DETERMINATION OF STRUCTURAL PROPERTIES OF RED SERAYA PLYWOOD USING EUROCODES COMPLIANT TESTING METHOD

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ABSTRACT

Bending strength (MOR) and modulus of elasticity (MOE) are the primary criteria to evaluate the mechanical properties of structural plywood. Ever since structural plywood was introduced, numerous studies have been conducted on its mechanical properties. Most of these studies were conducted on temperate timber species, less focus has been given to tropical timber species. Red seraya (*Shorea spp*.) was chosen to be studied in depth because it is found in abundance in East Malaysia and has been one of the largest sawnwood species exported by Malaysia. To address this issue, a comprehensive study on the mechanical properties of red seraya structural plywood was carried out.

Using test specimens of 4 mm to 15 mm thickness, the MOR and MOE of red seraya structural plywood were compared with the published values of better known structural plywood species – birch (*Betula pendula*) and spruce (*Picea abies*). They were chosen because they are two of the most important species in structural plywood industries. Furthermore, destructive and non-destructive bending tests were conducted to assess the mechanical properties of red seraya structural plywood. The MOR and MOE obtained from the Eurocode standards, EN 310 three-point bending and EN 789 four-point bending test, were compared and correlations between their values were established. In addition, finite element (FE) analysis was carried out to predict the mechanical properties of red seraya structural plywood.

The test results determined from EN 789 showed that, red seraya plywood maximum MOR was 38% lower than birch plywood but was 39% higher than spruce plywood. Meantime, the maximum MOE of red seraya plywood was 25% lower than

birch plywood but about the same when compared to spruce plywood. In addition, it was found that the maximum MOR and MOE of red seraya plywood determined using EN 310 were respectively 24% higher and 42% lower compared to the results obtained from EN 789. The linear regressions developed in this study can be used to predict the MOR and MOE values between the test methods. It was found that the MOR and MOE of EN 789 had a moderately strong correlation with those obtained by EN 310.

Simple FE models were proposed to predict the MOR and MOE proportionately for EN 789 and EN 310. The MOR determined by FE model for EN 310 and EN 789 gave maximum values that were respectively 23% and 16% higher than the results obtained experimentally. Similarly, the MOE determined by FE model for EN 310 and EN 789 gave maximum values that were respectively 39% and 14% higher than those obtained experimentally. Correlations between FE analysis and experimental results were established to study the feasibility of using FE analysis to predict the mechanical properties of structural plywood. The FE analysis showed satisfactory agreement with the experimental results, especially for EN 789.

This research showed that red seraya structural plywood is comparable to spruce plywood but gave lower values when compared with birch plywood. In addition, the mechanical properties of red seraya structural plywood determined using EN 310 and EN 789 were significantly different.

ABSTRAK

Kekuatan lenturan (MOR) dan modulus kekenyalan (MOE) merupakan kriteria yang penting untuk menilai sifat-sifat mekanikal papan lapis struktur. Sejak papan lapis struktur diperkenalkan, pelbagai kajian telah dijalankan ke atas sifat mekanikalnya. Kebanyakan kajian tersebut dijalankan keatas species kayu dari kawasan iklim bermusim, fokus tidak banyak ditumpuhkan keatas kayu species dari kawasan tropika. Seraya merah (*Shorea spp*.) dipilih untuk kajian mendalam kerana ia didapati diabaikan di Malaysia Timur dan ia merupakan salah satu species yang paling banyak dieksport sebagai sawnwood oleh Malaysia. Untuk menangani isu ini, kajian yang komprehensif telah dijalankan untuk mengkaji sifat mekanikal papan lapis struktur spesies seraya merah.

Dengan menggunakan spesimen ketebalan 4 mm hingga 15 mm, MOR dan MOE papan lapis struktur seraya merah dibandingkan dengan nilai-nilai MOR and MOE daripada papan lapis struktur species birch (*Betula pendula*) dan spruce (*Picea abies*) diperolehi daripada terbitan jurnal. Birch dan spruce dipilih kerana mereka adalah species yang penting dalam industri papan lapis struktur. Ujian musnah dan tanpa musnah telah dijalankan untuk menilai sifat mekanikal papan lapis struktur seraya merah. MOR dan MOE yang diperolehi daripada ujian lenturan dari piawaian Eropah, EN 310 ‘three-point bending test’ dan EN 789 ‘four-point bending test’ telah dibandingkan dan nilai-nilai tersebut telah dikolerasi antara satu sama lain. Di samping itu, analisis simulasi unsur terhingga (FE) telah dijalankan untuk meramalkan MOR dan MOE untuk papan lapis struktur seraya merah.

Ujikaji ditentukan daripada EN 789 menunjukkan bahawa papan lapis struktur seraya merah mempunyai nilai maksimum MOR 38% lebih rendah daripada birch, tetapi 39% lebih tinggi daripada spruce. Di samping itu, MOE maksimum papan lapis struktur seraya merah adalah 25% lebih rendah daripada birch tetapi lebih kurang sama apabila dibandingkan dengan spruce. Di samping itu, kajian ini juga mendapati bahawa maksimum MOR dan MOE papan lapis struktur seraya merah yang ditentukan dengan EN 310 adalah masing-masing 24% lebih tinggi dan 42% lebih rendah berbanding dengan bacaan dari EN 789. Regresi linear yang diperolehi dalam kajian ini boleh digunakan untuk meramalkan nilai ujian lenturan dari skala kecil ke scala serderhana. Kajian ini mendapati bahawa MOR dan MOE yang diperolehi oleh EN 789 mempunyai hubungan yang sederhana kukuh dengan nilai yang diperolehi daripada EN 310.

Model FE yang ringkas telah dicadangkan untuk meramalkan MOR dan MOE masing-masing bagi EN 789 dan EN 310. MOR yang diramalkan oleh model FE untuk EN 310 dan EN 789 masing-masing memberi nilai maksimum 23% dan 16% lebih tinggi daripada bacaan yang diperolehi daripada eksperimen makmal. Sementara itu, MOE yang diramalkan oleh model FE untuk EN 310 dan EN 789 masing-masing memberi nilai maksimum 39% dan 14% lebih tinggi daripada bacaan yang diperolehi oleh eksperimen makmal. Korelasi antara FE dan experimen diterbitkan untuk mengkaji kemungkinan FE dalam meramalkan sifat mekanikal papan lapis struktur. Korelasi antara nilai FE dan nilai eksperimen makmal adalah baik, terutamanya EN 789.

Kajian ini mendapati bahawa papan lapis struktur species seraya merah adalah setanding dengan spruce tetapi memberi nilai lebih rendah apabila berbanding dengan birch. Sementara itu, sifat mekanikal papan lapis seraya merah yang ditentukan daripada EN 310 dan EN 789 adalah jelas berbeza.

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LIST OF SYMBOLS

Symbol	Description
A_e	Rectangular area
b	Width of the test piece (mm)
b_1, b_2	Length and width of density test specimen
C	12 x 12 matrix
c	The distance from the highly-stressed flanges of the beam to its neutral axis
D	Elasticity matrix
E_1	Elastic moduli along the longitudinal direction of fibers
E_2	Elastic moduli along the transverse direction of fibers
E_a	Apparent MOE from experiment
E_X	Young modulus in X-direction
E_Y	Young modulus in Y-direction
E_Z	Young modulus in Z-direction
ε	Strain
F	Load applied (N)
F_{max}	Maximum load (N)
G_{12}	Shear modulus in 1-2 plane
g/ft^2	gram/square feet
G	Shear modulus
G_{XY}	Shear modulus in X-Y plane
G_{YZ}	Shear modulus in Y-Z plane
G_{XZ}	Shear modulus in X-Z plane
H	Moisture content
I	Moment of inertia of test specimen, $\frac{bt^3}{12}$
i, j, k, l	Four nodal point of a rectangular element
k_s	Statistical factor
K	Shape factor $\frac{6}{5}$ for the rectangular cross section test specimen
k	Element stiffness
L	Span length of the test piece (mm)

l_1	Distance between the centers of two supports (mm)
l_2 , l_1	Length of the test piece
L	Shape function
M	Maximum bending moment
m_{xq}, m_{yq}	Moments in x-y direction
E	Modulus of elasticity
f_m	Bending Strength
mm	millimeter
m	Mass of the test piece
m_H	Initial mass of the test pieces
m_O	Mass of the test pieces after drying
n	Number of test results (panel means) of the sample
NU_{XY}	Poisson's ratio in X-Y plane
N/mm^2	Newton/millimetre square
P_q	External concentrated force
p	Surface-distributed load
Q	Element nodal force
q	Rectangular nodal element
R	Element nodal force
R^2	Correlation coefficient
$s_{\overline{x}}$	Standard deviation between panels mean
$s_{\ln \overline{x}}$	Standard deviation between panel means of a log-normal distributed property $\overline{x}_j$
t	Thickness of the test piece (mm)
T	Transpose of a matrix
t_m	The statistical factor
U	Deflection produced by load F (mm)
$U_{\max}$	Maximum displacement at mid-span
U	Strain energy
ν_{12}	Poisson's ratio for loading parallel to grain
ν_{21}	Poisson's ratio for loading perpendicular to grain
w_q	Nodal deflection
W_e	Deflection in matrix form e

χ	Curvature
$\bar{x}_{\mathrm{j}}$	Panel means
$\bar{\bar{x}}_{32}$	Mean values of 32 panels
$\bar{\bar{x}}_{12}$	The 12 panel means
α	Coefficient
σ	Stress
δ	Deflection
Ω_{e}	Potential of external forces
ρ	Density
Π_{e}	Potential energy
$\{\ \}$	Matrix of one column
$[\ ]$	Matrix of both a square and row matrices
0°	Parallel to grain test specimen
90°	Perpendicular to grain test specimen
	Grain direction of the first layer of plywood panel

LIST OF ABBREVIATIONS

Abbreviations	Descriptions
EN	Eurocodes
FE	Finite element
MC	moisture content
MOE	Modulus of elasticity
MOR	Bending Strength
MOE_{4P}	Modulus of elasticity of four-point bending
MOE_{3P}	Modulus of elasticity of three-point bending
COV%	Coefficient of variation

CHAPTER 1

INTRODUCTION

1.1 General Background

Structural plywood is a very important material suited to a large variety of permanent structural applications. These include roofs and wall sheathing, structural diaphragms, flooring, concrete formwork systems, box beam, I-beam, pallets, shelving, containers, transport equipment, structural ramps, overhead protective barriers, housing for tools and implements and runways. Structural plywood has traditionally been made from temperate wood species, such as birch, spruce, fir and pine. However, the current Wood Handbook (2010) lists had classifies a large number of tropical hardwoods that qualify for use according to their strength (Stark *et al*., 2010). The species used in this research, red seraya (*Shorea spp.*), is one of the hardwoods listed in the Wood Handbook as being suitable for use in structural applications. Red seraya is one of the major local Sabah hardwood species also known as light red meranti, which depicts 38% of total volume of Yayasan Sabah Concession Area (YSCA) (Yayasan Sabah, 2007). However, there is very little published information available and research done concerning the mechanical properties of red seraya structural plywood.

The wide range of uses for different types of structural plywood makes it crucial for their respective mechanical properties to be reliably analysed and documented. Among the mechanical properties most commonly characterized are the bending strength, measured as the modulus of rupture (MOR), and elastic deformation, measured as the modulus of elasticity (MOE) (Kretschmann, 2010). These mechanical properties of structural plywood are commonly measured and determined by various destructive and non-destructive tests.

Destructive tests, such as the bending, compression and tension tests are usually regulated by various testing standards and may vary in different regions or countries. What is critical is that the mechanical properties specified by designers in structural analysis should be reliable enough to meet the required mechanical characterization (Baldassino *et al*., 1998). Among the many destructive tests, bending tests are often undertaken because they are simple (Yoshihara & Tsunematsu, 2006). In European standards BS EN 13986:2004, there are two bending test methods that can be used to determine the mechanical properties of structural plywood, namely EN 310 (small-scale three-point bending test method) and EN 789 (medium-scale four-point bending test method). While EN 310 is the quality control standard commonly adopted by plywood manufacturers, the mechanical properties stipulated by this method cannot be used as design values. On the other hand, the EN 789 procedure may be used to evaluate the mechanical properties of plywood acceptable as design values. Although most of the international practices are based upon four-point bending for determination of characteristic properties for plywood, most of the manufacturers still prefer three-point bending due to its simplicity. The mechanical properties obtained using different testing methods are deemed to be equivalent for the same material. However, different test setups may influence the test results (Harrison, 2006). Hence, there is a need to rationalize the bias between these two methods in order to obtain reliable and precise mechanical property values for structural plywood.

Non-destructive tests, such as finite element analysis, transverse vibration test, ultrasonic wave techniques and other numerical calculation methods are less regulated practices. Nowadays, researchers combine the latest technology into strength properties analysis to obtain more precise, cost and time effective solutions. Probably the most rigorous approach to the mechanical behaviour of plywood is the finite element analysis approach (Francisco *et al*., 2008). This computer stimulation-based methodology helps save raw material, time and enhances the credibility of the product without substantial investment in testing facilities. Moreover, this is an important means to realize quality control, raise work productivity, and to reach full automation in quality control of wood-based composite materials (Hu, 2008).

1.2 Problem Statement

Previous studies (Khaidzir & Youngquist (1990), Govic & Khebibeche (1994), Karshenas & Feely (1996), Baldassino *et al.* (1998), Sretenovic *et al*. (2005), Sugimoto & Sasaki (2006), Kawasaki *et al*. (2006), Francisco *et al*. (2008) and Ayrilmis & Winandy (2007)) on structural plywood have provided information regarding the mechanical properties of different wood species. However, few studies have been carried out on the mechanical properties of red seraya structural plywood. New basic information on red seraya structural plywood can extend its range of applications in the timber industry. To the best of the author's knowledge:

i. Very little research has been devoted to the mechanical properties of red seraya structural plywood. Although Khaidzir (1990) had categorized red seraya as weakest strength group wood species that suitable for structural application, there are still lack of supporting data on strength and moduli published since then. Therefore most of the red seraya species still being produced as normal utility plywood or exported as raw logs or sawnwood. According to ITTO (2011), red seraya is the 5th major raw log species and one of the largest sawnwood species exported by Malaysia in year 2010. Realizing this fact, there is a need to obtain reliable and consistent strength data for red seraya in order to upgrade its commercial value.

ii. Limited research has been conducted to verify the difference between the test method EN 310 and EN 789 using the same batch of red seraya structural plywood. An effective regression/correlation between these two methods has not been developed to predict the MOR and MOE of structural plywood. Such a regression/correlation is needed so that researchers can predict the results of small-scale tests to medium-scale tests. This would also reduce the time and cost incurred in research and testing.

iii. Most standard tests for strength properties are destructive in nature and they consume time and cost. The most rigorous technology that can be applied to analyse the mechanical behaviour of plywood is finite element analysis. This approach has been used to solve many specific problems in timber design. However, it has not been applied to analyse the mechanical properties of red seraya structural plywood of different thickness and ply constructions.

1.3 Objectives

The objectives of the research are to:

i. Compare the MOR and MOE of red seraya structural plywood with published values for spruce and birch structural plywood. Spruce and birch were chosen because they are two of the most important raw material in European structural plywood industries (Handbook of Finnish Plywood, 2002).

ii. Compare the MOR and MOE of red seraya structural plywood using the European Standards BS EN 310 and BS EN 789. Correlation equations will be developed to compare these two standards.

iii. Simulate the MOR and MOE of red seraya structural plywood using ABAQUS, a finite element analysis program, and to compare the results obtained from the experimental method and the finite element analysis.

1.4 Scope of Work

Red seraya species plywood with different thickness (4mm (3 plies), 7mm (5 plies), 9mm (7 plies), 12mm (9 plies) and 15mm (11 plies)) will be fabricated and tested under the European Standard bending test, EN 789 (four-point bending test). The results will be compared to birch and spruce structural plywood published in Handbook of Finnish Plywood (2002). After the comparison, the same batch of plywood panels will be tested under EN 310 (three-point bending test). Results of EN 789 and EN 310 will be compared to further study the mechanical properties of red seraya plywood under different test setup. Finite element analysis model for both EN 789 and EN 310 were simulated. The finite element results will then compared to those obtained from experimental bending test.

1.5 Thesis Overview

The thesis is divided into seven chapters and each of these chapters describes the different component of the research.

Chapter 1 consists of general background and brief explanation of the current research, research objectives, scope of work and overview of the content in current research. This will help readers to understand the basic ideas and fundamental areas of the research.

Chapter 2 gives general introductions to structural plywood including their background, manufacturing process, review of past experimental studies and classification of structural plywood. The mechanical properties of red seraya, birch and spruce species are also discussed in this chapter in order to give readers a brief comparison of mechanical properties among these wood species.

Chapter 3 is about the basic concept of MOR and MOE of plywood including the factors that affecting the mechanical properties of plywood. The test method to obtain the MOR and MOE of plywood is also included in this chapter. A general comparison among three-point bending test and four-point bending test was also discussed in this chapter.

In chapter 4, the explanation of basic concepts of finite element method is presented. This chapter also included researches that have been done for wood using finite element method. Simple basic concept of finite element theory was also included in this chapter.

Chapter 5 consists of research concepts, preparing the experimental material and also experimental set up for current research.

Chapter 6 contains the results obtained from the experiments and calculations. Furthermore, discussion of the results is also included in this chapter.

In chapter 7, conclusions have been made based on the results obtained. Discussion and some recommendations for future studies are also presented.

CHAPTER 2

STRUCTURAL PLYWOOD

2.1 Introduction

Plywood is one of the earliest wood composite materials to be widely used. Plywood is a flat panel built up of sheets of veneer called plies or layers, bonded under pressure by a bonding agent or adhesive to create a panel. Plywood was first issued and patented by John K. Mayo from New York City in year 1865. However, it was not developed into a business until year 1907 when plywood developers started to install the automatic glue spreader and sectional hand press. Although plywood industries in year 1929 once reached a production capacity of 358 million square feet within 17 mills in Pacific Northwest, it was not promoted for structural use. The lack of a waterproof adhesive that would transform plywood into exterior exposure and structural grade eventually led consumers to switch to other alternatives. In 1934, a breakthrough came when Dr. James Nevin, a chemist in the Harbor Plywood Corporation in the United States (USA), invented a fully waterproof adhesive. This advanced technology opened up a significant new market for structural grade plywood (www.apawood.org).

2.2 Manufacturing Process of Structural Plywood

The manufacturing process of structural plywood consists of nine main processes. Generally, the manufacturing process of structural plywood is similar to plywood. The differences between structural plywood and normal plywood are that special wood species, grade of veneer, thickness of board and adhesive bond are required (EWPAA, 2008). Figure 2.1 below provides a general process flow diagram for structural plywood manufacturing.

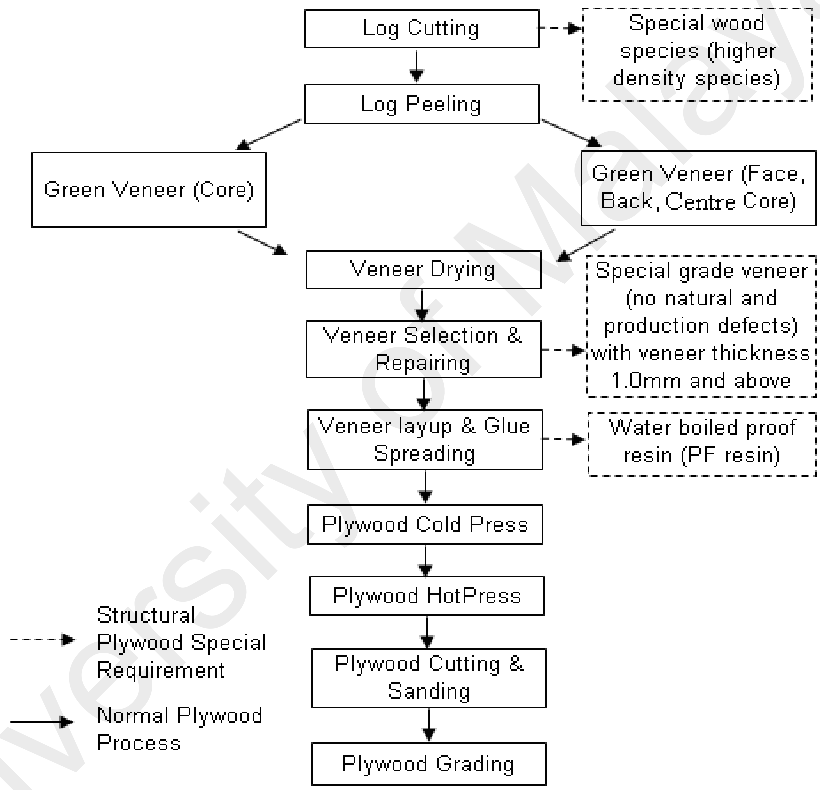


Figure 2.1: General process flows for structural plywood manufacturing.

The logs are cut into appropriate lengths before the debarking process. The debarking step is accomplished by feeding logs through one of several types of debarking machines or in a conventional way by using manpower. The purpose of this operation is to remove the outer bark of the tree without damaging the wood. After the bark is removed, the logs are then peeled into veneers using a lathe machine. The veneers that have longitudinal wood grain direction namely are referred to as face, back or centre core veneer while the transverse wood grain direction namely core veneer.

Veneers are taken to a veneer dryer where they are dried to moisture contents that range from around 6% to 15%, dry basis. The moisture content always depends on the type of resin used in the gluing process. The normal drying temperature ranges from 150° C to 200° C (300° F to 400° F). The veneers must be cooled to prevent glue from curing on the veneers during the glue spreading operations. This is to ensure the good bonding quality of the plywood (EPA, 2002).

After the drying process, they are conveyed for layup operation, where thermosetting resin is spread on the veneers. A permanent water boiled proof resin known as phenol formaldehyde (PF) resin is always used to bond the veneer for structural plywood. This distinctly dark colour resin is durable and permanent under full weather exposure conditions, long-term stress and a combination of exposure and stress. The resin is applied by glue spreaders, curtain coaters, or spray systems. The laid-up assembly of veneers is then sent to a hot press in which it is consolidated under heat and pressure. Hot pressing has two main objectives: (i) to press the glue into a thin layer over each sheet of veneer; and (ii) to activate the thermosetting resins. The plywood is then taken to a finishing process where the edges are trimmed; the face and back may or may not be sanded smooth. Lastly, the plywood will be sent for the grading process (EPA, 2002).

2.3 Review of Past Experimental Studies on Structural Plywood

A number of investigations on the mechanical properties of structural plywood have been conducted by researchers in recent decades. Little published information is available concerning the bending test for red seraya structural plywood. In this session, an overview on the mechanical properties of structural plywood fabricated with various wood species is presented.

Some of the early research was conducted by Khaidzir & Youngquist (1990) in which twenty-two Malaysian hardwood species were categorized into two major structural groups called Structural I and Structural II based on their specific gravity (Table 2.1). Group Structural II was further divided into two groups, namely, Structural IIA and Structural IIB. Keruing (*Dipterocarpus spp*.), kedondong (*Canarium spp*.) and light red meranti (*Shorea spp*.) were chosen to represent each of the groups.

Table 2.1: Categorization of Malaysian Timber Species by Specific Gravity and Ranking by Modulus of Elasticity (Khaidzir & Youngquist, 1990)

STRUCTURAL I
(S.G 0.55-0.75)

	MOE N/mm^2
Kasai (Pometia spp.)	2,200
Simpoh (Dillenia grandiflora)	2,080
Balau, Red (Shorea spp.)	1,990
Gerutu (Parashorea spp.)	1,920
Kapur (Dryobalanops spp.)	1,910
Keruing (Dipterocarpus spp.)	1,480

STRUCTURAL II
(S.G 0.40-0.59)

IIA	MOE N/mm^2	IIB	MOE N/mm^2
Merawan (Hopea spp.)	2180	Melunak (Pentace triptera)	1530
Mengkulang (Heritiera spp.)	1990	Meranti, Yellow (Shorea spp.)	1520
Mempisang (Monocarpia marginalis)	1880	Kungkur (Pithecellobium confertum)	1510
Meranti, White (Shorea spp.)	1840	Meranti, Dark Red (Shorea spp.)	1470
Bintangor (Calophyllum spp.)	1750	Nyatoh (Palaquim)	1420*
Melantai (Shorea macroptera)	1640	Meranti, Light Red (Shorea spp.)	1350*
Kedundong (Canarium spp.)	1600	Mersawa (Anisoptera spp.)	1340
		Durian (Durio oxyleyanus)	1250*
		Machang (Mangifera)	970

* Limited to species having specific gravity (S.G) of 0.41

These three species were tested for their strength properties using 4.80 mm (3 ply) plywood. Four mechanical tests of bending, compression, tension and panel shear were conducted according to the American Society for Testing and Material (ASTM) method. The results show that keruing and light red meranti plywood produced from Malaysian hardwoods are comparable in strength to plywood from the United States, Canada and Scandinavia.

