^{k} t \text{ (bottom surface)}$$

$$= -0.00555625 \text{ m} + 0.0079375 \text{ m}$$

$$2.38125 \times 10^{-3} \text{ m}$$

$$h_6 = -\frac{h}{2} + \sum_{=1}^{k} t \text{ (bottom surface)}$$

$$= -0.00555625 \text{ m} + 0.009525 \text{ m}$$

$$3.96875 \times 10^{-3} \text{ m}$$

$$h_7 = \frac{h}{2}$$

$$= 5.55625 \times 10^{-3} \text{ m}$$

4.11.1 7-plies extensional stiffness matrix of laminate

The analysis furthered to calculate 7-plies extensional stiffness matrix [A] as well as inverting them to obtain extensional compliance matrix of the laminate $[A]^{-1}$ for three types of wood. The extensional compliance matrix would allow this analysis to calculate in-plane engineering constants.

$$A_{ij} = \sum_{k=1}^{n} \left[\left(\overline{Q}_{ij} \right) \right]_k (h_k - h_{k-1})$$

$$[A]_{Bakau} = \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_1 (1.588 \times 10^{-3})$$
$$+ \begin{bmatrix} 5.0561 \times 10^{7} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_2 (1.587 \times 10^{-3})$$
$$+ \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_3 (1.587 \times 10^{-3})$$
$$+ \begin{bmatrix} 5.0561 \times 10^{7} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_4 (1.588 \times 10^{-3})$$
$$+ \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_5 (1.587 \times 10^{-3})$$
$$+ \begin{bmatrix} 5.0561 \times 10^{7} & 1.5168 \times 10^{7} & 0 \\ 1.5168 \times 10^{7} & 1.0976 \times 10^{10} & 0 \\ 0 & 0 & 2.0333 \times 10^{8} \end{bmatrix}_6 (1.587 \times 10^{-3})$$
$$+ \begin{bmatrix} 1.9227 \times 10^{10} & 7.7139 \times 10^{7} & 0 \\ 7.7139 \times 10^{7} & 2.5713 \times 10^{8} & 0 \\ 0 & 0 & 5.334 \times 10^{8} \end{bmatrix}_7 (1.588 \times 10^{-3})$$

$$[A]_{Bakau} = \begin{bmatrix} 1.233\times10^{8} & 8.572\times10^{5} & 0 \\ 8.572\times10^{5} & 9.32\times10^{7} & 0 \\ 0 & 0 & 5.927\times10^{6} \end{bmatrix} \mathrm{Pa.m}$$

$$[A]^{-1}_{Bakau} = \begin{bmatrix} 8.11\times10^{-9} & -7.459\times10^{-11} & 0 \\ -7.459\times10^{-11} & 1.073\times10^{-8} & 0 \\ 0 & 0 & 1.687\times10^{-7} \end{bmatrix} (\mathrm{Pa.m})^{-1}$$

$$\begin{aligned}[A]_{Merawan} &= \begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_1 (1.58\times10^{-3}) \\ &+ \begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_2 (1.587\times10^{-3}) \\ &+ \begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_3 (1.587\times10^{-3}) \\ &+ \begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_4 (1.588\times10^{-3}) \\ &+ \begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_5 (1.587\times10^{-3}) \\ &+ \begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_6 (1.587\times10^{-3}) \\ &+ \begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_7 (1.588\times10^{-3})\end{aligned}$$

$$[A]_{Merawan} = \begin{bmatrix} 6.536\times10^{7} & 1.962\times10^{6} & 0 \\ 1.962\times10^{6} & 5.065\times10^{7} & 0 \\ 0 & 0 & 2.693\times10^{6} \end{bmatrix} \mathrm{Pa.m}$$

$$[A]^{-1}_{Merawan} = \begin{bmatrix} 1.532\times10^{-8} & -5.932\times10^{-10} & 0 \\ -5.932\times10^{-10} & 1.977\times10^{-8} & 0 \\ 0 & 0 & 3.713\times10^{-7} \end{bmatrix} (\mathrm{Pa.m})^{-1}$$

$$[A]_{Laran} = \begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_1 (1.588\times10^{-3}) + \begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_2 (1.588\times10^{-3}) + \begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_3 (1.588\times10^{-3}) + \begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_4 (1.588\times10^{-3}) + \begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_5 (1.588\times10^{-3}) + \begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_6 (1.588\times10^{-3}) + \begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_7 (1.588\times10^{-3})$$

