APPLICATION OF EUROCODE 5 RECOMMENDATIONS TO THE BOLTED JOINTS OF SRI LANKAN TIMBER SPECIES

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by

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DECLARATION

I, Arawinda Dayanath Nawagamuwa, hereby declare that the content of the thesis is the original work carried out over a period of two and half (2 ½) years at the Department of Civil Engineering, University of Moratuwa. Whenever others' work is included in this thesis, it is appropriately acknowledged as a reference.

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SUMMARY

Eurocode 5 “Common Unified Rules for Timber Structures” is the latest structural design code, which provides guidelines for structural timber design. Eurocode 5 procedures for the design of bolted and nailed timber joints are based on an analytical model, which developed by Johansen in 1949. This model is often referred to as European Yield Model (EYM) and provides more reliable design procedure than older empirical models.

This thesis provides information of the research work, which was carried out at the University of Moratuwa to check the applicability of Eurocode 5 design procedure to bolted timber joints made from local timber species. The test programme was conducted using two local timber species and three bolt diameters, which are commonly used in the construction industry, with wider range of joint geometries while most of past research were conducted using only one or two joint geometries.

Based on the results obtained from this test programme, it was possible to propose a new model for the determination of embedment strength of local timber species and a modification factor, which is determined based on the joint geometry. This modification factor modifies the Eurocode 5 predictions for the strength of bolted timber joints of different geometry to reasonably acceptable conservative values.

Reasons and the methodology of this research programme are explained briefly in the first chapter while the second chapter describes, in detail, the background for this research programme. From the third chapter the reader is able to obtain much information on Eurocode 5 and European Yield Model, which are found from a thorough literature survey carried out on the available research papers, journals and textbooks. Scheduled experimental programme adopted according to the recommendations of previous research and guidelines obtained from the literature survey is provided in Chapter 4. Chapters 5 and 6 provide the results obtained from embedment strength test programme and joint strength test programme and the analysis of those results. Conclusions based on the analysis and recommendations for further works are provided in chapter 7.

CONTENTS

Chapter One

INTRODUCTION

Chapter 1: INTRODUCTION

As a guideline for structural design and construction of timber elements, Sri Lankan engineers use the British Standards. Design guidelines provided in British Standards are based on several empirical approaches developed by early researchers. British Standards used different empirical approaches to provide design specifications for bolted and nailed timber joints although the behaviour of these fastener types is similar to each other when they transfer applied load through the connection. This causes the lack of confidence about the design specifications provided in these structural timber design codes. As a result, an analytical approach was developed recently to provide the guidelines for structural timber design with above mentioned fastener types. Latest revision of British Standards used this analytical approach to provide its guidelines for structural timber design. More recent structural timber design codes such as Eurocode 5 also use this analytical approach.

Although this new analytical approach provides more versatile design procedure, similar to old empirical approaches, supporting guidelines for this method were developed based on some empirical approaches, which were developed by research conducted using large number of European softwood species and lesser amount of tropical hardwood species. For example, only two tropical hardwood species were used to develop the formulae for embedment strength while seven European softwood species were used (Smith et al. 1987). Therefore, it is necessary to check the applicability of these guidelines to the local timber species in which all species belong to hardwood category.

Therefore, this test series was carried out to check the applicability of Eurocode 5 recommendations for bolted timber joint design using the local timber species. According to a thorough literature survey and market survey, timber species, bolt types, member sizes and bolt diameters were selected. Experimental results obtained from the test series were then compared with the Eurocode 5 recommendations.

In 1998, Dias et al. conducted a preliminary test programme to check the applicability of Eurocode 5 recommendations to bolted timber joint made from Sri Lankan timber species. The favourable results, which were obtained from that test programme, prompted to conduct an expanded test programme. Based on the recommendations proposed by Dial et al. and results obtained from thorough literature survey and market survey, test programme was divided into two parts namely embedment strength test programme and joint strength test programme. Embedment strength is a system property of joint and it depends on the bolt diameter and the density of the species and Eurocode 5 recommendations for the joints strength are based on embedment strength and the bolt yield moment. Because embedment strength depends on density of timber species, it is necessary to conduct test programmes to check the applicability of recommendations given in Eurocode 5 to determine the embedment strength to the local timber species. Embedment strength test programme was carried out using five local timber species and three bolts diameters for several member thickness according to EN 383:1993. Based on the results of this test programme a new model is proposed for the determination of embedment strength of local timber species.

Two timber species and three bolt diameters were selected for the joint strength test programme. Symmetrical double shear joints were loaded in both parallel and perpendicular to grain directions according to the specifications given in BS 6948:1989. According to results obtained from this test programme, a modification factor, which is based on the joint geometry, is proposed to modify the Eurocode 5 prediction for the bolted timber joints.

Following chapters describe the background to this test programme, literature review conducted on available research papers, structure of the experimental programme and the results and discussion on results obtained from two test series. Conclusions, which are drawn from analysis of test results and recommendations for further works are also included.

Chapter Two

BACKGROUND

Chapter 2: BACKGROUND

2.1 INTRODUCTION

This chapter briefly discusses the behaviour of bolted/nailed timber connections, factors affecting the strength of bolted connections and the change of structural timber design procedure from empirical models to the analytical models, which give more realistic design methods. Also, design method proposed by the Eurocode 5 is briefly discussed.

2.2 NECESSITY OF BETTER KNOWLEDGE OF STRUCTURAL BEHAVIOUR OF TIMBER

Various forms of round pins are used to connect structural members made from many different materials. These connections are called mechanical connections because they use the mechanism of the pin to transfer loads between members. Common forms of pin-type joints are bolts, nails and dowels. The bolted connection is an important and common connection type used in timber construction. It is quick and easy to install, allows field assembly with no surface preparation. One only needs to be able to drill properly aligned holes, install bolt, and provide finger tightening of the nut. Although, the bolted joint is simple in appearance, its behaviour under load is quite complex.

The strength of timber connections depends not only on material properties such as timber bearing strength and fastener bending yield strength and connection geometry such as member dimensions and fastener diameter, but also on the duration of the load applied to the connection. Timber has a property of exhibiting greater strength for shorter duration loads than longer sustained loads. Table 2.1 summarises the various factors that affect the strength of timber connections.

The fundamental requirement for efficient design of structural timberwork, whether it is on working stress approach or a limit state basis, is the knowledge of the load-deformation and strength properties for various types of mechanical joints. Usually attention was paid on the effects of stress concentrations resulting from the presence of a load applied to a localized region in a member containing a hole. This behaviour is a function of material geometric factors such as timber species, bolt diameter, end/edge distances, spacing and member of bolts. The lack of consideration of salient features of connection design and fabrication can lead to disastrous structural consequences. In fact, more than 80% of all timber structure failures initiate at connections (Kermani, 1999).

Unfortunately the data on the strength and stiffness of many types of mechanical fastenings for timber are rare to find. Although numerous attempts have been made to develop predictive relationships for strength and stiffness of some joint types, most of them have been aimed to develop empirical models (McLain and Thangjitham, 1983). This empiricism is mainly due to the complexity of the interaction of a fastener in an orthotropic, non-homogeneous material such as timber, and resulting in the lack of a unified failure theory for timber.

It is prohibitive to obtain by mass testing of joint specimens, all the information on mechanical joints required for inclusion in design codes. This is because of many possible combinations of geometric, material, loading and environmental variables (Table 2.1) that must be considered. Although, during the past century, several studies on bolted connections have been conducted, each study has investigated one or more of the properties that affect connection behaviour. Furthermore, current information is limited and difficult to analyse due to the variation of test procedures and test geometries that have been adopted by research in the past. To undertake a new programme of testing covering the full range of timber species, joint types and jointing systems would be massive and a very expensive exercise. A better approach was considered to be the use of appropriate analytical modelling techniques, which would enable characteristic properties of joints to be predicted from knowledge of joint geometry, and certain basic material properties of the components themselves. As a result, there has been considerable research over the last six decades aimed at providing suitable analytical models, which predict the short-term strength and/or stiffness properties under lateral loading.

Table 2.1: Factors governing the strength of bolted timber connection

Internal Factors	Mechanical Properties	Joint member	Compressive strength Specific gravity
		Fastener	Bending strength Yield strength
	Joint	Diameter of fastener Thickness of joint members Ratio of thickness/diameter Number of fasteners Pattern Spacing, end & edge distances Number of shear planes Size of pre-drilled holes	
	Other than mechanical properties	Coefficient of friction Moisture absorption Natural defects	
External Factors	Applied Load	Type	Lateral or withdrawal
		Direction	Parallel Perpendicular Other
		Duration	Short Medium Long
	Service Conditions	Moisture content Temperature Humidity	

2.3 DEVELOPMENT OF STRUCTURAL TIMBER DESIGN CODES FROM EMPIRICAL TO ANALYTICAL MODELS

Sri Lankan engineers and designers use BS 5268:Part 2: 1984 "Code of practice for permissible stress design, material and workmanship" for timber design and construction. In Britain, softwoods are predominantly used for timber construction and therefore, BS 5268:Part 2: 1984 has given its priority for softwood design although it contains guidelines for hardwood design. In Sri Lanka, most of timber species, which are used in construction industry, belong to the hardwood category. Softwoods are used for only decorative works, partitions, temporary and false work. Furthermore, the range of hardwood included in BS 5268:Part 2: 1984 is quite limited. As a result, designers have to follow the recommendations of BS 5268:Part 2: 1984 but use alternative species.

Until recently, BS 5268:Part 2: 1984 tabulated the capacity of dowel type (nailed/bolted) fasteners based on empirical data obtained by testing typical joints under specific conditions and for particular geometries. Empirical models, are however limited in their applications, in that they are restricted to a particular range of design parameters and hence cannot be used with confidence for different materials and joint geometries.

As the design community turns towards new approaches in philosophy and methodology, a major stumbling point is lack of information on the strength of mechanically fastened joints. Current design values for many fasteners are based solely on limited empirical results. For some fasteners such as bolts and timber connection design loads for many combinations of member and fastener sizes are based on extrapolation of existing data. The uncertainty due to extrapolation has resulted in typically conservative design values, which for low carbon steel bolts, are aimed at keeping the service load well below the joint proportional limit.

2.4 EUROPEAN YIELD MODEL (EYM) AND EUROCODE 5 (EC5)

More recently, countries in Europe adopted a unified code named European Code. Eurocodes are civil and structural engineering design standards, that are published by the European Committee for Standardisation (CEN). Among the nine Eurocodes, Eurocode 5:Part 1.1 (EC5) for timber structures was published in the UK in late 1994 in the draft form. The publication of the definitive EC5 was planned for around 2001 and is expected to be used in parallel with BS 5268 until the year 2005. At the transition, BS 5268 will not be withdrawn but is likely to be termed ‘obsolete’. In this state it would not be updated and as such would become less usable with time. The BS 5268:Part 2: 1984 was first published in 1984 and was revised in 1988 and 1996. The latest revision has included the EC 5 recommendations for dowel type joints. Deign values for nailed, screwed, bolted or dowel joints have been changed in the 1996 revision of BS 5268:Part 2 to bring them in line with EC5. EYM based equations are also the basis of reliability based codes in the United States (McLain et al. 1993, Wilkinson 1993).

Eurocode 5:Part 1-1 “Common unified rules for timber structures” (EC5) uses analytical model referred to as European Yield Model (EYM) as the basis for the calculation of lateral load capacity of dowel type joints such as nailed and bolts. Assuming both fastener and timber are ideal rigid-plastic materials, Johansen (1949) derived the EYM, which is capable of predicting ultimate and yield strength of joints with dowel type fasteners. This analytical model describes a set of yield modes that are based on the bending resistance of the fastener, the embedment strength of the member material, some geometric parameters of the joints and assumed mechanical relationships and thus gives a rational approach to design and is adaptable to various material properties. These predicted failure loads are due to either bearing failure in the timber members or simultaneous development of a bearing failure in the timber members and plastic hinge formation within the fastener. The minimum of the failure loads determined gives the resistance of the joint. The exact failure mode is governed by the joint geometry and the material properties such as fastener yield moment and embedment strength of the joint member material.

However, as local timber species are not incorporated in above codes, they do not guide the Sri Lankan designers as well, apart from broadly providing design procedure. Hence the designer has to guess or use his discretion to decide suitable values for strength data of local timber species. This could lead to either conservative designs or serious structural failures.

In permissible stress design, as used in BS 5268:Part 2:1984, the permanent loads and the characteristic values of the variable loads on a structure are already used to derive the stress in its various components. The designer then ensures that these stresses do not exceed the permissible values for the materials, which are computed from their characteristic values, reduced by appropriate safety factors and tabulated in the code.

Most of specification provided in EC5 for the design of timber connections are given in the form of formulae, rather than in the form of tables as given in BS 5268:Part 2. A number of formulae, provided to determine the characteristic properties of joints, include appropriate modification and safety factors. Therefore, it is possible to apply the EC5 design method for different material types by applying suitable modification and safety factors.

EC 5 recommendations for the design of bolted joints consider limiting the deformation of the joint and limiting the load carrying capacity of the joint as two separate design considerations. Unlike in the empirical models, where an appropriate point of load-deformation curve is taken as the limiting load, the slip in the joint is not incorporated within the yield model. Instead the deformation of the joint is dealt with separately under serviceability conditions.

2.5 APPLICABILITY OF EC5 TO BOLTED JOINTS OF LOCAL TIMBER SPECIES

Although EC 5 provides better design procedure for bolted timber joints, it is essential to decide the appropriate safety and modification factors to bring EC5 to suit local timber species. Carrying out a test programme covering all the factors affecting the behaviour of bolted joints (Table 2.1) is massive and expensive. Hence this research programme was designed to test single bolt three member symmetrical double shear joints made from Ginisapu and Kumbuk, loaded in both parallel and perpendicular to grain directions. The project investigates the effect of bolt diameter, thickness ratio, loading direction and density of joint members to the strength of the joint and aims to modify the EC5 recommendation by applying suitable factors to suit local species.

Chapter Three

LITERATURE REVIEW

Chapter 3: LITERATURE REVIEW

3.1 GUIDELINES FOR BOLTED TIMBER DESIGN AND THEIR BASIS

In the past the working load design values for bolted joints have been determined from the results of short duration tests on relatively small numbers of replicate joints. Some approaches made estimates of lower percentile value, eg: lower first percentile value, assuming a normal distribution, and these were then divided by a factor to account for safety and workmanship and to reduce the strength to an equivalent long-duration value. Data available from the above tests are generally insufficient to enable reliable estimates.

3.1.1 BS 5268:Part 2:1984

BS 5268:Part 2:1984 uses the working stress approach to provide design resistance values for structural timber joints based on experimentally fit empirical data.

The design data for nailed and bolted joints presented in BS 5268:Part 2:1984 have been obtained by substituting basic material properties into appropriate empirical equations. The basic lateral load, *(p)*, for nailed timber-to-timber joints are based on work by Brock in 1950's using the equation:

$$p = 262\frac{Gd^2}{Load\ Factor} \quad \text{N} \qquad \text{(Eq. 3.1)}$$

where,

d = nail diameter in mm
G = specific gravity

Load factors were selected as 3.0 for solid timber and 4.0 for hardboard (Hilson et al. 1990). The values of G vary from 0.24 to 0.43 depending on the strength groups.

The basic lateral loads for bolted joints loaded parallel to the grain were derived from the original work by Trayer in 1932 using the equation:

$$p = 0.8\frac{K_1 f_{//} l d}{2000} \quad \text{kN} \qquad \text{(Eq. 3.2)}$$

where,

d = bolt diameter in mm
l = twice the thickness of member under consideration in mm
$f_{//}$ = basic bolt bearing stress parallel to the grain in N/mm^2
K_l = modification factor which varies with the l/d ratio and the strength class of the timber

The values of $f_{//}$ vary from 5.5 to 13.9 in N/mm^2 depending on the strength group.

Trayer's design loads were based on not exceeding the experimental proportionality limit load (Hilson et al. 1990). Thus, there is no consistency in the methods used for deriving design loads for nailed and bolted joints in BS 5268:Part 2:1984.

The British Standards have now incorporated the European grading system and terminologies. The most recent revision of Part 2 of BS 5268 in 1996 was to bring this code as close as possible and to run in parallel with EC5. The overall aim has been to incorporate material specifications and design approaches from EC5. In this respect design methodology for dowel-type connections has been subjected to considerable change and while it remains permissible stress design method, it takes the EC5 approach to design of nailed, bolted and dowelled connections.

3.1.2 NDS-86

The NDS-86 also uses empirical equations fit to varied test data to provide allowable lateral strengths for nail, bolt and wood-screw and lag-screw connections. These equations were developed at different times by different workers resulting in an inconsistent basis for design loads between fastener types. Also, allowable connection strengths have been derived from experimental results using disparate methods (McLain et al. 1993).

The design values for bolted connections that are published in the NDS-86 are based on research conducted by Trayer in 1932.

The connection design loads for bolted connections that are published in the NDS use a formula similar to what Trayer recommended. The only difference is that the variability is stated separately from the factor of safety. The NDS adjusts the mean ultimate stress (compression parallel to grain) by following multiplicative factors:

- 1-1.645*CV* (where *CV* is the coefficient of variation of the ultimate stress parallel to grain of green clear wood published in ASTM D 2555); this formula calculates a 5th percentile lower exclusion limit.
- 1/1.9 for duration of load adjustment and factor of safety
- 0.8 adjust the seasoned lumber condition
- factor to account for connection *L/D*
- fastener bearing area (*LD*)

If the *CV* = 27% on green strength in parallel to grain, the two methods give similar results. Furthermore, the connection geometries in the tables have side members only half the thickness of the central members.

NDS-86 considers the load carrying capacity of two member connections is equal to half the load that would be carried by three member connections (Patton-Mallory 1989).

EYM is the basis for conversion of NDS-86 to an equation format in the NDS-91, since it would be able to predict the yield strengths for various connection geometries and material combinations for two and three member joints (Wilkinson 1993). Many of these connections are not addressed by NDS-86.

3.1.2 Trayer's Work

Trayer tested three member connections loaded in compression with side members one half the thickness of the central member and a range of main member thickness to bolt diameter ratio from 2 to 12 (Patton-Mallory et al. 1997). Bolt diameters ranged from ¼ inch to 1 inch and were of two yield strengths only (Soltis et al. 1986), whereas larger diameter bolts and different yield strengths are usually used today.

The characteristic connection load in Trayer's research was the mean proportional limit load of connections with steel side members. Connections were made from both green and seasoned lumber. Also, limited numbers of connections with wood side members were also tested.

Trayer proposed a method for determining allowable bolted connection loads from clear wood compression strength. For softwoods, he recommended adjusting mean green parallel to grain ultimate compression stress by the following factors:

- 1.2 to adjust the seasoned condition
- 0.8 to account for differences between softwood and hardwoods
- 0.8 to adjust short-term to long-term duration
- 0.8 to adjust steel side plates to wood side plates values
- 1/2.25 to account for variability and as a factor of safety
- factor to account for connection *L/D* (where *L* is length of fastener bearing in the thicker member, and *D* is bolt diameter)
- fastener bearing area (*LD*)

Historically, most changes to design values have arisen from research topics, such as effect of metal side plates and interpretation of results for geometries not considered by Trayer. Extrapolating beyond Trayer's results has been controversial. The uncertainty due to extrapolation has resulted in typically conservative design values, which are aimed at keeping service load well below the estimated joint proportional limit.

3.2 THEORY OF EUROPEAN YIELD MODEL

3.2.1 Introduction

Fundamental to an efficient utilization of bolted joints is an understanding of their mechanical behaviour under load. A number of models have been developed to determine the strength, of bolted timber joints, analytically. Examples of models include beam on elastic foundation, force-displacement equations, and finite element and yield theory model. Joints with dowel type fasteners are usually analysed as two-dimensional problems in which a beam representing the fastener, loads a foundation representing the joint members (Figure 3.1).

The load-deformation problem then reduces to the solution of the differential equation,

$$\frac{d^2M}{dx^2} = q \qquad \text{(Eq. 3.3)}$$

where,

M: Fastener bending moment

q: Force per unit length of the foundation beneath the fastener at point x

q is known as the embedment force per millimeter thickness.

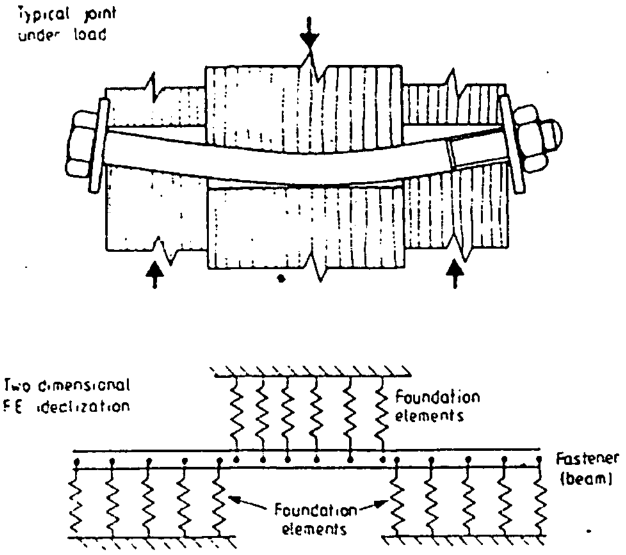


Figure 3.1: Two dimensional finite element idealization for joints with dowel type fasteners ***(Source: Smith and Whale 1987)***

3.2.2 Solutions for Equation (3.3)

There are several models, which were developed to solve the Eq. 3.3. Among them, three important models are briefly described below.

Wilkinson's Model

In 1972 Wilkinson derived a solution to Eq. 3.3 capable of predicting slip in dowel-type joint by assuming the joint deforms linear elastically. The ratio joint load to joint slip is given by,

$$\frac{P}{\delta} = 0.16642 E^{1/4} K_1^{3/4} d^{7/4} \qquad \text{(Eq. 3.4)}$$

where,

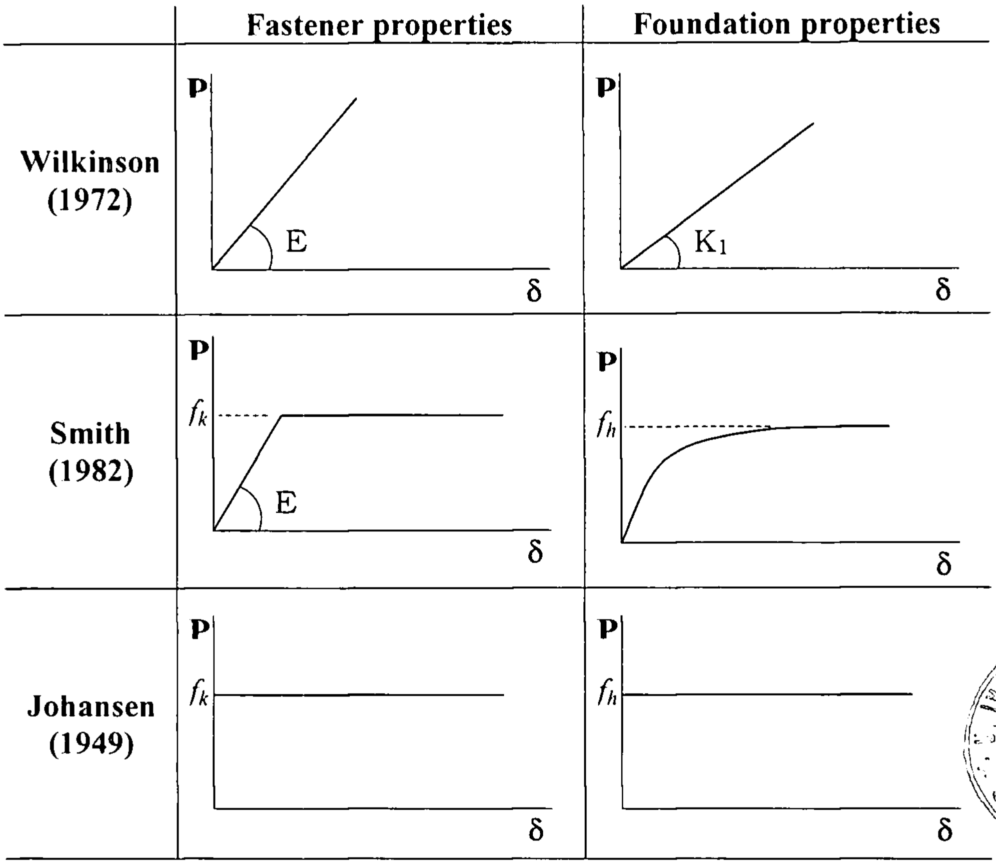
P = joint load (N)

δ = joint slip (mm)

E = modulas of elasticity of fastener (N/mm^2)

d = fastener diameter (mm)

K_1 = joint member elastic bearing constant (N/mm^2) – *refer figure 3.2*



f_k : bending properties of fastener
f_h : embedment properties of member

Figure 3.2: Assumed material properties of various analytical model for joints with dowel-type fasteners

Smith's Model

In 1983, Smith proposed a more complete finite element solution for Eq. 3.3 capable of predicting both the short-term strength and stiffness properties of joints with a single dowel type fastener (Smith et al. 1987). This assumes the fastener is ideal elastic-plastic material (Figure 3.2) and makes no approximation of the non-linear load-embedment characteristics for the joint members. Validatory experiments have shown this model predicts short-term initial stiffness of joints to ±20% and ultimate loads to ±10% (Smith et al. 1987).