Govic & Khebibeche (1994) performed the tension and compression test using five types of structural plywood consisting of okoume-poplar; okoume; poplar; pine-okoume or maritime pine; and pine. The modulus and strength for the five types of plywood were studied based on ISO/DIS 8982 to EN TC 124.102, a standard submitted to public inquiry under reference EN 789.

Karshenas & Feely (1996) carried out the pure-moment large panels bending test in ASTM D3043-87 using structural grade used plywood sampling from a construction project site. The test was conducted to determine the bending stiffness and interlaminar shear strength of the samples. Baldassino *et al.* (1998) tested the structural poplar plywood using bending, compression, tension, panel shear and planar shear tests in accordance with EN 789. The experimental results of poplar plywood demonstrated the potential for this type of veneered product in structural applications. Sretenovic *et al*. (2005) tested the structural plywood – 15 Norway spruce (*Picea abies*) and birch (*Betula sp.*) - of total thickness 20.5 mm to assess the interlaminar shear strength by using five-point bending test and shear test according to EN 789. Additionally, the linear elastic finite element analysis of both test set-ups was also performed to visualize the distribution of shear stress.

Sugimoto & Sasaki (2006) studied the fatigue behaviour of Russian larch (Larix sibirica Ledebour) made structural plywood tested according to ASTM D2719 (2005) ‘‘Method C: Two Rail Shear Test’’. At the same time, Kawasaki *et al*. (2006) also investigated the optimum design values of Japanese larch (*Larix gmelini Gordon*) structural plywood. The MOE with and without shear effect (E_L, E_0) and shear modulus (G_b) were evaluated using four-point bending test. They also investigated the bending stiffness in relation to weight for fixed core densities.

Francisco *et al*. (2008) conducted the European standards (EN 789 and EN 1058) bending test to assess the mechanical properties and characteristic values of radiata pine plywood for structural use. Eight different compositions of panels with thicknesses from 9 mm to 30 mm were tested. Their mechanical properties were compared to spruce plywood manufactured from Europe. Ayrilmis & Winandy (2007) tested the hardwood structural plywood commercially manufactured by rotary cut veneer of akaba (*Tetraberlinia bifoliolata*) logs. The akaba structural plywood was evaluated using two ASTM D2718 test methodologies: the plate-shear method and the five-point flexural shear method.

2.4 Classification of Structural Plywood

Structural plywood is also known as construction application plywood. Structural plywood is specially designed for engineered applications such as structural components and residential construction (NIST, 2007). In addition, the structural plywood sheets also show broad use in transport, material handling applications and other specialist industries. This composite has been welcomed by the construction industry for a number of reasons including:

(i) high strength and stiffness to weight ratio

(ii) high puncture resistance

(iii) resistance to impact and short-term overload

(iv) improved dimensional stability under changes in moisture content

(v) two-way strength and stiffness

(vi) easy repair

As some of the structural components may have to withstand weather exposure, long-term stress, and combinations of exposure and stress, it must be durable and permanent. Therefore, it is common that special species, grade of veneer, thickness of board and adhesive bond are required in order to achieve the high quality of structural plywood (EWPAA, 2008).

The selection of wood species is an important criterion in manufacturing structural plywood. Many factors are involved in the selection of particular wood species in structural plywood, but from the solely structural view, it is the grade stresses that became the prime importance. For some applications, it may be necessary to specify particular species (or exclude them) from within a strength class to take account of particular characteristics, e.g., natural durability, amenability to preservatives, ability of glues and fasteners (BS 5268-2, 2002). Thus, to provide guidance concerning the strength for the designer, wood species are normally classified into several strength classes according to different international standards. The classification of timber species that are suitable for structural plywood, as given in BS 5268-2 according to the US Voluntary Product Standard (NIST, 2007), are listed in Table 2.2.

Table 2.2: Classification of Timber Species for Structural Plywood in BS 5268-2

Group 1	Group 2
apitong [a,b]	cedar, Port Orford
beech, American	cypress
birch	Douglas fir No. 2 [c]
sweet	fir
yellow	balsam fir
Douglas fir No. 1 [c]	California red
kapur [a]	grand
keruing [a,b]	noble
larch, western	pacific silver
maple, sugar	white
pine	hemlock, western
Caribbean	lauan
ocote	almon
pine, southern	bagtikan
loblolly	mayapis
longleaf	red lauan
shortleaf	tangile
slash	white lauan
tanoak	maple, black
	mengkulang [a]
	meranti, red [a,d]
	mersawa [a]
	pine
	pond
	red
	Virginia
	western white
	spruce
	black
	red
	Sitka
	sweet gum
	tamarack
	yellow poplar

[a] Each of these names represents a trade group of woods consisting of a number of closely related species.

[b] Red meranti is limited to species having a relative density of 0.41 or more based on green volume and oven dry mass.

Table 2.3: Strength group of Malaysian Timber in MS 544: Part 2: 2001

S.G.1	S.G.2	S.G.3	S.G.4	S.G.5	S.G.6	S.G.7
A) Naturally Durable						
Balau	Belian	Bekak	Giam	Teak		
Bitis	Mata ulat	Delek	Malabera	Tembusu		
Chengal	Kekatong	Keranji	Merbau			
Penaga			Resak			
B) Requiring Treatment						
	Dedaru	Agoho	Berangan	Alan bunga	Bayur	Ara
	Kempas	Balau, red	Dedali	Babai	Damar minyak	Batai
	Merbau	Kelat	Derum	Balek angin bopeng	Durian	Geronggang
	Mertas	Kembang semangkok	Kapur	Bintangor	Jelutong	Laran
		Kulim	Kasai	Brazil nut	Jenitri	Pelajau
		Pauh Kijang	Keruntum	Gerutu	Jongkong	Pulai
		Penyau	Mempening	Kayu kundur	Kasah	Sesendok
		Perah	Meransi	Kedondong	Machang	Terentang
		Petaling	Meranti bakau	Keledang	Medang	
		Ranggu	Merawan	Keruing	Melantai/Kawang	
		Durian batu	Merpauh	Ketapang	Meranti, light red	
		Tualang	Nyalin	Kungkur	Meranti, yellow	
			Perupok	Melunak	Mersawa	
			Punah	Mempisang	Terap	
			Rengas	Mengkulang		
			Simpoh	Meranti, dark red		
				Meranti, white		
				Nyatoh		
				Penarahan		
				Petai		
				Ramin		
				Rubberwood		
				Sengkuang		
				Sepetir		

Notes:
1. For naturally durable timbers, sapwood should be excluded. If sapwood is included, preservative treatment is necessary. (Source: MS360, 1986)
2. For timber requiring treatment, they should be amenable to preservative treatment

The BS 5268-2 standard classified birch in the strongest group of strength classes and spruce in the lower group of strength classes. Red seraya has been included in the red meranti group (*Shorea spp*.); its strength class is the same as spruce. At the same time, Malaysian Standard MS 544 had classified red seraya in strength group 6 (S.G. 6) (Table 2.3). MS 544: Part 4: 2001 had details at the procedure in determining the properties of structural plywood made from Malaysian timber species. The classification of the wood species list in BS 5268-2 is in accordance with ASTM D2555, where solid wood is used to obtain the strength classes. The strength grouping of MS 544 was also based upon small clear wood specimen. However, according to Francisco *et al*. (2008), the mechanical properties of solid timber could be used to estimate the properties of plywood, but would give lower values of veneer properties. Thus, there is a need to obtain more reliable and precise strength properties for red seraya plywood in order to promulgate red seraya species as structural wood based panel material in addition to the better-known temperate structural application wood species, such as birch and spruce. Moreover, it is common that the mechanical properties of wood species always determine the economic value and application of plywood panels. However, most of the consumers still prefer to use well-known species rather than less renowned wood species even when their prices are lower and their mechanical properties are competitive to the better-known species.

2.5 Mechanical Properties of Red Seraya

Red seraya wood species is one of the major wood species in Sabah plywood production. Red seraya plywood is known for being light in weight and easy to work with nails, adhesives and various kinds of finishing. Its easy to dry characteristic without distortion makes it suitable to form plywood without checking. The strength properties of red seraya vary due to the difference in density and species. The mean density of red seraya may vary from 385 kg/m^3 to 755 kg/m^3. The Forest Research Institute Malaysia (FRIM) has categorized the static bending strength and modulus of elasticity of red seraya in the range of 63 N/mm^2 to 83 N/mm^2 and 8400 N/mm^2 to 13600 N/mm^2, respectively. Red seraya plywood is generally used in interior and exterior panelling, furniture, boxes and crates, flooring and general construction, moulding and millworks (Wiemann, 2010). To illustrate the mechanical properties of red seraya, the MOR and MOE that have been conducted on red seraya are summarized in Table 2.4.

Table 2.4: Mechanical properties of red seraya

MOE (N/mm^2)	MOR (N/mm^2)	References
8400 – 13600	63.0 – 83.0	FRIM Malaysia[a]
8500	65.5	Kretschmann (2010)
13620	86.0	Tropix 6.0 Database[b]

[a] http://timbertech.frim.gov.my/TimberSpeciesDb2.aspx?IDTIMBER=29&tes=0
[b] http://tropix.cirad.fr/asia/asia.html

2.6 Mechanical Properties of Birch

Birch (*Betula pendula*) is known as the most important wood species in European countries. According to the Handbook of Finnish Plywood (2002), the popularity of birch plywood in European countries is explained by its excellent strength, stiffness and resistance to creep. Its high planar shear strength and impact resistance has made birch plywood very suitable for heavy-duty floor and wall structures. In addition, birch plywood also has excellent weather and moisture resistance and surface hardness, which provides resistance to damage and wear. The smooth surface of birch plywood after the sanding process makes its pleasant, light-colour visual appearance suit almost all types of finishing.

Birch plywood is mostly applied in concrete formwork systems, floors subjected to heavy wear, walls and roofs in buildings, container floors, scaffolding materials, shelves, load bearing special structures, traffic signs, furniture and die boards (Handbook of Finnish Plywood, 2002). To illustrate the mechanical properties of birch wood, some of the research on the MOR and MOE that has been conducted on birch is summarized in Table 2.5. In order to compare with the current research, the bending characteristic strength (MOR) and mean modulus of elasticity (MOE) of birch structural plywood from the Handbook of Finnish Plywood (2002), which were tested in accordance with EN 789 are tabulated in Table 2.6.

Table 2.5: Mechanical properties of birch

MOE (N/mm^2)	MOR (N/mm^2)	References
14100 – 15400	98.6 – 110.9	Jalava (1945)
8500 - 14000	93.1 – 132.3	Dunham *et al.* (1999)
7800-19900	69.8 – 156.6	Herajarvi (2004)
14500 – 16500	76.0 – 155.0	www.matbase.com[a]

[a] http://www.matbase.com/material/wood/class4-5-10-years/birch/properties

Table 2.6: MOR and MOE for birch from Handbook of Finnish Plywood (2002)

Nominal Thickness t	Plies	t mean Value	Birch MOE (N/mm^2)		Birch MOR (N/mm^2)	
mm		mm	0°	90°	0°	90°
4.0	3	3.6	16471	1029	65.9	10.6
6.5	5	6.4	12737	4763	50.9	29.0
9.0	7	9.2	11395	6105	45.6	32.1
12.0	9	12.0	10719	6781	42.9	33.2
15.0	11	14.8	10316	7184	41.3	33.8

2.7 Mechanical Properties of Spruce

Norway spruce (*Picea abies*) is the third most important wood species in European countries. According to the Handbook of Finnish Plywood, spruce plywood is well known because of its less dense surface compared to birch. Spruce plywood has a prominent grain structure as well as a larger number of knots. Due to the low weight of spruce plywood, it is easier to work and nail. The strength and stiffness properties of spruce plywood are good enough and its dimensional changes in respect of moisture variation are minimal.

Normally, the end uses of spruce plywood include floors, walls and roofs in house construction, wind bracing panels, vehicle internal body work, packaging material, fencing and temporary works. Due to the wide applications of spruce, many studies on the mechanical characteristics of spruce have been carried out over the years (Handbook of Finnish Plywood, 2002). To illustrate the mechanical properties of spruce, the research on the MOR and MOE that has been conducted on spruce is summarized in Table 2.7. In order to compare with the current research, the MOR and MOE of spruce structural plywood from the Handbook of Finnish Plywood, which were tested under EN 789 are tabulated in Table 2.8.

Table 2.7: Mechanical properties of spruce

MOE (N/mm^2)	MOR (N/mm^2)	References
10600	42.0	Larsson *et al.*(1998)
10600 -13200	43.1 – 51.6	Chrestin (2000)
5500 – 15800	13.0 – 79.0	Solli (2000)
-	30.5 – 33.6	Ranta-Maunus (2001)
11900	78.0	Tropix 6.0 Database[a]

[a] http://tropix.cirad.fr/asia/asia.html

Table 2.8: MOR and MOE for spruce from Handbook of Finnish Plywood (2002)

Nominal Thickness t	Plies	t mean Value	Spruce			
			MOE (N/mm^2)		MOR (N/mm^2)	
mm		mm	0°	90°	0°	90°
4.0	3	3.6	12235	765	37.6	6.0
6.5	5	6.4	9462	3538	29.1	16.6
9.0	7	9.2	8465	4535	26.0	18.3
12.0	9	12.0	7963	5037	24.5	19.0
15.0	11	14.8	7663	5337	23.6	19.3

CHAPTER 3

MECHANICAL PROPERTIES OF STRUCTURAL PLYWOOD

3.1 Introduction

The mechanical properties of plywood include its ability to withstand the applied forces. The applied forces tend to deform the plywood in any manner. Owing to the wide application of plywood, it is necessary to determine the mechanical properties of plywood in order to use it to its best advantage and effectiveness. Normally, the mechanical properties are obtained through laboratory experimentation. The study of the mechanical properties of plywood concerns the behaviour between stresses and strains, and the factors affecting this behaviour (Samuel, 1914).

Stress is a measure of the internal forces exerted in a material as a result of the application of an external force (Winandy & Rowell, 2005). An external force is always balanced by the internal stresses when the body is in equilibrium. If an adequate external force is applied, the original shape and size will be changed. This distortion or deformation of the material is known as strain (Samuel, 1941). The stress is always directly proportional to strain under the linear elastic limit, as depicted in Figure 3.1. This elastic theory brings forth one of the most significant engineering properties of a material, the modulus of elasticity. This theory is known as Hooke's law:

$$E = \frac{\sigma}{\varepsilon} \tag{3.1}$$

Where,

E = modulus of elasticity (N/mm^2)

σ = stress (N/mm^2)

ε = strain

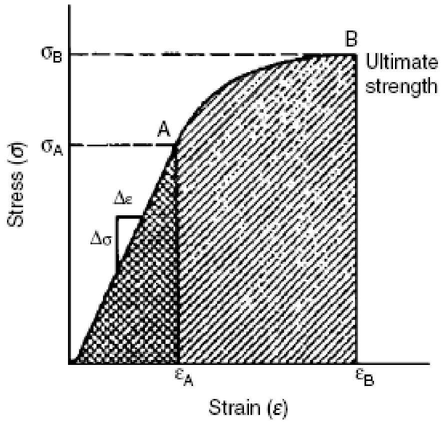


Figure 3.1: The relationship between stress-strain diagram (Winandy & Rowell, 2005).

3.2 Mechanical Properties of Plywood

The evaluation of the mechanical properties of wood has to be properly conducted in laboratory experiments. This is because the mechanical properties of wood do not have a constant value due to the complexity of wood structures even though the exact test is repeated with no error. The most that can be achieved is to find average values, the upper and lower limit values, and the laws that govern the variation (Samuel, 1914). The bending strength (MOR) and modulus of elasticity (MOE) are the primary criteria to evaluate the mechanical properties of structural plywood.

3.2.1 Bending Strength (MOR)

The MOR is the maximum load required to cause a wood beam to fail in bending (Winandy & Rowell, 2005). The MOR is derived by using the flexure formula:

$$f_m = \frac{Mc}{I} \tag{3.2}$$

Where,

f_m = MOR (N/mm^2)

M = maximum bending moment

c = the distance from the highly-stressed flanges of the beam to its neutral axis

I = the moment of inertia, which relates the bending moment to the geometric shape of the beam

From the formula, it is obvious that the geometric shape, bending moment and thickness can affect the MOR. Although MOR is not a true stress because the computed formula for stress is only valid to the elastic limit, MOR is an accepted criterion of strength (Kretschmann, 2010). In the European standard, the strength classes for MOR are classified in accordance with BS 12369-2:2004 and tested in accordance with EN 789 and calculated in accordance with EN 1058. Table 3.1 shows the classes of characteristic bending strength in BS 12369-2:2004. Characteristic bending strength is related to the population 5th percentile values obtained from the test results.

Table 3.1 Characteristic bending strength values MOR for a series of strength classes for plywood complying with EN 636 (EN 636, 2003)

Class	Minimum value $f_{m,k}$ characteristic bending strength (N/mm^2)
F 3	3
F 5	5
F 10	10
F 15	15
F 20	20
F 25	25
F 30	30
F 40	40
F 50	50
F 60	60
F 70	70
F 80	80

3.2.2 Modulus of Elasticity (MOE)

Elasticity is the ability of a material to recover completely after deformation once the cause of the stress is removed. When a higher stress is exerted, plastic deformation or failure occurs. There are three moduli of elasticity in wood, denoted by E_L, E_R and E_T in accordance with the longitudinal, radial and tangential axes of wood.

The formula for MOE for plywood from Samuel (1914) is:

$$MOE = \frac{Fl^3}{4Ubt^3} \tag{3.3}$$

Where,

MOE = modulus of elasticity (N/mm^2)

F = load at or below elastic limit (N)

l = span length of the test piece (mm)

U = deflection produced by load F (mm)

b = width of the test piece (mm)

t = thickness of the test piece (mm)

The MOE includes the effect of shear deflection; eliminating this effect can increase the modulus of elasticity by 10% (Kretschmann, 2010). Table 3.2 shows the classes of mean MOE in BS 12369-2:2004.

Table 3.2: Mean bending modulus values MOE for a series of modulus classes for plywood complying with EN 636 (EN636, 2003)

Class	Minimum value $E_{m, mean}$ mean bending modulus (N/mm^2)
E 5	500
E 10	1 000
E 15	1 500
E 20	2 000
E 25	2 500
E 30	3 000
E 40	4 000
E 50	5 000
E 60	6 000
E 70	7 000
E 80	8 000
E 90	9 000
E 100	10 000
E 120	12 000
E 140	14 000

3.3 Factors that Affect the Mechanical Properties of Plywood

A numbers of studies have found that the MOR and MOE in the bending of plywood are affected by many factors, such as tree species, tree quality, specific gravity, wood moisture, wood density, wood structure, temperature, number of plies, adhesive and penetration, permanent load, fatigue and joint strength.

3.3.1 Moisture Content

Wood is a hygroscopic material and exchanges its moisture content with air; the amount and direction of the exchange (gain or loss) depend on the relative humidity and temperature of the air and the current amount of water in the wood. This moisture relationship has an important influence on wood properties and performance (Aydin *et al*., 2006).

Hrazsky & Kral (2005) reported that the moisture content of veneers in the production of plywood panels ranges between 4% and 10%. The moisture content of wood and wood-based materials up to the fibre saturation point is directly influences the strength and elastic properties of the product. The properties do not change any more above the point. With the moisture range from 8% to 18%, the properties of wood and plywood sheets change linearly. With the moisture change by 1% (at a range of 5%–30%) the MOR is changed by 4% and MOE by 1%. Winandy & Rowell (2005) also found similar characteristics for the change in MOR 4% and MOE 2% with a moisture change of 1%.

Aydin *et al*. (2006) found that most of the mechanical properties are affected by the changes in moisture content below the fibre saturation point. Generally, most mechanical properties increase as wood is dried. Although most properties continue to increase while wood is dried to very low moisture content levels, some properties for most wood species may reach a maximum value and then decrease with further drying.

3.3.2 Density

Hrazsky & Kral (2005) and Francisco *et al*. (2008) concluded that the MOE and MOR in bending increased as density increased. Hrazsky & Kral (2005) found that the relationship is expressed linearly. The relationship between the density and the mechanical properties of wood is more complex. This is because wood strength very much depends on its density and anatomical structure. The effects of density are most apparent in dry wood but are insignificant above the hygroscopic point.

Francisco *et al.* (2008) also found that the linear regression between characteristic values parallel to the grain and density of radiata pine structural plywood for bending strength shows a coefficient of 0.596. This shows that there is certain dependency of characteristic values to the source material and there is a need to increase the number of sampling test pieces.

3.3.3 Thickness

Hrazsky & Kral (2006) related the density of a plywood sheet to the thickness of plywood sheet. The density of plywood sheet increases with the decreasing of thickness of plywood sheet. The MOE in bending in transverse specimens grows with the increasing thickness of plywood (i.e., with increasing veneer thickness in plywood). In longitudinal specimens, the MOE in bending decreases with the increasing thickness of plywood.

Francisco *et al*. (2008) concluded that strength values increase as the thickness of panel increases. The bending strength shows this trend more clearly. The difference between the characteristic values of bending strength parallel and perpendicular to the grain decreased with the increasing thickness of the panel, as could be expected. Francisco *et al*. (2008) show that the relationship between thickness and ratio MOR 0°/ MOR 90° gives a coefficient of determination of 0.98.

3.3.4 Grain Direction

The construction of a veneer with the grain direction of adjacent layers oriented perpendicular to each other results in plywood panels with dimensional stability across their width and a similarity of strength and stiffness properties in perpendicular directions within the panel plane. It also evenly distributes the defects and improves resistance to checking.

Hrazsky & Kral (2005) demonstrated that the relationships of bending strength or MOE show a reversible character for test specimens, parallel and perpendicular to face grain direction. The trend shows that there is an increase in bending strength or MOE in bending for perpendicular face grain direction test specimens while there is a decrease for parallel face grain direction test specimens with the increasing thickness of plywood. This is caused by the construction of the layup of the plywood.

Baldassino *et al.* (1998) found that the mechanical behaviour of the panels examined is influenced by their layup. The research found that the parallel test specimens of 12 mm and 24 mm plywood panel show a reduced contribution to the mechanical behaviour compared to the perpendicular test specimens, fibre layers, while the 18 mm layup shows the opposite behaviour. This indicates that the strength of parallel to grain direction of the 18 mm plywood is higher than the perpendicular to grain direction. The data also reveal that there is a certain variability of results and no significant behaviour was identified, whether within a group of tests or within the same test. This is partly due to the different layup of the panels tested and the different mechanical response of a notoriously heterogeneous material like wood.

3.3.5 Anatomical Structure

Hrazsky & Kral (2005) and Francisco *et al*. (2008) stated that the mechanical properties of plywood fabricated from different tree species having different mechanical properties. Gungor *et al*. (2007) proved that plywood with different thicknesses and the minor differences in strength properties of plywood are the result of the anatomical properties of the different species used in the plywood manufacturing process.

As stress is applied to a wooden member, minute cracks initiate, propagate, and terminate throughout the collective cellular system in all directions. In the tangential direction, the concentric ring structure of softwoods, and porous vessels and fibers in hardwoods act as the elements of elastic stress transfer. In the same time, the ray structures and the linear arrangement of fibers and vessels in the radial direction are the elements of elastic stress transfer. In the radial direction, every cell is aligned closely to each other as they are originated from the same cambial mother cell. Thus, the material can transfer stress elastically until an induced crack or a natural growth defect interrupts this orderly cellular arrangement (Winandy & Rowell, 2005). This elastic transfer mechanism can simply affect by the variation of wood species as anatomical structure is different among wood species. As a result, the mechanical properties of wood are influence by the anatomical structure of wood.

3.3.6 Size of Test Specimen

Samuel (1914) reported that the mechanical properties of plywood are always governed by the size of the test specimen. In larger test specimens, it tends to be more difficult to eliminate the influence of moisture content on the mechanical properties. Furthermore, it is difficult to ensure the homogeneity within the test specimen. However, larger test specimens tend to be less influenced by inherent factors, such as knots, decay and wormholes. For example, the effect of a knot of a given size is more serious in a small test specimen than a larger one. On the other hand, it is easier to control the moisture content in small test specimens. Moreover, the selection of clear and straight-grained test specimens, which means a better grade small test specimen, is easier compared to larger size test specimens. Nevertheless, the mechanical properties of larger test specimens are considered necessary for architects and designers.

3.4 Test Methods for MOR and MOE Determination

Many tests have been developed to evaluate the mechanical properties of structural plywood. However, bending tests are often chosen to measure the MOE and MOR of structural plywood due to their simplicity. Several major standards can be used to determine the bending test - American Society for Testing and Materials (ASTM), Japanese Industrial Standard (JIS), British Standard (BS) and International Organization for Standardization (ISO).