$$[A]_{Laran} = \begin{bmatrix} 6.994\times10^{7} & 1.686\times10^{5} & 0 \\ 1.686\times10^{5} & 5.259\times10^{7} & 0 \\ 0 & 0 & 2.26\times10^{6} \end{bmatrix} \mathrm{Pa.m}$$

$$[A]^{-1}_{Laran} = \begin{bmatrix} 1.43\times10^{-8} & -4.582\times10^{-11} & 0 \\ -4.582\times10^{-11} & 1.901\times10^{-8} & 0 \\ 0 & 0 & 4.426\times10^{-7} \end{bmatrix} (\mathrm{Pa.m})^{-1}$$

4.11.2 In-plane engineering constants of 7-plies laminate

From the extensional compliance matrix $[A]^{-1}$, this analysis would be furthered to calculate in-plane engineering constants which consist of E_x, E_y, G_{xy}, ν_{xy}, and ν_{yx} for 7 plies laminate.

$$E_x = \frac{1}{hA_{11}}$$

$$E_{x,Bakau} = \frac{1}{(0.0111125\ \mathrm{m})(8.11 \times 10^{-9}\ (\mathrm{Pa.m})^{-1})}$$

$$= 11.096\ \mathrm{GPa}$$

$$E_{x,Merawan} = \frac{1}{(0.0111125\ \mathrm{m})(1.532 \times 10^{-8}\ (\mathrm{Pa.m})^{-1})}$$

$$= 5.874\ \mathrm{GPa}$$

$$E_{x,Laran} = \frac{1}{(0.0111125\ \mathrm{m})(1.43 \times 10^{-8}\ (\mathrm{Pa.m})^{-1})}$$

$$= 6.293\ \mathrm{GPa}$$

$$E_y = \frac{1}{hA_{22}}$$

$$E_{y,Bakau} = \frac{1}{(0.0111125\ \mathrm{m})(1.073 \times 10^{-8}\ (\mathrm{Pa.m})^{-1})}$$

$$= 8.387\ \mathrm{GPa}$$

$$E_{y,Merawan} = \frac{1}{(0.0111125\ \mathrm{m})(1.977 \times 10^{-8}\ (\mathrm{Pa.m})^{-1})}$$

$$= 4.552\ \mathrm{GPa}$$

$$E_{y,Laran} = \frac{1}{(0.0111125\ \mathrm{m})(1.901 \times 10^{-8}\ (\mathrm{Pa.m})^{-1})}$$

$$= 4.734\ \mathrm{GPa}$$

$$G_{xy} = \frac{1}{hA_{66}}$$

$$G_{xy,Bakau} = \frac{1}{(0.0111125\ \text{m})(1.687 \times 10^{-7}\ (\text{Pa.m})^{-1})}$$

$$= 0.533\ \text{GPa}$$

$$G_{xy,Merawan} = \frac{1}{(0.0111125\ \text{m})(3.713 \times 10^{-7}\ (\text{Pa.m})^{-1})}$$

$$= 0.242\ \text{GPa}$$

$$G_{xy,Laran} = \frac{1}{(0.0111125\ \text{m})(4.426 \times 10^{-7}\ (\text{Pa.m})^{-1})}$$

$$= 0.203\ \text{GPa}$$

$$\nu_{xy} = -\frac{A_{12}}{A_{11}}$$

$$\nu_{xy,Bakau} = -\left[\frac{-7.459 \times 10^{-11}\ (\text{Pa.m})^{-1}}{8.11 \times 10^{-9}\ (\text{Pa.m})^{-1}}\right]$$

$$= 9.197 \times 10^{-3}$$

$$\nu_{xy,Merawan} = -\left[\frac{-5.932 \times 10^{-10}\ (\text{Pa.m})^{-1}}{1.532 \times 10^{-8}\ (\text{Pa.m})^{-1}}\right]$$

$$= 0.039$$

$$\nu_{xy,Laran} = -\left[\frac{-4.582 \times 10^{-11}\ (Pa.m)^{-1}}{1.43 \times 10^{-8}\ (Pa.m)^{-1}}\right]$$