Johansen's European Yield Model

By assuming both fastener and timber are ideal rigid-plastic materials (Figure 3.2), in 1949, Johansen derived explicit solutions (equations 3.5 to 3.14) to Eq. 3.3 capable of predicting the strength (ultimate/yield) of dowel-type joints. The proposed model is referred to as European Yield Model (EYM). In 1973, Larsen expanded this model to describe the joint strength where wood members have different embedment properties (McLain & Thangjitham 1993). The yield theory provides an analytical method to predict the strength of a two or three member dowel-type joint. It is based on equilibrium equations resulting from free body diagrams of a dowel in a wood member. EYM assumes that the failure of dowel type joint occurs due to either bearing failure of the joint member or bending failure of the fastener. These assumptions provide several modes of failures (Figures 3.4 & 3.5) depending on connection member dimensions, member strength and bolt strength. In an actual joint the load carrying capacity will correspond to the lowest value obtained for R_d by substituting into the full set of equations. The equation giving the lowest capacity will also identify the failure mode. This model is often referred to as the "yield theory" or "yield model" because it describes how fastener yielding contributes to bolted-dowel joint strength.

Yield theory is the basis for the design of bolted connections in the Eurocode 5 (EC5) and in the limit state design version of the Canadian wood design code (Patton Mallory 1997).

3.2.3 Different Definitions of Yield Load

The yield strength predicted by the EYM can be defined at any point on the load-deformation curve (Figure 3.3) obtained from a test of dowel-type joint.

In the United States, the yield strength is defined by offsetting the initial slope of the load-deformation curve by a deformation equal to 5% of the bolt diameter and locating the load at which the offset intersects the curve (Figure 3.5a). This definition has been adopted for both the LRFD specifications and NDS-91 (McLain et al. 1993).

In their publications, Soltis et al. (1986) and Soltis and Wilkinson (1987) have used the method explained in Figure 3.3a to define the yield load while McLain et al. (1993) and Wilkinson (1993) have used the method shown in Figure 3.5b.

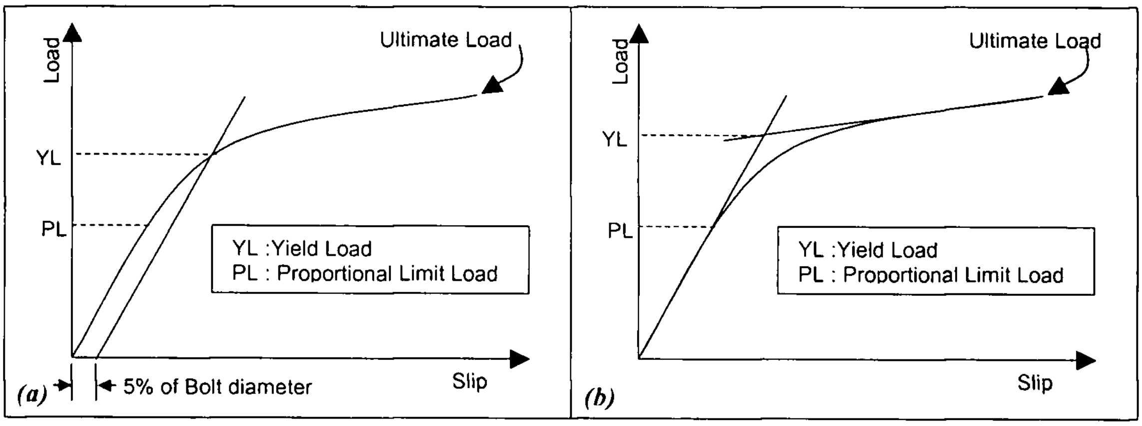


Figure 3.3: Schematic diagrams of load-slip curve showing different definitions of yield load, proportional limit load and ultimate load

Design resistance equations for single shear joints are:

Mode 1: $R_d = \frac{f_{h,1,d} t_1 d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left(1+\alpha+\alpha^2\right)+\beta^3\alpha^2} - \beta(1+\alpha)\right]$ N (Eq. 3.5)

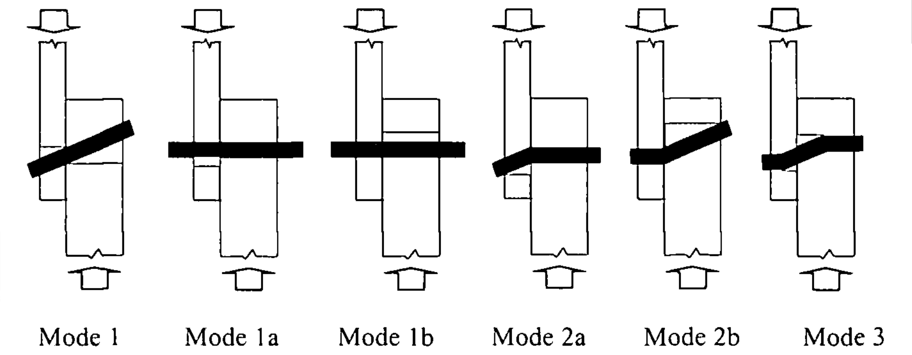
Mode 1a: $R_d = f_{h,1,d} t_1 d$ N (Eq. 3.6)

Mode 1b: $R_d = \beta f_{h,1,d} \alpha t_1 d$ N (Eq. 3.7)

Mode 2a: $R_d = 1.1\frac{f_{h,1,d}t_1 d}{(2+\beta)}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(1+\beta)M_{y,d}}{f_{h,1,d}dt_1^2}}-\beta\right]$ N (Eq. 3.8)

Mode 2b: $R_d = 1.1\frac{f_{h,1,d}\alpha t_1 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)M_{y,d}}{f_{h,1,d}d\alpha^2 t_1^2}}-\beta\right]$ N (Eq. 3.9)

Mode 3: $R_d = 1.1\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,d}f_{h,1,d}d}$ N (Eq. 3.10)



Mode 1 : Rotation of fastener with bearing failure in side and main members
Mode 1a : Bearing failure in side member
Mode 1b : Bearing failure in main member
Mode 2a : Formation of plastic hinge within side member
Mode 2b : Formation of plastic hinge within main member
Mode 3 : Formation of plastic hinge within side and main members

Figure 3.4: Failure patterns for single shear wood joints

Design resistance equations for double shear joints are:

Mode 1a: $R_d = f_{h,1,d}t_1 d$ N (Eq. 3.11)

Mode 1b: $R_d = 0.5\beta f_{h,1,d}\alpha t_1 d$ N (Eq. 3.12)

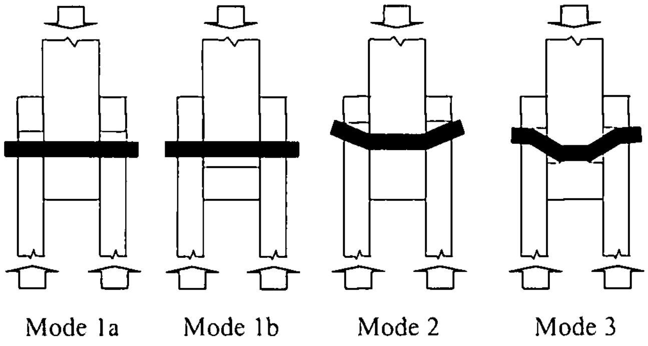
Mode 2: $R_d = 1.1\frac{f_{h,1,d}t_1 d}{(2+\beta)}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,d}}{f_{h,1,d}dt_1^2}}-\beta\right]$ N (Eq. 3.13)

Mode 3: $R_d = 1.1\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,d}f_{h,1,d}d}$ N (Eq. 3.14)

in which,

α $= t_2/t_1$
t_1, t_2 = thickness of side and main members respectively in mm
β $= f_{h,2,d}/f_{h,1,d}$

$f_{h,1,d}$, $f_{h,2,d}$ = design embedment strength of side and central members respectively in N/mm^2
d = bolt diameter in mm, and
$M_{y,d}$ = design bolt yield moment in Nmm



Mode 1a : Bearing failure in side members
Mode 1b : Bearing failure in central member
Mode 2 : Formation of plastic hinges within side members
Mode 3 : Formation of plastic hinges within side and central members

Figure 3.5: Failure patterns for double shear wood joints

These equations, which are derived from static analysis, predict failure loads due to either bearing failure of joint members (Mode 1, 1a and 1b) or the simultaneous development of bearing failure of the joint member and formation of plastic hinges in the fastener (Mode 2, 2a, 2b and 3).

The EYM for bolted connections is well developed and is fully documented by Soltis and Wilkinson (1987), McLain and Thangjitham (1983), Patton-Mallory (1989) and others. Numerous researchers have published verification of EYM for several connection types [Soltis et al. (1986, 1987), McLain and Thangjitham (1983), Whale and Smith (1986)]. Test programmes and results obtained by some of them will be described later in this chapter.

The design embedment, $f_{h,d}$, strength of the joint member is given by,

$$f_{h,d} = \frac{k_{mod} f_{h,k}}{\gamma_m} \quad \text{N/mm}^2 \qquad \text{(Eq. 3.15)}$$

in which,

k_{mod} = modification factor for service class and duration
$f_{h,k}$ = characteristic embedment strength in N/mm^2
γ_m = partial safety factor for timber

and, the design yield moment, $M_{y,d}$, of dowel fastener is given by,

$$M_{y,d} = \frac{M_{y,k}}{\gamma_m} \quad \text{N/mm}^2 \qquad \text{(Eq. 3.16)}$$

in which,

$M_{y,k}$ = characteristic yield moment of fastener in Nmm
γ_m = partial safety factor for bolts

The EYM recommends the following approximation to the characteristic yield moment, $M_{y,k}$, for round steel bolts.

$$M_{y,k} = 0.8 f_{u,k}\left(\frac{d^3}{6}\right) \text{ Nmm} \qquad \text{(Eq. 3.17)}$$

in which $f_{u,k}$ is the characteristic yield strength of bolt in N/mm^2

Since R_d is the design resistance per shear plane, in symmetrical double shear joints the lateral load capacity is equal to $2R_d$.

3.3 EMBEDMENT STRENGTH

Embedment strength is an important system property and is essential to calculate the design resistance capacity of the bolted or dowel-type joint. The load-slip characteristic for a fastener embedment on wood or wood-based sheet material is a fundamental property for estimating both the load carrying capacity and the displacement performance of laterally loaded timber joints. For the given combination of joint material, fastener type and diameter and direction of loading with respect to grain the strength of the bolted timber or timber based sheet material joint is determined using the embedment strength of the system and yield strength of the fastener.

Hilson et al. (1990) stated that timber density can be used to predicting parameter for the determination of maximum embedment strength for nails or bolts bearing on timber both parallel and perpendicular to the grain. The data gathered from a comprehensive series of tests encompassing seven timber species with density ranging between 350 kg/m^3 and 900 kg/m^3 and nine fastener diameters, which was carried out by Smith et al. (1987) and Rodd et al (1987), in order to obtain embedment strength data for wood and wood-based sheet materials. According to the analysis of the results obtained, Hilson et al (1990) proposed following relationships for embedment strength.

For nails,

non-predrilled $f_h=0.09\rho d^{-0.36}$ (Eq. 3.18)
pre-drilled $f_h=0.13\rho d^{-0.36}$ (Eq. 3.19)
plywood $f_h=0.012(10-d)\rho$ (Eq. 3.20)
tempered hardboard $f_h=0.00316(10-d)\rho t^{0.6}$ (Eq. 3.21)

For bolts,

parallel to grain $f_{h,0}=0.082(1-0.01d)\rho$ (Eq. 3.22)

for other angles $f_{h,\theta} = \dfrac{f_{h,0}}{2.3Sin^2\theta + Cos^2\theta}$ (Eq. 3.23)

The embedment strength can be determined, experimentally, in accordance with EN 383: (1993) “Timber structures – Test methods – Determination of embedding strength and foundation values for dowel type fasteners”. This test can be regarded as a symmetrical three-piece joint test, using steel side members and a wood or wood-based sheet material central member in which a bearing failure is enforced under lateral load (Figure 3.6). EN 383: (1993) defined the embedment strength as average compressive stress at maximum load in a piece of wood or wood-based sheet material product under the action of a stiff linear fastener while the fastener's axis is perpendicular to the surface of specimen and the fastener is loaded perpendicular to its axis.

Following formulae to calculate the characteristic embedment strength, $f_{h,k}$, for bolts up to 30mm diameter are given in Annex A of EC5.

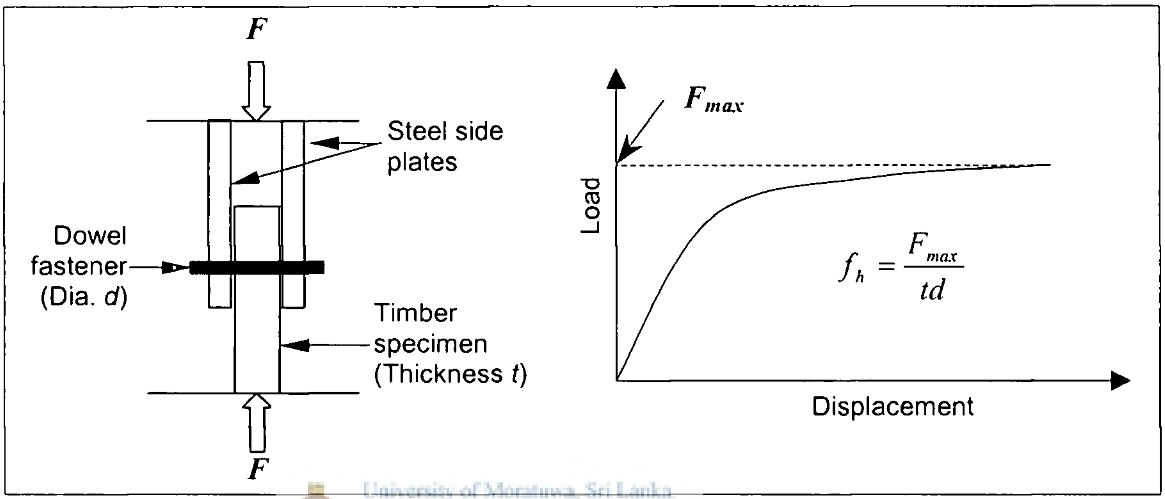


Figure 3.6: Schematic diagram illustrating the embedment strength test apparatus and determination of embedment strength using load-displacement curve

timber loaded parallel to the grain,

$$f_{h,0,k} = 0.082(1-0.01d)\rho_k \quad \text{N/mm}^2 \qquad \text{(Eq. 3.24)}$$

timber loaded at an angle to the grain,

$$f_{h,\alpha,k} = \frac{0.082(1-0.01d)\rho_k}{k_{90}Sin^2\alpha + Cos^2\alpha} \quad \text{N/mm}^2 \qquad \text{(Eq. 3.25)}$$

in which

ρ_k = characteristic density of member material in kg/m^3

α = direction of load with respect to the grain direction of timber (degrees) and,

for hardwoods: $k_{90} = 0.90 + 0.015d$ (Eq. 3.26)

for softwoods: $k_{90} = 1.35 + 0.015d$ (Eq. 3.27)

The embedment strength depends on the type of fastener (nails, bolts etc.) the direction of loading (for bolts only), the wood density or quality of wood based material and diameter of the fastener. Thus, the embedment strength is not a special material property, but a system property.

It may be seen from Johansen's equations that the input required in order to predict the ultimate load capacity of a joint comprises some geometric parameters, the plastic moment capacity of the fastener and the embedment strength of the timber.

3.4 ADVANTAGES OF THE EYM

The EYM provides not only a simple but also a rational design procedure for bolted timber joints based on the joint geometry, member properties and fastener properties.

EYM equations are easily incorporated into computer programs; alternatively, tables of design values may be readily generated. Also, they can be rewritten in different forms to suit different purposes.

EYM would allow designers to calculate the appropriate load for any joint arrangement and would identify the mode of failure to be expected. It would also enable engineers to assess the sensitivity of joint strength to variation in the design parameters. A further advantage of this approach would be that joints made from new sheet materials could easily be introduced in to the code. All that would be required would be knowledge of the appropriate embedment strength equation for the sheet material.

3.5 PREVIOUS EXPERIMENTAL INVESTIGATIONS ON EYM

It is important to note that many researchers have presented their results of bolted timber joints in the form of normalized strength. Normalized strength is calculated by dividing the joint strength by a known strength property *(P)* and the bearing area under the fastener, and is usually plotted versus the t_2/d, thus in the dimensionless form. The normalization strength, R_n, can be calculated as,

$$R_n = \frac{R_d}{P t_2 d} \qquad \text{(Eq. 3.28)}$$

There are two different methods, which the researchers have usually used to normalize the joint strength results. Soltis and Wilkinson (1987) have used compressive strength as the known strength property *(P)* while McLain and Thangjitham (1993) have used the embedment strength. Trayer also used compressive strength for normalization of his results.

3.5.1 Soltis, Lawrence A., Hubbard, Finn K., Wilkinson, Thomas L. (1986)

Soltis et al. (1986) conducted test programme to check the validity of Johansen's yield theory. Soltis et al. (1986) tested single bolt three member symmetrical double shear joints made from Glulam beams[1]. Using three bolt diameters [1/2 inches (13.7mm), 1 inch (25.4mm) and 1 ½ inches (38.1mm)]. The thickness of each side member was one-half that of the central member. Bolts were of low carbon steel. Joints were tested

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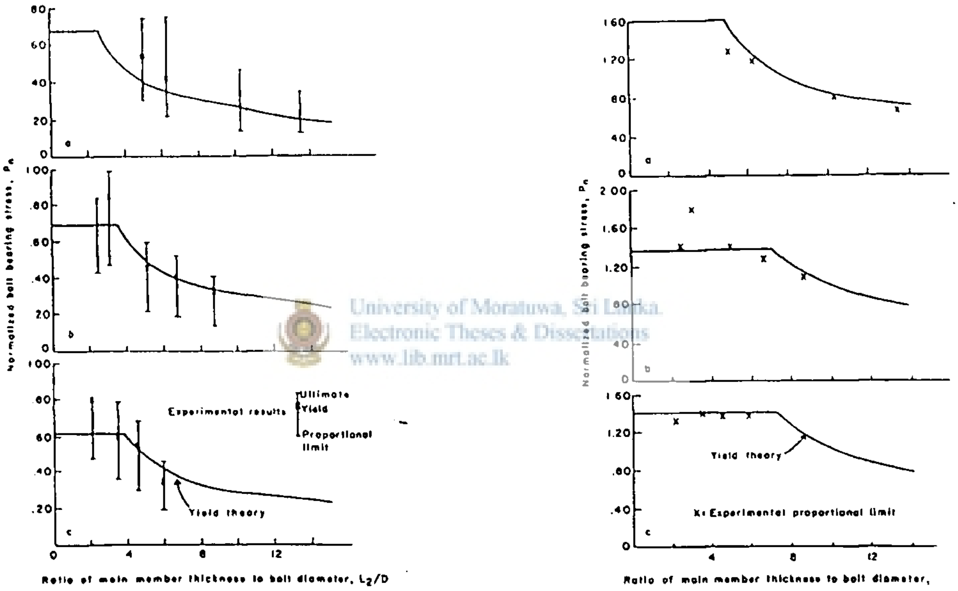
[1] Glulam beams were constructed of Douglas-fir laminated grade L1 lumber using phenol resorcinol adhesives

in both parallel and perpendicular to grain directions. Soltis et al. (1986) used NDS and ASTM D1761-77 specifications to prepare and test the joints respectively.

The comparison between the yield theory and experimental results for parallel to grain load indicate good agreement (Figure 3.7i). The theory overestimates the proportional limit and underestimates the ultimate strength. The yield theory slightly overestimates the experimental proportions limit loads of perpendicular to the grain tests (Figure 3.7ii).

The thickness of each side member was one-half that of the central member. Also, the central and side members were cut from adjacent locations in the wood specimen and are assumed to have equal embedment strength. Both above limitations are unable to achieve in general practice. Soltis and others (1986) used low carbon steel bolts having the diameters of ½, 1 and 1-½ inches whereas larger diameter bolts and bolts of different strength are used today.



(i) Parallel to grain loading *(ii) Perpendicular to grain loading*

Figure 3.7: Comparison of experimental results (Soltis et al.) with EYM a). ½ inch b). 1 inch and c). 1 ½ inch bolts – *(Source: Soltis et al. 1987)*

3.5.2 Whale, Luke R.J. (1987)

Whale (1987) conducted two test series aiming to develop a model for embedment strength and a simplified model to predict the joint strength capacity. Only the test programme and their results relevant to bolted joints are described here.

For embedment strengths, Whale tested two timber species (Keruing and Greenheart). Tests were conducted using two bolt diameters (M20 and M12) with approximately 1.5mm oversized boltholes. Those metric black bolts complied with BS 4190:1967 specifications. Specimens were tested in tension parallel to grain, compression parallel to grain and compression perpendicular to grain. Twenty replicates were tested for each bolt diameter and for each loading configuration.

Analysis of results obtained from above test series yielded following relationships,

for embedment strength parallel to grain,

$$f_{h,0} = 0.082(1-0.01d)\rho \qquad \text{(Eq. 3.29)}$$

and, embedment strength in other arbitrary angle (θ),

$$f_{h,\theta} = \frac{f_{h,0}}{(2.3Sin^2\theta + Cos^2\theta)} \qquad \text{(Eq. 3.30)}$$

Whale (1987) recommended following simplified form for the characteristic strength capacity of bolted joints (R_d) using the Johansen's set of equations for the condition of side member thickness greater than 5 times of bolt diameter (i.e. t_1>5d) ensuring the mode 3 failure.

$$R_d = 3.62^{1.96}\sqrt{\rho_k}\sqrt{\frac{1}{2+1.3(Sin^2\theta_1 + Sin^2\theta_2)}} \quad \text{N/mm}^2 \qquad \text{(Eq. 3.31)}$$

in which,

θ_1 : angle of loading to grain in side member
θ_2 : angle of loading to grain in central member

To validate above simplified model for joint strength capacity, Whale (1987) tested three member symmetrical double shear joints made from Keruing using M20 bolts. Member thicknesses were selected as they give two thickness combinations such as 1 (20mm side: 20mm central) and 2 (15mm side: 30mm central). Joints were loaded in compression in the direction of parallel to grain. Results of validatory tests were compared with the proposed model are given in Table 3.1 below.

Table 3.1: Comparison of Predicted Model (Whale 1987) with Validatory Test Results

Side member thickness (mm)	Central member thickness (mm)	Mean experimental failure load (N) (a)	Eq. 3.31 x (t_1/5d) (b)	(b)/(a)
20	20	19690	9390	0.48
15	30	18200	5360	0.29
			Average error =	-61.5%

3.5.3 Patton-Mallory, Marcia (1989)

Patton-Mallory compared the specifications for bolted timber joint design given in NDS-86 with the yield load predicted by European Yield Model. The objectives of this comparison is to investigate suitable adjustment factors to be used to derive design loads from the yield theory and investigate the appropriateness of the 5%D (Figure 3.3a) offset method for experimentally determining connection yield point. Load-slip data of Soltis et al. (1986) was used to determine the 5%D-offset yield point in this investigation.