Most of these test standards are standardized based on the elementary beam theory in which the deflection caused by bending moment is taken into account and the additional shear deflection and other factors are ignored. Besides the difference in test standards, the difference in bending test methods in each test standard - three-point, four-point or five-point bending test – could provide varying results for the mechanical properties of wood. The extreme difference of each bending test method in test setup and test conditions results in the mechanical properties obtained not being comparable with each other (Yoshihara & Nakano, 2006). Thus, it is important to reveal the differences between the mechanical properties obtained by different test methods (Yoshihara & Nakano, 2011).

3.4.1 EN 789 Four-point Bending Test

The EN 789 four-point bending is a two-point loading flexure test, as shown in Figure 3.2. The EN 789 four-point bending test in the BS standard is currently a more reliable test method in determining the mechanical properties of plywood. This is because the deflection due to shear is ignored in this bending test and the evaluation of deformation is in the zero shear force area. However, it requires a larger test specimen and more powerful testing machine in order to carry out the test.

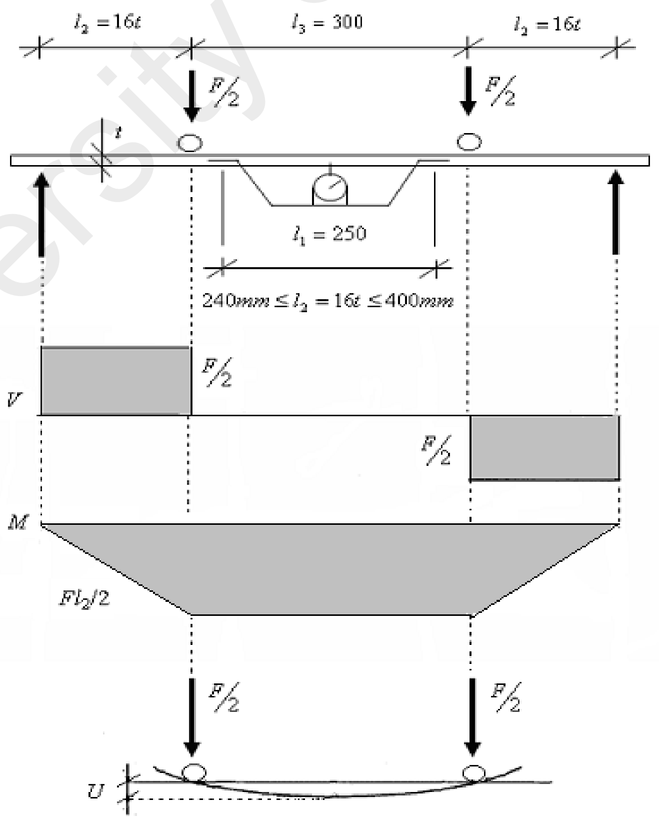


Figure 3.2: EN 789 four-point bending test setup, shear force (*V*) and bending moment (*M*) diagram, measurement of deflection (*U*).

The equations used to calculate the MOR and MOE are as follows:

$$MOR = \frac{3F_{\max} l_2}{bt^2} \tag{3.4}$$

$$MOE = \frac{l_1^{\,2} l_2 (F_2 - F_1)}{16I(u_2 - u_1)} \tag{3.5}$$

Where,

MOR = bending strength (N/mm^2)

MOE = modulus of elasticity (N/mm^2)

b = width of the test pieces (mm)

t = thickness of the test pieces (mm)

l_2 , l_1 = length of the test piece as depicted in Fig 3.2 (mm)

$F_{\max}$ = maximum load (N)

I $= \frac{bt^3}{12}$, moment of inertia of test specimen (mm^4)

$F_2 - F_1$ = the increment of load on the straight line portion of the load-deflection curve, where F_1 shall be approximately 10% and F_2 shall be approximately 40% of the maximum load $F_{\max}$(N)

$u_2 - u_1$ = the increment of deflection corresponding to ($F_2 - F_1$) (mm)

3.4.2 EN 310 Three-point Bending

The EN 310 three-point bending is a centre point loading flexure test, as shown in Figure 3.3. The EN 310 bending test is a more convenient test method that only requires small plywood samples and a simple universal tensile bending test machine. According to the Handbook of Finnish plywood (2002), this method results in higher MOR and lower MOE values and is only suitable for quality control purposes, and, therefore, should not be used as a basis for any design data. The MOE obtained from the three-point bending test is the apparent MOE where the deflection due to both bending and shear are included in its calculation. The true MOE differs from the apparent MOE because true MOE ignores deflection due to shear (Harrison, 2006).

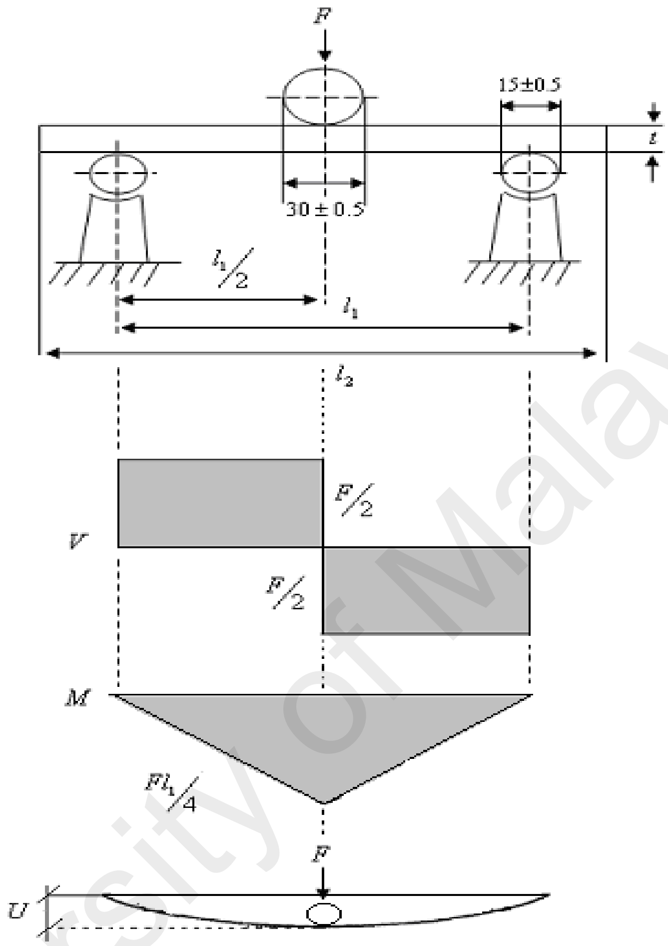


Figure 3.3: EN 310 three-point bending test setup, shear force (*V*) and bending moment (*M*) diagram, measurement of deflection (*U*).

The equations used to calculate the MOR and MOE are as follows:

$$MOR = \frac{3F_{\max} l_1}{2bt^2} \tag{3.6}$$

$$MOE = \frac{l_1^3 (F_2 - F_1)}{48I(u_2 - u_1)} \tag{3.7}$$

Where,

MOR = bending strength (N/mm^2)

MOE = modulus of elasticity (N/mm^2)

l_1 = distance between the centres of two supports (mm)

b = width of the test pieces (mm)

t = thickness of the test pieces (mm)

F_{max} = maximum load (N)

I = $\frac{bt^3}{12}$, moment of inertia of test specimen (mm^4)

$F_2 - F_1$ = the increment of load on the straight line portion of the load-deflection curve where F_1 shall approximately 10% and F_2 shall be approximately 40% of the maximum load F_{max}, (N)

$u_2 - u_1$ = the increment of the deflection at the mid-length of the test piece, which is proportional to ($F_2 - F_1$), (mm)

3.5 Review of Past Studies on the Three-point and Four-point Bending Tests

A few researchers have shown that there are differences between the results of the three-point and four-point bending tests in which the results are affected by other factors. The review of past experimental studies that focus on the three-point and four-point bending tests will be summarized. Although the method and material used by some of the researchers is not identical to the current research, it has been included for comparative purposes.

McNatt (1984) conducted the four-point and three-point bending test to study the MOR and MOE of eight different structural panel products including veneered composite panels (strand core and particle core as centre core), oriented strandboard, wafer-boards, and flakeboards. Four different large panel sizes were tested using four-point bending whereas three-inch wide small panel size were tested using three-point bending, as given in ASTM D1037. The objective of the studies was to assess the effect of panel size on the bending properties and variability of test values. The results found that the MOE values determined from the four-point loading averaged 10% to 20% higher than those obtained from three-point loading. In contrast, the MOR determined from the four-point loading was as much as 29% lower than that determined from the three-point loading. The study also suggested that large-panel bending tests should be used when developing design stresses for some structural-use panels.

McNatt *et al.* (1990) carried out four different test methods to assess the mechanical properties of commercial plywood, oriented strandboard, and waferboard manufactured in Canada and the United States. The machine stress rating, pure-moment bending (ASTM D3043 - 1987) of 1220 mm by 1220 mm panels, third-point loading (RILEM/CIB - 1981) of 300 mm by 1000 mm panels, and mid-span loading (ASTM D1037 – 1987) of 76 mm by 24 times thickness small specimens were conducted to determine the MOR and MOE of each test method. The results show that the mid-span loading of small specimens yielded lower MOE but higher MOR values compared to the larger panel tests. Besides that, linear regression was used to correlate between the test methods. The relationship between third-point loading and mid-span loading obtained from linear regression line is shown as the equation below:

$$MOR_Y = 0.66MOR_x + 281 \ (R^2 = 0.93) \tag{3.8}$$

$$MOE_Y = 1.41MOE_x + 83 \ (R^2 = 0.99) \tag{3.9}$$

Where,

MOE_x = modulus elasticity of mid-span loading (N/mm^2)

MOE_Y = modulus elasticity of third-point loading (N/mm^2)

MOR_x = bending strength of mid-span loading (N/mm^2)

MOR_Y = bending strength of third-point loading (N/mm^2)

Theobald *et al.* (1997) carried out a study on the variation of bending properties for composite materials using the three-point and four-point bending test. Theobald *et al.* (1997) found that the MOR varied in a significant manner when the load span varied. The results indicated that the MOR of composite laminates is directly dependent on the load span. The MOR decreases as the span increased. When the load span reached the maximum value for the span-to-depth ratio 40:1, the excessive bending and slippage came into play resulting in a significant reduction in flexural strength. However, the MOE is independent of the load and support span. The MOE was only slightly different from other span-to-depth ratios and is not significant. The variation of the MOE was most likely due to the test specimen experiencing excessive deformation and slipping on the roller support.

Brancheriau *et al.* (2002) reported that a three-point bending test of wooden samples had underestimated the MOE value by about 19% in relation to the four-point bending. This difference could be directly caused by the density or by other wood anatomical differences between the species tested. In addition, Brancheriau *et al.* (2002) also included supports and loading head indentation as other factors that influence the MOE between three-point and four-point bending.

Mujika (2006) observed that the flexural moduli of carbon/epoxy composite material obtained by three-point and four-point bending tests are different for the same specimen. In addition, Mujika (2006) also investigated the effect of various support span and load spans of the specimen using the classical beam theory. He reported that without taking into account the shear effects, the MOE obtained by four-point bending test overestimated by more than 5% for the same specimen tested by the three-point bending test. He concluded that this overestimation is due to the bending rotation at supports and loading nose, which is much greater in four-point bending than in three-point bending. However, the MOE does not depend on material properties or load span used but depends on the thickness of the specimen and on the radius of supports and loading nose.

Tuherm & Zudrags (2006) carried out a study of the characteristic bending properties of birch plywood using the EN 310 and EN 789 test method. Tuherm & Zudrags (2006) correlated the results between EN 310 and EN 789. Figures 3.4 and 3.5 tabulated the correlations between EN 310 and EN 789 for both parallel and perpendicular grain direction. From the experimental results, it was found that the MOR for EN 789 is 0.8 times and 0.7 times that of EN 310 for respectively parallel and perpendicular to the grain test specimens. In addition, the MOE for EN 789 is 1.3 times and 1.2 times, respectively. The difference in test results is due to the difference in the size of the test pieces, loading schema and calculation of results. Meanwhile, they also found that the correlation of results for samples with perpendicular grain direction is weaker than the parallel grain direction. They explained that this could be due to the high variance of the test results. Although they correlated with both EN 789 and EN 310, the suitability of the correlation equations applying to other wood species remains unknown.

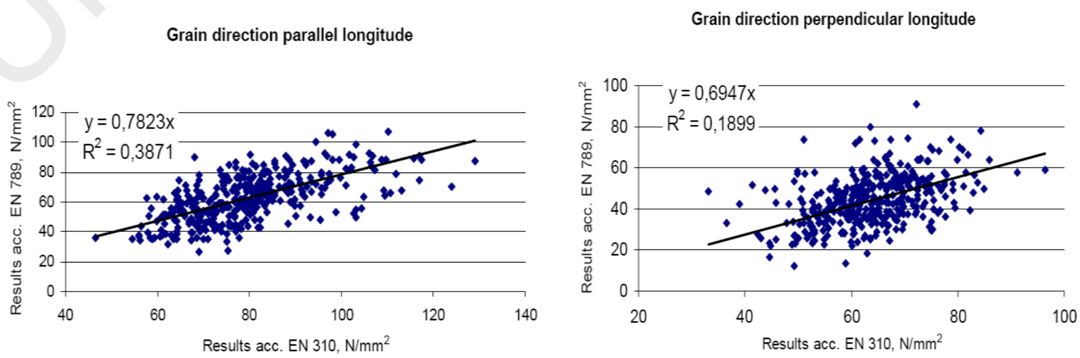


Figure 3.4: Linear regression of MOR between EN 789 and EN 310 for parallel (0°) and perpendicular (90°) to grain (Tuherm & Zudrags, 2006).

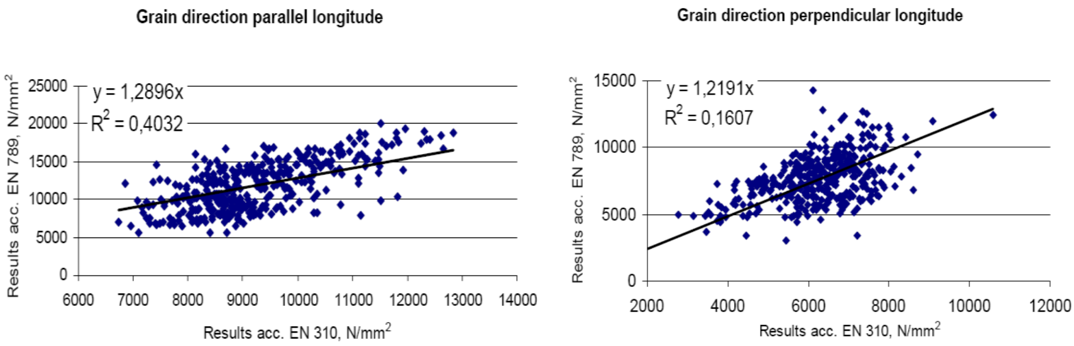


Figure 3.5: Linear regression of MOE between EN 789 and EN 310 for parallel (0°) and perpendicular (90°) to grain (Tuherm & Zudrags, 2006).

Yoshihara & Tsunematsu (2006) reported that the span/depth ratio under the four-point bending test is recommended to be larger than 20 in orders to obtain the proper bending properties using the elementary bending theory. They also stated that the slenderness of a beam should be enough to reduce the influence of additional deflection. The slenderness is often evaluated by the span/depth ratio where the span/depth ratio is defined as the value of the span length per depth of beam. It is reported that the MOE of the three-point bending test with span/depth ratio under range is about 10% smaller than the actual value.

Buchelt & Wagenfuhr (2008) studied the mechanical properties of beech and European oak veneer parallel and perpendicular to the grain direction. They reported that the bending properties of the veneers depend on the bending stiffness, mechanical strength and structure of the material. They also noted that the three-point bending test procedure is not suitable to determine the MOR.

Yoshihara & Nakano (2011) also carried out the four-point bending test with a span 45 times of the thickness and the three-point bending test with a span 20 times of the thickness. They reported that the MOR of the three-point bending for plywood is usually larger than four-point bending due to the difference in the evaluation point of the span. They also found that the MOR for three-point bending is 8% and 20% larger than the four-point bending for parallel and perpendicular to the grain test samples, respectively. In the three-point bending test, the MOR is evaluated pointwise at the mid-span, whereas the MOR is evaluated at the weakest point between the loading nose in the four-point bending test (Adams *et al.*, 2003). Therefore, the MOR obtained by the three-point bending test is usually larger than those obtained by the four-point bending test. From the experimental results, it proves that the three-point bending had a MOE of 33% and 41% less than the four-point bending for the parallel and perpendicular grain test specimens, respectively.

Nandanwar *et al.* (2011) investigated the effect of loading methods of the three-point and four-point bending test on the MOR and MOE of plywood and bamboo mat board. The results showed that the MOR had increased 6%-10% whereas the MOE had reduced 3%-6% for plywood, when tested under the four-point bending test compared to the three-point bending test. Nandanwar *et al.* (2011) correlated the three-point bending test with the four-point bending test for both parallel and perpendicular grain direction plywood specimens, as tabulated in Figures 3.6 and 3.7. From the linear regression correlation, both the MOR and MOE of the four-point bending were approximately equal to the three-point bending.

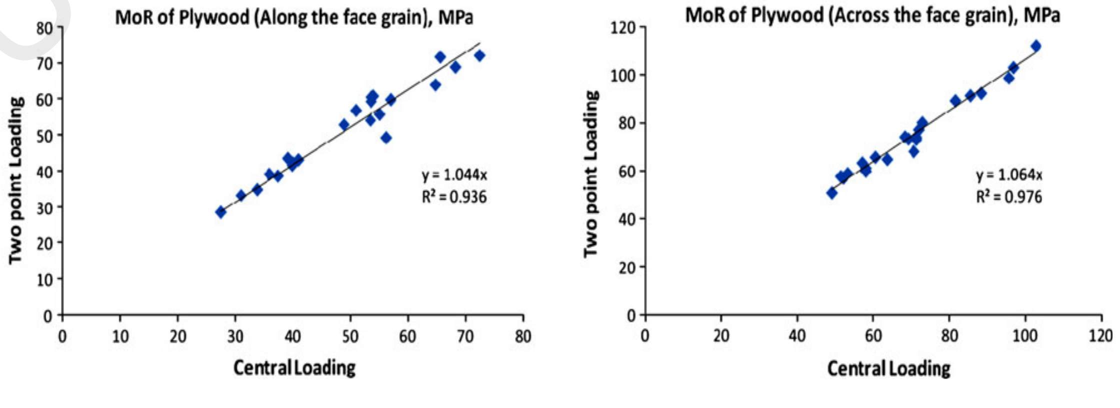


Figure 3.6: Linear regression of MOR between two point loading and central point loading for parallel (0°) and perpendicular (90°) to grain (Nandanwar *et al.*, 2011).

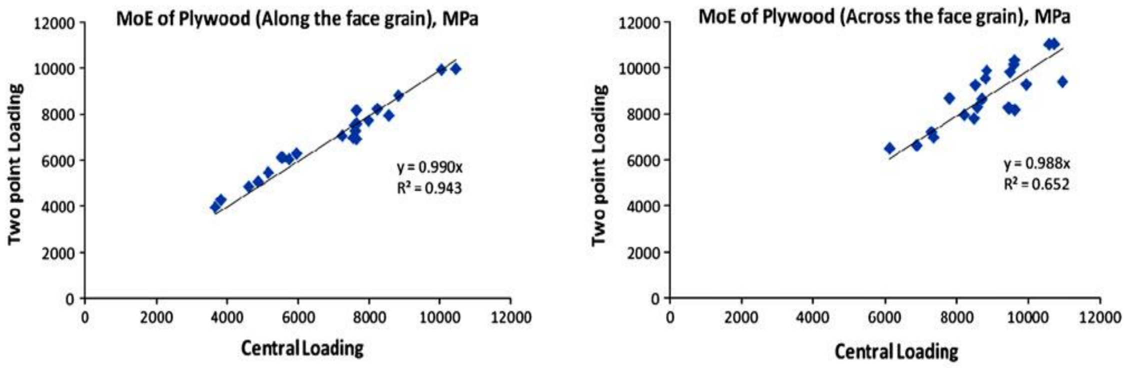


Figure 3.7: Linear regression of MOE between two point loading and central point loading for parallel (0°) and perpendicular (90°) to grain (Nandanwar *et al*., 2011).

Fernandez *et al*. (2011) studied the mechanical properties of structural plywood using the bending test and artificial neural network. The MOR and MOE were determined through EN 789 medium-sized test pieces and EN 310 small-size test pieces. The artificial neural network predictive model was used to predict the complex relations between board thickness, moisture content, specific gravity, bending strength, modulus of elasticity of small-sized test pieces and medium-sized test pieces. This model linearly relates the mechanical properties obtained by testing with small test pieces to the mechanical properties of medium-sized test pieces. The results found that the neural network is a very useful and easy model for production control in relating the structural bending properties to other physical and mechanical properties of structural application plywood.

CHAPTER 4

FINITE ELEMENT METHOD

4.1 Introduction

The conventional method to study the mechanical properties of wood is by the bending, compression and tension testing method. In recent years, researchers have used numerous non-destructive approaches to study the mechanical properties of wood. Among these, finite element method (FEM) is one of the most widely adopted methods to study the mechanical properties of wood. The application of the FEM in laminate wood composites, such as plywood, still require deeper understanding and research in order to apply it in practice.

4.2 Finite Element Method in Wood and Wood Composites

Mackerle (2005) summarized a total of 300 articles containing papers and conference proceedings published between year 1995 and 2004 on the subject of FEM's application to the analysis of wood. The bibliographical review summarized topics relating to the analysis of wood and wood composites using FEM and also describes the application of FEM on the analysis of different types of wood product and its structure. The FEM has been used to solve problems concerning wood as a construction material in respect of its material and mechanical properties, wood joining and fastening, fracture mechanics problems, drying process and thermal properties. In general, FEM has been used:

i. to analyse tension, compression, shear and the stress-strain relationship of wood;
ii. to analyse softwoods and hardwoods crack propagation;
iii. to analyse shear strength of wood;
iv. to predict fracture mechanics of glulam beams for different loads;

v. in crack predictions for different combinations of load;

vi. in interlaminar fracture by energy approach;

vii. in actual stresses in structural members/structures and checked against the allowable stresses;

viii. in structures/infrastructures using structural wood subjected to static or dynamic loads;

ix. in studying the behaviour of wood under static or quasi-static loads is used for example in trusses, buildings, bridges;

x. to study the impact loading of wood used in roadside safety structures;

xi. to study the failure of structural glulam joist due to splitting parallel to the timber grain;

xii. to study the static and dynamic loadings of wood frame structures;

xiii. to predict the static and dynamic response of wood-based floor structures with and without lateral reinforcements;

xiv. to study the load-sharing properties of wood-joist floor systems subjected to a concentrated load;

xv. to study the shear and flexural deflection of joisted oriented strand board (OSB) floor panels with edge support, subjected to concentrated load;

xvi. to predict the dynamic displacement of wood bridges that subjected to traffic and wind loading;

and

xvii. to predict the Young's modulus and shear modulus of free-free flexural vibration tests and three-point static bending tests with different depth/span ratios.

Maki (1968) developed an orthotropic model for wood and plywood. Two types of finite element techniques, framework method and stiffness element method were studied to examine each of the methods and determine their capability in handling problems in orthotropic plane stress and plate analysis problems. The maximum deflection obtained by plate analysis was close to but slightly lower than that obtained from mathematical calculation. He found that these methods have merit, especially when large systems of equations are utilized.

Masuda & Maku (1970) studied the mechanical characteristics of plywood using an orthotropic shallow shell. The objective of this paper is to address the applications of finite difference methods to the problems of layered orthotropic shallow shells. The influence of the curvature, shape of the shell, ratio of the side lengths, modulus of elasticity, direction of the elastic principal axis and the type of load applied were analysed. Solutions with good approximate accuracy are obtained.

Tohgo *et al*. (2001) applied the finite element method in order to analyse the ply-cracking damage and stress/strain distribution of the structures made of 90° and 0° cross-ply laminate composites. The FEM shows that the transverse cracking damage in 90° plies extends widely on the ligament of the plate and the splitting damage in 0° from the edge of the hole plies extends in the longitudinal direction.

Constant *et al*., (2003) also modelled a FEM numerical model that was used to predict the warping of plywood panels from the intraveneer properties. The response of intraveneer to moisture content changes is presented and compared with experimental measurements. At panel conditions of 17% moisture content (MC), the shape of the plywood was measured, then at the fibre saturation point, in order to calculate the maximum displacements along six profiles (three longitudinal and three tangential) on each panel. The results of the simulation ‘‘heterogeneous’’ and ‘‘homogeneous’’ model were compared with the experimental data. The results of the ‘‘heterogeneous’’ model show underestimated results while the ‘‘homogeneous’’ model was much less accurate in the longitudinal direction but was satisfactory in the tangential direction.