$$= 3.204 \times 10^{-3}$$

$$\nu_{yx} = -\frac{A_{12}}{A_{22}}$$

$$\nu_{yx,Bakau} = -\left[\frac{-7.459 \times 10^{-11}\ (Pa.m)^{-1}}{1.073 \times 10^{-8}\ (Pa.m)^{-1}}\right]$$

$$= 6.952 \times 10^{-3}$$

$$\nu_{yx,Merawan} = -\left[\frac{-5.932 \times 10^{-10}\ (Pa.m)^{-1}}{1.977 \times 10^{-8}\ (Pa.m)^{-1}}\right]$$

$$= 0.03$$

$$\nu_{yx,Laran} = -\left[\frac{-4.582 \times 10^{-11}\ (Pa.m)^{-1}}{1.901 \times 10^{-8}\ (Pa.m)^{-1}}\right]$$

$$= 2.41 \times 10^{-3}$$

The result has been summarized (see Table 4.4). The elastic properties as predicted in the in-plane direction shows higher possessed by Bakau whereas, the elastic properties for Merawan and Laran possesses slightly less than each other.

Table 4.4 In-plane engineering constants of 7-plies laminate

Type of woods	E_x **(GPa)**	E_y **(GPa)**	G_{xy} **(GPa)**	ν_{xy}	ν_{yx}
Bakau	11.096	8.387	0.533	0.009197	0.006952
Merawan	5.874	4.552	0.242	0.039	0.03
Laran	6.293	4.734	0.203	0.003204	0.00241

4.11.3 Bending stiffness matrix of 7-plies laminate

Similarly, the bending stiffness matrix of 7-plies of laminate would be calculated as the cruiser board will be subjected with out of plane load that is on the z-direction. Therefore by inverting stiffness matrix to compliance matrix, this analysis can be furthered to calculate for flexural engineering constants.

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}\left[\left(\overline{Q}_{ij}\right)\right]_k \left(h_k^3 - h_{k-1}^3\right)$$

$$\begin{aligned}
D_{Bakau} &= \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_1 (1.09\times10^{-7}) \\
&+ \frac{1}{3}\begin{bmatrix} 2.5713\times10^{8} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 1.9227\times10^{10} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_2 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_3 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 2.5713\times10^{8} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 1.9227\times10^{10} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_4 (1\times10^{-9}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_5 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 2.5713\times10^{8} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 1.9227\times10^{10} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_6 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.9227\times10^{10} & 7.7139\times10^{7} & 0 \\ 7.7139\times10^{7} & 2.5713\times10^{8} & 0 \\ 0 & 0 & 5.334\times10^{8} \end{bmatrix}_7 (1.09\times10^{-7})
\end{aligned}$$

$$D_{Bakau} = \begin{bmatrix} 1.573\times10^{3} & 8.821 & 0 \\ 8.821 & 655.527 & 0 \\ 0 & 0 & 60.997 \end{bmatrix} \mathrm{Pa.m^3}$$

$$D_{Bakau}{}^{-1} = \begin{bmatrix} 6.359\times10^{-4} & -8.558\times10^{-6} & 0 \\ -8.558\times10^{-6} & 1.526\times10^{-3} & 0 \\ 0 & 0 & 0.016 \end{bmatrix} (\mathrm{Pa.m^3})^{-1}$$

$$
\begin{aligned}
&D_{\text{Merawan}} \\
&= \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_1 (1.09\times10^{-7}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_2 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_3 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_4 (1\times10^{-9}) \\
&+ \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_5 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.8842\times10^{8} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 9.8512\times10^{9} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_6 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 9.8512\times10^{9} & 1.7653\times10^{8} & 0 \\ 1.7653\times10^{8} & 5.8842\times10^{8} & 0 \\ 0 & 0 & 2.4236\times10^{8} \end{bmatrix}_7 (1.09\times10^{-7})
\end{aligned}
$$

$$
D_{\text{Merawan}} = \begin{bmatrix} 820.802 & 20.187 & 0 \\ 20.187 & 373.018 & 0 \\ 0 & 0 & 27.715 \end{bmatrix} \text{Pa.}\,\text{m}^3
$$