According to the analysis, Patton-Mallory (1989) stated that the yield theory can be adopted to predict working stress design loads. Dividing the predicted yield theory loads by 3.63 resulted in design loads within about 20% of the NDS-86 design loads for connections with $t_2/d>4$. The 5%D-offset method of define the experimental yield load for bolted connections correlated well with predicted yield theory connection loads when embedment strength were defined as 65% of the clear wood ultimate compression stress. Above relationship for embedment strength was proposed by Soltis et al. (1986).

3.6 COMPARISON OF EYM WITH OTHER RESEARCHERS'S MODELS

Soltis et al. (1987) analyse the Johansen's European Yield Model. In this technical report, Soltis discussed the factors that affect the connection strength and did a complete review of available literature. He also, discussed the modifying factors used in multiple bolt connections. Studies on single bolted connections of 12 researchers including Trayer from1925 to 1986 were analysed and the results were then compared with the Yield Theory. Geometric and material parameters of above studies are reproduced here in the Table 3.2.

Table 3.2: Geometric and material properties for various studies of single-bolt connections (Source: Soltis et al. 1987)

Source reference	Main member	Side member	Number of members in connection	Bolt diameters *(inch)*	t_2/d	Load angle to grain	Number of replications
Grenoble (1925)	White ash. Sitka spruce	¼ inch steel plate and wood[1]	2,3	0.16 to 0.5	1to16.5	Parallel	4
Trayer (1927)	Sitka spruce	¼ inch steel plate	2,3	¼ to ½	2 to 12	30^0 to 90^0	3
Trayer (1932)	Douglas-fir, Yellow pine, Sitka spruce, oak and Maple	¼ inch steel[2] and wood	3	¼ to 1	0 to 12	Parallel	4 or 5
-do-	-do-	-do-	3	½	0 to 12	Perpendicular	4 or 5
Goodell and Phillips (1944)	Douglas-fir, Sitka spruce	Steel	3	¼ to ½	3 to 4	Parallel	5, 13

[1] Wood side members are the same species as the main member

[2] Except for connections with 1 inch bolts which used 5/8 inch steel plate

Table 3.2: Geometric and material properties for various studies of single-bolt connections (Source: Soltis et al. 1987) *(Contd.)*

Source reference	**Main member**	**Side member**	**Number of members in connection**	**Bolt diameters *(inch)***	**t_2/d**	**Load angle to grain**	**Number of replications**
Pitz (1952)	Douglas-fir	Steel	3	½ to 1	4	0 to 90 in 7 ½^0 increments	3
Doyle and Scholten (1963)	do	5/16 steel plate or wood	3	½ to 1	3.6 to 5.3	Parallel and Perpendicular	3
Wilkinson (1978)	do	Wood	2,3,4	3/8 to ¾	2 to 16	Parallel	6
Smith (1982)	Canadian and Polish spruce	Wood	3	5/8	6	Parallel and Perpendicular	50
Hirai and Sawada	Spruce and fir	1/8 inch steel plate	3	5/16 to ½	2 to 10	Parallel	3
Hirai and Sawada	Spruce and fir	Wood	3	3/8	2 to 10	Parallel	3
Soltis et al. (1986)	Douglas fir	Wood	3	½ to 1 ½	2 to 13.5	Parallel and Perpendicular	15

Figure 3.8 to 3.18 shows the comparison of yield theory prediction with experimental results of each researcher. In some cases, Soltis et al. (1987) had to assume the compression strength of the wood and/or yield strength of the bolt.

Figures 3.8 to 3.9 show the results from Grenoble (1925) as plots normalized proportional limit-bearing stress vs. t_2/d (L_2/D in the figure) ratio for two and three member connections with steel side plates and loading parallel to grain.

Figures 3.10 to 3.14 show results from Trayer (1932). Three member connections with steel side plates, with softwood species (Figure 3.10), and hardwood species (Figure 3.10), were loaded parallel to grain. And same both softwood and hardwood species loaded perpendicular to grain is shown in the Figure 3.12. Three member connections with steel and wood side plates are compared in Figures 3.13 and 3.14.

Figures 3.15 to 3.16 show results from Doyle and Scholten (1963). Three member connections with steel side plates (Figure 3.15) and wood side plates (Figure 3.16) were loaded parallel to grain.

Results from Wilkinson (1978) are presented in Figures 3.17 and 3.18 for connections loaded parallel to grain with various ratios of main to side member thickness.

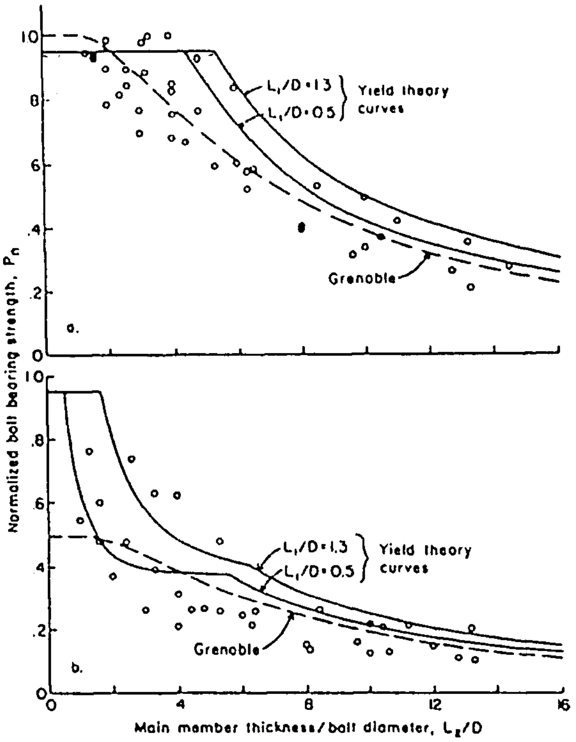


Figure 3.8: Results for proportional limit (Grenoble 1925) and yield load (EYM) for (a) three member and (b) two member connections of ash with steel side plates. Parallel to grain loading *(Source: Soltis et al. 1987)*

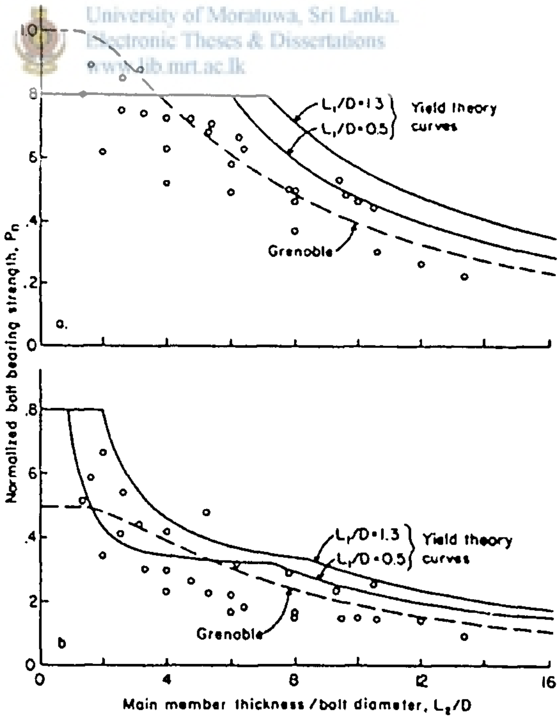


Figure 3.9: Results for proportional limit (Grenoble 1925) and yield load (EYM) for (a) three member and (b) two member connections of Sitka spruce with steel side plates. Parallel to grain loading *(Source: Soltis et al. 1987)*

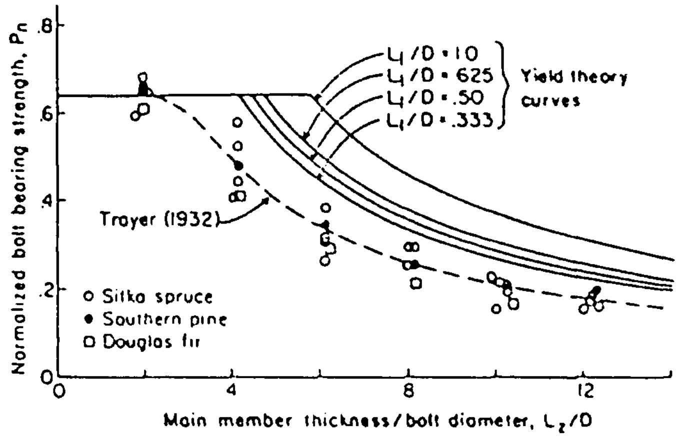


Figure 3.10: Results for proportional limit (Trayer 1932) and yield load (EYM) for three member connections of softwood species with steel side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

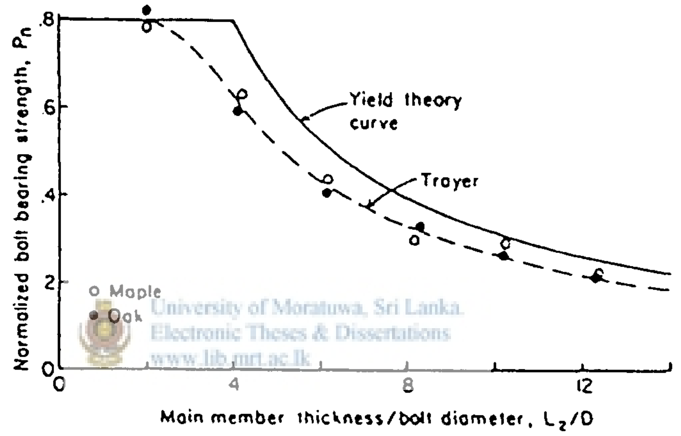


Figure 3.11: Results for proportional limit (Trayer 1932) and yield load (EYM) for three member connections of hardwood species with steel side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

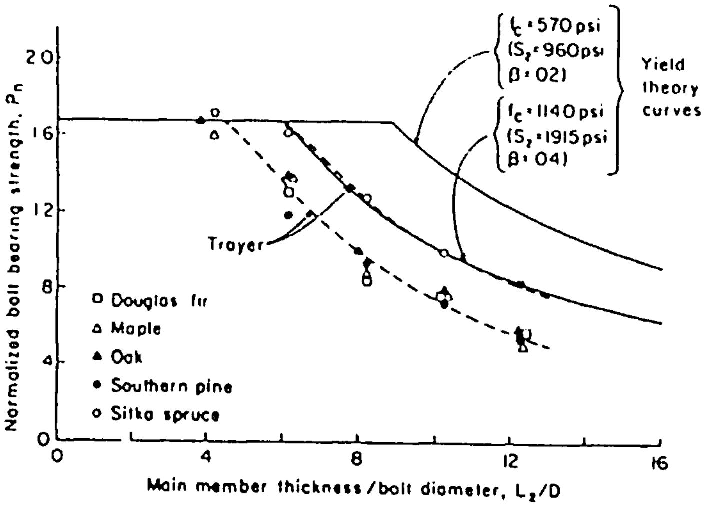


Figure 3.12: Results for proportional limit (Trayer 1932) and yield load (EYM) for three member connections with steel side plates. Perpendicular to grain loading. *(Source: Soltis et al. 1987)*

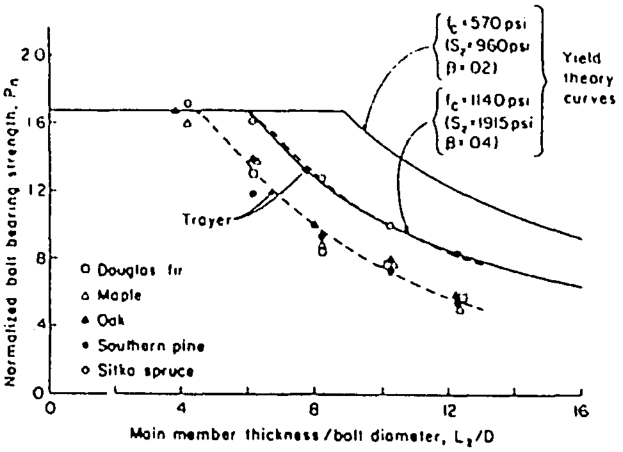


Figure 3.13: Results for proportional limit (Trayer 1932) and yield load (EYM) for three member connections of hardwood species with steel and wood side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

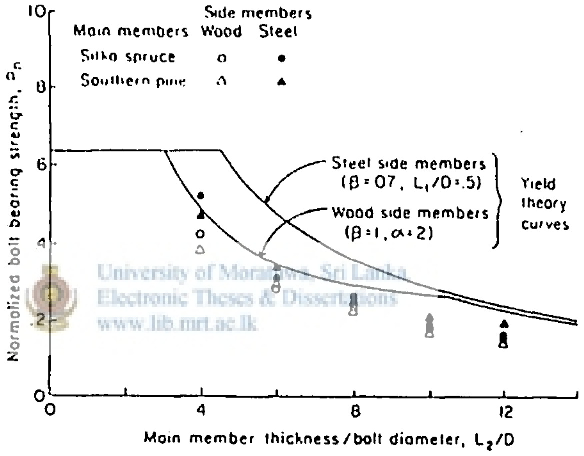


Figure 3.14: Results for proportional limit (Trayer 1932) and yield load (EYM) for three member connections of softwood species with steel and wood side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

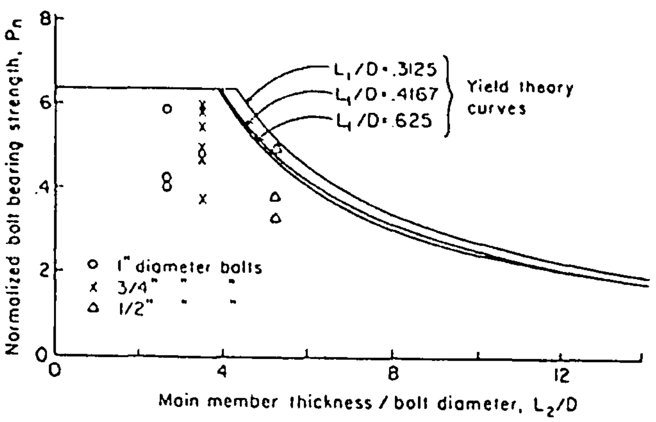


Figure 3.15: Results for proportional limit (Doyle and Scholten 1963) and yield load (EYM) for three member Douglas-fir connections with steel side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

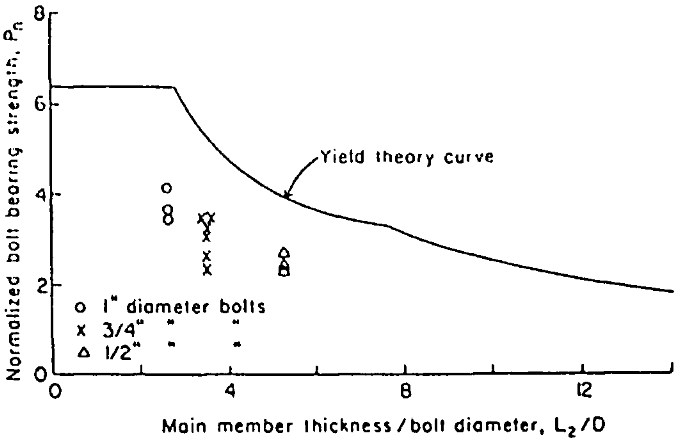


Figure 3.16: Results for proportional limit (Doyle and Scholten 1963) and yield load (EYM) for three member Douglas-fir connections with wood side plates. Parallel to grain loading. *(Source: Soltis et al. 1987)*

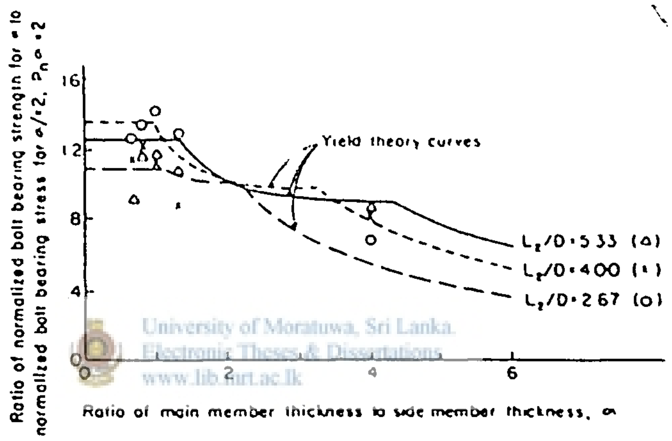


Figure 3.17: Results for proportional limit (Wilkinson 1978) and yield load (EYM) for three member all wood connections with various side member thicknesses. Parallel to grain loading. *(Source: Soltis et al. 1987)*

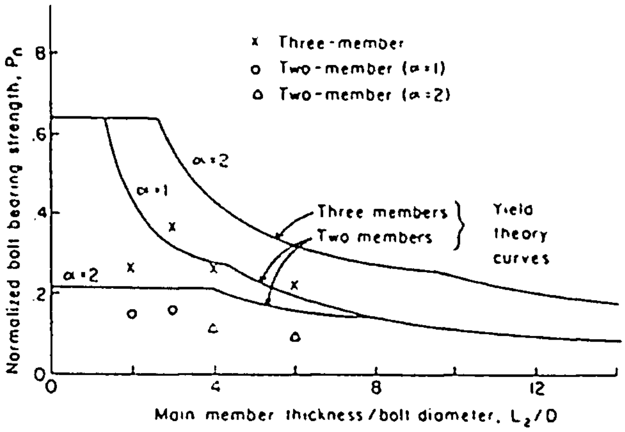


Figure 3.18: Results for proportional limit (Wilkinson 1978) and yield load (EYM) for two and three member all wood connections. Parallel to grain loading. *(Source: Soltis et al. 1987)*

The yield theory appears to predict the trend seen in the results of all researchers. In general, experimental values fall below the yield theory curves. This is because the proportional limit loads defined by all researchers is smaller than the yield load defined using the methods give in Figure 3.3. Soltis et al (1986) give yield loads that agree closely with the yield theory curves (Figure 3.7).

Much of the research has been done with parallel to the grain loading. Results of parallel to grain loading appear to agree more closely with the yield theory than results for perpendicular to grain loading, for which fewer data exists.

Most tests of three member wood connections have been with a main member twice the thickness of the side member. Doyle and Scholten in 1962 (Soltis et al. 1987) used a main member thickness 1.6 times that of side member (Figure 3.15). Wiliknson in 1978 examined several ratios of central to side member thickness (Figure 3.17) (Soltis et al. 1987).

Hilson et al. (1990) have used Johansen's theory to appraise the values for nails and bolts presented in BS5268:1984. The results of this analysis show that, for nailed timber to timber joints, the BS5268:1984 values are on average about 23% higher than the theoretical predictions. This is due to the fact that in the original tests, nail heads were driven home, thus enabling an axial force to develop which, after deformation, provides an additional resistance component. In nailed sheet material to timber joints a similar effect applies, but to a lesser degree and the BS 5268:1984 values are found to be about 12% higher than theoretical. Direct comparison between the ultimate strength values predicted by the yield theory and the permissible strength values given in the BS 5268:Part 2:1984 are difficult since the code did not adopt a load factor approach. Therefore the theory was used to calculate the load factor implicit in the BS 5268:1984 data. This was found to vary from 1.41 to 4.39 for various joint geometries. Since the load factor has to account for load duration as well as safety, some of these values are far too low.

A more logical approach to bolted joints would be would be to use the yield theory in conjunction with a fixed load factor and, since presumably the current loads have proved satisfactory in practice, the value could be at the lower end of the above ranges. This approach would also be more logical than the current code approach since the yield theory can cope with both single shear joints and double shear joints. The code gives single shear values but they are calculated by halving the double shear value, an assumption that is not generally correct.

3.7 LIMITATIONS AND SHORTCOMINGS OF EYM

There are several assumptions made in the derivation of yield theory equations, which are not met in general practice.

- The degree of the fixity of the bolt ends due to heads, nuts and washers. This fixity will serve to reduce the likelihood of the occurrence of some failure modes. Additionally, the end fixity will result in a tensile force in the bolt and cause the normal force between joint members to increase. Consequently, there will be an increase in the influence of friction between the joint members, which is not accounted for by the model.

- Additionally, as the bolts bend there will be a component of the tensile force in the direction of loading.

Therefore, the predicted values are most likely to be conservative compared to actual test results and the degree of conservatism will depend on the governing failure mode. This frictional influence could be predicted if the coefficient of the friction and tensile force in the bolt were known. However because of the relaxation and hygroscopic characteristics of wood, the influence of friction would be widely varied in practice. Thus, for design purpose, it should be ignored.

Examination of failure modes indicates that bolt end fixity will likely preclude model failure in single shear joints due to end fixity provided by bolt head, nut and washers, oversize holes and especially the lack of symmetry. The only exception to this would be with thin members with large bolt diameters, which are to be unlikely in practice. Therefore, mode 1a is disregarded as a practical failure mode. However they may occur if there is a significant difference between the resistance capacity of the two members. Modes 2a and 2b in single shear joints will be possible only if one member is much thinner or weaker than another. Therefore, the end fixity will tend to force the single shear joints towards mode 3. In double shear joints, mode 1a is unlikely unless the side members are very thin or very weak or if the bolt is quite large. Any flexure in the bolt will retard the formation of mode 1a failure (McLain and Thangjitham 1983).

However, Patton-Mallory (1989) argued if the washers are undersized, if the member shrinks after tightening the nuts or if local crushing of fibers beneath the washers, allows the bolt ends to rotate, above disregarding failure modes can be occur. Besides, assuming the ability to occur all failure modes is helps to estimate conservative connection yield load.

The applicability of the yield model for developing design values is subject to several limitations;

- Deformation, which is an important characteristic in limit state design, in a joint may be as important as a limiting load. The model does not incorporate this criterion.
- The yield load predictions assume that the joints do not fail due to the axial load on the net section and the end/edge distances are sufficient to prevent failure due to shear or splitting.
- The model assumes that the joint is well manufactured and that the fit of the bolt in the hole is nearly perfect. This second assumption is unrealistic in practice.
- Friction is ignored in the model since it is unpredictable and will change with the time and the environment experienced by the joint.
- The loads predicted by the model cannot be used directly in a working stress design without some rational compensation for safety.

3.8 EUROCODE 5 PROCEDURE FOR BOLTED JOINT DESIGN BASED ON EYM

The EC 5 uses Johansen's theory as the basis for the calculation of the ultimate strength of joints made from nails, staples, screws, bolts and dowels, but uses simplified forms of the equations. For bolted joint design, EC 5 requires fewer bolts than designs to BS 5268:1984 because of the high load factors implicit in most of the BS 5268:1984 values (Hilson et al. 1990).

As the fastener deforms under applied load, axial force could be developed for failure modes 2 and 3. These are caused by friction between the fastener and the timber and also by the constraints produced by the head of fastener and the washer assemblies in bolts. The force in the inclined part of the fastener will have a component parallel to the applied load and will therefore, enhance the resistance. EC5 takes this effect in to account by enhancing the resistance for modes 2 and 3 failures by 10%.

3.9 SUMMARY ON LITERATURE REVIEW

Based on embedment strength of joint members, yield moment of the fastener and some geometric parameters, the EYM proposed a more logical approach to bolted timber joint design and it is adaptable to various material properties. It expresses the general trend of existent data. As expected, experimental results at the proportional limit usually fall below the yield theory curves, because of the proportional limit load is smaller than the yield load (Figure 4). Trayer's empirical curve also fits the yield theory reasonably well.

The yield theory provides an insight in to the joint parameters. For example, diameter of bolt (*d*) and the main member thickness (t_2) are the determining properties for joint yield strength. The effect of changing of member materials (wood, wood-based sheet materials, hardboard etc.) and bolt yield strength on the joint strength can be predicted well.

In developing the existing codes of practice, it is better that, rather than using tabulated data, basic material property equations and full set of Johansen's equation be presented instead.

Because of discrepancies between the assumptions in the model and actual practice discussed above, some modifications are required to suit the local conditions of relevant countries.

Many researchers have tested only the joints, in which the side member thickness is equal to one-half of that of the main member. Moreover, most results are available for parallel to grain loading. Therefore, it is required to verify the model for a wider range of member thickness and different loading directions.

Chapter Four

EXPERIMENTAL PROGRAMME – JOINT STRENGTH TEST SERIES

Chapter 4: EXPERIMENTAL PROGRAMMEME – JOINT STRENGTH TEST SERIES

4.1 INTRODUCTION

This chapter presents the background to the development of the experimental programme. Identification and control of the important variables in such a manner, that the objectives of the study could be attained, are also discussed.