Moses & Prion (2004) carried out research using the FE model to predict the brittle failure of structural wood composites. This paper proposes a material model that is based on orthotropic elasticity and anisotropic plasticity for non-linear behaviour under the compression test. The Weibull weakest link theory was used to predict the brittle failure. This model is implemented using finite element analysis for two sample cases: the notched shear block specimen and a single-bolt connection specimen. The results of the FE model are compared against laboratory test results and provide detailed information concerning load displacement, ultimate strength and mode of failure. The proposed new material model for wood composites was shown to perform well for the two sample cases as mentioned.

Sretenovic *et al.* (2005) assessed the interlaminar shear strength of spruce plywood and oriented strand board (OSB) using a five-point bending test and shear test according to EN 789. A linear elastic FEM of both test set-ups was performed to visualize the distribution of shear stresses. Higher shear strength for plywood compared to OSB was observed in the experiments. It was concluded that the bias in the measured apparent shear strength of plywood according to the five-point bending test is due to the differences in the structure of OSB and plywood. The apparent shear strength values determined by the five-point bending tests are not only dependent on the span to thickness ratio but also on the composite structure. Thus, EN 789 is recommended for interlaminar shear testing of wood composites.

Baere *et al.* (2007) studied the different bending set-ups for thin composite laminates. He concluded that the mid-span displacement of the three-point bending test was influenced by the friction of the sliding movement between the specimen and the outer roller supports as well as the bending stiffness of the specimen. It was recommended that the roller support in three-point bending test be modelled correctly in order to capture the accurate bending force and displacement. As discussed by Baere *et al.* (2007), the four-point bending setup has an advantage when it comes to modeling as the area between the two loading nose has a constant bending moment. However, it was found that low bending stiffness specimens lead to large displacement in mid-span.

A new method was developed by Nagai *et al*. (2009) for detecting localized defects of wood, such as edge knots using a bending deflection curve. A FE model of the beams including defects as simplified knot structure was performed and the results between the bending experiment and FE analysis were compared. Comparison between the bending experiment and FE analysis shows that due to the reductions of cross sectional and local grain distortions, the characteristic variations in the bending deflection curves always depends on the position of the encased knots and the direction of spike knots.

Further research was carried out by Yoshihara (2009) on the dynamic and static square-plate twist and beam flexure tests using various size specimens of 5-ply Lauan wood in order to obtain measurements of the edgewise shear modulus of this representative plywood material. FE simulations were performed and the validity of the measurement methods was examined. The experimental and numerical analyses reveal that the dynamic beam flexure test method is the most reliable method available for measuring the edgewise shear modulus of this material.

Kljak *et al.* (2009) also highlight the application of the FEM to investigate the influence of plywood grain direction on the bending properties of a sandwich panel and also the stress distribution in each layer. The bending properties of a sandwich panel were determined by the three-point bending method and the stress in each layer was determined by using the FEM. The research results show that the grain direction has a great influence on the bending properties of the sandwich panel and stress values in each layer. The results also indicate the importance of analysing the stress in each layer of the plywood that can avoid stress concentration in particular layers and to optimize structural applications of the sandwich panel in construction.

4.3 Basic Theory

The derivations of generalized displacements and the corresponding forces at the nodal points as shown in Figure 4.1 is based on the classical (Kirchhoff's) plate bending theory from Ventsel & Krauthammer (2001). There are few assumptions are made in order to simplify the model. The thickness of the lamina is assumed to be small compared to its other dimensions and the bonding between layer and layer are perfect adhesion. Besides that, plane sections remain plane after the deformation and the laminate are linear elastic. Consider a flat rectangular, the geometrical position of a rectangular FE model is determined by four nodal *i, j, k, l* as show in Figure 4.1. At each nodal q (q= *i, j, k, l*), the possible nodal deflection w_q and two rotations $\left(\frac{\partial w}{\partial y}\right)_q$ and $\left(\frac{\partial w}{\partial x}\right)_q$ are referred as nodal displacements.

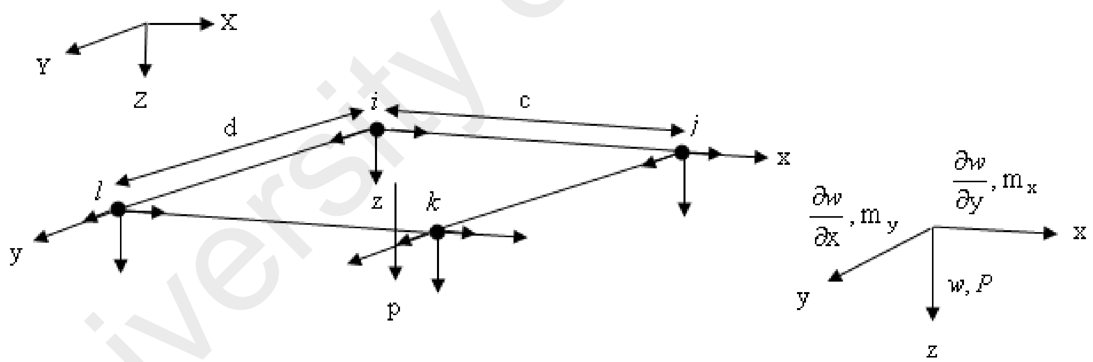


Figure 4.1 Rectangular finite elements with dimension c and d (Ventsel & Krauthammer, 2001).

Assumed nodal point q subjected to surface-distributed load p(x,y), external concentrated force P_q and moments m_{xq} and m_{yq}. A 12 degrees of freedom, *w*, $\frac{\partial w}{\partial y}$ and $\frac{\partial w}{\partial x}$ at each of the four nodal points *i, j, k, l* of the above mention element is selected. The polynomial selected is:

$$w(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 x^2 + \alpha_5 y^2 + \alpha_6 xy + \alpha_7 x^2 y + \alpha_8 xy^2 + \alpha_9 x^3 + \alpha_{10} y^3 + \alpha_{11} x^3 y + \alpha_{12} xy^3 \quad (4.1)$$

Assumed the above polynomial approximating the deflection field over the FE designated by *e* in the matrix form as follows,

$$w_e = [N]\{\alpha\} \quad (4.2)$$

Where,

$w_e =$ deflection in matrix form *e*

[N] = [1, x, y, x^2,y^2, xy, x^2y, xy^2, x^3, y^3, x^3y, xy^3]

$\{\alpha\} = [\alpha_1, \alpha_2, ..., \alpha_{12}]^T$

The superscript *T* represents the transpose of a matrix. The element displacement matrix was introduced as follows,

$$\{\delta\}_e = [\delta_i, \delta_j, \delta_k, \delta_l]^T \quad (4.3)$$

Where,

$\{\delta_i\} = [w_i, (\partial w/\partial y)_i, (\partial w/\partial x)_i]^T \quad ; \quad \{\delta_j\} = [w_j, (\partial w/\partial y)_j, (\partial w/\partial x)_j]^T \quad ; etc.$

The nodal displacements w_q, $\left(\frac{\partial w}{\partial y}\right)_q$ and $\left(\frac{\partial w}{\partial x}\right)_q$ in the local coordinate system *x*,*y* and *z* then can be written as follows,

$$\{\delta\}_e = [C]\{\alpha\} \quad (4.4)$$

Where,

C = 12 x 12 matrix depend on x-y coordinates of nodal points.

$\{\alpha\} = [\alpha_1, \alpha_2, ..., \alpha_{12}]^T$

The unknown constants then can be written as,

$$\{\alpha\} = [C]^{-1}\{\delta\}_e \quad (4.5)$$

Upon substitution of $\{\alpha\}$ from formula 4.5 above into formula 4.2, the deflection over the FE designated can be written as,

$$w_e = [L]\{\delta\}_e \tag{4.6}$$

Where,

$[L] = [N][C]^{-1}$

The strain-displacement relationship in FE can be express as follows,

$$\{\varepsilon\}_e = z\{\chi\}_e \tag{4.7}$$

Where,

$\{\varepsilon\}_e = [\varepsilon_x, \varepsilon_y, \gamma_{xy}]^T$ is the strain matrix

$\{\chi\}_e = [\chi_x, \chi_y, 2\gamma_{xy}]^T$ is the curvature matrix

The matrix $\{\chi\}_e$ can represent in terms of deflections as follows,

$$\{\chi\}_e = [-(\partial w/\partial x^2), -(\partial^2 w/\partial y^2), -2(\partial^2 w/\partial x \partial y)]^T \tag{4.8}$$

Substituting formula 4.6 into 4.8, the curvature matrix can be express as follows,

$$\{\chi\}_e = [B]\{\delta\}_e \tag{4.9}$$

Where,

[B] $= \left[[B]_i, [B]_j, [B]_k, [B]_l \right]$

$$[B]_i = \left[-\frac{\partial^2 [L]_i}{\partial x^2}, -\frac{\partial^2 [L]_i}{\partial y^2}, -2\frac{\partial^2 [L]_i}{\partial x \partial y} \right]^T$$

$$[B]_j = \left[-\frac{\partial^2 [L]_j}{\partial x^2}, -\frac{\partial^2 [L]_j}{\partial y^2}, -2\frac{\partial^2 [L]_j}{\partial x \partial y} \right]^T$$; etc.

The stress resultants and stress couples relationship in the matrix form is as follows,

$$\{M\}_e = \begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = D \begin{bmatrix} \frac{E_1}{1-\upsilon_{12}\upsilon_{21}} & \frac{E_1\upsilon_{21}}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ \frac{E_2\upsilon_{12}}{1-\upsilon_{12}\upsilon_{21}} & \frac{E_2}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \chi_x \\ \chi_y \\ 2\chi_{xy} \end{Bmatrix} \tag{4.10}$$

Or symbolically as follows,

$$\{M\}_e = [D]\{\chi\}_e \tag{4.11}$$

Where,

$[D]$ is the elasticity matrix of wood veneer.

The stress-strain now can be written as,

$$\{\sigma\}_e = z[D^*]\{\chi\}_e \tag{4.12}$$

It is necessary to define the set of discrete nodal forces corresponding to prescribed nodal degrees, it can be written as follows,

$$\{R\}_e = [R_i, R_j, R_k, R_l]^T \tag{4.13}$$

Where,

$\{R_q\} = [P_q, M_{xq}, M_{yq}]^T;\ q = i,\ j,\ k,\ l$

To derive the element stiffness matrix, $[k]_e$ and element nodal force matrix $\{R\}_e$, the strain energy in the element can be written as

$$U_e = \frac{1}{2}\iint_{Ae} [x]_e^T \{M\}_e dA_e \tag{4.14}$$

Substituting formula 4.9 and 4.11 to formula 4.14 above,

$$U = \frac{1}{2}\{\delta\}_e^T [k]_e \{\delta\}_e \tag{4.15}$$

The potential of external forces, Ω_e, acting upon the element is,

$$\Omega_e = \underbrace{-\{\delta\}_e^T\{R\}_e}_{discrete\ nodal\ force} - \underbrace{\iint_{Ae} pwdA_{Ae}}_{distributed\ load\ p(x,y)} \tag{4.16}$$

Where,

A_e = rectangular area c x d

Substituting formula 4.6 to formula 4.16 above,

$$\Omega_e = -\{\delta\}_e^T \{R\}_e - \iint_{Ae} p[L]\{\delta\}_e \, dA_e \tag{4.17}$$

Since potential external forces is a scalar quantity, formula 4.17 above can be written in the form

$$\Omega_e = -\{\delta\}_e^T \{Q\}_e \tag{4.18}$$

Where,

$$\{Q\}_e = \{R\}_e + \iint_{Ae} p[L]^T dA_e$$

is element nodal force matrix.

The total potential energy associated with the element is

$$\Pi_e = U_e + \Omega_e \tag{4.19}$$

Substituting formula 4.15 and 4.18 into formula above,

$$\Pi_e = \frac{1}{2}\{\delta\}_e^T [k]_e \{\delta\}_e - \{\delta\}_e^T \{Q\}_e \tag{4.20}$$

Applied the principle of minimum potential energy to formula 4.20 above,

$$\frac{\partial \Pi_e}{\partial \{\delta\}_e} = 0 \text{ or } \frac{\partial \Pi_e}{\partial \{\delta_q\}} = 0 \quad ; q = i, j, k, l \tag{4.21}$$

If the operation prescribed above performed and arrange terms, the following expression that related nodal displacements and corresponding nodal forces is expressed as follows,

$$[k]_e \{\delta\}_e = \{Q\}_e \tag{4.22}$$

4.4 Modelling of Finite Element Method

There are three categories of shell in the ABAQUS library, consisting of general-purpose, thin, and thick shell elements. The thin shell elements provide solutions that satisfy the classical Kirchoff shell theory; thick shell elements provide a solution for structures that describe the Mindlin shell theory; and general-purpose shell elements can provide solutions to both thin and thick shell problems. In general, the use of shell elements in modelling structures is when one dimension (thickness) is significantly smaller than the other dimensions. This means that the stresses in the thickness direction are negligible (ABAQUS Finite Element User Manual, 2007). In the ABAQUS FEM program, the shell elements assume that the plane sections perpendicular to the plane remain plane after deformation. The S4R shell was selected in this study. The linear, finite-membrane-strain, reduced-integration, quadrilateral shell element (S4R) was selected in this study because this shell type is robust and is suitable for a wide range of applications. Moreover, this shell is suitable for laminated composite shell models to account for the influence of shear flexibility (ABAQUS Finite Element User Manual, 2007).

CHAPTER 5

METHODOLOGY

5.1 Material

The red seraya species tree from Borneo tropical rainforest was cut into eight log sections each. The length of each section was around 2.50 m. The logs were peeled using a rotary lathe machine into two types of veneer – face veneer and core veneer, as shown in Figure 5.1. The thickness of the both face veneer and core veneer was 1.40 mm, width was 1200mm and length was 2400mm. All the veneers were dried at the mill using a continuous dryer for the parallel to the grain veneer and roller dryer for the perpendicular to the grain veneer. The moisture content for all the veneers was control at approximately (8 ± 2)%. Then, the veneers were laid up in cross-laminated construction with face plies parallel to the grain as shown in Figure 5.2.

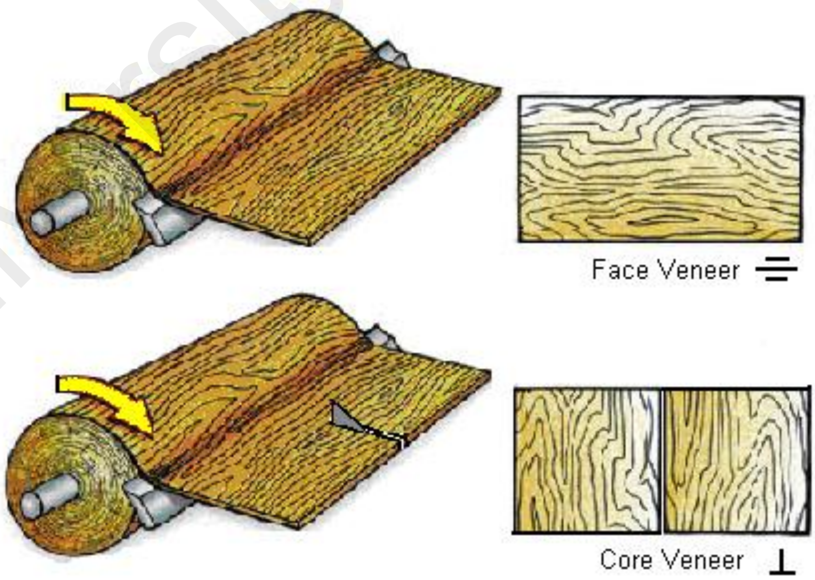


Figure 5.1: Face veneer and core veneer.

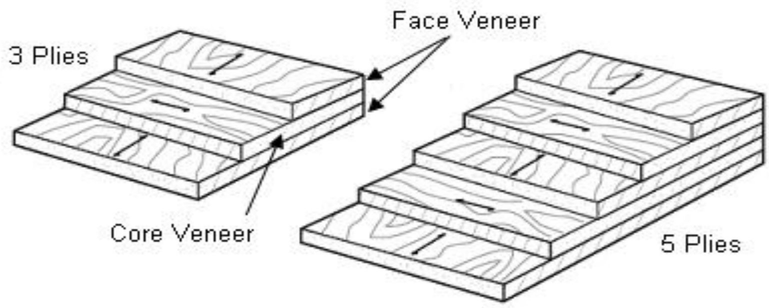


Figure 5.2: Cross-laminated construction of plywood.

Phenol formaldehyde resin was used to laminate the veneer to form a plywood panel. The spread of phenol formaldehyde resin on the veneers was controlled at about 28 g/ft^2. After the glue spread process, the plywood was cured in a hot press machine at a temperature of 130° C and pressure of 8 kg/cm^2. The plywood was then trimmed to 1.20 m by 2.40 m. The panel thickness of plywood in this work is given in Table 5.1. The mean thickness and compression (%) of each category of ply is given in Table 5.2.

Table 5.1: The thicknesses of red seraya plywood panel

Thickness[c] (mm)	Number of Plies	Construction of Plywood (mm)
4.2	3	1.40+**1.40**+1.40
7.0	5	1.40+**1.40**+1.40+**1.40**+1.40
9.8	7	1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40
12.6	9	1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40
15.4	11	1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40+**1.40**+1.40

[a] Veneer thickness with bolted character was in perpendicular to the grain direction
[b] Veneer thickness with non-bolted character was in parallel to grain direction
[c] Thickness = Nominal thickness

Table 5.2: The mean thickness and compression (%) of red seraya plywood panel

Nominal Thickness (mm)	Number of Plies	Mean Thickness (mm)	Compression (%)
4.2	3	4.0	95
7.0	5	6.5	93
9.8	7	9.1	93
12.6	9	12.0	95
15.4	11	15.0	97

5.2 Determination of Dimensions, Density and Moisture Content of Test Specimen

The plywood panel was measured for its thickness, straightness of edges and squareness in accordance with EN 315. The dimensions, density and moisture content of the test specimens were determined accordingly before the bending test.

5.2.1 EN 315:2000 (Tolerances for Dimensions of Plywood)

The tolerances of dimensions for the plywood were determined in accordance with Table 5.3 below.

Table 5.3: Tolerance of dimensions for plywood

Nominal thickness (t)	Sanded Panels			
	Thickness tolerance within one panel	Tolerances on nominal thickness	Tolerance for straightness of edges	Tolerance for squareness
mm	mm	mm		
4.0	0.6	3.40 – 4.60	1 mm/m	1 mm/m
7.0	0.6	6.40 – 7.60		
9.0	0.6	8.40 – 9.60		
12.0	0.6	11.40 – 12.60		
15.0	0.6	14.40 – 15.60		

5.2.2 EN 325:1993 (Determination of Dimensions)

The thickness of the test specimen was measured using a micrometer with flat and parallel circular measuring surfaces of (16 ± 1) mm diameter and an operation force of (4 ± 1) N. The graduation of the apparatus allows readings to 0.01 mm. The length and width of the test specimen was measured using a sliding calliper with a measuring surface of at least 5 mm width and graduated to allow a reading to 0.1 mm. For measuring the length and width, the jaw of the sliding calliper was slowly applied without excessive pressure to the test specimen at an angle of approximately 45° to the plane of the test specimens. The thickness, length and width of each test specimen were recorded.

5.2.3 EN 323:1993 (Determination of Density)

The density test pieces for the test specimens were cut according to the cutting plan for EN 310 and EN 789. The test pieces were square in shape with sides of a nominal length and width of 50 mm. The test pieces were conditioned to constant mass in an atmosphere with a relative humidity of (65 ± 5)% and a temperature of (20 ± 2)° C. The mass of the test pieces was considered as constant when the results of the two successive weighing operations carried out at an interval of 24 hours do not differ by more than 0.1% of the mass of the test pieces. The accuracy of the weighing balance allows readings to 0.01 g. The thickness of the test pieces was then measured in accordance with EN 325. The thickness, *t*, of the test pieces was measured at the point of the intersection of the diagonals, as shown in Figure 5.3. The length and width of the test pieces were measured at two points b_1 and b_2 where both were parallel to the edges of the test piece and along lines that pass through the centres of opposite edges, as shown in Figure 5.3.

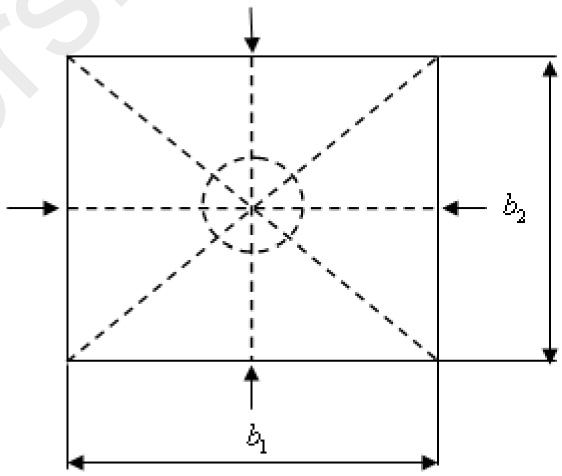


Figure 5.3: Thickness point of measurement for density test pieces (EN 323, 1993).

The density (in kg/m^3) of each test piece was calculated from the formula below:

$$\rho = \frac{m}{b_1 \times b_2 \times t} \times 10^6 \tag{5.1}$$

Where,

ρ = density (kg/m^3)

m = mass of the test piece (g)

b_1, b_2 = as depicted in Figure 5.1 (mm)

t = thickness of test piece (mm)

5.2.4 EN 322:1993 (Determination of Moisture Content)

The moisture content of the test specimens was determined according to EN 322. The test pieces for the moisture content test were cut from the plywood panel. The dimensions for the test pieces were not important but the weight of the test pieces should have a minimum initial mass of 20 g. The test pieces were weighed immediately after sampling to avoid changes in the moisture content of the test pieces. The test pieces were weighed using a balance with an interval scale of 0.01 g and placed in a drying oven at a temperature of (103 ± 2)° C until a constant mass was reached. The constant mass in the density test is considered constant when the results of two successive weighing operations carried out at an interval of 6 hours do not differ by more than 0.1% of the mass of the test pieces. After the test pieces were cooled to approximately room temperature in the desiccator, the test pieces were weighed again to an accuracy of 0.01 g. The moisture content (MC) of the test pieces was calculated as a percentage of the mass to the nearest 0.1% in accordance with the formula below:

$$MC = \frac{m_H - m_O}{m_O} \times 100 \tag{5.2}$$

Where,

m_H = initial mass of the test pieces (g)

m_O = mass of the test pieces after drying (g)

5.3 Experimental Testing Methods

The test methods used in this research project were four-point bending (EN 789), three-point bending (EN 310), three-point bending (to obtain true MOE) and finite element analysis program (ABAQUS). Figure 5.4 is a flow chart of the experimental design.

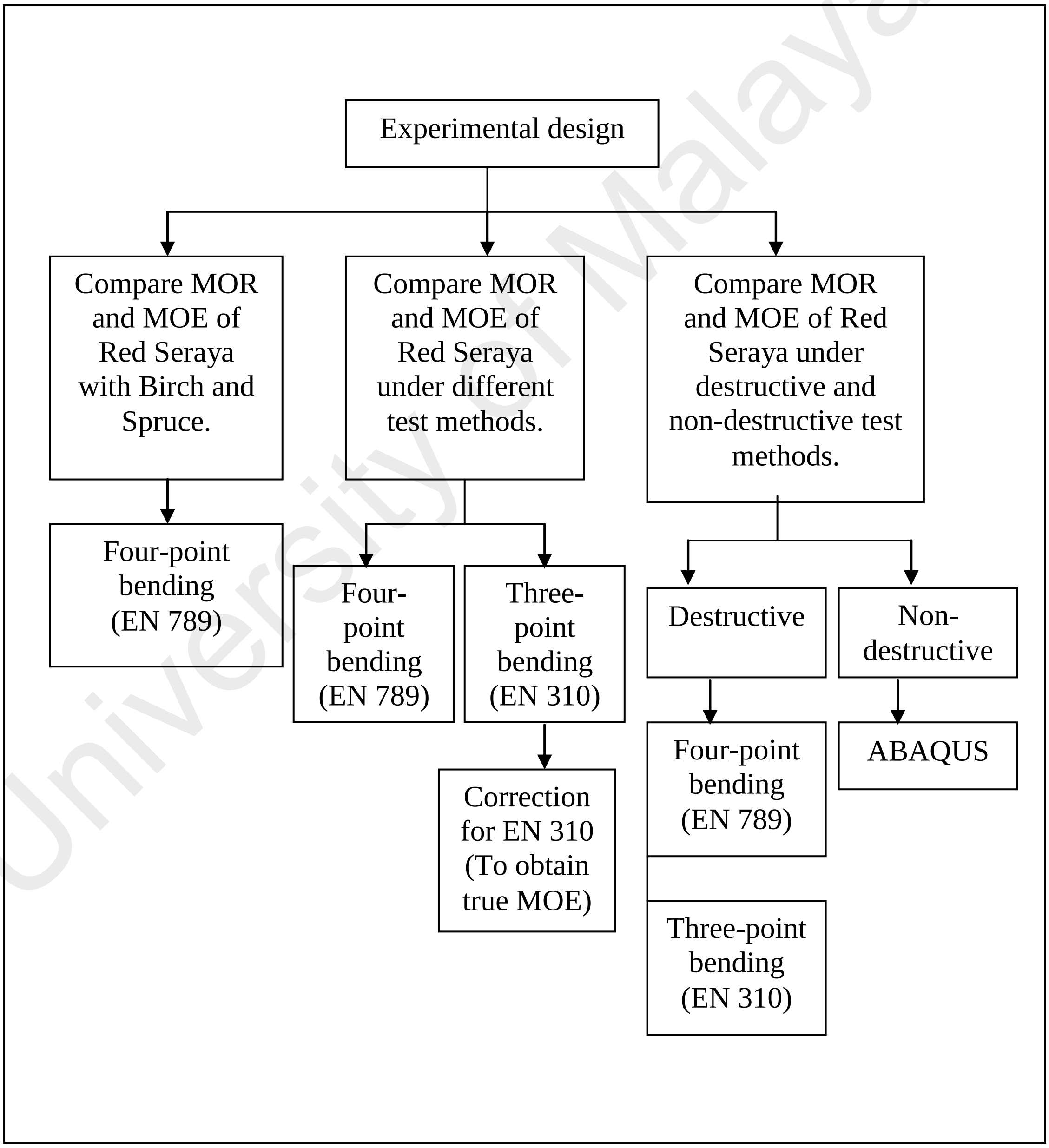


Figure 5.4: Flow chart of the experimental design.