$$
D_{\text{Merawan}}{}^{-1} = \begin{bmatrix} 1.22\times10^{-3} & -6.602\times10^{-5} & 0 \\ -6.602\times10^{-5} & 2.684\times10^{-3} & 0 \\ 0 & 0 & 0.036 \end{bmatrix} (\text{Pa.}\,\text{m}^3)^{-1}
$$

$$
\begin{aligned}
D_{Laran} &= \frac{1}{3}\begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_1 (1.09\times10^{-7}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_2 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_3 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_4 (1\times10^{-9}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_5 (1.3\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 5.0561\times10^{7} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 1.0976\times10^{10} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_6 (4.901\times10^{-8}) \\
&+ \frac{1}{3}\begin{bmatrix} 1.0976\times10^{10} & 1.5168\times10^{7} & 0 \\ 1.5168\times10^{7} & 5.0561\times10^{7} & 0 \\ 0 & 0 & 2.0333\times10^{8} \end{bmatrix}_7 (1.09\times10^{-7})
\end{aligned}
$$

$$
D_{Laran} = \begin{bmatrix} 894.55 & 1.735 & 0 \\ 1.735 & 366.389 & 0 \\ 0 & 0 & 23.252 \end{bmatrix} Pa.m^3
$$

$$
{D_{Laran}}^{-1} = \begin{bmatrix} 1.118\times10^{-3} & -5.292\times10^{-6} & 0 \\ -5.292\times10^{-6} & 2.729\times10^{-3} & 0 \\ 0 & 0 & 0.043 \end{bmatrix} (Pa.m^3)^{-1}
$$

4.11.4 Flexural engineering constants of 7-plies laminate

The laminate will be subjected with the force from z-direction. Therefore, the flexural engineering constants which consist of $E_x^f, E_y^f, G_{xy}^f, \nu_{xy}^f$, and ν_{yx}^f would be calculated. The results have been summarized on the following table (see Table 4.5).

$$
E_x^f = \frac{12}{h^3 D_{11}^{-1}}
$$

$$E^{f}_{x,Bakau} = \frac{12}{(0.0111125\ \mathrm{m})^3(6.359 \times 10^{-4}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 13.752\ \mathrm{GPa}$$

$$E^{f}_{x,Merawan} = \frac{12}{(0.0111125\ \mathrm{m})^3(1.22 \times 10^{-3}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 7.168\ \mathrm{GPa}$$

$$E^{f}_{x,Laran} = \frac{12}{(0.0111125\ \mathrm{m})^3(1.118 \times 10^{-3}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 7.822\ \mathrm{GPa}$$

$$E^{f}_{y} = \frac{12}{h^3 D_{22}^{-1}}$$

$$E^{f}_{y,Bakau} = \frac{12}{(0.0111125\ \mathrm{m})^3(1.526 \times 10^{-3}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 5.73\ \mathrm{GPa}$$

$$E^{f}_{y,Merawan} = \frac{12}{(0.0111125\ \mathrm{m})^3(2.684 \times 10^{-3}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 3.258\ \mathrm{GPa}$$

$$E^{f}_{y,Laran} = \frac{12}{(0.0111125\ \mathrm{m})^3(2.729 \times 10^{-3}\ (\mathrm{Pa.m^3})^{-1})}$$

$$= 3.204\ \mathrm{GPa}$$

$$G^f_{xy} = \frac{12}{h^3 D^{-1}_{66}}$$

$$G^f_{xy,Bakau} = \frac{12}{(0.0111125\ m)^3 (0.016\ (Pa.m^3)^{-1})}$$

$$= 0.547\ GPa$$

$$G^f_{xy,Merawan} = \frac{12}{(0.0111125\ m)^3 (0.036\ (Pa.m^3)^{-1})}$$

$$= 0.243\ GPa$$

$$G^f_{xy,Laran} = \frac{12}{(0.0111125\ m)^3 (0.043\ (Pa.m^3)^{-1})}$$

$$= 0.203\ GPa$$

$$\nu^f_{xy} = -\frac{A_{12}}{A_{11}}$$

$$\nu^f_{xy,Bakau} = -\left[\frac{-8.558 \times 10^{-6} (Pa.m^3)^{-1}}{6.359 \times 10^{-4} (Pa.m^3)^{-1}}\right]$$

$$= 0.013$$

$$\nu^f_{xy,Merawan} = -\left[\frac{-6.602 \times 10^{-5}\ (Pa.m^3)^{-1}}{1.22 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.054$$