4.2. BACKGROUND

In 1997, Dias et al. conducted a preliminary investigation on the applicability of Eurocode 5 on the bolted joints of Sri Lankan timber species. They tested three member symmetrical double shear joints made from Palu (high density) and Lunumidella (low density) species of timber. A total of 36 number of joints were assembled using three bolt diameters (9.5mm, 12.7mm and 15.9mm) and were tested in parallel to grain loading. Outer member thickness was selected as a constant (38mm) and thickness of central member was varied as they provide three thickness ratios (side:center) such as 1:1 (38mm), 1: 1 ½ (50mm) and 1:2 (75mm). Two replicates from each joint were tested. Dias et al. was able to obtain favorable results from their investigation. They emphasized, however, the necessity of further investigation using a large-scale test programme. Suggestions for a future test programme and shortcomings of that preliminary test programme are stated below.

1. Embedment strength of each joint member was calculated using the relationship given in EC 5. Therefore, it is necessary to conduct test series to check the validity of this relationship for local timber species.
2. Applicability of EC5 recommendations to the bolted joints, which were made from intermediate densities need to be verified.
3. Loading in the directions other than parallel to grain too needs to be tested.
4. It is strongly suggested to conduct a test programme on a wide range of joint geometries by changing the main and side member thickness.

4.3 IMPORTANT VARIABLES AND THEIR CONTROLS

There are lots of variables that affect the strength behaviour of the bolted timber connections (Table 2.1). To conduct a test programme that covers every factor given in Table 2.1 is a massive and expensive task. It is thus necessary to identify the factors that affect in considerable level the strength properties and their controls. Therefore, based on the recommendations of Dias et al. and a thorough literature survey on past research papers and market survey, the following test programme was adopted for this investigation.

4.3.1 Timber Species

To determine the timber species, the following factors were considered.

- Availability
- Adequate durability
- Cost

- Structural Strength
- Popularity among the prospective user

Following timber species belonging to each density *(ρ)* range were considered initially.

Table 4.1: Timber Species Belonging to Each Density Range

High Density *($\rho < 850\ kg/m^3$)*	Medium Density *($850\ kg/m^3 < \rho < 700\ kg/m^3$)*	Low Density *($\rho < 700\ kg/m^3$)*
Hora	Halmilla	Ginisapu
Naa	Dawata	Mahogany
Palu	Gammalu	Murutha
Alubo	Helamba	Sabukku
Mee	Hik	Suriyamara
Siyambala	Kolon	Lunumidella
Kumbuk	Jack (Kos)	
Satin (Burutha)	Liyan	
Teak	Neralu	
Dun	Pelen	
Hedawaka	Tawenna	
Kirikon		
Kon		
Milla		

According to the market survey, immediate availability and cost, the test programme had to be restricted to low and high range, and finally, Kumbuk (high density) and Ginisapu (low density) were adopted. Both the above timber species are frequently used for construction purposes.

4.3.2 Member Thickness

According to the information given by timber merchants based on their sales records, 38mm (1 ½ inches), 50mm (2 inches) and 75mm (3 inches) thickness has higher popularity than others. Also many roof structures are currently assembled using the sections of 38x150mm (1 ½ x 6 inches) and 50x150mm (2 x 6 inches). Thus aiming to a wide range of joint geometry, it was decided to select 25mm (1 inch), 38mm (1 ½ inches), 50mm (2 inches), 75mm (3 inches) and 100mm (4 inches) timber thickness.

4.3.3 Loading Direction

Anisotropic behaviour of timber makes bolted joint strength vary with the angle measured between the direction of grain and the direction of the load. Considering the recommendations given by Dias et al. and the possibility to conduct using available testing equipments both parallel and perpendicular to grain directions were adopted.

4.3.4 Moisture Content

Strength properties of timber are highly affected by the moisture content. Strength properties reduces with the increase of moisture content up to fiber saturation point (FSP) which is approximately between 25% and 30%, and remains unaffected for moisture content greater than that at fiber saturation point. Therefore it was decided to conduct moisture content tests on each joint member of each joint tested. A small piece was cut from each joint member just after the test and the moisture content of each piece was determined using oven-dried method. Since the freshly felled timber contains a considerable amount of moisture, timber merchants were asked to supply seasoned timber. Both government and private sector timber merchants were unable to supply seasoned timber because they usually store timber in the mode of timber logs. These logs are sawn in accordance with the orders, which they receive. Because they usually store these logs under natural sky, there is no control on the moisture content. Therefore to minimize the effect of higher moisture content it was decided to follow a natural seasoning period after purchasing the timber and before preparing the joints. But due to time restriction, some joints had to be prepared and tested before the moisture content of joint members reached the equilibrium moisture content (EMC).

4.3.5 Density of Timber Species

Due to anisotropic behaviour and the effect of moisture content the density of timber species varies not only among the species but also place to place within one timber piece. Although, the control of timber density is very difficult, necessary data (dimensions and weight) of each member of the joint were recorded at the time of preparation of the joint.

4.3.6 Spacing, End and Edge Distance

Not only the strength but also the serviceability of the timber joint depends on the spacing, end and edge distance of the bolted timber joint. Therefore, it is necessary to minimize effect on the spacing, end and edge distance on the test results as much as possible. BS 6948:1989"British Standard method of test for mechanically fastened joints in timber and wood-based materials" was used as a guide to determine the spacing, end and edge distances. Figure 4.1 illustrates the spacing, end and edge distances, which are specified in BS 6948:1989, in the terms of bolt diameter *(d)*.

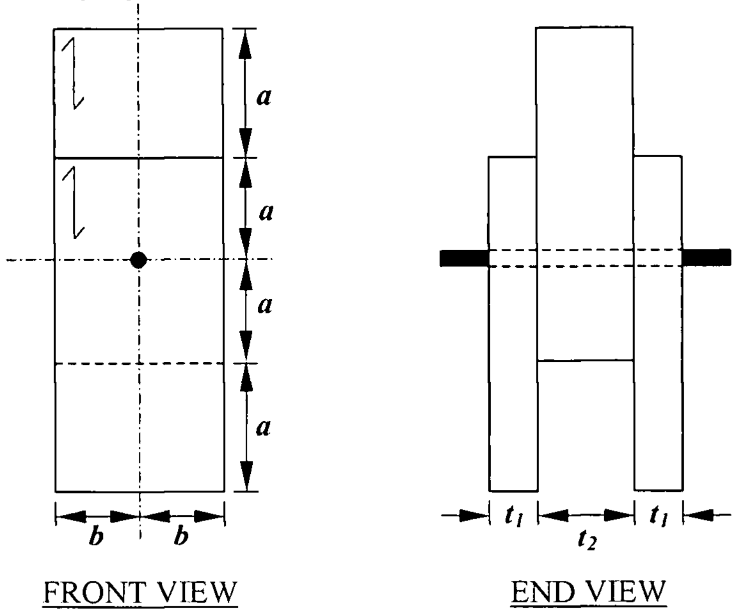
4.3.7 Bolt Diameter and Number of bolts per joint

Information gathered from the market survey showed that 9.5mm (3/8 inch.), 12.7mm (½ inch.) and 15.9mm (5/8 inch.) diameter mild steel bolts are more popular in the industry. This is the same result obtained by Dias et al. in 1997/98. Thus, this test programme too was conducted using the same bolt diameters.

When deciding the number of bolts per joint, following factors were considered.

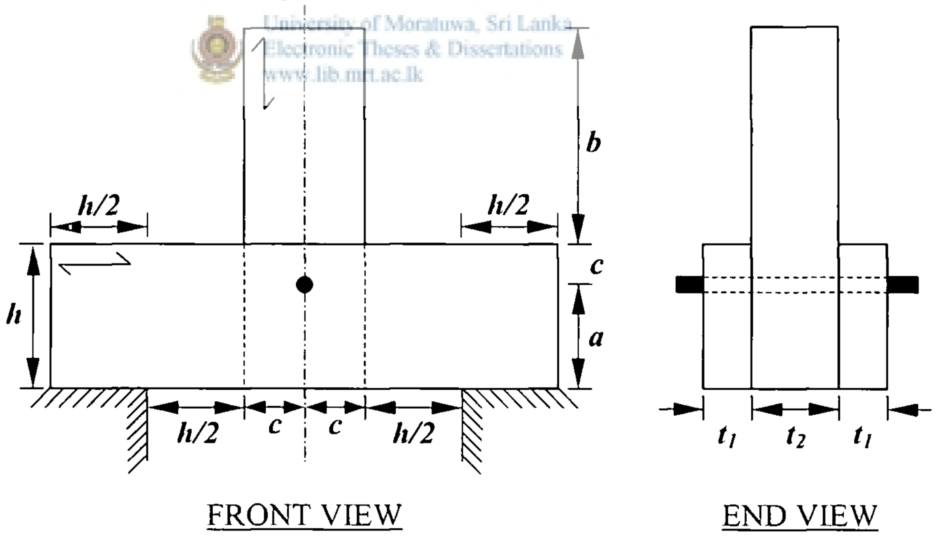
- Simplicity
- Saving in timber
- Ease of fabrication
- Saving in bolts
- Ability to achieve the intended failure load using available loading equipments
- Ability to achieve the intended deformation using available loading equipments
- Occurrences of experimental errors

Hencs single bolted joint was adopted to this test programme although BS 6948 recommends 4 bolts per joint for the bolt sizes less than 12mm in diameter.



a = *10d* or *25 mm* whichever smaller
b = *5d* or *12 mm* whichever smaller
(d is the diameter of the bolt)

(i): Parallel to Grain Loading



a = *10d* or *25 mm* whichever smaller *(pre-drilled holes)*
b = *10d* or *25 mm* whichever smaller
c = *5d* or *12 mm* whichever smaller
h = Width of timber member loaded perpendicular to grain
(d is the diameter of the bolt and ⟷ direction of grain)

(ii): Perpendicular to Grain Loading

Figure 4.1: Spacing, End and Edge Distances of Joints

Also, according to EC 5 recommendations, R_d is the joint strength per shear plane, per bolt. Thus, the decision does not violate the theory.

4.3.8 Presence of Timber Defects

Codes recommend that no defects are allowed in the test specimen. But this condition cannot be perfectly achieved in practice due to the higher cost of timber in the market. Therefore, it was decided to prepare the joint members free of defects as much as possible. Joint members were prepared so that there are no visible defects near the region subjected to loading. (refer Figure 4.2).

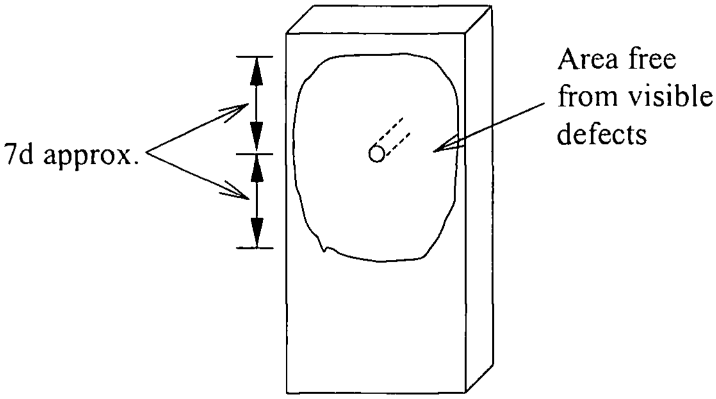


Figure 4.2: A typical joint member with the area free from visible defects

4.3.9 Yield Strength of Bolt/Fastener and Embedment Strength of Joint Member

According to the EC5 recommendations, the strength of the joint mainly depends on the embedment strength of the joint member and yield strength of the fastener. The embedment strength was calculated using the given relationship in EC5 (Equations 3.24 & 3.25) substituting the member density and corresponding bolt diameter. A subsidiary test series was conducted to check the validity of Equations 3.24 & 3.25 to the local species, and it will be described later.

Characteristic bolt yield moment of each bolt was calculated using the Equation 3.17 given in EC5, substituting the average bolt tensile strength, which was determined experimentally using randomly selected bolts.

4.3.10 Washers

Presence of washer is very important to improve the strength capacity of timber joints. These washer sizes should comply with the specifications given in relevant design codes. Use of inappropriate washers, such as washer sizes specified for steel fabrication, leads to considerable reduction in joint strength (Chandrakeerthi 1995). According to the BS 5268:Part 2:1996, the joint should be assembled using the washers of which the thickness is not less than 0.25d and the diameter is not less than 3.0d, in which d is bolt diameter. It was decided to turn out the washers because there are no washers that comply with BS 5268 specifications in the free market. Washers were turned out from 3mm steel plate and in square shape because, turning out of round washers needs special type of instruments and a very time consuming task.

4.4 TEST PROGRAMME – JOINT STRENGTH TEST SERIES

Symmetrical three-member bolted timber joints were tested in a direction parallel to grain (Figure 4.3) and perpendicular to grain (Figure 4.4). The joints, which were made from Ginisapu species were tested in both parallel and perpendicular to grain directions while the joints made from Kumbuk species were tested in parallel to grain direction only. Both above timber species belongs to low and high density groups respectively and are frequently used for construction purposes.

Fig: 4.3: Test set-up of joint loaded parallel to the grain

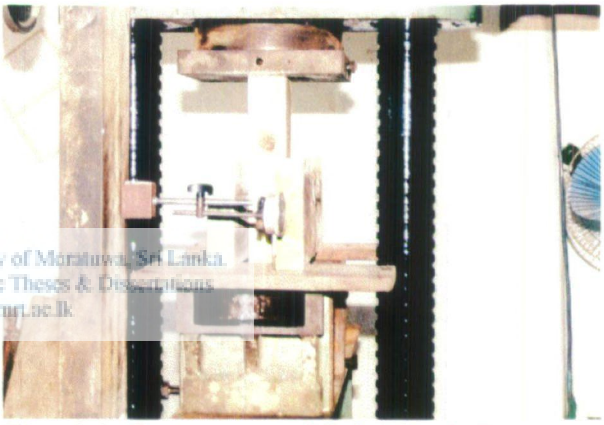


Fig: 4.4: Test set-up of Joint loaded perpendicular to the grain

Each joint consisted of a timber central member and two timber side members with a single bolt. Three bolt diameters were used to prepare the joints. The outer members were of 25,38 and 50mm thickness while the central members were 38,50,75 and 100mm thickness. Arrangement of these thicknesses produced ten thickness combinations (See Table 4.2). The ratio of central member thickness to outer member thickness (t_2/t_1) varied from 1.0 to 4.0.

The diameters of bolts tested were 9.5 mm (3/8 inches), 12.7 mm (1/2 inches) and 15.9 mm (5/8 inches). The ratio of central member thickness to bolt diameter (t_2/d) ranged from 2.38 to 10.53 (twelve t_2/d ratios).

Three replicates from each joint geometry were tested. A total of 180 parallel to grain and 90 perpendicular to grain tests were performed (Table 4.2).

The joint geometries were based on BS 6948:1989 and BS 5268:1996. The dimensions of test specimen and end/edge distances are shown in Figure 4.5 and Table 4.3. Bolt holes were drilled 10% larger than the bolt diameter. Square steel washers, of which side dimension equal to 3.0 times of bolt diameter, having a hole diameter 10% larger than the bolt diameter and thickness equal to or larger than 0.25 times the bolt diameter were used at each end of the bolt. Bolt lengths were selected such that at least two or more threads protruded beyond the nut after tightening. Joints were made at least 24 hours before the time of testing and all the joints were prepared under normal environment conditions. A small piece was cut from each member of the joint immediately after the test and the moisture content of each member was determined by the method of oven drying.

Table 4.2: Test Programme – Joint Strength Tests

Direction of loading	Timber Species Tested	No of replicates	Bolt dia. (mm)	Side member thickness (mm)	Center member thickness (mm)	Total number of tests
Parallel to grain	Ginisapu Kumbuk	3	9.5 12.7 15.9	25	38 50 75	180
				38	38 50 75 100	
				50	50 75 100	
Perpendicular to grain	Ginisapu	3	9.5 12.7 15.9	25	38 50 75	90
				38	38 50 75 100	
				50	50 75 100	

Table 4.3: Dimensions, End and Edge Distances of the Joint

w_1	15d*
w_2	10d*
w_3	10d*
t_1 *(mm)*	25,38,50
t_2 *(mm)*	38,50,75,100
l	40d*
h	30d*
Central member height *(perpendicular to grain)*	25d*
End distance	5d* *(Perp. to grain)* 10d* *(Para. to grain)*
Edge distance	20d* *(Perp. to grain)* 5d* *(Para. to grain)*
**d is bolt diameter*	

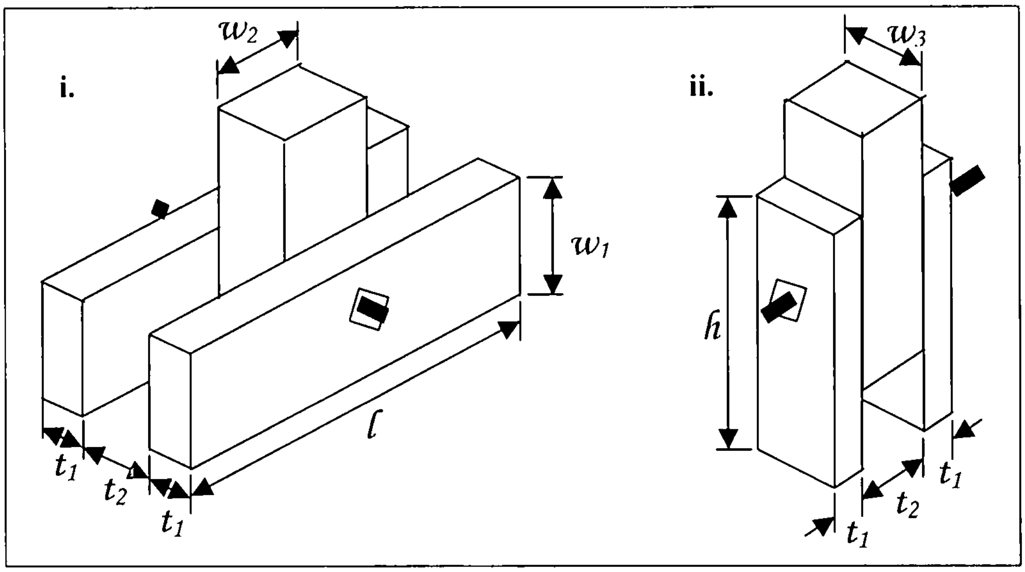


Figure 4.5: Joint Details for (i) Perpendicular and (ii) Parallel to Grain Test

Joints were tested in compression and load-slip values were continuously recorded until the ultimate load of the joint was reached.

The tensile strength of bolts was determined by tensile tests conducted according to BS 18: Part 1:1970. Six replicates were turned out from randomly selected bolts of each bolt diameter.

Chapter Five

EXPERIMENTAL PROGRAMME – EMBEDMENT STRENGTH TEST SERIES

Chapter 5: EXPERIMENTAL PROGRAMME - EMBEDMENT STRENGTH TEST SERIES

5.1 INTRODUCTION

Along with the joint strength test series a subsidiary test programme was conducted to check the validity of equations 3.24 and 3.25 for the embedment strength,. Factors affecting the embedment strength and their controls are described below. Proposed test programme is also included.

5.2 FACTORS AFFECTING THE EMBEDMENT STRENGTH AND THEIR CONTROLS

5.2.1 Bolt diameter

Bolt diameter is one of main factors that affect the embedment strength. According to the market survey results and consideration of bolt diameters used in the joint strength tests programme, same bolt diameters that were selected for the joint strength test programme were selected for the embedment strength test programme.

5.2.2 Timber species

Factors given in section 5.5.1 were also considered for the selection of timber species for embedment strength test programme. As a result, Ginisapu and Kumbuk, which were used for joint strength test programme, Palu and Lunumidella, which were used for the preliminary investigation by Dias et al. (1994) and Hora species were selected for the embedment strength test programme.

5.2.3 Thickness of the specimen

Thickness of the test specimen was determined according to the guidelines given in EN 383: 1993. It specifies that the thickness of the specimen should be within the range of 1.5d and 4d, in which d is fastener diameter, for bolts. According to the specifications and the available sizes in the market, 25mm, 38mm and 50mm were selected for the thickness of the specimen.

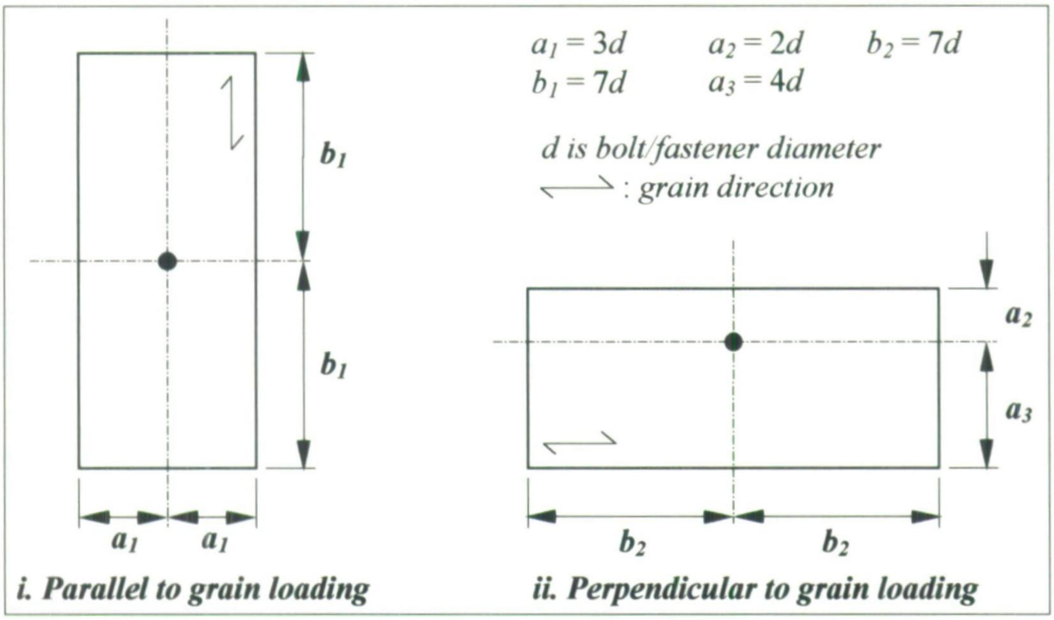
5.2.4 End and edge distances

EN 383:1993 was used as the guide for selection of end and edge distances of the test specimen. Specified end and edge distances are given in Figure 5.6 diagrammatically.

5.2.5 Presence of timber defects

As the size of specimen is relatively smaller than that of the member of joint strength test, it was possible to prepare the test specimens free of defects.

Other factors such as loading direction, moisture content and density of the specimen were controlled as described in the sections 5.5.3, 5.5.4 and 5.5.5 respectively.



i. Parallel to grain loading **ii. Perpendicular to grain loading**

Figure 5.6: End and edge distances of embedment strength test specimen

5.1 TEST PROGRAMME – EMBEDMENT STRENGTH TESTS

The test specimens, which were prepared from Ginisapu, Kumbuk, Hora, Lunumidella and Palu were tested in both parallel and perpendicular to grain directions. The thickness of test specimens, which were tested with 9.5mm diameter bolts, was limited to 25mm and 38 mm according to the requirements to maintain the specimen thickness within the range between 1.5 and 4 times the bolt diameter. For 12.7mm and 15.9mm diameter bolts, the thicknesses of the specimen were selected as 25mm, 38mm and 50mm. Three replicates from each specimen were tested and thus total of 240 tests was carried out (Table 5.4).

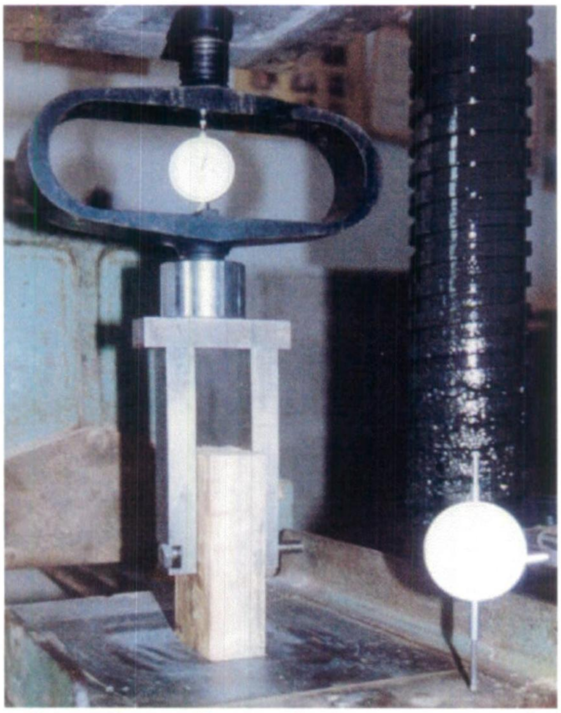


Figure 5.7: Testing of specimen for embedment strength in parallel to grain loading direction

Because the bending of the fastener must be prevented, a special type of loading apparatus (Figure 5.7) was used to load the fastener. This consisted of adjustable steel side plates, which have circular hole at the bottom portion of the plate. The apparatus was turned out using the Computer Numerical Control (CNC) machine and the hole diameters for fasteners were selected as there is no rotation or vertical movement of bolt within the hole is allowed. Side plates were attached to the horizontal beam as they can be adjusted according to the thickness of the test specimen. Details of the test apparatus are given in the Annex in Figure A1.