5.3.1 EN 789 Four-point Bending Test

Tests were performed on each panel thickness as designed in this research. The plywood was cut according to the cutting plan in the four-point bending test method of EN 789 for the determination of mechanical properties of wood based panels. Figure 5.5 shows the cutting plan for sampling test specimens. There were a total of 8 batches, with each batch consisting of 4 panels of plywood. One test piece parallel (0°) to the grain and one perpendicular (90°) to the grain were cut from each panel. The position of each test specimen for both parallel and perpendicular to grain were different within the same batch.

The bending test is based on a simply supported beam with two symmetrical loads (four-point bending test), as shown in Figure 5.6. The width of the test specimens was 300 mm and the length was 32 times the thickness of the panel plus 300 mm. The load and reaction forces were applied by rollers of (30 ± 1) mm diameter. Table 5.4 shows the dimensions of all test specimens with different thicknesses of panel and categories of ply. Due to the low bending stiffness, the distance between the two loading points and the length of the test specimens were reduced accordingly for categories 4.0 mm and 6.5 mm. In addition, smaller diameter rollers were used for categories 4.0 mm and 6.5 mm.

Table 5.4: Dimension of test specimen of EN 789

Thickness of Veneer (mm)	Categories of Ply	Dimension of Test Specimen (l_2 x w x t)(mm)
1.40	3 Plies	635.0 x 300.0 x 4.0
	5 Plies	670.0 x 300.0 x 6.5
	7 Plies	780.0 x 300.0 x 9.1
	9 Plies	780.0 x 300.0 x 12.0
	11 Plies	780.0 x 300.0 x 15.0

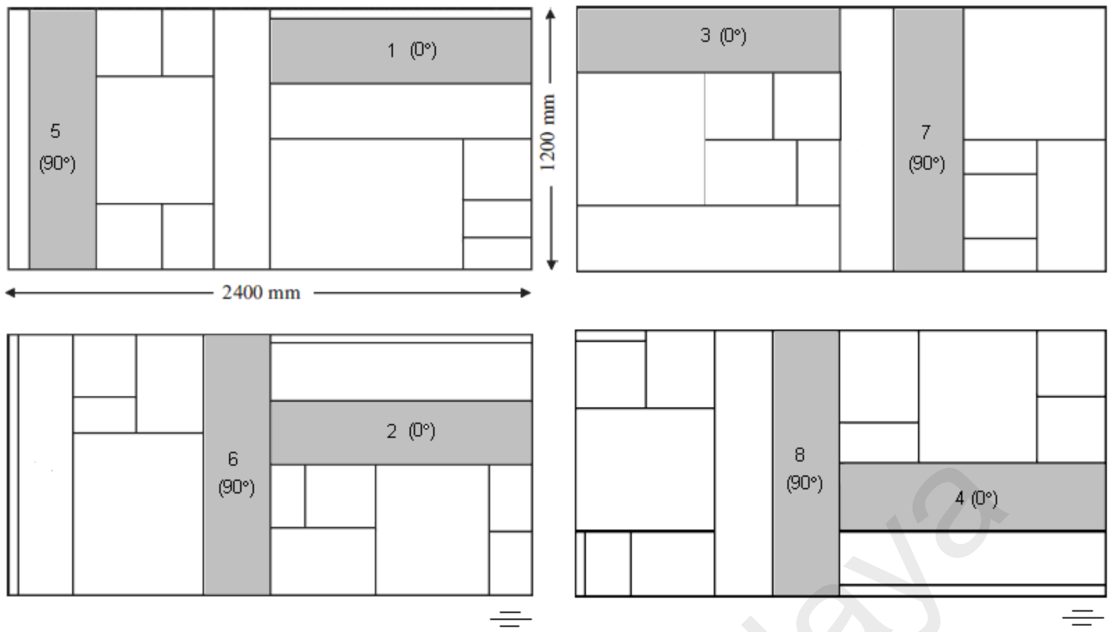


Figure 5.5: The cutting plan of four panels for sampling of specimens according to EN 789. Test specimen no.1 to no.4 is parallel (0°) grain direction while test specimen no.5 to no.8 is perpendicular (90°) grain direction. Symbol ═ indicated the grain direction of the first layer of plywood panels.

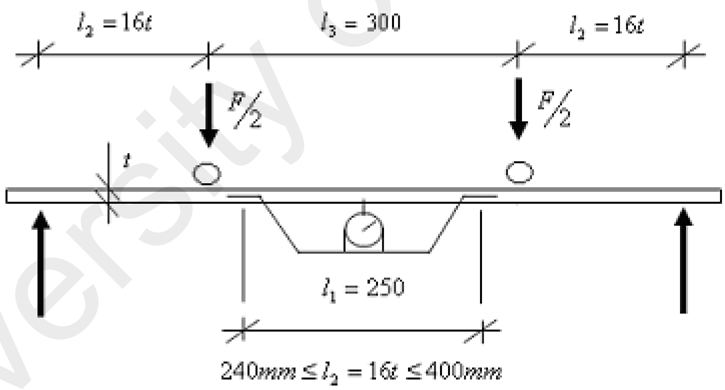


Figure 5.6: EN 789 bending test setup.

The bending strength and stiffness properties were obtained by testing according to EN 789. The test specimens were conditioned to constant mass in an atmosphere with relative humidity (65 ± 5)% and temperature (20 ± 2)° C. The deflection of the mid-span was recorded and the load-deflection curves were plotted. The MOE and MOR of the test piece were calculated according to formula 3.4 and formula 3.5 in Chapter 3.

5.3.2 Determination of MOE and MOR of EN 789

Mean MOE of 32 panels of plywood were calculated for each thickness. Calculation of the mean values of MOE, $\bar{\bar{x}}_{32}$ was in accordance with formula 5.3,

$$\bar{\bar{x}}_{32} = \frac{\sum_{j=1}^{j=n} \bar{x}_j}{n} \tag{5.3}$$

Where,

$\bar{\bar{x}}_{32}$ = mean values of 32 panels

n = number of test results (panel means) of the sample

$\bar{x}_j$ = panel means

Whereas standard deviation between panels mean $s_{\bar{x}}$ was calculated in accordance with formula 5.4,

$$s_{\bar{x}} = \sqrt{\frac{\sum_{j=1}^{j=n} (\bar{x}_j - \bar{\bar{x}})^2}{n-1}} = \sqrt{\frac{\sum_{j=1}^{j=n} \bar{x}_j{}^2 - \frac{\sum_{j=1}^{j=n} \bar{x}_j \times \sum_{j=1}^{j=n} \bar{x}_j}{n}}{n-1}} \tag{5.4}$$

Where,

$s_{\bar{x}}$ = standard deviation between panels mean

n = number of test results (panel means) of the sample

$\bar{x}_j$ = panel means

$\bar{\bar{x}}$ = mean values of 32 panels calculated from formula 5.3

The bending strength for all test specimens was analysed using the statistical method in EN 1058. The characteristic bending strength (MOR) was introduced, which is the 5-percentile values obtained from the bending strength of 32 panels of plywood. The MOR was calculated in accordance with formula 5.5,

$$f_m = \exp\left(\frac{1}{n} \times \sum_{j=1}^{j=n} \ln \bar{x}_j - k_s \times s_{\ln \bar{x}}\right) \qquad (5.5)$$

Where,

f_m = characteristic bending strength (MOR) (N/mm^2)

n = number of test results (panel means) of the sample

$\bar{x}_j$ = panel means

k_s = statistical factor as tabulated in Table 5.5

$s_{\ln \bar{x}}$ = standard deviation between panel means of a log-normal distributed property $\bar{x}_j$

Table 5.5: k_s value for EN 789

Number of test data, *n*	5	10	15	20	30	**32**	40	50	100
k_s value	2.46	2.10	1.99	1.93	1.87	**1.86**	1.83	1.81	1.75

Whereas standard deviation between panel means $s_{\bar{x}}$ was in accordance with formula 5.6,

$$s_{\bar{x}} = \sqrt{\frac{\sum_{j=1}^{j=n} (\bar{x}_j - \bar{\bar{x}})^2}{n-1}} = \sqrt{\frac{\sum_{j=1}^{j=n} \bar{x}_j^{\,2} - \frac{\sum_{j=1}^{j=n} \bar{x}_j \times \sum_{j=1}^{j=n} \bar{x}_j}{n}}{n-1}} \qquad (5.6)$$

Where,

$s_{\bar{x}}$ = standard deviation between panel means

n = number of test results (panel means) of the sample

$\bar{x}_j$ = panel means

$\bar{\bar{x}}$ = mean values of 32 panels

The coefficient of Variation (COV%) for both MOE and MOR was calculated in accordance with formula 5.7,

$$\text{COV\%} = \frac{s_{\bar{x}}}{\bar{\bar{x}}_{32}} \times 100\% \qquad (5.7)$$

Where,

COV% = coefficient of variation

$s_{\bar{x}}$ = standard deviation between panel means

$\bar{\bar{x}}_{32}$ = mean values of 32 panels

5.3.3 EN 310 Three-point Bending Test

There were a total of 12 panels of plywood for each panel thickness. Each plywood panel was cut into two groups of bending test specimens, 6 pieces parallel (0°) to the grain direction and 6 pieces perpendicular (90°) to the grain direction according to the cutting plan, as shown in Figure 5.7. There were a total of 144 test specimens for each panel thickness.

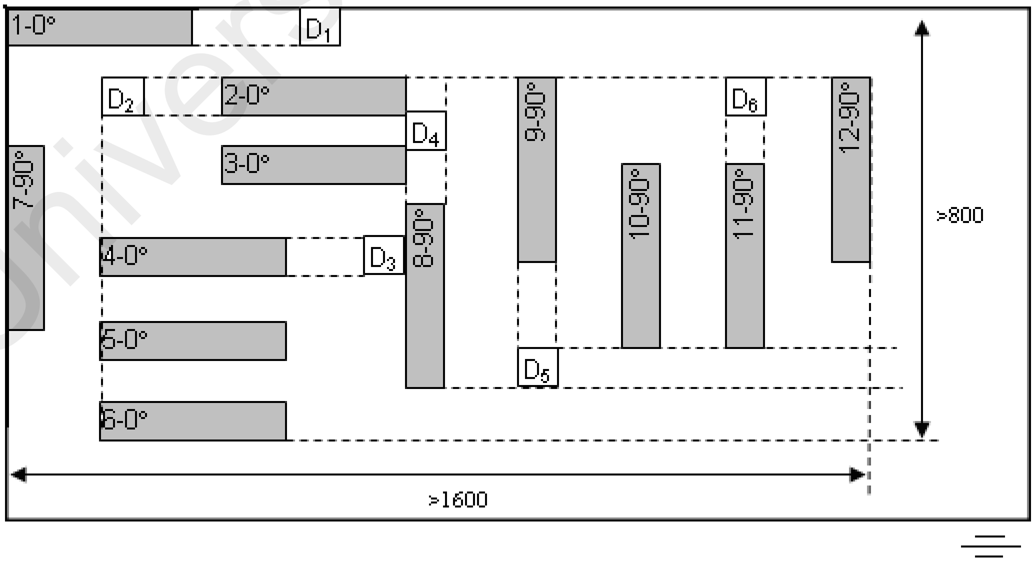


Figure 5.7: The cutting plan of EN 310. Test piece number 1 to 6 indicates parallel (0°) grain direction while test piece number 7 to 12 indicates perpendicular (90°) grain direction. The dimensions are in millimeters. Symbol ═ indicated the grain direction of the first layer of plywood panel.

The test specimen was rectangular with width *b*, (50 ± 1) mm and length was 20 times the nominal thickness (*t*) plus 50 mm. The test specimens were conditioned to constant mass in an atmosphere with relative humidity (65 ± 5)% and temperature (20 ± 2)° C. Table 5.6 shows the dimension of the test specimens with different thickness and ply categories.

Table 5.6: Dimension of test specimen of EN 310

Thickness of Veneer (mm)	Categories of Ply	Dimension of Test Specimen (l_2 x w x t)(mm)
1.40	3 Plies	130.0 x 50.0 x 4.0
	5 Plies	180.0 x 50.0 x 6.5
	7 Plies	232.0 x 50.0 x 9.1
	9 Plies	290.0 x 50.0 x 12.0
	11 Plies	350.0 x 50.0 x 15.0

Test specimens were tested in accordance with EN 310 for mechanical properties using the universal tensile machine with an accuracy of 1% of the measured value. A cylindrical loading head with diameter (30 ± 0.5) mm was placed parallel to the supports. The test specimen was set between the adjustable supports with the centre point under the load, as shown in Figure 5.8. The load applied to the test specimen was at a constant rate of cross-head movement throughout the test. The rate of loading was adjusted so that the maximum load reached within (60 ± 30) s. The deflection of the mid-span was recorded and the load-deflection curves were plotted. The MOE and MOR of the test pieces were calculated from formula 3.6 and 3.7 in Chapter 3.

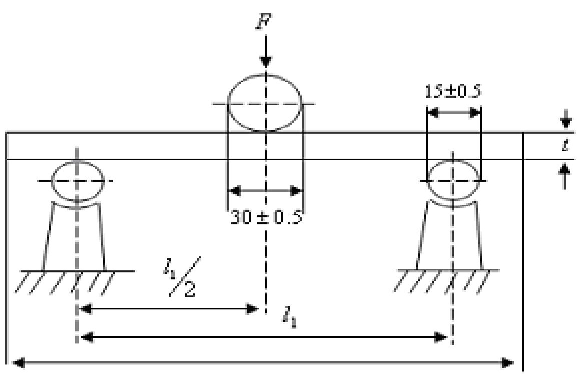


Figure 5.8: EN 310 bending test setup.

5.3.4 Determination of MOE and MOR of EN 310

The mean MOE of 12 panels $\bar{\bar{x}}_{12}$, were calculated for each thickness in accordance with formula 5.8,

$$\bar{\bar{x}}_{12} = \frac{\sum_{j=1}^{j=n} \bar{x}_j}{n} \tag{5.8}$$

Where,

$\bar{\bar{x}}_{12}$ = the 12 panel means

n = number of test results (panel means) of the sample

$\bar{x}_j$ = the panel means

The standard deviation between panels was calculated in accordance with formula 5.9,

$$s_{\bar{x}} = \sqrt{\frac{\sum_{j=1}^{j=n} (\bar{x}_j - \bar{\bar{x}})^2}{n-1}} = \sqrt{\frac{\sum_{j=1}^{j=n} \bar{x}_j{}^2 - \frac{\sum_{j=1}^{j=n} \bar{x}_j \times \sum_{j=1}^{j=n} \bar{x}_j}{n}}{n-1}} \tag{5.9}$$

Where,

$s_{\bar{x}}$ = standard deviation between panel means

n = number of test results (panel means) of the sample

$\bar{x}_j$ = the panel means

$\bar{\bar{x}}$ = the 12 panel means

The bending strength for all test specimens was analysed using the statistical method. The characteristic bending strength (MOR) was introduced, which is the 5-percentile values obtained from the bending strength of the test specimen. The characteristic bending strength for EN 310 according in EN 326-1:1994 was calculated in accordance with formula 5.10,

$$f_m = \bar{\bar{x}}_{12} - t_m s_{\bar{x}} \tag{5.10}$$

Where,

f_m = characteristic bending strength (MOR) (N/mm^2)

$\bar{\bar{x}}_{12}$ = mean of 12 panel means of plywood calculated in accordance with formula 5.11,

t_m = the statistical factor as tabulated in Table 5.7. The table values correspond to a 95% confidence limit, one-sided case in accordance with ISO 2602.

$s_{\bar{x}}$ = standard deviation between panel means

Table 5.7: t_m value for EN 310

Number of test data, *n*	4	5	6	8	10	**12**	16	18
t_m value	2.35	2.13	2.02	1.89	1.83	**1.80**	1.75	1.74

The mean MOR of 12 panels $\bar{\bar{x}}_{12}$, was calculated for each thickness in accordance with formula 5.11,

$$\bar{\bar{x}}_{12} = \frac{\sum_{j=1}^{j=n} \bar{x}_j}{n} \tag{5.11}$$

Where,

$\bar{\bar{x}}_{12}$ = the 12 panel means

n = number of test results (panel means) of the sample

$\bar{x}_j$ = the panel means

The standard deviation between 12 panel means, calculated in accordance with formula 5.12

$$s_{\bar{x}} = \sqrt{\sum_{j=1}^{n} (\bar{x}_j - \bar{\bar{x}})^2 / 11} \tag{5.12}$$

Where,

$s_{\bar{x}}$ = standard deviation between 12 panel means

$\bar{x}_j$ = the panel means

$\bar{\bar{x}}$ = the 12 panel means

The coefficient of variation (COV%) for both MOE and characteristic bending strength was calculated in accordance with formula 5.13,

$$\text{COV\%} = \frac{s_{\bar{x}}}{\bar{\bar{x}}_{12}} \times 100\% \tag{5.13}$$

Where,

COV% = coefficient of variation

$s_{\bar{x}}$ = standard deviation between panels mean

$\bar{\bar{x}}_{12}$ = the 12 panel means

5.3.5 Correction Method for EN 310

The MOE obtained from the three-point bending test is the apparent MOE where the deflection due to both bending and shear are included in its calculation. The three-point bending test adopted from EN 310 was performed to obtain the true MOE for thicknesses 4.0 mm, 6.5 mm, 9.10 mm, 12.0 mm and 15.0 mm. The true MOE is different from the apparent MOE. The true MOE ignores the deflection due to shear whereas apparent MOE includes deflection due to both bending and shear. Each thickness consists of five different spans with each span having one longitudinal and one transverse grain test specimen. The span was decreased from 300 mm to 100 mm in decrements of 50 mm. To obtain the true MOE, the following formula was used:

$$\frac{1}{E_a} = \frac{1}{E} + \frac{K}{G}\left(\frac{t}{l}\right)^2 \tag{5.14}$$

Where,

G = shear modulus (N/mm^2)

E_a = apparent MOE from experiment (N/mm^2)

E = true MOE (N/mm^2)

K = shape factor $\frac{6}{5}$ for the rectangular cross section test specimen

t = thickness of test specimen (mm)

l = span length of test specimen (mm)

Graph of relation between $\left(\frac{t}{l}\right)^2$ vs $\frac{1}{E_a}$ was plotted. The intercept of the graph to the y-axis, $\left(\frac{1}{E}\right)$ is the true MOE.

5.4 Finite Element Method

The EN 789 and EN 310 bending setup were modelled using FE analysis software, ABAQUS standard. To simplify the models, some parameters were neglected, such as glueline between each ply veneer, knots, moisture content and density variation. To model the EN 789 and EN 310 bending test, average maximum load obtained from the experiment were applied into the computer model using the point load. The size of the test specimen in EN 789 and EN 310 modelling was the real dimension, as shown in Table 5.4 and 5.6. All the test specimens were modelled in three dimensions.

The material properties of the red seraya plywood used in this study, which were taken from Yoshihara (2009) are given in Table 5.8. The orthotropic properties of the plywood were assigned using elastic and lamina type. Static general type analysis was performed in both EN 789 and EN 310 bending test and linear geometry simulation was toggle on. The mesh for both bending test specimens were model using reduced integration, four-noded quadrilateral shell elements, type S4R.

Table 5.8: Material properties of red seraya plywood used for FE analysis

Young Modulus ($x10^9$ N/m^2)			Shear Modulus ($x10^9$ N/m^2)			Poisson's ratio
E_X	E_Y	E_Z	G_{XY}	G_{YZ}	G_{XZ}	NU_{XY}
12.9	0.51	1.00	0.48	0.11	0.65	0.61

The boundary conditions for both EN 789 and EN 310 bending test are assumed as simply-supported where all the roller supports and loading nose are neglected. One of the roller support was not allowed to deform, it was constrained in the Z direction and the other roller support was constrained in the Z and Z_R direction. The uniform bending moment area of EN 789 bending test was constrained in the x and y direction so that the plane strain remained plane after bending. Figure 5.9 and 5.10 show the model of EN 310 and EN 789 bending test setup in ABAQUS.

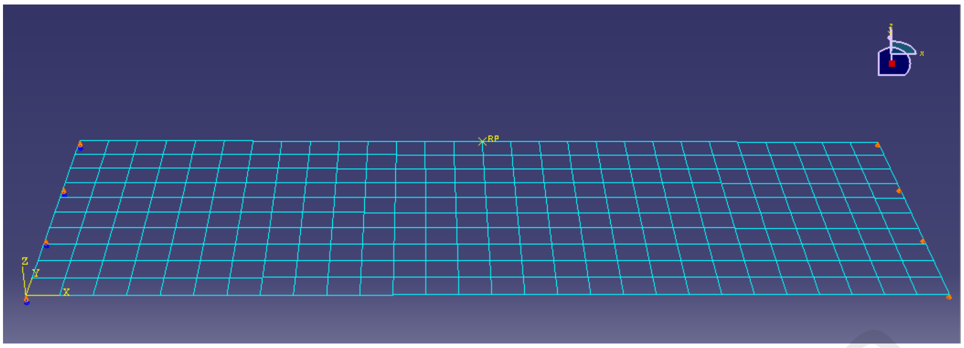


Figure 5.9: EN 310 bending test setup in Abaqus.

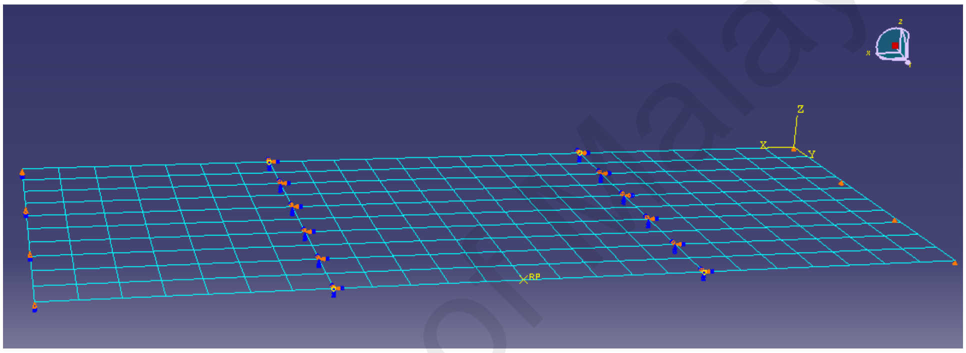


Figure 5.10: EN 789 bending test setup in Abaqus.

The maximum displacement at mid-span and total reaction force for both EN 310 and EN 789 bending simulation were collected. The MOR for both bending tests were calculated using formula 3.4 and formula 3.6 in Chapter 3, as tabulated in EN 789 and EN 310 method where F_{max} is the reaction force collected from roller support whereas MOE was calculated as the formula below ,

$$MOE\ (\text{EN 789}) = \frac{l_1^{2} l_2 F_{\max}}{16 I U_{\max}} \tag{5.15}$$

$$MOE\ (\text{EN 310}) = \frac{l_1^{3} F_{\max}}{48 I U_{\max}} \tag{5.16}$$

Where,

MOE = modulus of elasticity (N/mm^2)

F_{max} = maximum reaction force collected from roller support (N/mm^2)

U_{max} = maximum displacement at mid-span

I = moment of inertia

l_1, l_2 = as defined in Figure 3.2 and Figure 3.3.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 MOR and MOE of Red Seraya Structural Plywood using EN 789

The mechanical properties of red seraya structural plywood were examined and compared with corresponding characteristics in other commonly available plywood in the industry. To compare the mechanical properties of plywood for red seraya, birch and spruce, the published values for birch and spruce plywood from the Handbook of Finnish Plywood (2002) were adopted. The test method EN 789 (four-point bending) was used and the panel thickness was similar to those employed in the current research. These published values for birch and spruce plywood are given in Table 2.4 and Table 2.6.