$$\nu^{f}_{xy,Laran} = -\left[\frac{-5.292 \times 10^{-6}\ (Pa.m^3)^{-1}}{1.118 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 4.733 \times 10^{-3}$$

$$\nu^{f}_{yx} = -\frac{A_{12}}{A_{22}}$$

$$\nu^{f}_{yx,Bakau} = -\left[\frac{-8.558 \times 10^{-6}\ (Pa.m^3)^{-1}}{1.526 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 5.608 \times 10^{-3}$$

$$\nu^{f}_{yx,Merawan} = -\left[\frac{-6.602 \times 10^{-5}\ (Pa.m^3)^{-1}}{2.684 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 0.025$$

$$\nu^{f}_{yx,Laran} = -\left[\frac{-5.292 \times 10^{-6}\ (Pa.m^3)^{-1}}{2.729 \times 10^{-3}\ (Pa.m^3)^{-1}}\right]$$

$$= 1.939 \times 10^{-3}$$

Table 4.5 Flexural engineering constants for 7-plies laminate

Type of woods	$\mathbf{E^{f}_{x}}$ **(GPa)**	$\mathbf{E^{f}_{y}}$ **(GPa)**	$\mathbf{G^{f}_{xy}}$ **(GPa)**	$\boldsymbol{\nu^{f}_{xy}}$	$\boldsymbol{\nu^{f}_{yx}}$
Bakau	13.752	5.730	0.547	0.0130	0.0056
Merawan	7.168	3.258	0.243	0.0540	0.0250
Laran	7.822	3.204	0.203	0.0047	0.0019

4.12 Wood selection

All of the results predicted for laminate 3 layers (see Table 4.6) and 7 layers (see Table 4.7) have been summarized. From results obtained, it can be concluded that Bakau is the best material to build the electric cruiser board. The reason it has been chosen because of the elastic properties of Bakau has significantly higher then followed by Laran, and Merawan respectively in flexural z-direction. The 7 layers of laminate results have shown improvement of flexural modulus significantly in direction of E_y.

Table 4.6 In-plane and flexural engineering constants of 3 layers laminate

Type of woods		E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}	ν_{yx}
Bakau	In-plane	12.902	6.582	0.534	0.012	0.00598
	Flexural	18.519	0.959	0.534	0.08	0.0042
Merawan	In-plane	6.753	3.671	0.242	0.046	0.026
	Flexural	9.475	0.928	0.239	0.19	0.0190
Laran	In- plane	7.336	3.692	0.203	0.004109	0.002068
	Flexural	10.572	0.463	0.204	0.033	0.0015

Table 4.7 In-plane and flexural engineering constants of 7 layers laminate

Type of woods		E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}	ν_{yx}
Bakau	In-plane	11.096	8.387	0.533	0.009197	0.006952
	Flexural	13.752	5.730	0.547	0.0130	0.0056
Merawan	In-plane	5.874	4.552	0.242	0.039	0.03
	Flexural	7.168	3.258	0.243	0.0540	0.0250
Laran	In- plane	6.293	4.734	0.203	0.003204	0.00241
	Flexural	7.822	3.204	0.203	0.0047	0.0019

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The elastic properties which determined before proves that Bakau is the best candidate to be proposed for development of electric cruiser board due to higher elastic properties especially in flexural modulus. The three layers of laminate exhibits significantly higher flexural modulus in E_x The additional lamina to 7 layers improved significantly of flexural modulus in E_y direction and slightly diminished modulus in E_x direction.

The flexural modulus which mentioned in a literature undertaken shows that the composite made by Bamboo comprises of six stacking plies possesses 10.821 GPa on E_x direction and 0.5 GPa on E_y direction. Therefore, others such as Merawan and Laran also can be considered suitable to be used since they are also stiff in both direction of E_x, and E_y in just by using 3 layers of laminate.

5.2 Recommendation

However, it is very recommended if the prediction data could be validated with experiment data of actual multilayer board. This would give understanding about the differences of this evaluation should be aware and therefore it will facilitate the prediction analysis in future. This study could be furthered to design the composite multilayer board by optimizing the elastic properties through mixing the other plies of the wood together to become a composite rather than using a one type of the wood to produce a composite. The theory can also be used to identify what would be the best orientation of each plies.

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