Specimens were tested in compression and load-slip data were continuously recorded for each joint. Using the data, the embedment load was determined.

The embedment load, which is related to the embedment strength, is defined as the ultimate load resisted by the specimen for parallel to grain loading and the load at failure or the load at the formation of 1mm crack in the specimen at the fastener, whichever smaller for perpendicular to grain loading.

The test programme of embedment strength test is summarized in Table 5.4 below.

Table 5.4: Test Programme – Embedment Strength Test

Species Tested	Direction of loading	No of replicates	Bolt dia. (mm)	Member thickness (mm)	Total number of tests
Ginisapu Kumbuk Hora Lunumidella Palu	Parallel to Grain Perpendicular to Grain	3	9.5	25	240
				38	
			12.7	25	
				38	
				50	
			15.9	25	
				38	
				50	

Chapter Six

RESULTS AND ANALYSIS – EMBEDMENT STRENGTH TEST SERIES

Chapter 6: RESULTS AND ANALYSIS – EMBEDMENT STRENGTH TEST SERIES

6.1 INTRODUCTION

Following the comprehensive test programme described in Chapter 4, various information such as load-slip data, densities and moisture contents of specimens were collected. Test results obtained from the embedment strength test series and the analysis of results are provided in this chapter.

Although the embedment strength test programme was conducted as a subsidiary test programme, the results of this test series need to be discussed earlier because the results of embedment strength test programme may affect the results of joint strength test programme.

EC 5 provides Equation 3.24 and 3.25 to determine the characteristic embedment strength of timber or timber based sheet materials based on the characteristic density of the material and the diameter of the fastener. Embedment strength values predicted by these equations and experimental results of each member tested were compared.

6.2 RESULTS OBTAINED FROM EMBEDMENT STRENGTH TESTS

A load-slip curve was obtained for each embedment strength test. The ultimate load, which is resisted by the specimen was determined using the load-slip curve and the embedment strength was then calculated as the specification given in EN 383:1993 (*refer Figure 3.6*).

The density of each member was determined using the actual dimensions and the weight of the specimen measured just before start of the test. The moisture content was determined by following the oven-dried method using a piece of member cut from the specimen just after the test.

The results of density, moisture content and experimental embedment strength, which were obtained for each timber species, bolt diameter and specimen thickness are given in annex in Table A1 for parallel to grain loading and Table A2 for perpendicular to grain loading.

6.3 ANALYSIS OF EMBEDMENT STRENGTH TEST RESULTS

Figures 6.1 to 6.6 show the comparison of experimental embedment strength of each specimen determined according to EN 383:1993 and the theoretical embedment strength which is determined using Equations 3.24 and 3.25 for parallel and perpendicular to grain directions respectively.

As a whole, the experimental embedment strength and the embedment strength predicted by EC 5 agree closely with each other. When considering the parallel to grain loading test results (Figures 6.1 to 6.3), it can be seen that the agreement is best for smaller (9.5mm) bolt diameters while with the increasing of bolt diameter up to 15.9mm, deviation between embedment strengths predicted by EC 5 and experimental results increases. It can be seen that the opposite is true for perpendicular to grain

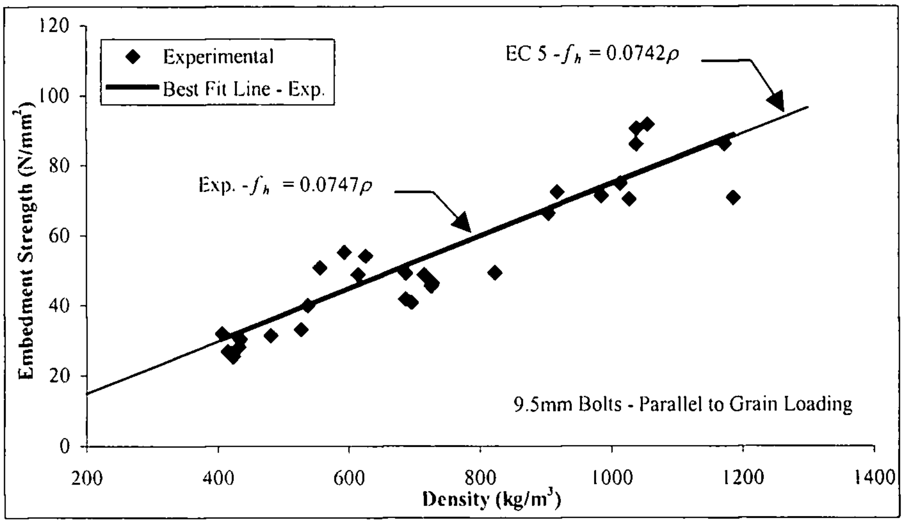


Figure 6.1: Comparison of experimental and EC 5 – 9.5mm bolts – parallel to grain loading

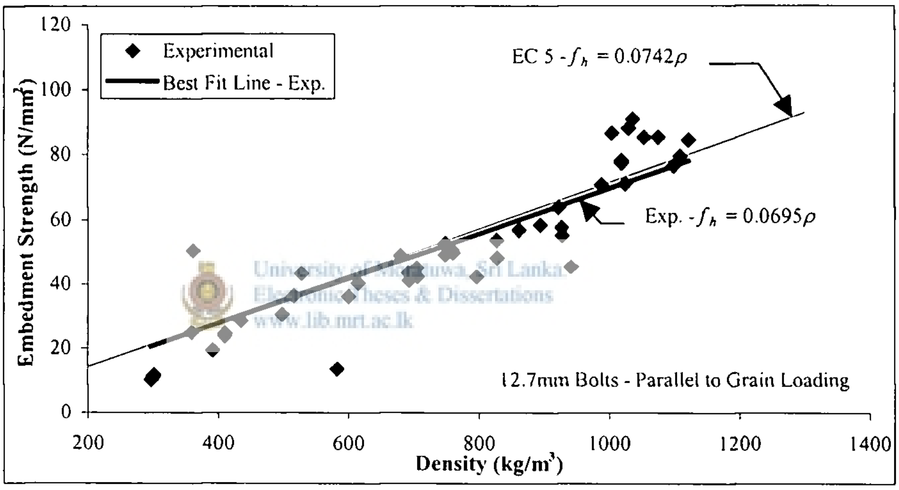


Figure 6.2: Comparison of experimental and EC 5 – 12.7mm bolts – parallel to grain loading

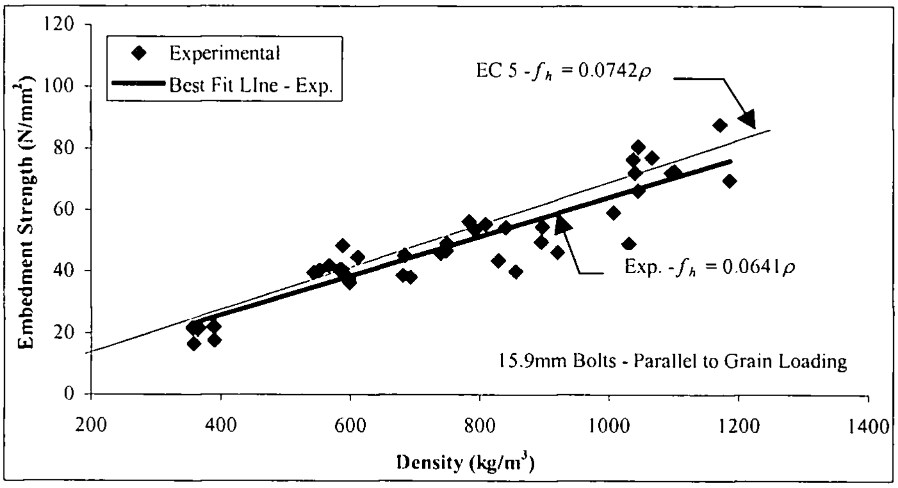


Figure 6.3: Comparison of experimental and EC 5 – 15.9mm bolts – parallel to grain loading

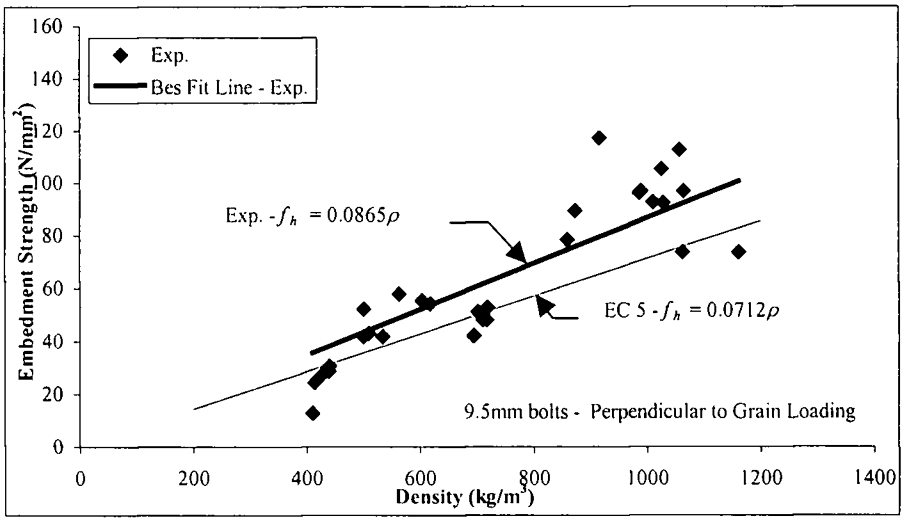


Figure 6.4: Comparison of experimental and EC 5 – 9.5mm bolts – perpendicular to grain loading

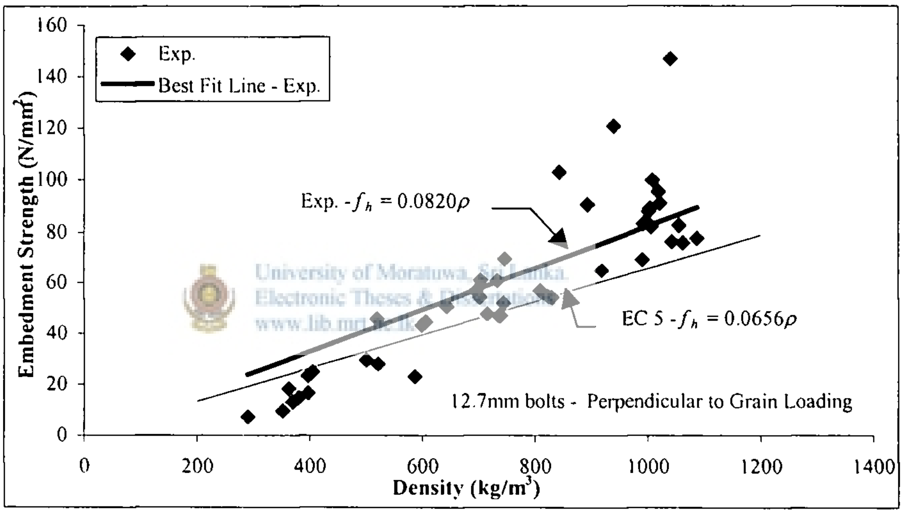


Figure 6.5: Comparison of experimental and EC 5 – 12.7mm bolts – perpendicular to grain loading

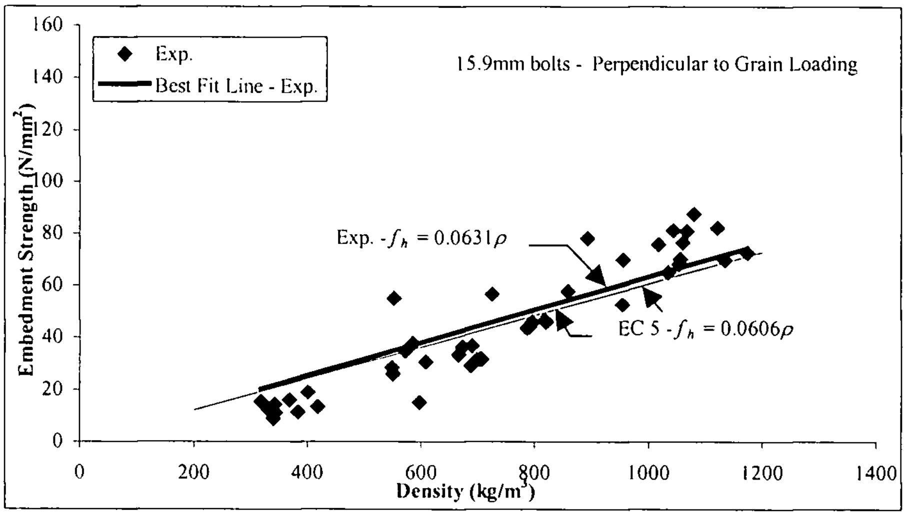


Figure 6.6: Comparison of experimental and EC 5 – 15.9mm bolts – perpendicular to grain loading

loading because the best agreement is seen for the specimens tested with 15.9mm bolts and the deviation of experimental results and the EC 5 prediction increases when the bolt diameter decreases to 9.5mm (Figures 6.4 to 6.6).

For parallel to grain loading tests, embedment strength of the specimens tested with 9.5mm bolts are predicted well by EC 5. For the specimens tested with 12.7mm bolts, only the embedment strength of species of which the density is less than 600kg/m^3 are predicted well by EC 5. The best fit is at about 400kg/m^3 in the case of the specimens tested with 15.9mm bolts. The prediction and the experimental results deviate from each other when the density of the species increases from 400kg/m^3. When considering the perpendicular to grain loading tests, it can be seen that the predictions are close to the experimental results, for lower densities about 400kg/m^3. The deviation between the prediction and the experimental results increases with increase in density.

Although the EC 5 compares well for parallel to grain loading tests, Figure 6.4 shows a big discrepancy between the EC 5 predictions and the experimental results. These discrepancies may be due to the EC 5 specifications for the determination of embedment strength of timber or timber-based sheet materials are based on the research conducted in Europe using more European soft timber species, which usually belong to lower densities, and lesser number of tropical hardwood, which has higher densities. In the test series, which was conducted to develop embedment strength formulae for bolts and nails, the proportion of hardwood species tested is less as 22% and is not enough to obtain a versatile relationship that suit both hardwood and softwood species. This indicates the necessity of a more realistic model, which is able to predict the embedment strength of local timber species, which belongs to hardwood category, well. This embedment strength test series is an initial step to develop a more versatile relation ship for the embedment strength of local hardwoods.

Table 6.1: Results of linear regression analysis of maximum embedment strength against timber density

Loading direction	Bolt diameter (mm)	No. of specimens tested	R^2 (Exp.)	Regression against density (Exp.)	Regression against density (EC 5)
Parallel to grain	9.5	30	0.8164	0.0747ρ	0.0742ρ
	12.7	45	0.8192	0.0695ρ	0.0716ρ
	15.9	45	0.8472	0.0641ρ	0.0690ρ
Perpendicular to grain	9.5	30	0.7514	0.0865ρ	0.0712ρ
	12.7	45	0.7175	0.0820ρ	0.0656ρ
	15.9	45	0.8040	0.0631ρ	0.0606ρ

The observed experimental results were subjected to a regression analysis against the density of the species. These regression analyses were done for each loading direction and each bolt diameter. Several types of regression were applied and, among them, the linear regression was selected as the most suitable method because it gives a more realistic and simple relationship. Table 6.1 provides the results of linear regression analysis.

Results of linear regression analysis show, again, that the close agreement between experimental results and the theory of smaller bolt diameters of parallel to grain loading and of larger bolt diameters of perpendicular to grain loading tests. These regression constants were then plotted against the bolt diameter for each loading direction (Figure 6.7 and 6.8) to find out the relationship among the embedment strength (f_h), bolt diameter (d) and the density of timber species (ρ_k) and following relationships were developed.

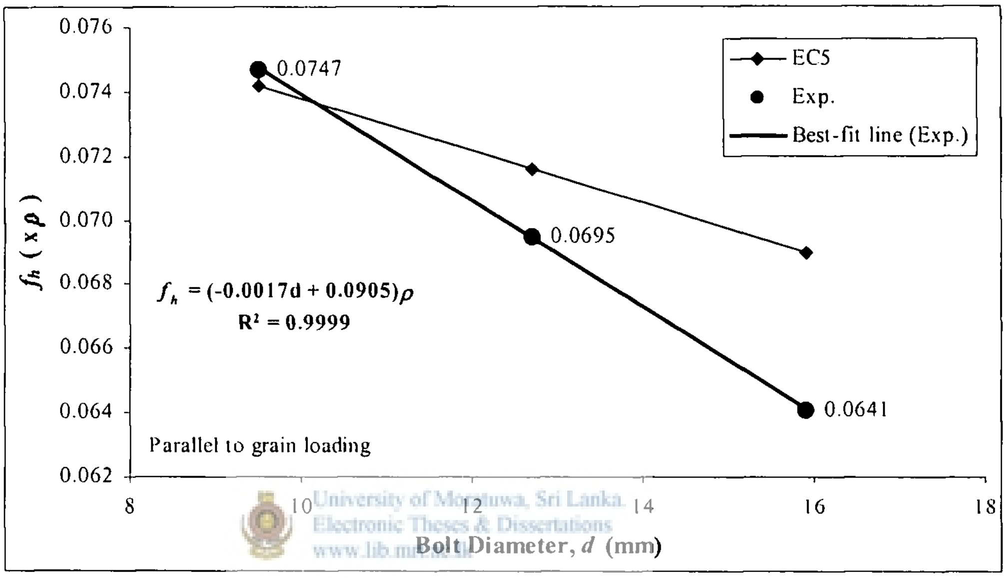


Figure 6.7: Combine relationship among the embedment strength, density and bolt diameter for parallel to grain loading

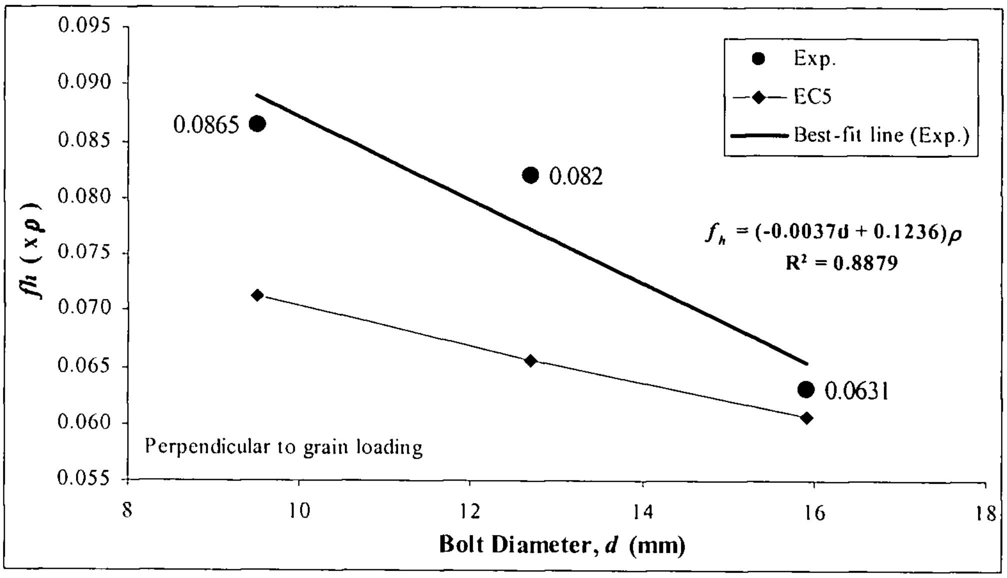


Figure 6.8: Combine relationship among the embedment strength, density and bolt diameter for perpendicular to grain loading

According to the Table 6.1 the embedment strength of the specimen is given by,

$f_h = 0.0747\rho$ for 9.5mm bolts & parallel to grain loading
$f_h = 0.0695\rho$ for 12.7mm bolts & parallel to grain loading
$f_h = 0.0641\rho$ for 15.9mm bolts & parallel to grain loading

Similarly, the relationship between the f_h and ρ of specimens loaded in perpendicular to grain direction can be written using the regression analysis results given in Table 6.1.

To find out the combined relationship among f_h, ρ and bolt diameter (d), above results were then plotted against the bolt diameter for each loading direction (Figure 6. 7 and 6.8).

From Figure 6.7, it can be shown that the variation of f_h with the specimen density and bolt diameter is given by,

$$f_h = (-0.0017d + 0.0905)\rho_k$$

$$\therefore f_h = 0.0905(1 - 0.019d)\rho_k$$

Simplifying,

$$f_h = 0.091(1 - 0.02d)\rho_k \qquad \text{(Eq. 6.1)}$$

Similarly, for perpendicular to grain loading,

From Figure 6.8,

$$f_h = (-0.0037d + 0.1236)\rho_k$$

$$\therefore f_h = 0.1236(1 - 0.039d)\rho_k$$

Simplifying,

$$f_h = 0.124(1 - 0.04d)\rho_k \qquad \text{(Eq. 6.2)}$$

The predicted joint strengths, which were calculated by using both EC 5 formulae and new formulae set (Equations 6.1 and 6.2) were then compared to check the effect of use of new embedment strength formulae (Equations 6.1 and 6.2) instead of EC 5 (Equations 3.24 and 3.25) specifications for the determination of characteristic embedment strength on the prediction of joint strength tested in this research programme. These comparisons are illustrated Figures 6.9 to 6.11 below and the comparison of predicted failure modes is shown in Table 6.2. The experimentally observed failure modes are also included in this table.

These figures show that the effect of changing the set of embedment strength formulae on the prediction of joint strength is very small. For the joints made from Ginisapu using 9.5mm bolts and loaded in parallel to grain direction, both values of predicted joint strengths are very similar. With increase in the bolt diameter from 9.5mm to 15.9mm the new set of embedment formulae tends to lower the predicted joint strength. But the difference between both predicted joint strengths is small and is not enough to change the mode of failure. Similar results are observed for the joints made of Kumbuk.

The predicted joint strength calculated using the proposed new embedment strength formulae set is higher than that calculated using the EC 5 embedment strength formulae of the joints made from Ginisapu loaded in perpendicular to grain direction. The difference between two predicted joint strength increases with increase in bolt diameter from 9.5mm to 15.9mm. As in parallel to grain loading, this difference too is not enough to cause a considerable change in predicted failure mode (Table 6.2).

It can be seen from Table 6.2 shows there is no significant effect on the prediction of failure mode due to the change of embedment strength formulae. Only 26 numbers of predictions were changed due to the use of new formulae set. The change of formulae set has little effect on parallel to grain loading tests for both Ginisapu and Kumbuk species. Only 8 numbers out of 180 joints were changed in the prediction of failure mode. In perpendicular to grain loading tests this number is 18 out of 90 tests. When considering the entire predictions of failure mode, 14 numbers out of 270 tests were changed in the manner that the new formulae set predict the experimentally observed failure mode. Further, the new formulae set had the opposite effect of changing the experimentally observed failure mode into another type in 5 numbers out of 270 joints.