Table 6.1 shows the strength and stiffness properties of red seraya plywood tested according to EN 789. Figure 6.1 tabulates the difference in percentage (%) for MOR and MOE between birch and red seraya, relative to birch. Figure 6.2 shows the difference in percentage (%) for MOR and MOE between red seraya and spruce, relative to red seraya.

Table 6.1: MOR and MOE for red seraya plywood using EN 789

t	Plies	MC	ρ	Bending Characteristic Strength, MOR (N/mm^2)		Bending Mean Modulus of Elasticity, MOE (N/mm^2)	
mm		%	Kg/m^3	0°	90°	0°	90°
4.0	3	8.1	510.3	48.9 (7.9)	-	15398 (7.3)	-
6.5	5	9.9	479.2	42.9 (2.9)	18.0 (11.5)	9834 (5.5)	3673 (12.9)
9.1	7	9.4	482.7	41.5 (3.5)	26.4 (3.5)	8904 (4.1)	4659 (3.7)
12.0	9	10.4	470.3	39.9 (2.1)	27.7 (3.0)	8319 (4.6)	5146 (2.5)
15.0	11	11.5	475.8	37.8 (4.0)	29.4 (2.5)	7782 (3.3)	5402 (4.3)

[a] MOR values are the 5-percentile of 32 readings. MOE values are the means of 32 readings, with the % coefficients of variation in brackets. *t* – Mean value for thickness, ρ – Density, 0° – Parallel to wood grain direction, 90° – Perpendicular to wood grain direction. Result of 4mm 90° is not displayed due to large deflection.

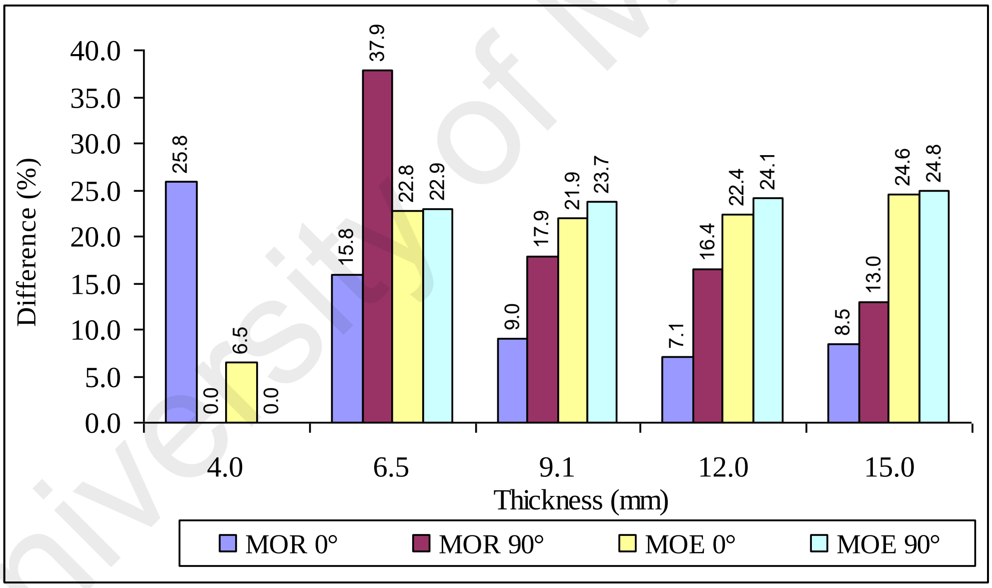


Figure 6.1: The percentage difference between birch and red seraya plywood results for MOR and MOE with respect to birch results.

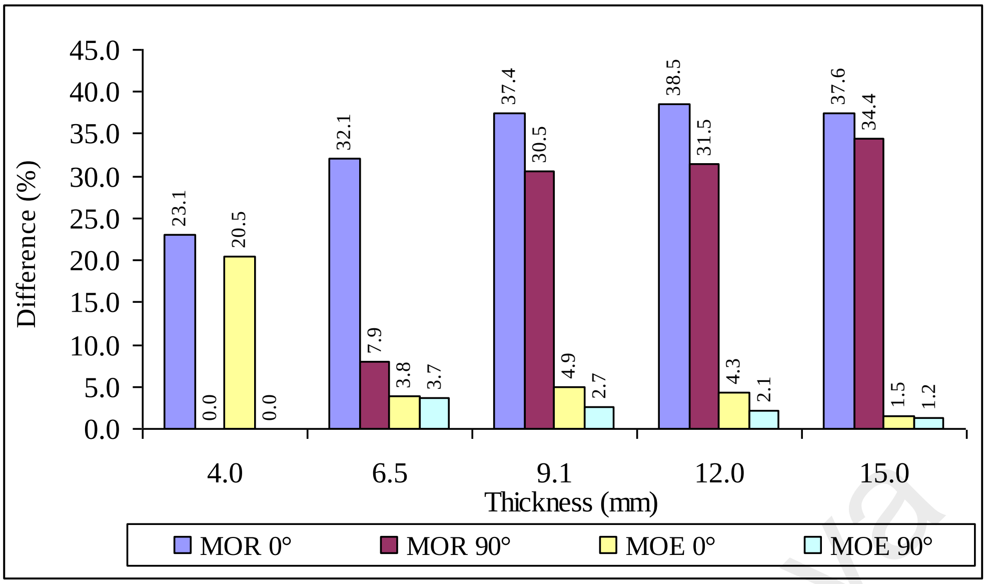


Figure 6.2: The percentage difference between red seraya and spruce plywood results for MOR and MOE with respect to red seraya results.

As reported in the literature (Kretschmann (2010), Jalava (1945), Dunham *et al.* (1999), Herajarvi (2004), Larsson *et al.* (1998), Chrestin (2000), Solli (2000), Ranta-maunus (2001)), the MOR and MOE of small clear wood samples, timber, sawn wood and plywood vary even within the same wood species. The MOR of red seraya lay within the range 63 N/mm^2 to 86 N/mm^2 whereas the MOE was 8500 N/mm^2 to 13600 N/mm^2. For birch, the MOR is around 76 N/mm^2 to 157 N/mm^2 and MOE is in the range 7800 N/mm^2 to 19900 N/mm^2. The MOR of spruce is reported as 13 N/mm^2 to 79 N/mm^2 while its MOE ranges from 5500 N/mm^2 to 15800 N/mm^2. Overall, the MOR of birch was the highest among the three wood species compared in this study, followed by red seraya. Spruce had the lowest MOR. With regard to the MOE, birch wood showed the highest value but no significant difference was observed between red seraya and spruce. The use of the mechanical properties of solid timber to estimate the properties of plywood is conservative, giving rise to lower values than the actual veneer properties. This is because the mechanical properties of plywood are influenced by the compression of each veneer layer, the effect of the glue and the construction of the cross plies of the veneers (Francisco *et al*., 2008).

We found that the MOR of birch plywood was, at most, 25.8% and 37.9% higher than that of red seraya, for tests parallel and perpendicular to the grain, respectively. At the same time, red seraya plywood had a MOR that was not more than 38.5% and 34.4% higher than the corresponding values for spruce plywood for tests parallel and perpendicular to the grain, respectively.

The MOE values parallel and perpendicular to the grain for birch plywood were also 24.8% higher than for red seraya plywood, which, in turn, the red seraya plywood had MOE values that were 20.5% higher than those for spruce plywood (3-plies parallel to the grain test specimens). However, other than the 3-plies samples, the differences in MOE between the red seraya and spruce samples were insignificant for test specimens 5, 7, 9 and 11 plies as the differences were less than 5% in the test samples both parallel and perpendicular to the grain. We surmise that this difference might have been due to the proportionately greater thickness of the 3-plies red seraya plywood. The discrepancy in plywood thickness between the three species decreased as the number of plies in the test sheets increased.

Taking the strength properties of MOR and MOE together, it can be said that red seraya gave lower readings for both measurements as compared to birch. On the other hand, red seraya was comparable to spruce in these properties. It should be noted, nevertheless, that the comparisons between readings from the present investigation and previously published studies are not fully conclusive although the same thickness of samples and the same testing method were used. It should be borne in mind that the differences in the testing condition such as variation of moisture content, density of wood and thickness of test specimens could influence the properties of MOR and MOE.

6.2 MOR and MOE of Red Seraya Structural Plywood using EN 310

The MOR and MOE of EN 310 three-point bending and EN 789 four-point bending tests were studied experimentally. Table 6.2 shows the MOR and MOE of five different plywood thicknesses obtained from EN 310. The results of the EN 310 readings were compared to the results of the EN 789 tests tabulated in Table 6.1.

Table 6.2: MOR and MOE for red seraya plywood using EN 310

t	Plies	MC	ρ	Bending Characteristic Strength, MOR (N/mm^2)		Bending Mean Modulus of Elasticity, MOE (N/mm^2)	
mm		%	Kg/m^3	0°	90°	0°	90°
4.0	3	8.1	510.3	56.3 (5.7)	11.2 (10.2)	9010 (6.3)	642 (18.6)
6.5	5	9.9	479.2	50.5 (5.0)	20.2 (6.4)	6454 (5.1)	2280 (8.5)
9.1	7	9.4	482.7	46.5 (3.0)	28.1 (4.6)	5807 (2.9)	3058 (6.1)
12.0	9	10.4	470.3	48.0 (3.5)	34.3 (4.5)	6008 (5.1)	3589 (4.6)
15.0	11	11.5	475.8	42.5 (1.8)	33.0 (2.9)	5253 (2.4)	3687 (1.5)

[a] MOR values are the 5-percentile of 72 readings. MOE values are the means of 72 readings, with the % coefficients of variation in brackets. *t* – Mean value for thickness, ρ – Density, 0° – Parallel to wood grain direction, 90° – Perpendicular to wood grain direction.

From their study, Hrazsky & Kral (2005) reported that plywood samples stressed parallel to the grain showed decreases in MOR and MOE as the thickness increased. When stressed in the direction perpendicular to the grain, however, the MOR and MOE increased as the thickness increased, similar to the trends presented in Tables 6.1 and 6.2. This is due to the construction layup of plywood. Nevertheless, there are still unexpected discrepant results that are due to the influence of inherent factors of wood relative to the size of the test specimen.

6.3 Comparison of MOR and MOE of EN 789 and EN 310

Table 6.3 shows the difference of MOR and MOE between EN 789 and EN 310 relative to EN 789. EN 310 showed higher MOR readings relative to EN 789 for test specimens, regardless of whether they were stressed parallel or perpendicular to the grain. The increase in MOR readings using EN 310 relative to EN 789 was in the range 12.0% to 20.4% and 6.7% to 23.6%, for test specimens stressed parallel and perpendicular to the grain, respectively.

Table 6.3: Difference of MOR and MOE between EN 789 and EN 310 relative to EN 789

t Mean Value	Plies	ρ [a]	Bending Characteristic Strength, MOR[b] (N/mm^2)		Bending Mean Modulus of Elasticity, MOE[c] (N/mm^2)	
mm		Kg/m^3	0° (%)	90° (%)	0° (%)	90° (%)
4.0	3	510.3	15.2	-	-41.5	-
6.5	5	479.2	17.8	12.1	-34.4	-37.9
9.1	7	482.7	12.0	6.7	-34.8	-34.4
12.0	9	470.3	20.4	23.6	-27.8	-30.3
15.0	11	475.8	12.4	12.2	-32.5	-31.7

[a] Density
[b] Difference (%) of MOR = $(MOR_{3P} - MOR_{4P})/MOR_{4p}*100$
[c] Difference (%) of MOE = $(MOE_{3P} - MOE_{4P})/MOE_{4P}*100$

Yoshihara & Nakano (2011) reported that the MOR of three-point bending for plywood was usually larger than four-point bending because of the difference of the evaluation point of the span. The three-point bending was evaluated point-wise at the mid-span whereas four-point bending was evaluated at the weakest point between the loading nose. They found that the MOR of three-point bending was 8% and 20% larger than four-point bending tests, where specimens were stressed parallel and perpendicular to the grain, respectively.

In comparison, the results in the present study were approximately 12% and 4% higher than those obtained by Yoshihara & Nakano (2011). These differences might be due to the differences arising from the tree species, moisture content of the test specimens and different test setup. In addition, the higher readings of EN 310 relative to EN 789 could be due to the load span. Theobald *et al.* (1997) also concluded that the MOR decreased as the span increased owing to excessive bending and slippage of test samples, resulting in a significant reduction in flexural strength. Accordingly, the MOR readings for EN 789 could be expected to be smaller than the readings obtained by EN 310 as the span of EN 789 is larger than that of EN 310. Contrary to this expectation, however, Nandanwar *et al.* (2011) found that the MOR for the four-point bending test was 6% to 10% greater than that for the three-point bending test for plywood from timber plantations. The reasons for such discrepancies require further investigation.

Table 6.3 also shows the lower MOE readings for EN 310 relative to EN 789. The EN 310 bending test gave MOE readings that were lower by 27.8% to 41.5% and 30.3% to 37.9% for test specimens parallel and perpendicular to the wood grain, respectively. Yoshihara & Nakano (2011), Theobald *et al.* (1997), Mujika (2006), and Brancherius *et al.* (2002) found that MOE readings obtained by three-point bending were less than the readings obtained by four-point bending. However, Nandanwar *et al.* (2011) reported contrary results. The current results agreed closely with those obtained by Yoshihara & Nakano (2011). They were slightly higher than the results reported by Brancherius *et al.* (2002), but considerably higher than those obtained by Theobald *et al.* (1997) and Mujika (2006). The results from the present study tended to be closer to the former because the materials used in the two studies were similar.

Yoshihara & Tsunematsu (2006) reported that the lower readings for MOE obtained using the three-point bending were due to the influence of the span-depth ratio whereas Theobald *et al.* (1997) and Mujika (2006) related the lower readings of the three-point bending test to the influence of shear deformation, slipping of material on the roller support, bending rotation at the support and loading nose and thickness of the material. In addition, Brancheriau *et al.* (2002) also related the low readings to the density or anatomical differences between the wood species. In the present study, it was surmised that the low MOE readings for the three-point bending measurements were mostly related to the shear deformation characteristic of the three-point bending test, as shown in Figure 6.3.

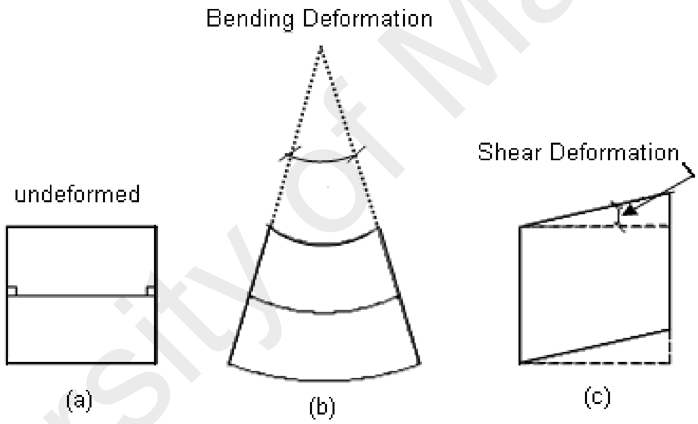


Figure 6.3: Bending deformation and shear deformation of three point bending test.

The MOE obtained from the three-point bending test is the apparent MOE where the shear deflection is included in its calculation. Thus, the MOE obtained from EN 310 is not recommended for use as design values in construction projects. To obtain the true MOE, the three-point bending test adopted from EN 310 was performed for thicknesses 4.0 mm, 6.5 mm, 9.1 mm, 12.0 mm and 15.0 mm, by using five different span length for each thickness. The correction eliminates the effect of shear deformation. The corrected MOE results and the difference to four-point bending MOE are tabulated in Table 6.4. According to Table 6.3, the initial maximum difference between the MOE obtained by the three-point and four-point bending tests was 41.5% and 37.9% for test specimens parallel and perpendicular to the grain, respectively. After the correction steps, the revised values obtained were close to the value obtained by the four-point bending test. The final difference between three-point bending and four-point bending procedures was reduced to not more than 3.0% and 6.0% for test specimens parallel and perpendicular to the grain, respectively. The remaining difference between EN 310 and EN 789 may be due to the influence of the inherent factors of the wood relative to the size of the test specimen. Inherent wood factors such as knots, decay and wormholes tend to affect smaller samples more seriously than larger samples. Nevertheless, the results point to shear deflection being a major factor responsible for the discrepancy in the readings obtained following the EN 310 and EN 789 methods.

Table 6.4: MOE for red seraya plywood using correction method

t Mean Value	Plies	True E (N/mm^2)		Difference of MOE_{3P} and MOE_{4P}[a] (%)	
mm		0°	90°	0°	90°
4.0	3	-	-	-	-
6.5	5	9967	3642	-1.4	0.9
9.1	7	8960	4385	-0.6	5.9
12.0	9	8556	4858	-2.8	5.6
15.0	11	7783	5237	0.0	1.4

[a] Difference (%) of MOE = $(MOE_{4P} - MOE_{3P})/MOE_{4P} * 100$

Based on the evaluation and comparison of the performance of EN 310 and EN 789, it can be concluded that EN 310 gave higher MOR readings and lower MOE readings as compared to EN 789. The higher MOR readings could be due to the different evaluation point of the span and also the load span. On the other hand, the lower MOE readings were mostly caused by the shear deformation that occurs in the EN 310.

6.4 Relationship between MOR and MOE from EN 310 and EN 789

The MOR and MOE determined by EN 789 for 32 panels of each thickness were correlated with the corresponding original MOR and MOE readings obtained by EN 310. The correlation is tabulated in Figures 6.4, 6.5, 6.6 and 6.7.

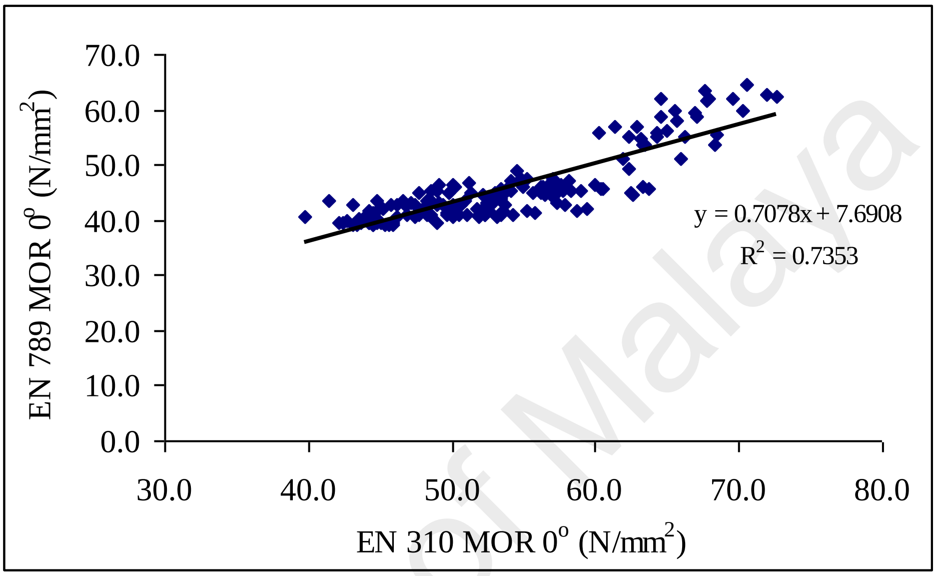


Figure 6.4: Linear regression line illustrating the relationship between MOR 0° measured according to EN 789 and MOR 0° measured according to EN 310.

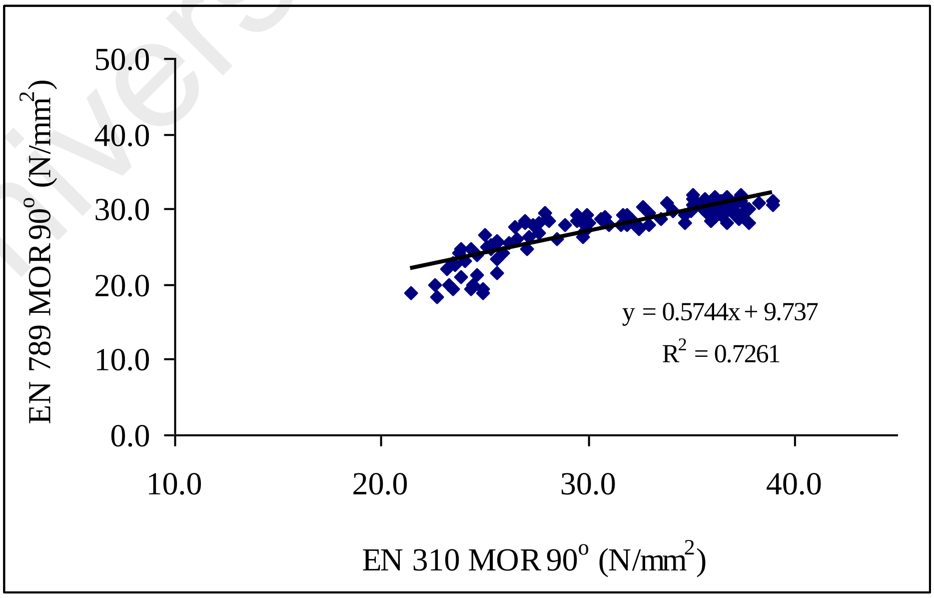


Figure 6.5: Linear regression lines illustrating the relationship between MOR 90° measured according to EN 789 and MOR 90° measured according to EN 310.

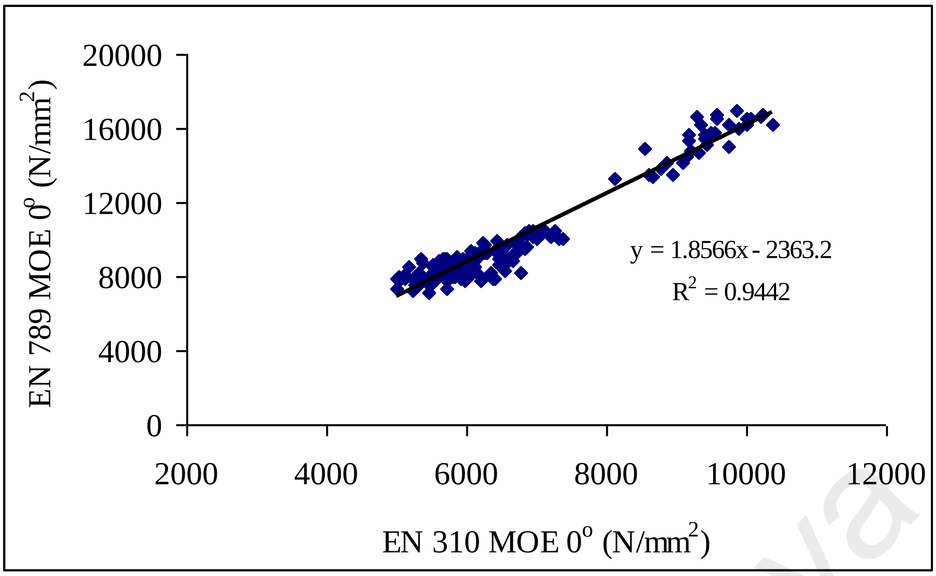


Figure 6.6: Linear regression lines illustrating the relationship between MOE 0° measured according to EN 789 and MOE 0° measured according to EN 310.

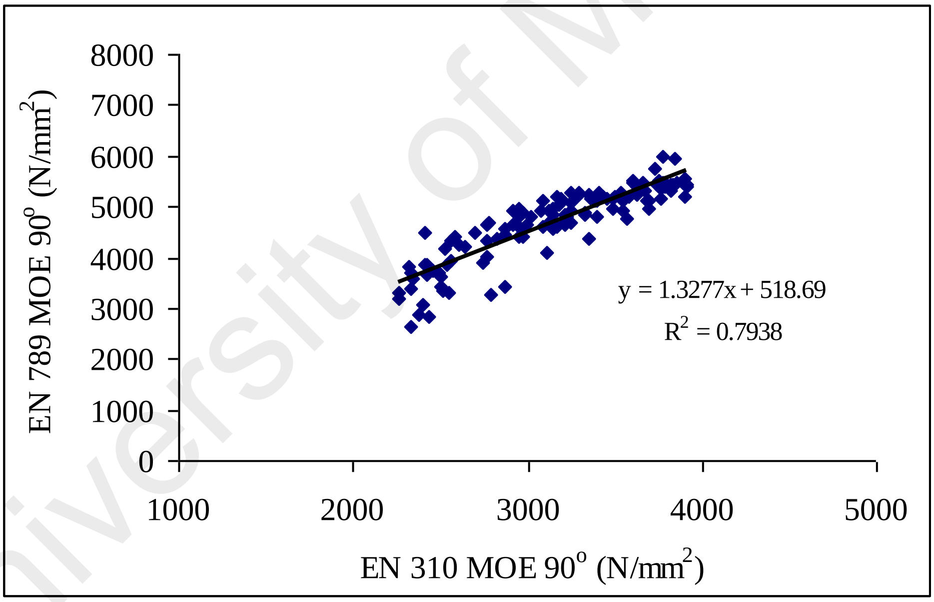


Figure 6.7: Linear regression lines illustrating the relationship between MOE 90° measured according to EN 789 and MOE 90° measured according to EN 310.

From the linear correlation equations, it was found that the MOR for EN 789 was approximately 0.71 times and 0.57 times of EN 310 for tests specimens parallel and perpendicular to the grain. At the same time, the MOE for EN 789 was 1.86 times and 1.33 times that of EN 310 for test specimens parallel and perpendicular to the grain, respectively. Tuherm & Zudrags (2006) previously reported that the MOR of birch plywood for EN 789 was about 0.78 times and 0.69 times that for EN 310, whereas the MOE was about 1.29 times and 1.21 times of EN 310 for specimens both parallel and perpendicular to the grain, respectively. McNatt *et al.* (1990) had also reported that the linear regression of MOR and MOE for four-point bending was about 0.66 times and 1.41 times that of three-point bending. However, the linear correlations performed by McNatt *et al.* (1990) were the combination of data for both parallel and perpendicular test specimens. On the other hand, Nandawar *et al.* (2011) asserted that both MOR and MOE readings from the four-point bending tests were almost equal to those obtained from the three-point bending tests.

The results from the present study were quite similar to those published by Tuherm & Zudrags (2006), except that the former data tended to be higher than the latter for MOE. This difference might be due to the difference in wood species, variation between the amount of data and also the quality of the test specimens. It was also found that the correlation coefficient (R^2) for specimens stressed parallel to the grain was stronger than the correlation coefficient obtained for tests carried out perpendicular to the grain. This trend was observed for both MOR and MOE, in agreement with those observed previously by Tuherm & Zudrags (2006).

Simple linear regression equations were obtained in order to extend the small-scale quality control method (EN 310) to the medium-scale design value method (EN 789). It was found that:

$$MOR_{EN789\,(0°)} = 0.71 MOR_{EN310\,(0°)} + 7.69 \qquad (R^2 = 0.7353) \qquad (6.1)$$

$$MOR_{EN789\,(90°)} = 0.57\, MOR_{EN310\,(90°)} + 9.74 \qquad (R^2 = 0.7261) \qquad (6.2)$$

$$MOE_{EN789\,(0°)} = 1.86 MOE_{EN310\,(0°)} - 2363.20 \qquad (R^2 = 0.9442) \qquad (6.3)$$

$$MOE_{EN\,789\,(90°)} = 1.33 MOE_{EN310\,(90°)} + 518.69 \qquad (R^2 = 0.7938) \qquad (6.4)$$

Where,

0° = parallel tests specimen

90° = perpendicular tests specimen

These are the linear regressions that predict the EN 789 MOR and MOE results (suitable for adoption as medium-scale design values in construction) based on EN 310 data obtained from small-scale testing. However, these correlation equations may only be applicable to specific wood species. Further research needs to be conducted to evaluate the applicability and precision of these correlation equations for more widespread and versatile use in the construction industry.

6.5 Results of EN 789 and EN 310 in FE Analysis

Deformation caused by the loads applied is one of the most important aspects in analysis of the mechanical properties of structural plywood. In order to predict the MOR and MOE of red seraya structural plywood, the reaction forces and deformation were collected from the FE analysis of both EN 310 and EN 789. From the FE analysis, the deformed shape of the proposed structural plywood under load is shown in Figures 6.8 and 6.9. The deformed contour diagram shows the uniformity of deformation for all thickness categories. Tables 6.5 and 6.6 show the MOR and MOE results for EN 789 and EN 310, respectively.

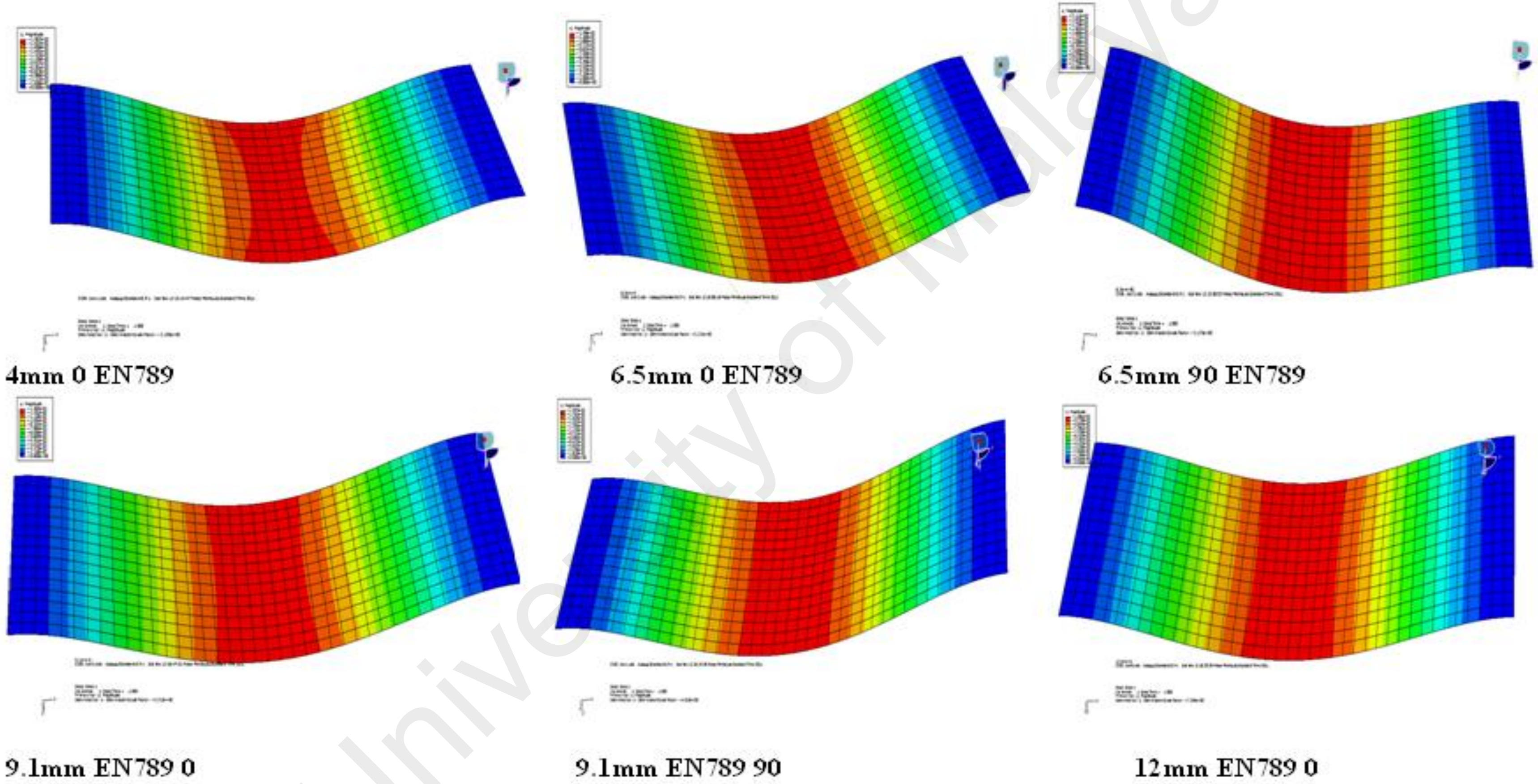
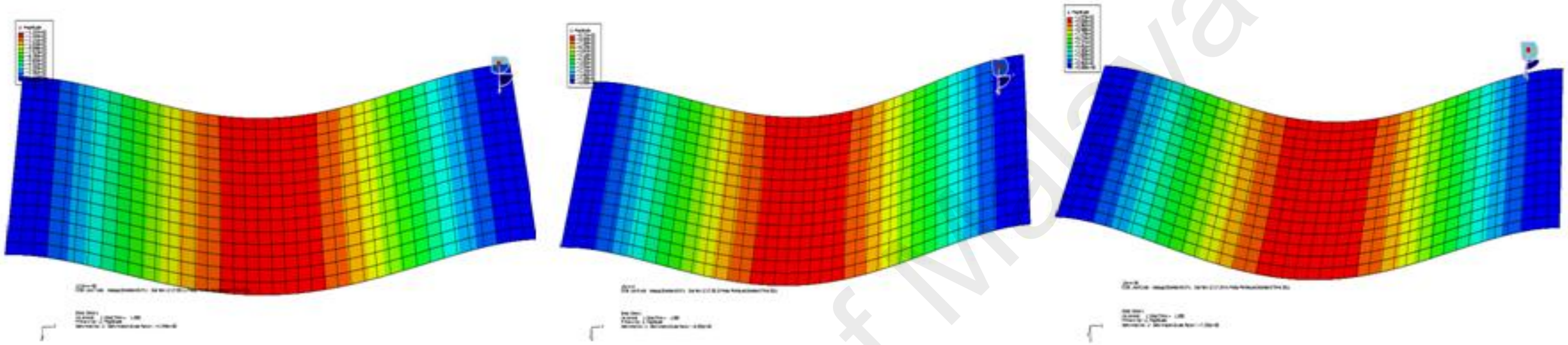


Figure 6.8 (a): Deformation contour diagram of EN 789 for parallel (0°) and perpendicular (90°) specimens for thickness ranging from 4mm to 9.1mm.



12mm EN789 90 | 15mm EN789 0 | 15mm EN789 90

Figure 6.8 (b): Deformation contour diagram of EN 789 for parallel (0°) and perpendicular (90°) specimens for thickness ranging from 12mm to 15mm.

Table 6.5: MOR and MOE of red seraya using EN 789 from FE analysis results

t	MOR From FE Analysis results (N/mm^2)		MOE From FE Analysis results (N/mm^2)	
mm	0°	90°	0°	90°
4.0	56.8	-	11814	-
6.5	45.2	18.7	9003	4202
9.1	44.4	28.2	8912	5254
12.0	41.7	29.6	8648	5632
15.0	40.0	30.3	7921	5625

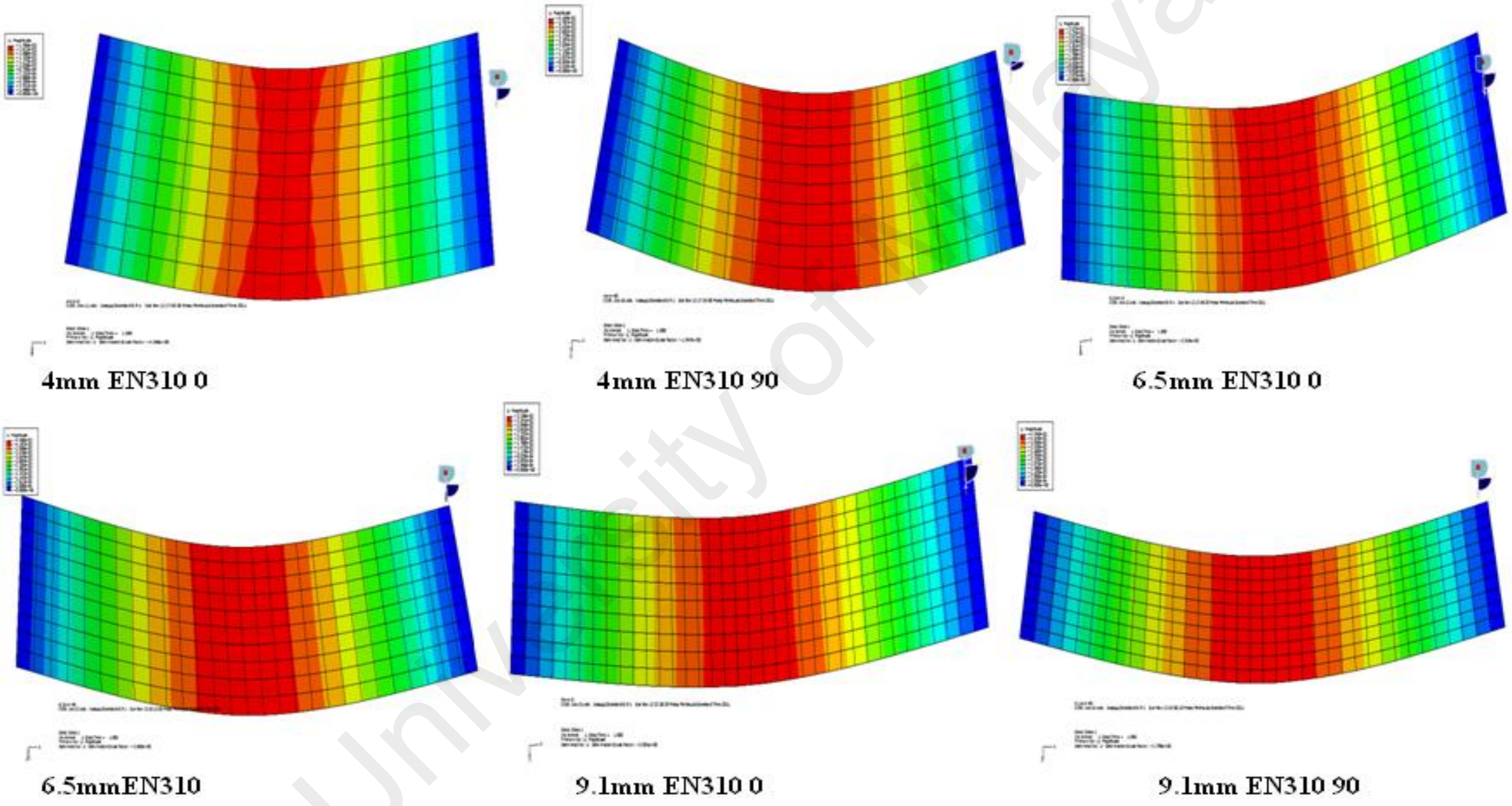


Figure 6.9 (a): Deformation contour diagram of EN 310 for parallel (0°) and perpendicular (90°) specimens for thickness ranging from 4mm to 9.1mm.

Figure 6.9 (b): Deformation contour diagram of EN 310 for parallel (0°) and perpendicular (90°) specimens for thickness ranging from 12mm to 15mm.

Table 6.6: MOR and MOE of red seraya using EN 310 from FE analysis results

t	MOR From FE Analysis results (N/mm^2)		MOE From FE Analysis results (N/mm^2)	
mm	0°	90°	0°	90°
4.0	62.7	13.8	9636	889
6.5	55.4	22.8	8827	2846
9.1	49.7	30.9	8013	3722
12.0	51.6	37.5	7711	4363
15.0	43.9	34.8	7169	4485

6.6 Comparison of MOR and MOE of FE Analysis and Experimental Results

Table 6.7 shows the differences of MOR and MOE between EN 310 and EN 789 of FE analysis and the experimental models. It was found that, overall, the FE results for EN 310 and EN 789 overestimated the MOR and MOE of plywood. The FE models gave readings of greater MOE than the readings from the experimental model for both EN 310 and EN 789, except test specimens of 4.0 mm and 6.5 mm tested according to EN 789.

Table 6.7: Difference in MOR and MOE from experimental and FE analysis results

t	EN 310				EN 789			
	0° (%)		90° (%)		0° (%)		90° (%)	
mm	MOR[a]	MOE[b]	MOR[a]	MOE[b]	MOR[a]	MOE[b]	MOR[a]	MOE[b]
4.0	11.3	6.9	22.5	38.5	16.1	-23.3	-	-
6.5	9.7	36.8	13.6	24.8	5.3	-8.5	3.7	14.4
9.1	6.8	38.0	10.0	21.7	7.0	0.1	6.7	12.8
12.0	7.4	28.3	9.5	21.6	4.5	4.0	6.7	9.4
15.0	3.3	36.5	5.5	21.6	6.0	1.8	3.1	4.1

[a] Difference (%) of MOR = $(MOR_{FE} - MOR_{EX}) / MOR_{EX} * 100$
[b] Difference (%) of MOE = $(MOE_{FE} - MOE_{EX}) / MOE_{EX} * 100$

The MOR readings derived from the FE model based on EN 310 had a maximum value 11.3% when compared to the experimental results for samples stressed parallel to the grain (Table 6.7). At the same time, test specimens stressed perpendicular to the grain were not more than 22.5% higher than the experimental results. On the other hand, the MOR readings from the FE model for EN 789 were not more than 16.1% and 6.7% higher than the experimental readings for tests conducted parallel and perpendicular to the grain, respectively. The overestimates of MOR readings were most probably because the input forces to the FE models were the mean maximum loads from a large number of experimental test specimens.

The MOE readings derived from the FE model for EN 310 were in the range 6.9% to 38.0% higher than the experimental model for specimens stressed parallel to the grain, whereas the FE model readings for specimens stressed perpendicular to the grain were 21.6% to 38.5% higher than the experimental readings. On the other hand, the results of the FE model for EN 789 were 0.1% to 4.0% and 4.1% to 14.4% higher than the corresponding experimental results for bending made parallel to and perpendicular to the grain, respectively. Whereas the FE readings were mainly higher than their corresponding experimental readings, it should be noted that the FE model results based on EN 789 for the 4 mm and 6.5 mm thick panel gave values lower than the respective experimental values. From the contour diagrams in Figure 6.8, it can be seen that the deformed area for 4.0 mm thickness model was not even. This was due to the low bending stiffness of the material that was attributed to the large displacement in the mid-span (Baere *et al*., 2007). Compared to the model developed by Maki (1968), the current FE models are still conservative in predicting the maximum deflection of bending test, especially for EN 310. The overestimation resulting from the FE model was probably because the effects of the roller supports had been ignored. The absence of slipping between the test samples and roller support might have reduced the deflection. As a result, the MOE obtained by FE analysis tended to predict higher readings compared to the experimental results. Another factor that could influence the deformation of plywood was the selection of the shell elements.

For MOR, the discrepancy between the FE readings and experimental readings generally decreased as the thickness of the plywood board increased (Table 6.7). This tendency was more significant in the MOR readings of EN 310. It was also observed that the FE model readings for EN 789 were closer to the experimental results compared with corresponding readings for EN 310. Based on this observation, it became apparent that the FE analysis was more suited to the prediction of the MOR and MOE from the four-point bending test, especially where the test specimen thickness was more than 9.0 mm.

6.7 Relationship between FE Analysis Results and Experimental Results

Linear regressions were used to determine how well a particular test method could predict the MOR or MOE values from another test method (McNatt *el al*., 1990). The MOR and MOE obtained by FE analysis and experimental results for both methods were correlated with each other (Figures 6.10, 6.11, 6.12 and 6.13). The R^2 values attempted through linear regressions range from 0.9726 to 0.9986.

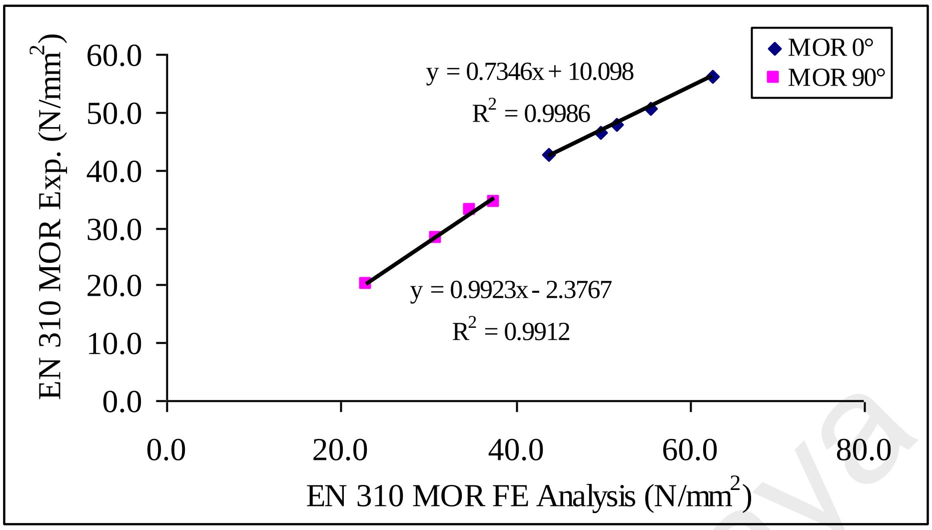


Figure 6.10: Correlation between EN 310 MOR readings obtained experimentally and readings obtained by FE analysis. The data points represent different panel thicknesses.

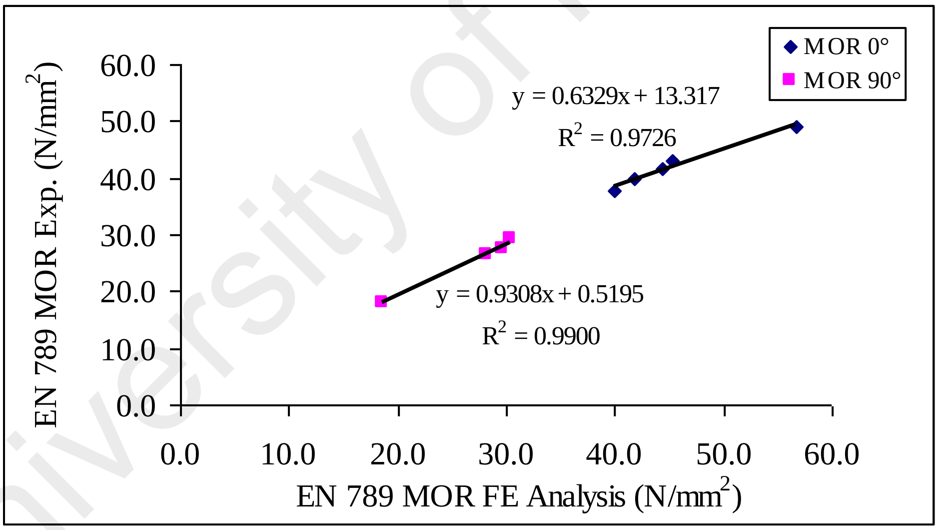


Figure 6.11: Correlation between EN 789 MOR readings obtained experimentally and readings obtained by FE analysis. The data points represent different panel thicknesses.

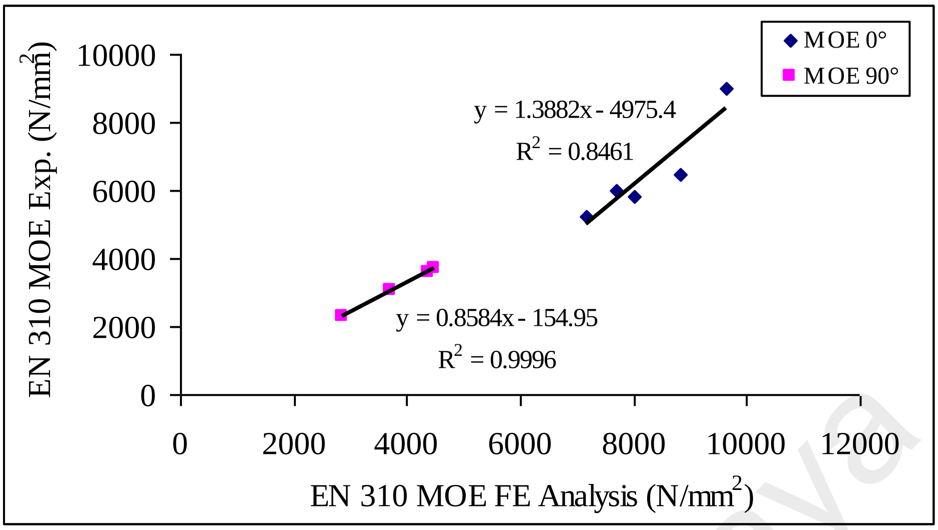


Figure 6.12: Correlation between EN 310 MOE readings obtained experimentally and readings obtained by FE analysis. The data points represent different panel thicknesses.