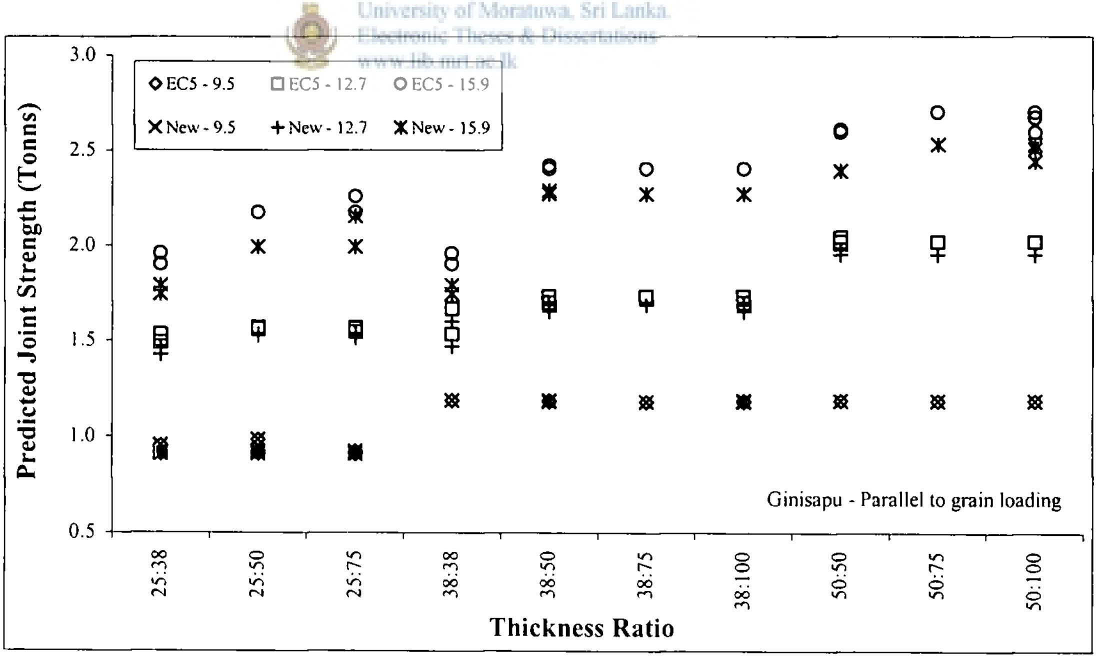


Figure 6.9: Comparison of the effect of two embedment strength formulae sets on the prediction of joint strength – Ginisapu – Parallel to grain loading

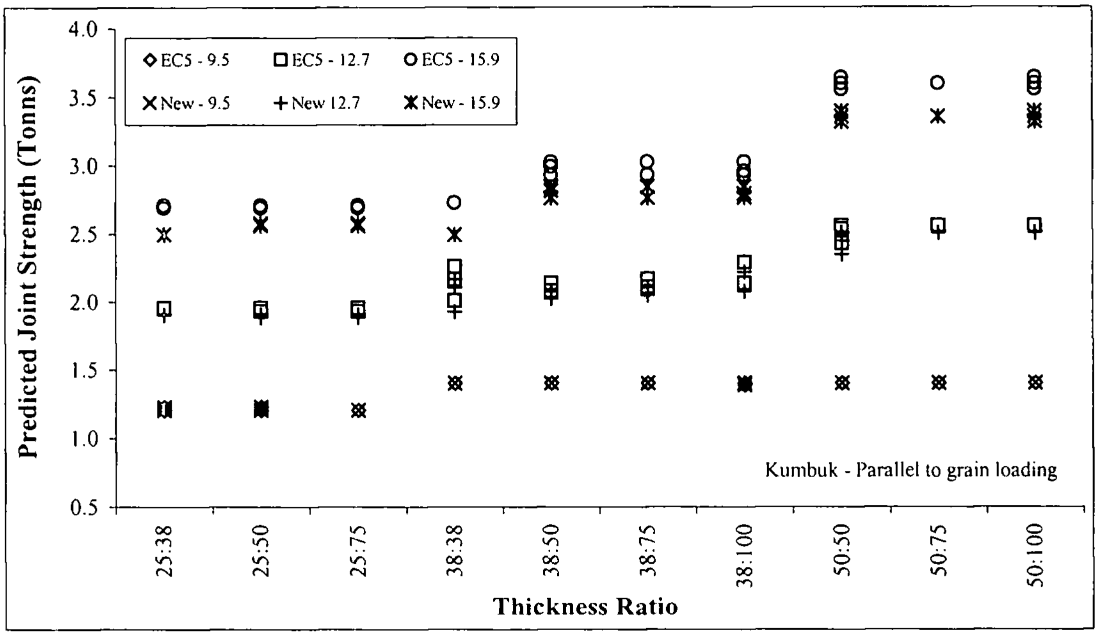


Figure 6.10: Comparison of the effect of two embedment strength formulae sets on the prediction of joint strength – Kumbuk – Parallel to grain loading

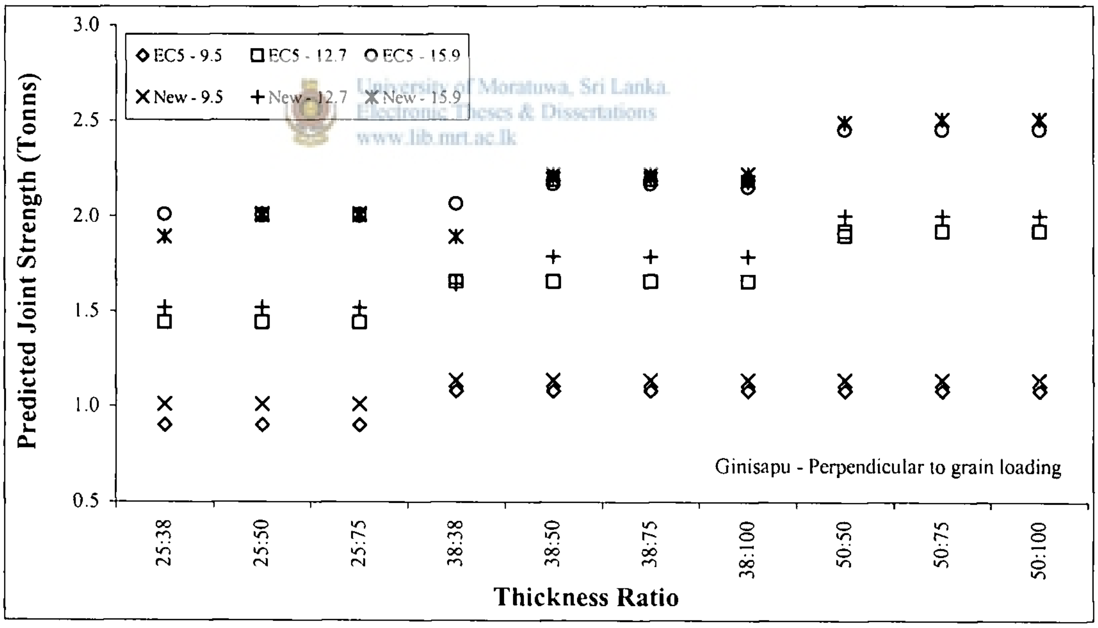


Figure 6.11: Comparison of the effect of two embedment strength formulae sets on the prediction of joint strength – Ginisapu – Perpendicular to grain loading

Table 6.2: Comparison of the effect of two embedment strength formulae sets on the prediction of failure mode

Thickness Ratio	Ginisapu - Parallel to grain loading									Ginisapu - Perpendicular to grain loading									Kumbuk - Parallel to grain loading								
	9.5mm Bolts			12.7mm Bolts			15.9mm Bolts			9.5mm Bolts			12.7mm Bolts			15.9mm Bolts			9.5mm Bolts			12.7mm Bolts			15.9mm Bolts		
	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.	EC 5	New	Exp.
25:38	2	2	1b	1b	1b	1b	1b	1b	1a	2	2	1b	2	2	1b	**2**	**1b**	1a	2	2	1b	2	2	1b	**2**	**1b**	1a
	2	2	1b	1b	1b	1b	1b	1b	1b	2	2	1b	2	2	1b	**2**	**1b**	1b	2	2	1b	2	2	1b	**2**	**1b**	1b
	2	2	1b	1b	1b	1b	1b	1b	1b	2	2	1b	2	2	1b	**2**	**1b**	1b	2	2	1b	2	2	1b	**2**	**1b**	1b
25:50	2	2	2	2	2	2	1a	1a	1a	2	2	2	2	2	2	2	2	1a	2	2	2	2	2	2	2	2	1a
	2	2	1b	2	2	1b	1a	1a	1a	2	2	1b	2	2	1b	2	2	1a	2	2	1b	2	2	1b	2	2	1a
	2	2	1b	2	2	1b	1a	1a	1a	2	2	1b	2	2	1b	2	2	1a	2	2	1b	2	2	1b	2	2	1a
25:75	2	2	1a	2	2	2	1a	1a	2	2	2	1a	2	2	2	2	2	2	2	2	1a	2	2	2	2	2	2
	2	2	1a	2	2	2	1a	1a	1a	2	2	1a	2	2	2	2	2	1a	2	2	1a	2	2	2	2	2	1a
	2	2	1a	2	2	1b	2	2	1a	2	2	1a	2	2	1b	2	2	1a	2	2	1a	2	2	1b	2	2	1a
38:38	3	3	2	1b	1b	1b	1b	1b	1b	3	3	2	2	1b	1b	1b	1b	1b	3	3	2	**2**	**1b**	1b	1b	1b	1b
	3	3	1b	1b	1b	1b	1b	1b	1b	3	3	1b	2	1b	1b	1b	1b	1b	3	3	1b	1b	1b	1b	1b	1b	1b
	3	3	1b	1b	1b	1b	1b	1b	1b	3	3	1b	2	1b	1b	1b	1b	1b	3	3	1b	2	2	1b	1b	1b	1b
38:50	3	3	3	2	2	2	2	2	1b	3	3	3	2	2	2	2	2	1b	3	3	3	2	2	2	2	2	1b
	3	3	1b	2	2	2	2	2	1b	3	3	1b	2	2	2	2	2	1b	3	3	1b	2	2	2	2	2	1b
	2	2	1b	2	2	2	2	2	1b	3	3	1b	2	2	2	2	2	1b	3	3	1b	2	2	2	2	2	1b
38:75	2	2	1a	2	2	2	2	2	2	3	3	1a	2	2	2	2	2	2	3	3	1a	2	2	2	2	2	2
	2	2	3	2	2	2	2	2	2	3	3	3	2	2	2	2	2	2	3	3	3	2	2	2	2	2	2
	2	2	1b	2	2	2	2	2	2	3	3	1b	2	2	2	2	2	2	3	3	1b	2	2	2	2	2	2
38:100	3	3	3	2	2	2	2	2	2	3	3	3	2	2	2	2	2	2	**2**	**3**	3	2	2	2	2	2	2
	2	2	1a	2	2	2	2	2	2	3	3	1a	2	2	2	2	2	2	3	3	1a	2	2	2	2	2	2
	2	2	1b	2	2	2	2	2	2	3	3	1b	2	2	2	2	2	2	3	3	1b	2	2	2	2	2	2
50:50	3	3	2	2	2	1b	**2**	**1b**	1b	3	3	2	**2**	**3**	1b	**2**	**1b**	1b	3	3	2	2	2	1b	2	2	1b
	3	3	1b	2	2	1b	1b	1b	1b	3	3	1b	**2**	**3**	1b	**2**	**1b**	1b	3	3	1b	**3**	**2**	1b	2	2	1b
	3	3	1b	2	2	1b	**2**	**1b**	1b	3	3	1b	**2**	**3**	1b	**2**	**1b**	1b	3	3	1b	3	3	1b	2	2	1b
50:75	3	3	1b	2	2	2	2	2	2	3	3	1b	**2**	**3**	2	2	2	2	3	3	1b	3	3	2	2	2	2
	3	3	1b	2	2	1b	2	2	2	3	3	1b	**2**	**3**	1b	2	2	2	3	3	1b	3	3	1b	2	2	2
	3	3	1b	2	2	2	2	2	2	3	3	1b	**2**	**3**	2	2	2	2	3	3	1b	3	3	2	2	2	2
50:100	3	3	1a	2	2	2	2	2	2	3	3	1a	**2**	**3**	2	2	2	2	3	3	1a	3	3	2	2	2	2
	3	3	3	2	2	2	2	2	3	3	3	3	**2**	**3**	2	2	2	3	3	3	3	3	3	2	2	2	3
	3	3	1b	2	2	2	2	2	1b	3	3	1b	**2**	**3**	2	2	2	1b	3	3	1b	3	3	2	2	2	1b

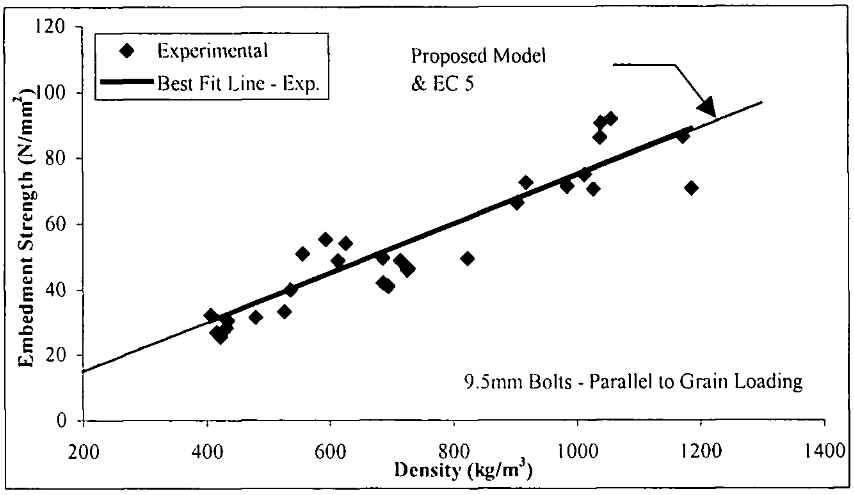


Figure 6.12: Comparison of EC 5 and new model with the experimental results – 9.5mm bolts – parallel to grain loading

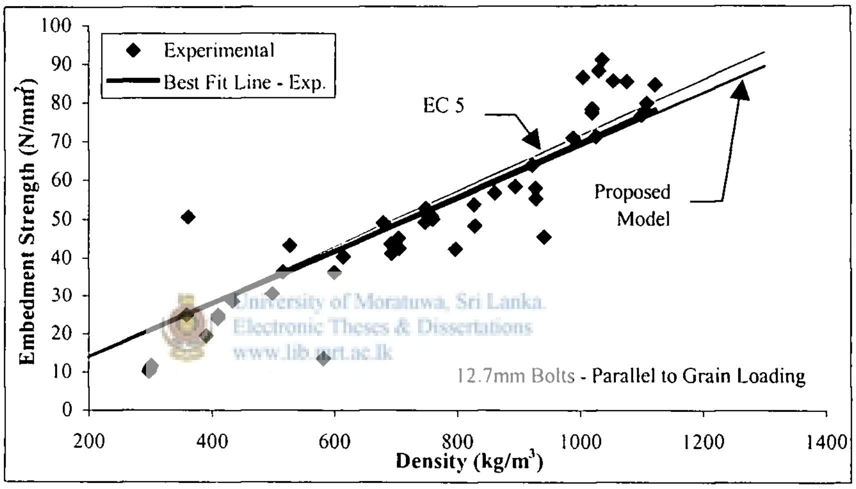


Figure 6.13: Comparison of EC 5 and new model with the experimental results – 12.7mm bolts – parallel to grain loading

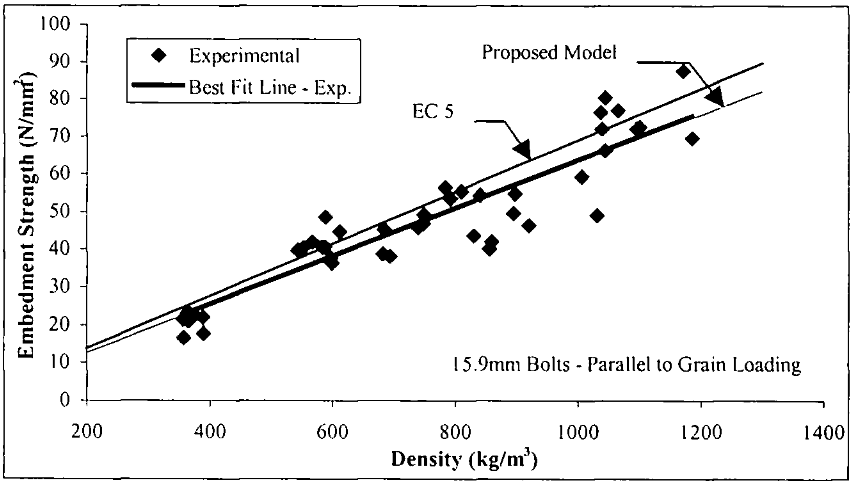


Figure 6.14: Comparison of EC 5 and new model with the experimental results – 15.9mm bolts – parallel to grain loading

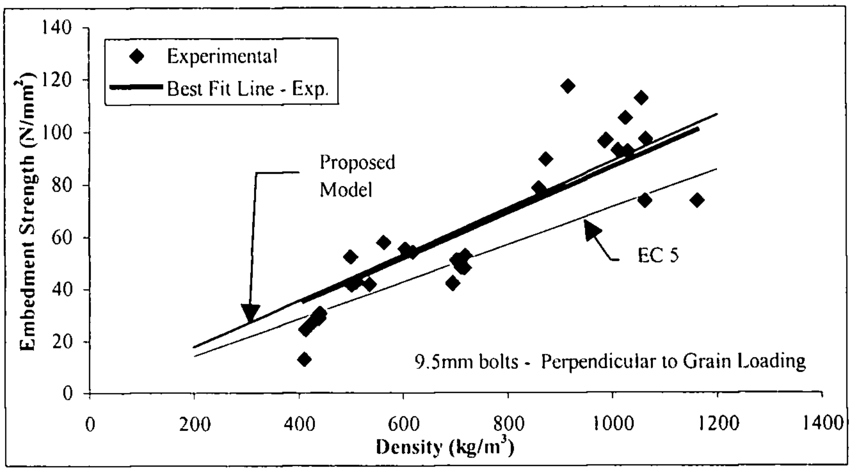


Figure 6.15: Comparison of EC 5 and new model with the experimental results – 9.5mm bolts – perpendicular to grain loading

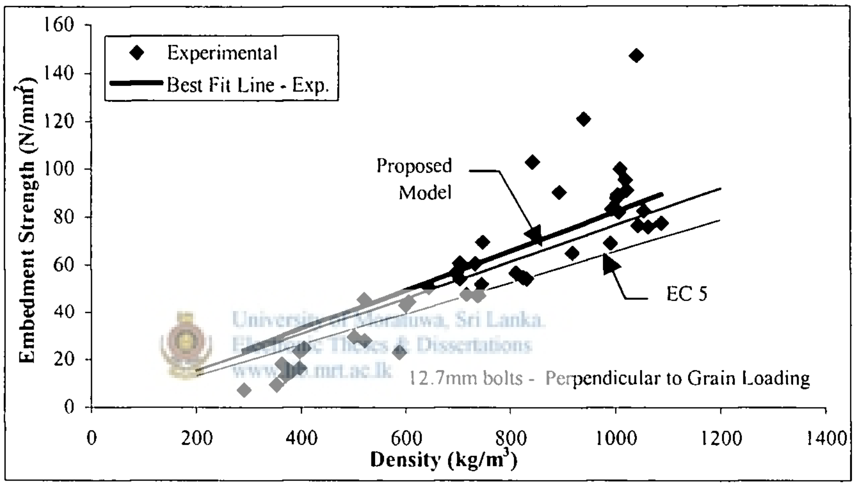


Figure 6.16: Comparison of EC 5 and new model with the experimental results – 12.7mm bolts – perpendicular to grain loading

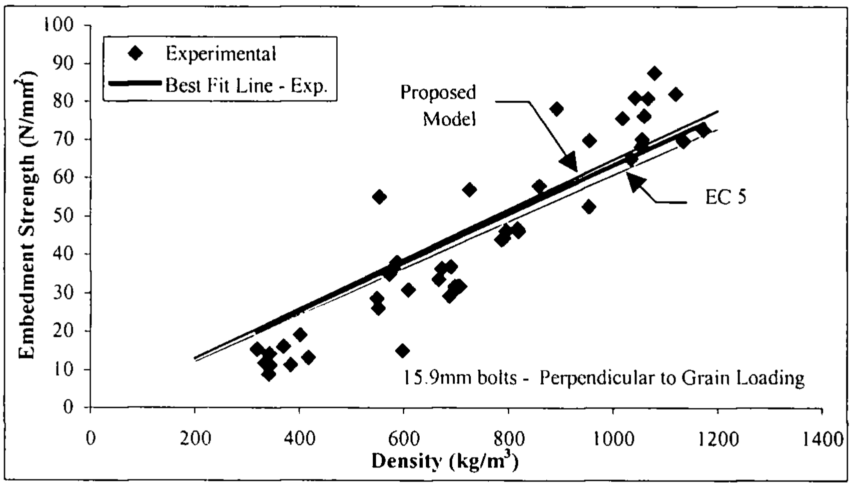


Figure 6.17: Comparison of EC 5 and new model with the experimental results – 15.9mm bolts – perpendicular to grain loading

Figure 6.12 shows that prediction of embedment strength by the proposed formulae and EC 5 formulae sets are almost same for 9.5mm bolt specimens loading in parallel to grain direction. Figures 6.13 and 6.14 show that new formulae set predicts lower values than EC 5 set for embedment strength of parallel to grain loading tests and the difference between new and EC 5 predictions increases when increasing the bolt diameter up to 15.9mm and prediction of new formulae set agree well with the experimental results for the specimens tested. When considering the perpendicular to grain loading tests, predictions of the new formulae set are higher than that of EC 5 formulae set. The difference between the predictions decreases when increasing the bolt diameter up to 15.9mm and the both predictions are very close for the specimens tested with 15.9mm bolts. It is important to note that in this perpendicular to grain loading tests, the experimental results agree very closely with the predictions of new embedment formulae set for all bolt diameters considered.

Although there is no significant effect on prediction of joint strength and failure modes due to use of the proposed embedment strength formulae instead of embedment strength formulae given in EC 5, it is required to conduct further investigations on new embedment strength formulae to verify the proposed model for other timber species as well as bolt diameters too. Further, this test programme was conducted using only local timber species, which belongs to tropical hardwood species. Therefore, it is required to check the applicability of this model to the European softwood species too. Therefore, it is recommended to conduct a verification test programme including a wide range of parameters, which affect the embedment strength.

Chapter Seven

RESULTS AND ANALYSIS – JOINT STRENGTH TEST SERIES

Chapter 7: RESULTS AND ANALYSIS – JOINT STRENGTH TEST SERIES

7.1 INTRODUCTION

Following the comprehensive test programme described in chapter 4, various data such as load-slip data of joints, moisture content and densities of members and also failure patterns and bolt compressive strength were collected. This chapter provides above-mentioned results collected from the test series and analysis of these results. Modifications done for the EC5 recommendations are also described.

7.2 RESULTS OBTAINED FROM THE JOINT STRENGTH TESTS

A load-slip curve (Figure 3.3) for each joint was obtained for each 180 parallel to grain and 90 perpendicular to grain joint strength tests. From each load-slip curve, the yield load as well as the ultimate load was determined. The yield load is defined as the load at the intersection of the tangents to the linear and non-linear portions of the curve (Figure 3.3b). The ultimate load is defined as the load at failure. Also, failure pattern of each joint was observed after the test. The data necessary for moisture content determination and density were also obtained for each member of each joint.

7.2.1 Failure Patterns

It was possible to observe every type of failure pattern form the joint strength test series. All four types of failure patterns were observed from the joints, which were loaded parallel to grain direction while all failure types except mode 1a failure pattern were observed from the joints, which were loaded in perpendicular to grain direction.

Figures 7.1 to 7.4 show some observed failure patterns.