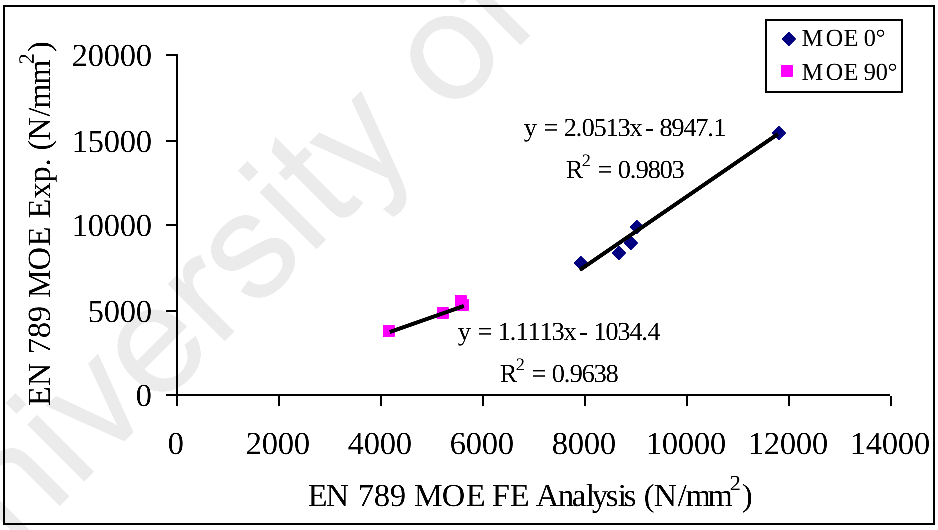


Figure 6.13: Correlation between EN 789 MOE readings obtained experimentally and readings obtained by FE analysis. The data points represent average values from different panel thicknesses.

In addition, the average values of MOR and MOE from each thickness were also correlated between EN 789 and EN 310 for both experimental and FE analysis accordingly, as tabulated in Table 6.8. Based on the correlation coefficients (R^2) in Table 6.8, the correlations between EN 310 and EN 789 FE analysis results were better than the correlations using data from experimental results. This is expected as the FE analysis was not affected by the presence of knots in the structural plywood. Most reports in the literature such as Maki (1968), Masuda & Maku (1970), Nagai *et al.* (2009), Tohgo *et al.* (2001) suggested that FE analysis offers a good solution for solving many problems of industrial wood and wood composite applications.

Table 6.8: Linear regression lines illustrating the relationship between EN 789 and EN 310 of experimental results and FE analysis results

Test Method		Slope	Intercept	Correlation coefficients
Y	X	A	B	R^2
		$MOR_Y = AMOR_X + B$		
EN789 $_{EX (0°)}$	EN310 $_{EX (0°)}$	0.8649	0.086	0.8363
EN789 $_{EX (90°)}$	EN789 $_{EX (90°)}$	0.7956	1.600	0.8874
EN789 $_{FE (0°)}$	EN310 $_{FE (0°)}$	0.7862	3.849	0.9214
EN789 $_{FE (90°)}$	EN789 $_{FE (90°)}$	0.7569	3.504	0.9105
		$MOE_Y = AMOE_X + B$		
EN789 $_{EX (0°)}$	EN310 $_{EX (0°)}$	1.394	-2270.2	0.8246
EN789 $_{EX (90°)}$	EN789 $_{EX (90°)}$	0.879	1790.5	0.9583
EN789 $_{FE (0°)}$	EN310 $_{FE (0°)}$	2.087	-3533.5	0.9810
EN789 $_{FE (90°)}$	EN789 $_{FE (90°)}$	1.178	1003.8	0.9924

* The correlation obtained from mean MOE and characteristic MOR values from five different panel thickness of EN 310 and EN 789. EX – Experimental, FE – Finite element, 0° - Parallel to grain, 90° - Perpendicular to grain.

Results from this preliminary study indicate that FE analysis provides a reliable prediction of MOE and MOR for EN 310 and EN 789. Although, overall, the FE analysis model tended to overestimate the MOE and MOR readings for both EN 310 and EN 789, the correlation between FE analysis results and the experimental results was strong, as indicated by the R^2 values obtained for both EN 310 and EN 789. FE analysis is more suited to predicting the EN 789 bending test results, especially where the plywood sample is more than 9.0 mm thick. However, the predictions of MOR and MOE using FE analysis in this study have exposed a few limitations, such as the predictions of MOR and MOE were entirely dependent upon the material properties and input force that were assigned for the element. This means that the FE analysis fails to study the influence of manufacturing variables, such as the effectiveness of bond between veneers that had great influence on the mechanical properties of the plywood. Furthermore, the input force assumed to be linear elastic. Obviously, this was not true since force is non-linear and variable in this case. Consequently, this could lead to the inaccurate prediction of MOR and MOE.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

From the study that was carried out the following conclusions can be drawn,

i. the maximum MOR of red seraya plywood determined by the EN 789 method was 39% higher than spruce plywood and 38% lower value compared to birch plywood. The MOE of red seraya plywood was 25% lower than birch but about the same compared to spruce. Thus, red seraya can be a suitable alternative for structural plywood.

ii. the mechanical properties of red seraya plywood obtained by EN 310 and EN 789 were significantly different. EN 310 had MOR value of 24% higher and MOE value of 42% lower than that obtained by EN789.

iii. MOR and MOE of EN 789 had a moderately strong correlation with those of EN 310. It was found that the MOR of EN 789 was approximately 0.71 times and 0.57 times whereas the MOE of EN 789 was 1.86 times and 1.33 times of EN 310 for parallel and perpendicular test specimens, respectively. Linear regression correlations derived in section 6.4 can be used to convert the small-scale bending test to the medium-scale bending test. The correlation between EN 310 and EN 789 was influenced by wood species, variation between amount of data and also the quality of the test specimens.

iv. the MOR values obtained from EN 310 and EN 789 FE model when compared to the corresponding experimental results had maximum values not exceeding 23% and 16%, respectively. On the other hand, the MOE from FE models were 39% and 14% higher than the experimental results for EN 310 and EN 789, respectively.

v. it was observed that FE analysis was more suitable to predict the MOR and MOE value of EN 789.

vi. the FE analysis results had a strong correlation with the experimental results (R^2 value ranging from 0.9726 to 0.9986).

7.2 Recommendations for Future Work

Based on the current research results, there are some future research efforts that should be considered. These include the followings,

i. the correlation between EN 310 and EN 789 should be done with different wood species to further study the influence of wood species on both bending test methods.

ii. the correlation equations between EN 310 and EN 789 should be further verified for its accuracy of prediction and its reliability.

iii. more study and research should be carried out to reduce the limitations in the FE models.

iv. the effectiveness of the bond between veneers in FE analysis should be studied further to verify its influence on the mechanical properties of plywood.

v. the results of the FE analysis of the current research indicate that the FE analysis program had underestimated the deflection of both bending tests. Therefore, investigation into the effect that influenced the deflection of the bending test should be studied in order to improve the FE model. Regarding this, further research can be done on EN 310 and EN 789 with the presence of the roller supports, loading nose and moisture content to study the MOR and MOE of plywood samples.

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PUBLICATION

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Comparison of Eurocodes EN310 and EN789 in Determining the Bending Strength and Modulus of Elasticity of Red Seraya Plywood Panel

S.F. Tsen and M. Zamin Jumaat

Abstract—The characteristic bending strength (MOR) and mean modulus of elasticity (MOE) of tropical hardwood red seraya (Shorea spp.) plywood were determined using European Standard EN310 and EN789. The thickness of the test specimen was 4.0mm, 7.0mm, 9.0mm, 12.0mm and 15.0mm. The experiment found that the MOR of red seraya plywood in EN310 is about 12% to 20% and 7% to 24% higher than EN789 whereas MOE were about 28% to 41% and 30% to 36% lower than those obtained from EN 789 for test specimens parallel and perpendicular to the grain direction. The linear regression shows that MOR and MOE for EN789 is about 0.8 times less and 1.5 times more than EN310. The experiment also found that the MOR and MOE of EN310 and EN789 also depend on the wood species that used in the experiment.

Keywords—Bending strength, Modulus of elasticity, EN310, EN789

I. Introduction

CONSTRUCTION and industrial plywood has traditionally been made from softwoods, but the current Wood Handbook has listed and classified the strength of a large number of hardwoods that are suited for a similar purpose [1]. Red seraya (*Shorea* spp.), a tropical hardwood also known as light red meranti, is one of the hardwoods listed. Red seraya species is widely used in plywood as it is easily machined, dried without degradation and its smooth surface is suited to all kind of finishes. However, there have been few studies on the strength properties of plywood made from Malaysian red seraya timber originating from Sabah. The strength properties of plywood are normally determined using different testing standards in different region of the world. In Europe, structural wood-based panels are regulated by European Standards BS EN13986, Wood-based panels for used in construction - Characteristics, evaluation of conformity and marking. While in US, structural panels have to comply with the Performance Standard PS 2–07 for wood-based structural-use panels (NIST 04) where ASTM method were adopted. In European Standards [2], there are two testing methods that can be used to determine the strength properties for plywood, EN310 (three-point bending test) and EN789 (four-point bending test).Generally, the strength properties obtained using different testing methods are considered to be equivalent. However, the different in test set up may affect the strength properties of wood-based panel. Thus, the objective of this paper is to compare the MOR and MOE between EN310 and EN789 using red seraya plywood panel.

II. Material and Method

A. Material

Logs of red seraya from the Sabah rainforest were harvested and manufactured into 1200mm by 2400mm plywood sheets, with a nominal thickness of 4.0 mm (3 plies), 6.5 mm (5 plies), 9.0 mm (7 plies), 12.0 mm (9 plies) and 15.0 mm (11 plies).

B. EN789 (Four-Point Bending Test)

The plywood was cut according to the cutting plan (Fig 1) in the four-point bending test method of EN789 for the determination of mechanical properties of wood based panels. The cutting plan shows a batch of four plywood panels for specimen sampling. There were a total of 8 batches, with each batch consisting of 4 panels of plywood. One test piece parallel (0) to the grain and one perpendicular (90) to the grain were cut from each panel. The specimens for the bending test in each direction were not sampled from the same position in different panels of the same batch; only one specimen was sampled from each panel. The width of the test specimen was 300±5 mm and the length was (l_2 + l_3) as depicted in Fig. 2, which shows the arrangement of the bending test according to EN789.

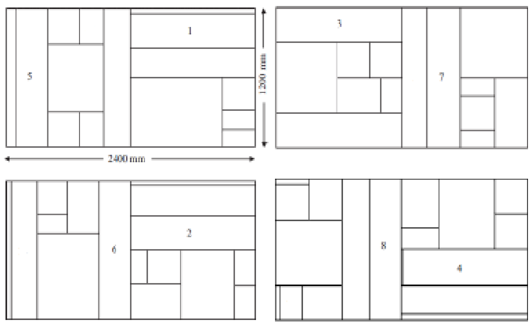

Fig. 1 The cutting plan shows on a sample of four panels for sampling of specimens according to EN 789. Test specimen no.1 to no.4 is longitudinal grain direction while test specimens no.5 to no.8 is transverse grain direction

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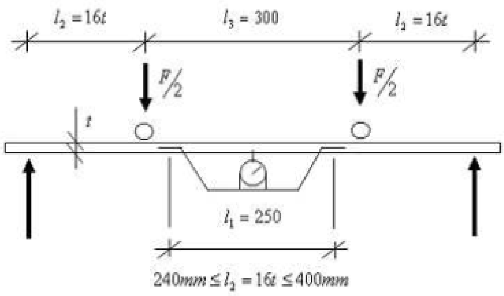

Fig. 2 Arrangement for the bending test, Dimensions are in mm

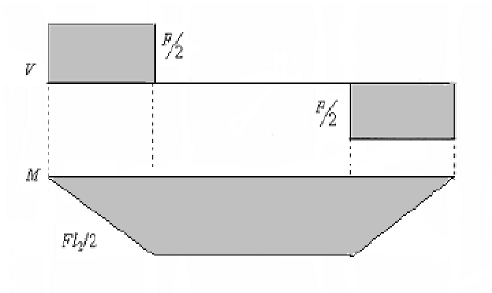

Fig. 3 Shear force (V) and bending moment (M) diagram of EN789.

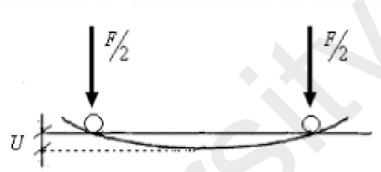

Fig. 4 Measurement of deflection (U) of EN789

The deflection of the mid-span was measured and the load-deflection curves were plotted. The MOR of the test piece was calculated from the following formula:

$$MOR = \frac{3F_{max} l_2}{bt^2} \quad (1)$$

Where, MOR is bending strength (N/mm^2), F_{max} is maximum load (N), l_2 is 16 times thickness (mm), b is the width of test specimen (mm), t is thickness of test specimen (mm) as depicted in Fig. 2. The MOE of the test piece was calculated from the following formula:

$$MOE = \frac{3(F_2 - F_1) l_1^{\,2} l_2}{4bt^3 (U_2 - U_1)} \quad (2)$$

where $(F_2 - F_1)$is the increment of load on the straight line portion of the load-deflection curve, where F_1 was approximately 10% and F_2 was approximately 40% of the maximum load F_{max} , $(U_2 - U_1)$ is the increment of deflection corresponding to $(F_2 - F_1)$ in load-deflection curve. The MOR used in this paper was the 5-percentile value while MOE was the mean value of the results for 8 batches.

C. EN310 (Three-Point Bending Test)

There were a total of 12 panels of plywood for each thickness in the cutting plan of EN310 (Fig. 5). Each plywood panel was cut into two groups of bending test specimens, 6 pieces of parallel and 6 pieces of perpendicular grain directions. The test specimen is rectangular with width b, (50±1)mm and length is 20 times the nominal thickness (t) plus 50mm. The test specimens are conditioned to a constant mass in an atmosphere with relative humidity (65±5)% and temperature (20±2)^{0}C. A cylindrical loading head with diameter (30.0±0.5)mm was placed parallel to the supports. The test specimen was set between the adjustable supports with the centre point under the load as shown in Fig. 6. The load that applied to the test specimen was adjusted so that the maximum load reached within (60±30)s throughout the test.

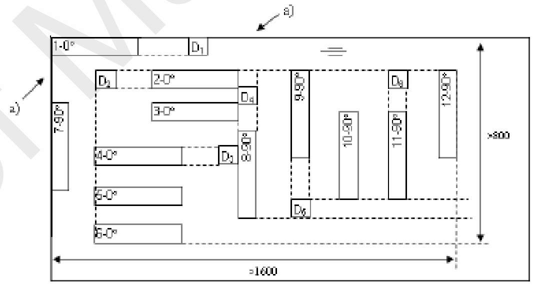

Fig. 5 The cutting plan of EN310, Test piece number 1 to 6 indicates the orientation of face plies parallel to the span whereas test piece number 7 to 12 indicates the orientation of face plies perpendicular to span. The dimensions are in milimetres. Symbol a) means outer edge trimmed

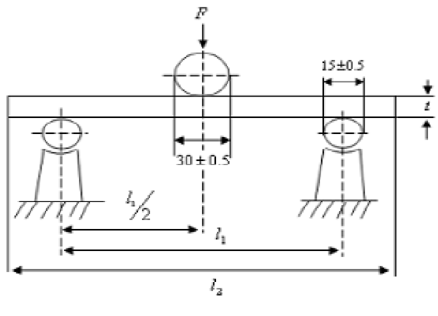

Fig. 6 Bending apparatus setup. Dimensions are in mm

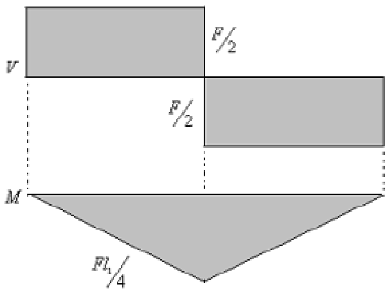

Fig. 7 Shear force (V) and bending moment (M) diagram of EN310

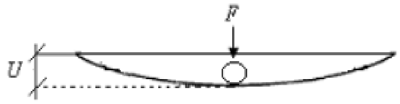

Fig. 8 Measurement of deflection (U) of EN310

The deflection of the mid-span was measured and the load-deflection curves were plotted. The MOR of the test piece was calculated from the following formula:

$$MOR = \frac{3F_{\max} l_1}{2bt^2} \quad (3)$$

Where F_{Max} is maximum load (N), l_1 is the distance between the centres of two supports (mm), b is the width of the test pieces (mm), t is the thickness of the test pieces (mm) as depicted in Fig. 6. The modulus of elasticity (MOE) of each test pieces is given by formula:

$$MOE = \frac{l_1^3 (F_2 - F_1)}{4bt^3 (U_2 - U_1)} \quad (4)$$

Where l_1, b and t is as defined in above and depicted in Fig. 6. $(F_2 - F_1)$is the increment of load on the straight line portion of the load-deflection curve, where F_1 was approximately 10% and F_2 was approximately 40% of the maximum load F_{max} , $(U_2 - U_1)$ is the increment of deflection corresponding to $(F_2 - F_1)$ in load-deflection curve.

The MOR for all test specimens were analyzed using the 5-percentile value and the MOE for all test specimens were analyzed using mean values.

III. Results and Discussion

TABLE I
STRENGTH AND STIFFNESS PROPERTIES FOR RED SERAYA (*SHOREA SPP*) USING EN789

t	Plies	MOR (Nmm^{-2})		MOE (Nmm^{-2})	
(mm)		0	90	0	90
4	3	48.9 (3.3)	9.5 (4.0)	15202 (4.1)	-
6.5	5	42.9 (4.0)	18.0 (3.6)	9686 (4.5)	3539 (3.2)
9	7	41.5 (3.5)	26.3 (3.5)	8904 (4.1)	4659 (3.7)
12	9	39.9 (2.1)	27.7 (3.0)	8319 (4.6)	5146 (2.5)
15	11	37.7 (4.0)	29.4 (2.5)	7782 (3.3)	5402 (4.2)

[a]MOR values are the 5-percentile of 32 readings. MOE values are the means of 32 readings, with the % coefficients of variation in brackets. t – thickness, 0 – Parallel to wood grain direction, 90 - Perpendicular to wood grain direction. Result of 4mm 90 is not displayed due to large deflection.

TABLE II
STRENGTH AND STIFFNESS PROPERTIES FOR RED SERAYA (*SHOREA SPP*) USING EN310

t	Plies	MOR (Nmm^{-2})		MOE (Nmm^{-2})	
(mm)		0	90	0	90
4	3	56.3 (5.7)	11.2 (10.2)	9010 (6.3)	642 (18.6)
6.5	5	50.5 (5.0)	20.2 (6.4)	6454 (5.1)	2280 (8.5)
9	7	46.5 (3.0)	28.1 (4.6)	5807 (2.9)	3058 (6.1)
12	9	48.0 (3.5)	34.3 (4.5)	6008 (5.1)	3589 (4.6)
15	11	42.5 (1.8)	33.0 (2.9)	5253 (2.4)	3687 (1.5)

[a]MOR values are the 5-percentile of 144 readings. MOE values are the means of 144 readings, with the % coefficients of variation in brackets. t – thickness, 0 – Parallel to wood grain direction, 90 - Perpendicular to wood grain direction.

TABLE III
DIFFERENCE OF MOR AND MOE BETWEEN EN310 AND EN789 IN PERCENTAGE (%)

t	Plies	MOR (Nmm^{-2})		MOE (Nmm^{-2})	
(mm)		0 (%)	90 (%)	0 (%)	90 (%)
4	3	-15.2	-17.3	40.7	-
6.5	5	-17.8	-12.1	33.4	35.6
9	7	-12.0	-6.7	34.8	34.4
12	9	-20.4	-23.6	27.8	30.3
15	11	-12.6	-12.2	32.5	31.7

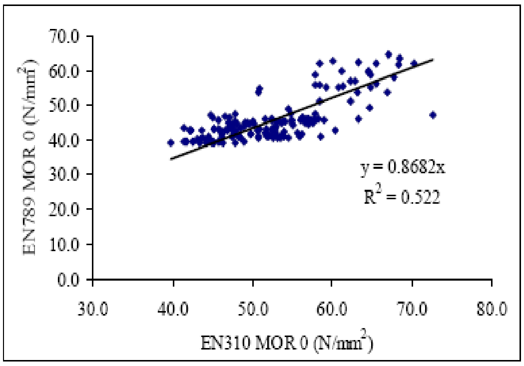

Fig. 9 Linear regression lines illustrating the dependence of MOR 0 for EN789 to EN310

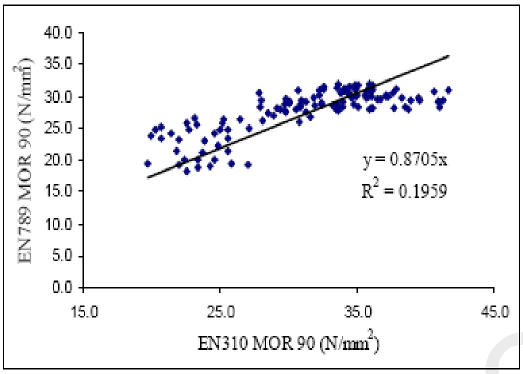

Fig. 10 Linear regression lines illustrating the dependence of MOR 90 for EN789 to EN310

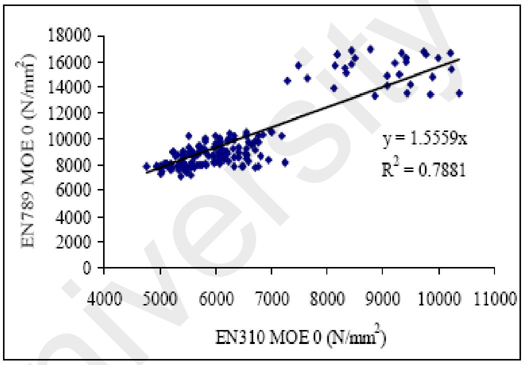

Fig. 11 Linear regression lines illustrating the dependence of MOE for EN789 to EN310

The MOR and MOE of three-point bending and four-point bending test have been studied experimentally. Table I and II shows the MOR and MOE of 5 different plywood thickness obtained by EN310 and EN789.

In general, the MOR obtained by three-point bending test is higher than four-point bending test. The overestimation of MOR of three-point bending is due to the evaluation point of bending strength and also the depth and length of test specimen. The evaluation point of bending strength for three point bending test is located pointwise at the mid-span whereas the four point bending test is located at the weakest point between the loading noses [5].

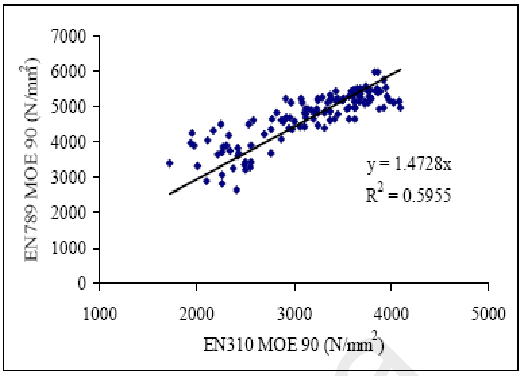

Fig. 12 Linear regression lines illustrating the dependence of MOE 90 for EN789 to EN310

Thus, the strength properties obtained by the three-point bending test are usually larger than those obtained by the four-point bending test [6].The MOR values obtained by EN310 are larger than EN789. The overestimation of MOR for EN310 compared to EN789 was about 12% to 20.4% and 6.7% to 23.6%, for specimens parallel and perpendicular to grain, respectively.

It was expected that MOE under three-point bending test would be smaller than four-point bending [6]. In four-point bending test, the evaluation point of deformation was located in the uniform bending moment area, this could highly reduced the influence of deformation induced by shear force. In addition, the span/depth ratio for four-point bending test was larger than three-point bending. Hence, the MOE of four-point bending would be larger than three-point bending test. Reference [7] had reported that a three-point bending test had underestimates about 19% the MOE value in relation to a four-point bending test. This is due to the influence from the shear effect and the indentation effect of the loading head and the supports are neglected. Table III shows the underestimation (%) of MOE for EN310 compare to EN789. The EN310 had significantly underestimated the MOE in range 27.8% to 40.7% and 30.3% to 35.6% for both test specimens parallel and perpendicular, respectively.

The MOR and MOE of EN789 were correlated with MOR and MOE of EN310, respectively. The correlation was tabulated in Fig. 9 to Fig. 12. The linear correlation is considered to be significant as the data was in large amount. Reference [8] had reported that the MOR of Birch plywood for EN789 is about 0.7 times of EN310 whereas the MOE is about 1.3 times of EN310 for both parallel and perpendicular test specimen. In comparison with the current results, the MOR for EN789 is 0.9 times of EN310 whereas the MOE is 1.5 times of EN310 for both parallel and perpendicular test specimen. It was also observed that the coefficient correlation (R^2) for parallel test specimens is stronger than perpendicular test specimens for both MOR and MOE.

IV. CONCLUSION

Plywood tested under EN310 had MOR larger and MOE smaller than EN789. In addition to the already known dependence of MOR and MOE to the location of evaluation point, radius of support and loading noses, a biasing effect of different wood species was observed in this study. We found that the different wood species could influence the MOR, MOE and correlation between EN310 and EN789.

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