Figure 7.1: Different failure patterns observed for joints made with 15.9mm bolts – t_1 = 25mm – t_2 = 38mm(A); 50mm(B) and 75mm(C) – Parallel to grain loading - Kumbuk species

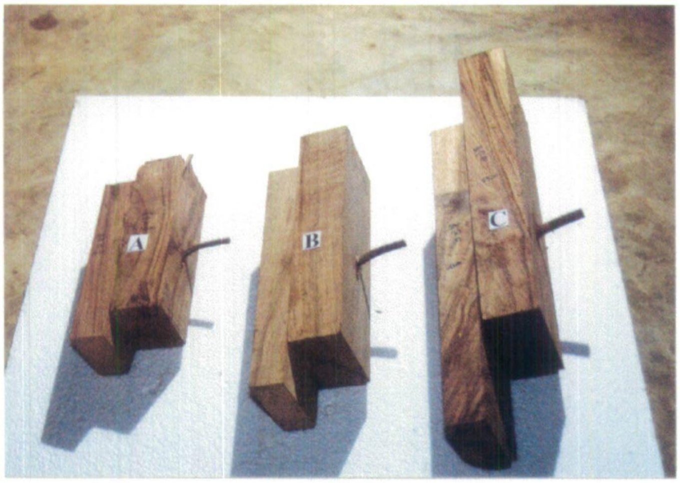


Figure 7.2: Different failure patterns observed for joints made with 9.5mm(A); 12.7mm(B) and 15.9mm(C) bolts – t_1 = 50mm – t_2 = 75mm – Parallel to grain loading - Kumbuk species

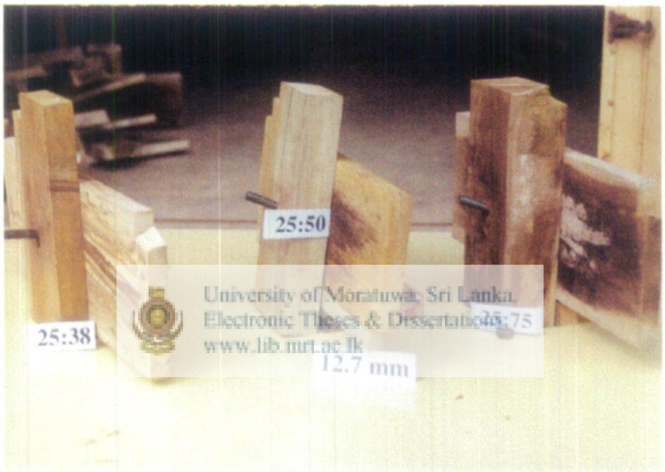


Figure 7.3: Different failure patterns observed for joints made with 12.7mm bolts – Perpendicular to grain loading – Ginisapu species *(Thickness details as shown in figure)*

Figure 7.4: Different failure patterns observed for joints made with 15.9mm bolts – Perpendicular to grain loading – Ginisapu species *(Thickness details as shown in figure)*

Table 7.1: Comparison of predicted and observed failure modes

		Parallel to grain loading					Perpendicular to grain loading				
		Predicted failure mode *(Percentage on prediction)*				Total Obsrvd.	Predicted failure mode *(Percentage on prediction)*				Total Obsrvd.
		Mode 1a	Mode 1b	Mode 2	Mode 3		Mode 1a	Mode 1b	Mode 2	Mode 3	
Observed failure mode	Mode 1a	**4** ***(80.0)***	1 *(7.9)*	15 *(12.9)*	4 *(9.5)*	24	-	-	9 *(13.6)*	3 *(14.3)*	12
	Mode 1b	-	**16** ***(94.1)***	45 *(38.8)*	23 *(54.8)*	84	-	**3** ***(100)***	27 *(40.9)*	12 *(57.1)*	42
	Mode 2	1 *(20.0)*	-	**52** ***(44.8)***	9 *(21.4)*	62	-	-	**29** ***(43.9)***	2 *(9.5)*	31
	Mode 3	-	-	4 *(3.5)*	**6** ***(14.3)***	10	-	-	1 *(1.6)*	**4** ***(19.1)***	5
Total Predicted		5	17	116	42	180	-	3	66	21	90

In joints where the thickness ratio is close to unity and for the bolt sizes considered, the load capacity is generally governed by a crushing failure of the timber. Among 180 parallel to grain joint strength tests, 24 numbers of mode 1a failures were observed while 5 numbers of same type failures were predicted. These predicted failure modes were determined using the characteristic density of each species and other required parameters. Determination of characteristic density will be described in section 7.2.2 later. The observed and predicted results for failure modes 1b, 2 and 3 are 84 & 17, 62 & 116 and 10 & 42 respectively. While, zero, 3, 66 and 21 numbers of joints were expected to fail in the modes 1a, 1b, 2 and 3 respectively, 12, 42, 31 and 5 number of failures were observed experimentally for 90 perpendicular to grain loading tests. Comparison between predicted and observed failure modes is provided in Table 7.1 above.

The EYM predicted failure modes of types 1a, 1b, 2 and 3 for bolted joint tested in parallel to grain direction according to the actual joint geometric properties, characteristic density of joint members and average bolt yield strength of the fastener used. All types of failure modes except mode 1a were predicted for the joints loaded perpendicular to grain direction based on same factors mentioned above. Failure modes were predicted correctly only for 78 number of joints from the 180 joints tested (43.3%) in parallel to grain loading tests while 36 numbers of joints out of 90 (40%) were predicted correctly for the joints tested in the direction of perpendicular to grain. The best accuracy of prediction is with mode 1b that predicted failure mode matching the same type of observed failure mode for the joints loaded in both parallel and perpendicular to grain directions. For this mode of failure, 94.1% and 100% of joints were predicted accurately for parallel to and perpendicular to grain loading tests respectively. In other predicted failure modes the predicted failure mode matched the observed failure mode in 80% for mode 1a, 44.8% for mode 2 and 14.3% for mode 3 failures. For perpendicular to grain loading tests these value are 0%, 43.9%, and 19.1% respectively for mode 1a, 2 and 3 (See the values highlighted in Table 7.1).

Predicted and observed failure modes for each joint are given in Tables A3 to Table A11 in the annex.

7.2.2 Characteristic density of timber species

The density of each joint member was calculated by using the observations collected for each member of the joint as described in previous chapter. The characteristic density (ρ_k) at 5% confidence limit for the each species was determined by analyzing the resulting densities using the computer software "SPSS for Windows" (Release 10.0.1: 1999). Results of the analysis are given below.

Table 7.2: Results of density analysis

	Ginisapu	**Kumbuk**
N	540	270
Mean ($\bar{x}$)	640.41	890.50
Standard deviation (σ)	91.29	79.87
Characteristic density (ρ_k) in kg/m^3	632.70	880.97

7.2.3 Bolt tensile strength

Bolt tensile strength of each bolt diameter was determined according to the BS 18:Part 1:1970 using 6 specimens per each bolt diameter. Specimens were turned out from randomly selected bolts. The proportional limit strength determined from the stress-strain curve of each specimen was adopted as the bolt tensile strength and the average values of these results, which were used to determine the characteristic bolt yield moment (f_y), are given in the Table 7.3 below.

Table 7.3: Average bolt tensile strength

Bolt diameter (mm)	**Average bolt tensile strength (N/mm^2)**
9.5	393.44
12.7	424.37
17.9	380.12

7.3 ANALYSIS OF JOINT STRENGTH TEST RESULTS

Results of all joints tested in the joint strength test programme are given in Tables A3 to Table A11 in the annex. The density and moisture content values given in these tables are of average of three members of each joint. Moisture content of each member was determined as described in the previous chapter. Because the data available to compare the effect of new formulae on the prediction of joint strength and failure modes is not adequate to reach to a reliable decision, embedment strength formulae given in EC5 (Equations 3.25 & 3.25) were used for the analysis of joint strength test results. For each joint, joint strength, which is predicted the EYM, was calculated by substituting the characteristic density (ρ_k) of each timber species in the equations 3.25 & 3.25 and average bolt yield strength (f_u) of each bolt diameter in the equation 2.17 and substituting the adjusted design embedment strength using Equation 3.16 and design bolt yield moment using Equation 3.15 in the Equations 3.11 to 3.14. The lowest value predicted by Equations 3.11 to 3.14 was the design resistance load of the particular joint and the failure mode governing the lowest design resistance load was the failure mode predicted by the EYM theory.

The factor of Safety (FoS) was then calculated for each joint. The FoS is defined as the ratio of experimentally observed yield strength of the joint to the joint strength predicted by the EYM. These calculated factors of safety were then plotted against the thickness ratio (side member thickness to central member thickness) of each joint (Figures 7.5 to 7.13).

As a whole, the EYM seems to be good in predicting the strength of the joints tested because more than 95% of joints have the FoS than 1.0. It is important to note that all joints made from Ginisapu species loaded in the direction of perpendicular to grain have the FoS greater than 1.0. An interesting trend was also observed in Figures 7.5 to 7.13 in that on average, the experimental to predicted values were in better agreement where the thickness ratio was closer to unity; and as this ratio increased the magnitude by which the EYM underestimated the yield load also increased. In joints where the thickness ratio is close to unity and for the bolt sizes considered, the load capacity is generally governed by a crushing failure of the timber.

It can be seen from Figures 7.5 to 7.13 that the FoS of each joint increases in a considerable level when increasing the central member thickness while keeping the side member constant in thickness. Some of these factors of safety are too high about 4.0 or more and resulting in more conservative joint design. The reason for this behaviour is best shown in Figures 7.14 to 7.22 where although the experimentally determined joint strength increases when the central member thickness is increased, the predicted joint strength does not increase considerably. The predicted joint strength is almost the same for a particular bolt diameter considered.

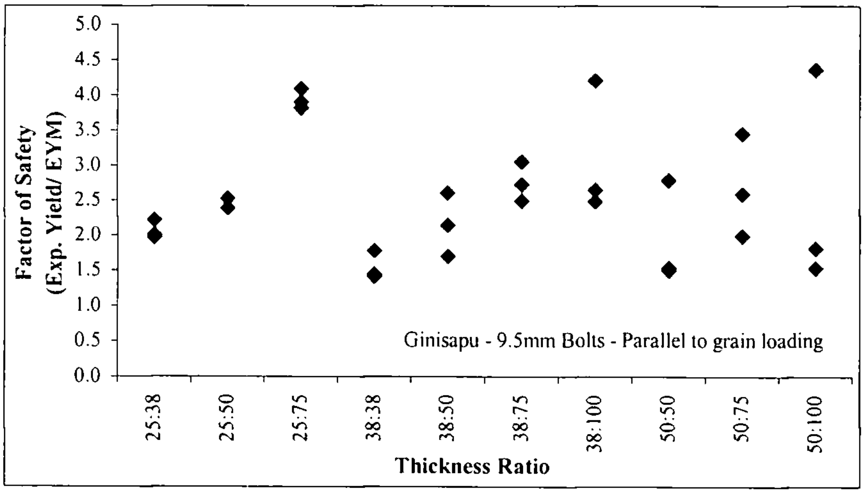


Figure 7.5: Variation of FoS of joints made from Ginisapu with 9.5mm bolts loaded parallel to grain

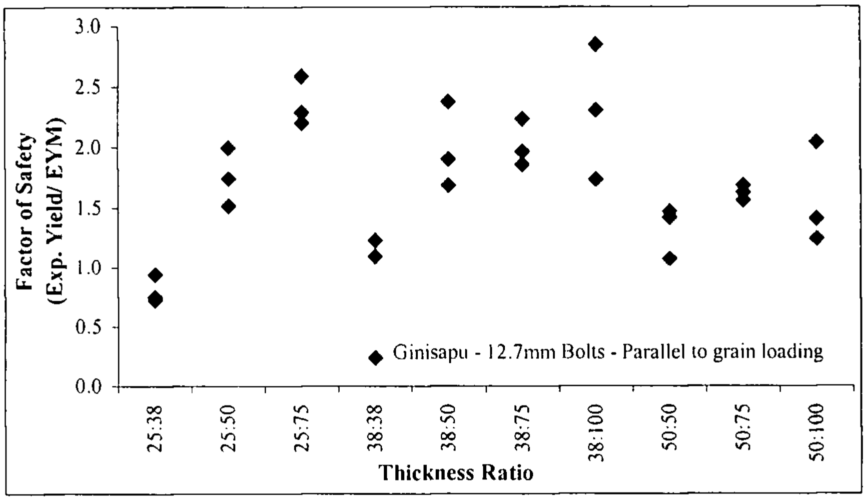


Figure 7.6: Variation of FoS of joints made from Ginisapu with 12.7mm bolts loaded parallel to grain

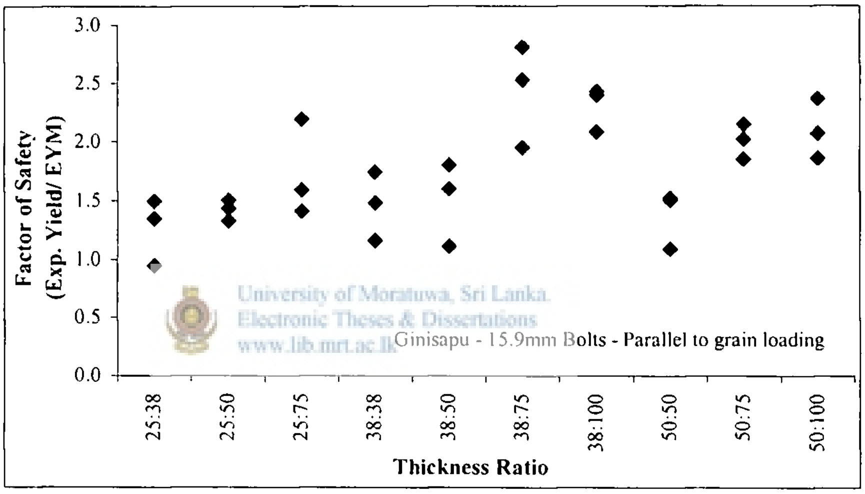


Figure 7.7: Variation of FoS of joints made from Ginisapu with 15.9mm bolts loaded parallel to grain

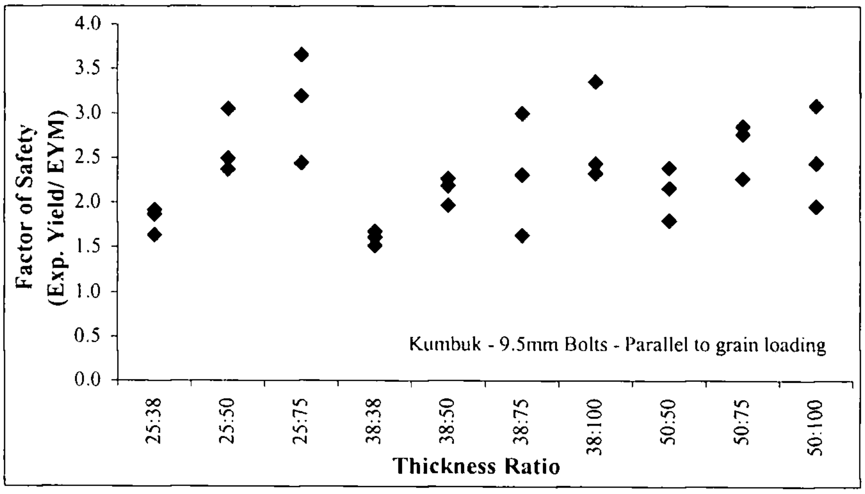


Figure 7.8: Variation of FoS of joints made from Kumbuk with 9.5mm bolts loaded parallel to grain

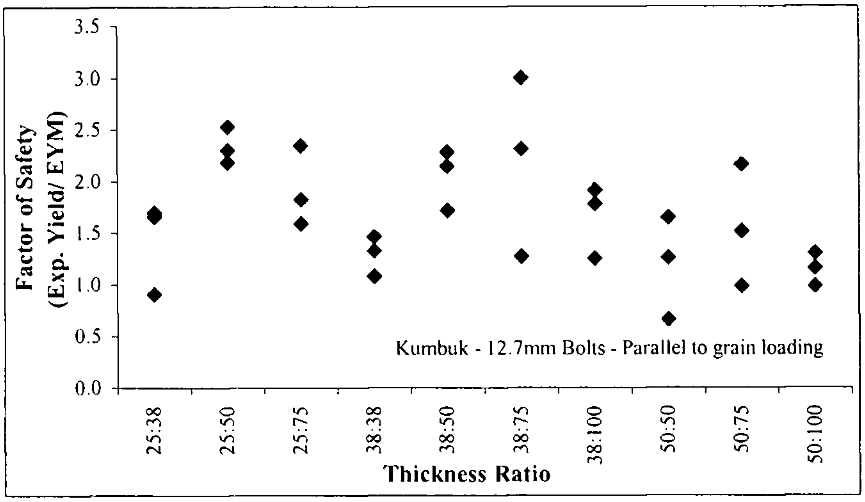


Figure 7.9: Variation of FoS of joints made from Kumbuk with 12.7mm bolts loaded parallel to grain

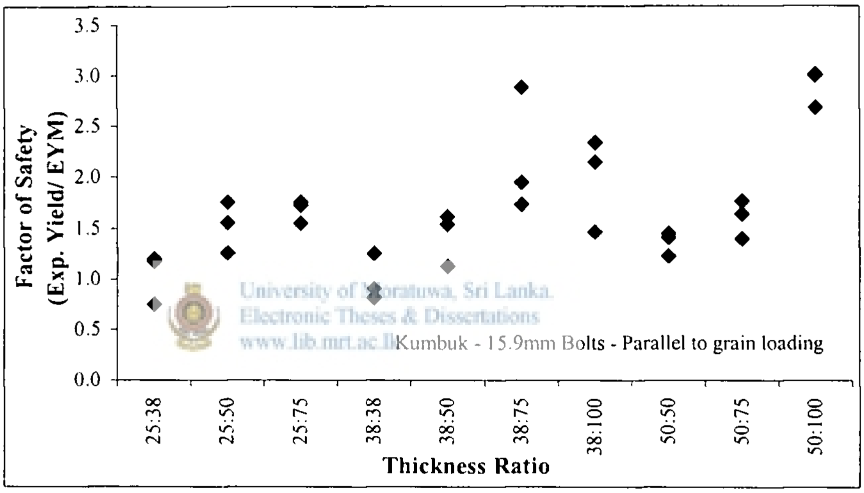


Figure 7.10: Variation of FoS of joints made from Kumbuk with 15.9mm bolts loaded parallel to grain

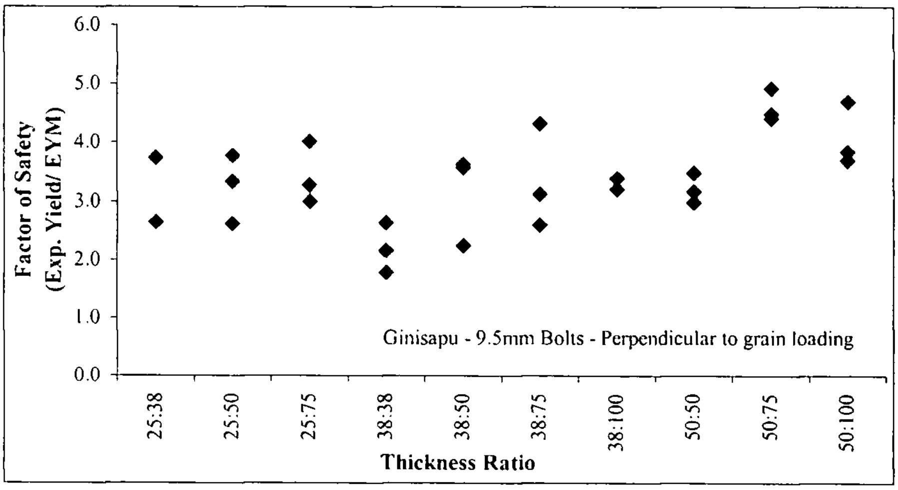


Figure 7.11: Variation of FoS of joints made from Ginisapu with 9.5mm bolts loaded perpendicular to grain

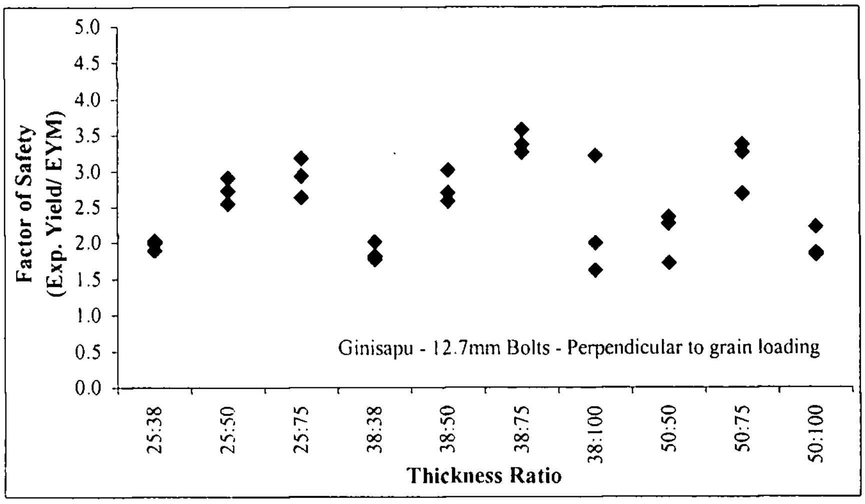


Figure 7.12: Variation of FoS of joints made from Ginisapu with 12.7mm bolts loaded perpendicular to grain

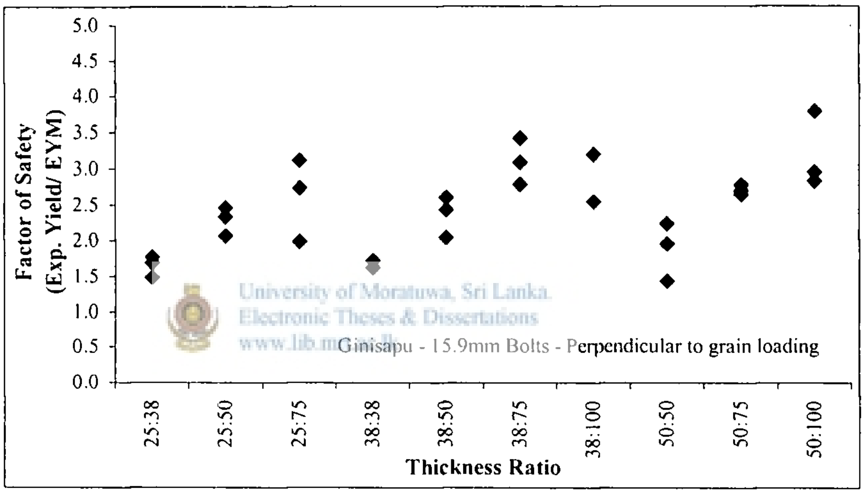


Figure 7.13: Variation of FoS of joints made from Ginisapu with 15.9mm bolts loaded perpendicular to grain

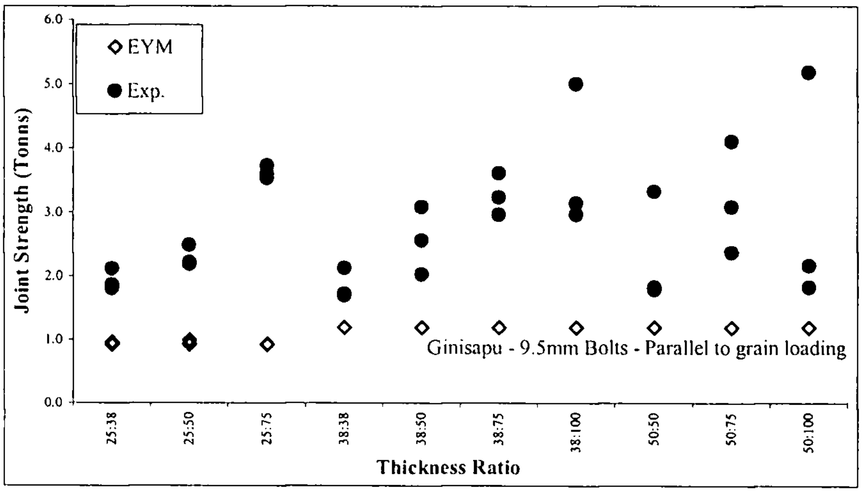


Figure 7.14: Variation of predicted and experimental joint strengths – Ginisapu – 9.5mm bolts – Parallel to grain loading

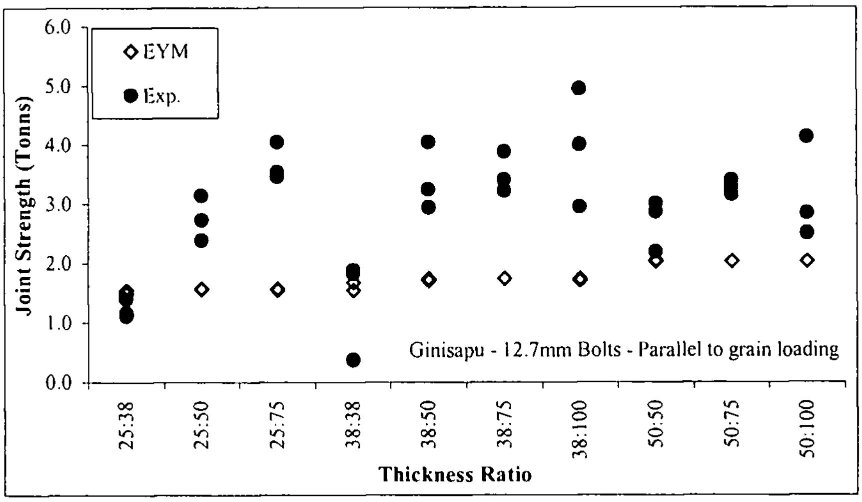


Figure 7.15: Variation of predicted and experimental joint strengths – Ginisapu – 12.7mm bolts – Parallel to grain loading

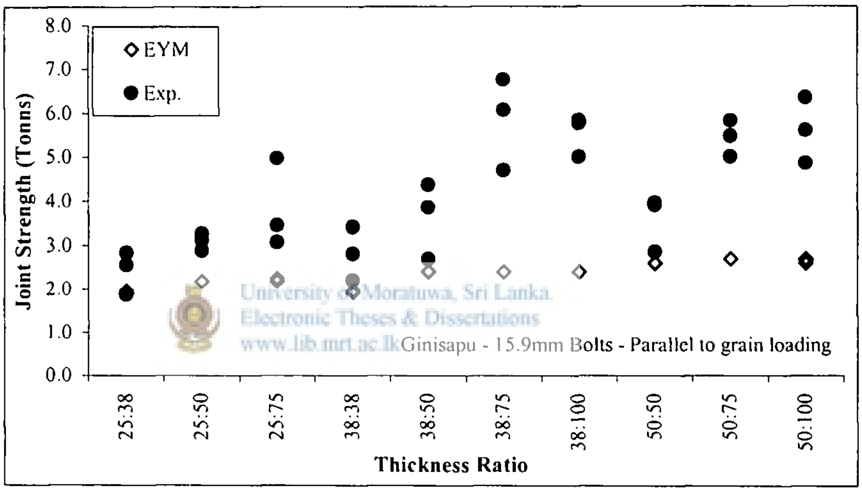


Figure 7.16: Variation of predicted and experimental joint strengths – Ginisapu – 15.9mm bolts – Parallel to grain loading

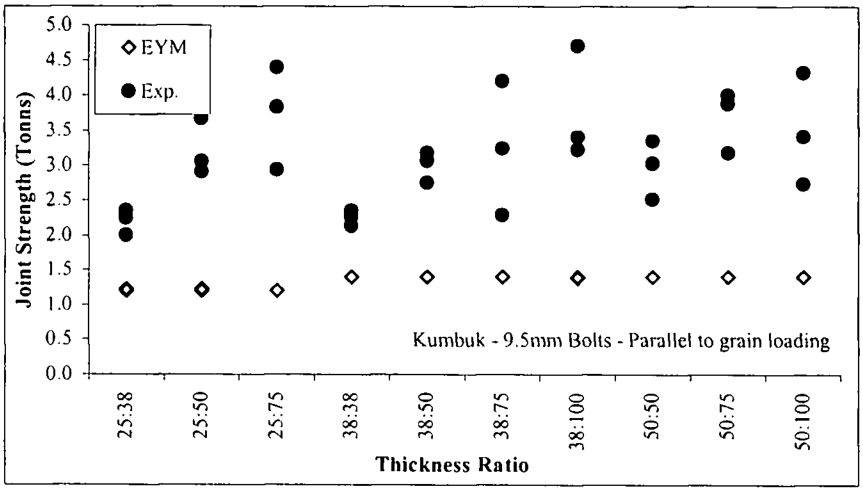


Figure 7.17: Variation of predicted and experimental joint strengths – Kumbuk – 9.5mm bolts – Parallel to grain loading

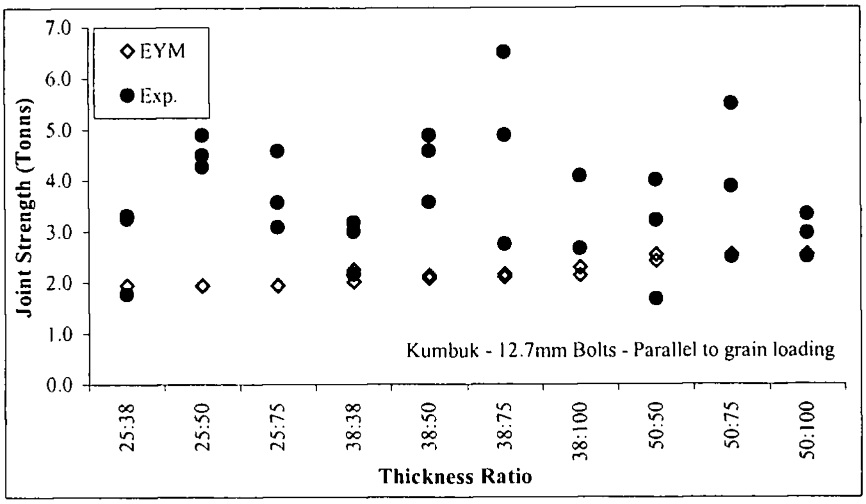


Figure 7.18: Variation of predicted and experimental joint strengths – Kumbuk – 12.7mm bolts – Parallel to grain loading

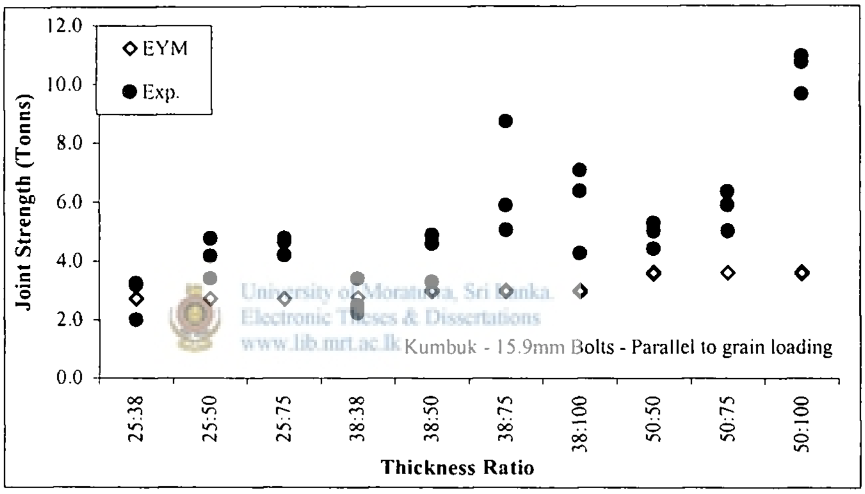


Figure 7.19: Variation of predicted and experimental joint strengths – Kumbuk – 15.9mm bolts – Parallel to grain loading

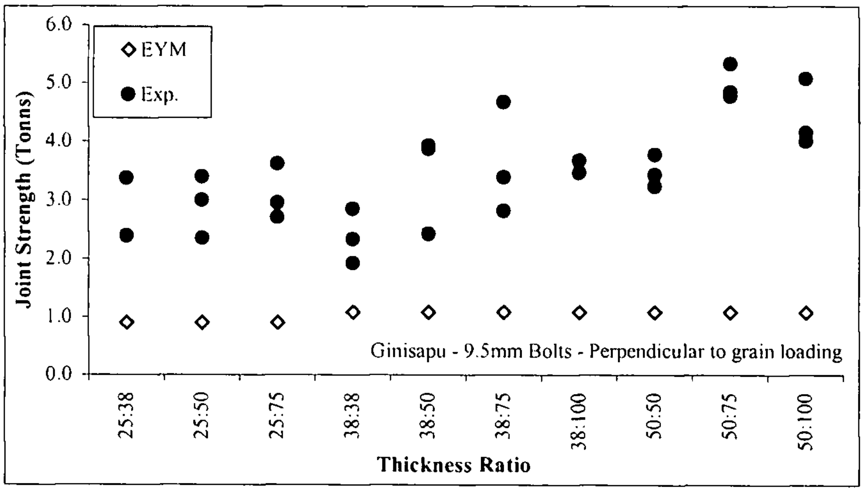


Figure 7.20: Variation of predicted and experimental joint strengths – Ginisapu – 9.5mm bolts – Perpendicular to grain loading

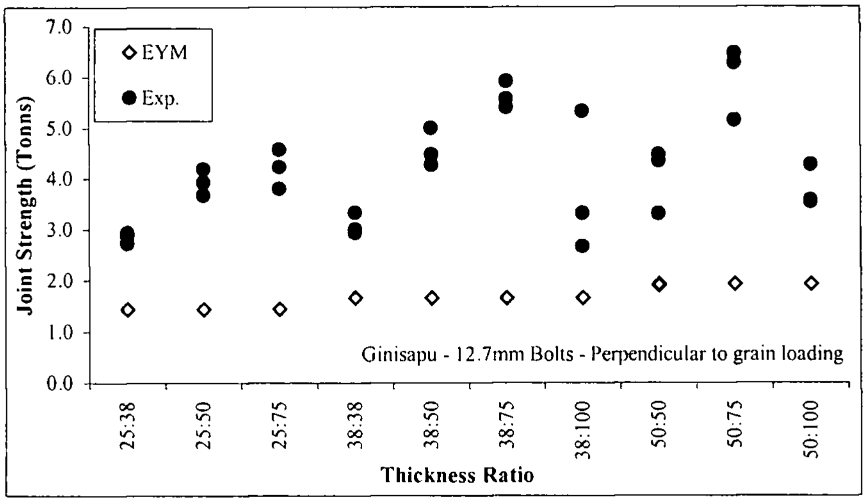


Figure 7.21: Variation of predicted and experimental joint strengths – Ginisapu – 12.7mm bolts – Perpendicular to grain loading

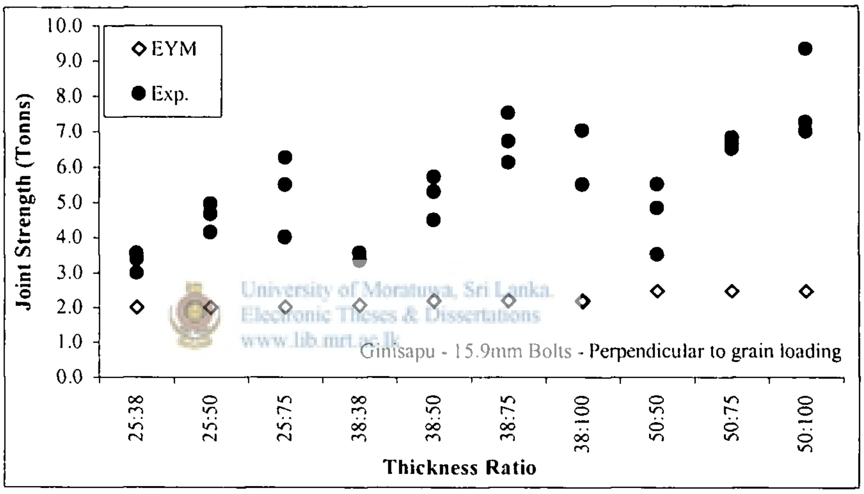


Figure 7.22: Variation of predicted and experimental joint strengths – Ginisapu – 15.9mm bolts – Perpendicular to grain loading

This reveals that the EYM does not consider the thickness of joint members as a critical factor that affects the joint strength of the bolted timber joint. But the figures show that the thickness of central member has a considerable effect on the strength of the timber joint. These figures also show that the predictions and the experimental results agree closely for the joints that have lower values for central member thickness.

Consider the joints, which have central member thickness equal or greater than 75mm for all side member thickness. Among these joints, more than 95% were predicted to fail in mode 2 and 3 failure types. Equations 3.13 and 3.14 show that the design joints strength of the symmetrical double shear joints, which fail in above failure types, is independent of the central member thickness (t_2). But when increasing the central member thickness, the bearing area under the bolt is also increased. This causes the joint to fail due to bolt bending instead of crushing of the central member. The final result is an increase of actual joint strength depending on the bolt yield moment. Also it can be noted from Table 7.4 that, considerable amount of joints, which were predicted to fail in mode 2 and 3 failure types, failed in mode 1b, in which the central member thickness is a critical factor (Equation 3.12).

Table 7.4: Comparison of predicted and observed failure modes of joints with large central members

Thickness Ratio	Mode 1a		Mode 1b		Mode 2		Mode 3	
	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.
25:75	15	2	3	-	9	25	-	-
38:75	3	-	3	-	18	21	3	6
38:100	3	-	3	-	18	21	3	6
50:75	-	-	12	-	15	15	-	12
50:100	3	-	6	-	12	15	6	12

The inability to predict the joint strength accurately of the joints, which have larger central member thickness, resulting in loss of confidence about the strength of the joint although the actual strength of the joint is much higher than the predicted value. Moreover this tends to more conservative design of bolted timber joints and, thus resulting in wastage of materials. Therefore, to overcome this problem, it is suggested to apply a modification factor based on the joint geometry to the EYM.

Therefore, aiming to reduce the discrepancy between the prediction and actual joint strength that causes either more conservative or unsafe design, an adjustment factor based on the ratio of central member thickness to the diameter of bolt (t_2/d) is proposed to apply to the EYM. The main target of applying this adjustment factor is to bring the FoS of the joint close to 2.0, so that it is neither unsafe nor too conservative. Thus,

$$\frac{Experimental\ Strength}{Predicted\ Strength\ by\ EYM\ x\ Adjustment\ Factor} \approx 2.0 \qquad \text{(Eq. 7.1)}$$

Thus,

$$Adjustment\ Factor = \frac{Experimental\ Strength}{2.0\ x\ Predicted\ Strength\ by\ EYM} \qquad \text{(Eq. 7.2)}$$

First the entire numbers of joints were divided into several groups depending on their t_2/d ratio. The adjustment factor was then calculated for each joint and the average of each adjustment factor belong to each group (Table 7.5) was then plotted against the average t_2/d of same group (Figure 7.23). The regression analysis on the average adjustment factors against the average t_2/d were done and, among the several regression analysis, the power regression is selected as it gives not only the simple but also more realistic relationship with $R^2 = 0.7$. The resulting relationship is stated below.

Table 7.5: Average adjustment factors

Bolt Diameter, d (mm)	Central member thickness, t_2 (mm)	Average t_2/d	Average adjustment factor
9.5	38	3.89	1.02
	50	5.11	1.28
	75	7.82	1.60
	100	10.50	1.52
12.7	38	2.83	0.68
	50	3.81	1.01
	75	5.77	1.17
	100	7.76	0.91
15.9	38	2.29	0.67
	50	3.07	0.84
	75	4.69	1.11
	100	6.17	1.29

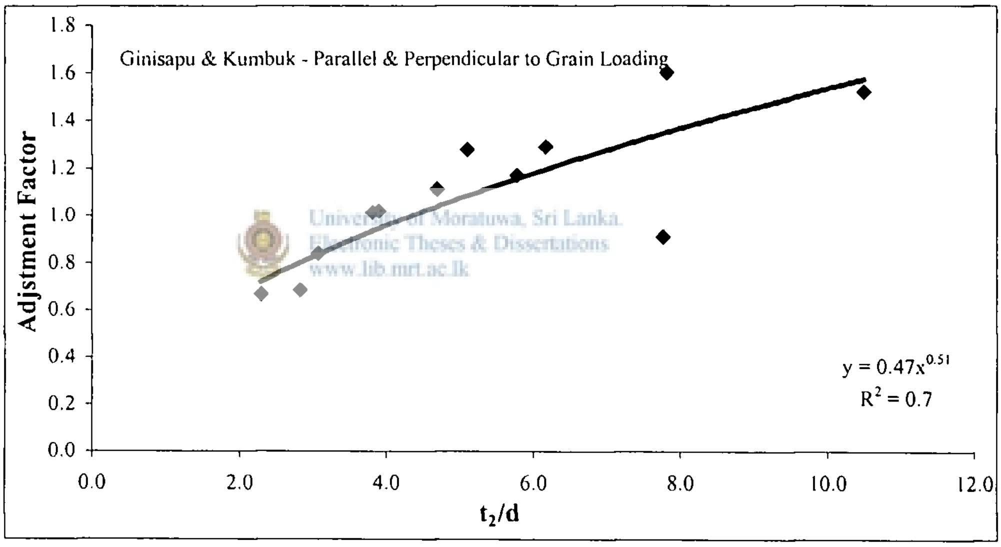


Figure 7.23: Regression analysis of adjustment factors

$$Adjustment\ Factor = 0.47\left(\frac{t_2}{d}\right)^{0.51} \qquad \text{(Eq. 7.3)}$$

and, is further simplified to,

$$Adjustment\ Factor = 0.5\left(\frac{t_2}{d}\right)^{0.5} \qquad \text{(Eq. 7.4)}$$

because Equation 7.4 gives more simple relationship and both equations are almost same for the range of t_2/d considered (Figure 7.24).

This adjustment factor is independent from the member density, the side member thickness of the joint and the direction of loading.

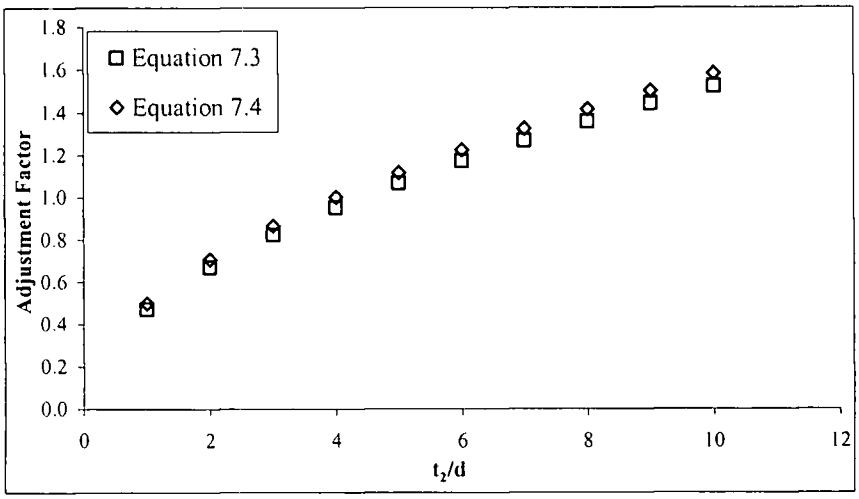


Figure 7.24: Comparison of adjustment factor given by Eq. 7.3 and 7.4

Table 7.6: Factors of Safety (after adjustment)

Thickness Ratio	Ginisapu Parallel to grain loading			Kumbuk Parallel to grain loading			Ginisapu Perpendicular to grain loading		
	Bolt Diameter (mm)								
	9.5	12.7	17.9	9.5	12.7	17.9	9.5	12.7	17.9
25:38	2.22	1.17	2.01	1.67	1.96	1.56	2.64	2.19	1.93
	1.98	0.92	1.26	1.99	1.09	0.99	2.64	2.38	2.30
	2.01	0.88	1.81	1.91	1.92	1.60	3.74	2.31	2.19
25:50	2.11	1.56	1.73	2.71	2.57	2.09	2.30	2.59	2.78
	2.29	2.06	1.65	2.24	2.22	1.48	2.96	2.75	2.63
	2.11	1.79	1.51	2.13	2.37	1.85	3.36	2.93	2.35
25:75	2.93	2.20	1.48	2.60	1.51	1.60	2.35	2.41	1.83
	2.72	1.85	1.32	2.29	1.32	1.43	2.88	2.17	2.54
	2.77	1.92	2.04	1.75	1.95	1.62	2.15	2.61	2.86
38:38	1.45	1.50	1.98	1.56	1.58	1.66	2.64	2.04	2.23
	1.78	1.28	1.56	1.76	1.36	1.07	1.78	2.32	2.23
	1.42	0.29	2.00	1.75	1.76	1.20	2.15	2.09	2.10
38:50	1.50	1.94	2.08	1.95	2.40	1.25	3.19	2.72	2.31
	1.87	2.45	1.28	1.77	1.80	1.80	1.97	3.07	2.75
	2.27	1.74	1.83	1.98	2.23	1.82	3.18	2.60	2.93
38:75	1.79	1.93	2.59	2.15	2.49	1.60	2.24	2.79	2.56
	1.94	1.65	2.34	1.66	1.05	2.66	1.86	2.68	2.84
	2.17	1.56	1.82	1.17	1.93	1.79	3.12	2.94	3.15
38:100	2.61	1.25	1.70	1.43	1.38	1.87	1.97	1.15	2.55
	1.54	2.05	1.99	1.51	0.90	1.17	1.97	2.29	2.03
	1.64	1.66	1.96	2.08	1.29	1.72	2.09	1.42	2.55
50:50	1.35	1.10	1.75	1.60	1.79	1.37	2.60	1.73	1.62
	1.32	1.51	1.26	2.15	0.69	1.60	3.04	2.37	2.52
	2.44	1.45	1.73	1.94	1.27	1.57	2.79	2.28	2.21
50:75	1.41	1.41	1.81	2.06	1.26	1.52	3.16	2.68	2.50
	2.46	1.31	2.00	1.98	0.81	1.62	3.21	2.77	2.43
	1.85	1.36	1.72	1.61	1.78	1.29	3.53	2.20	2.55
50:100	0.94	1.01	1.94	1.50	0.83	2.14	2.90	1.31	2.35
	1.14	0.89	1.70	1.91	0.70	2.40	2.37	1.32	2.26
	2.69	1.47	1.53	1.20	0.94	2.42	2.28	1.57	3.02

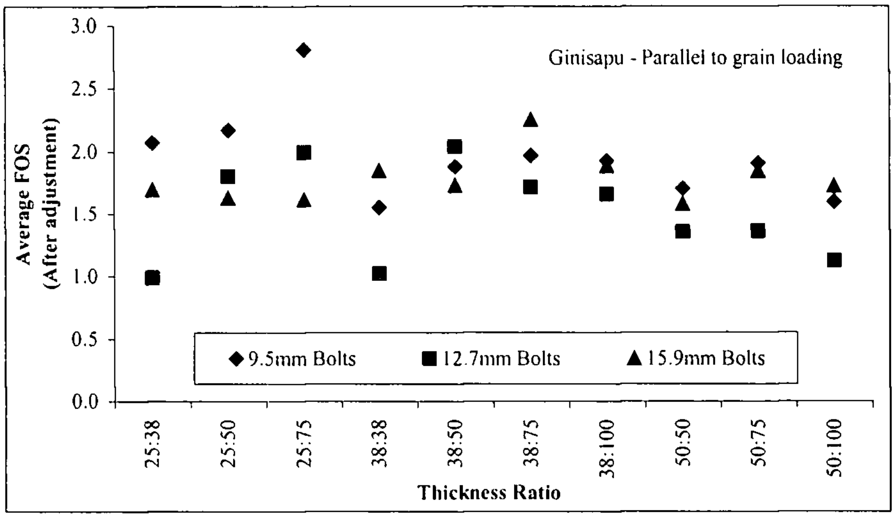


Figure 7.25: Variation of new Factors of Safety – Ginisapu – Parallel to grain loading

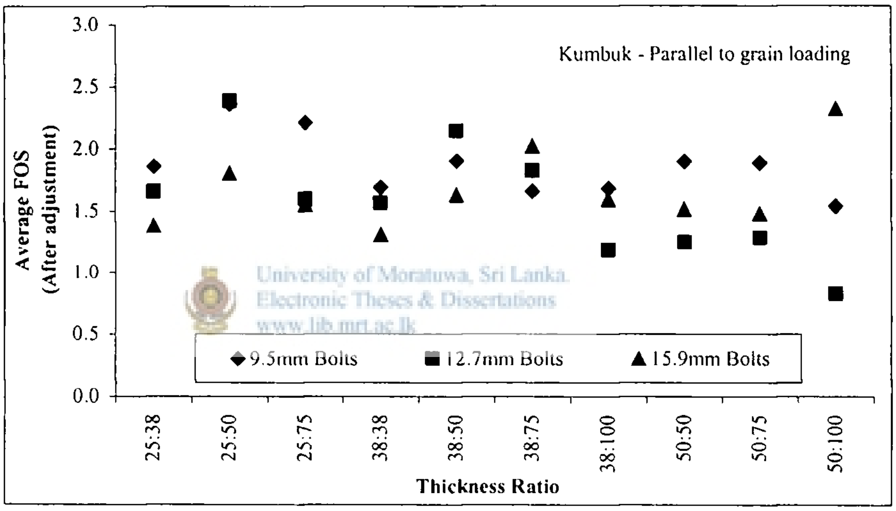


Figure 7.26: Variation of new Factors of Safety – Kumbuk – Parallel to grain loading

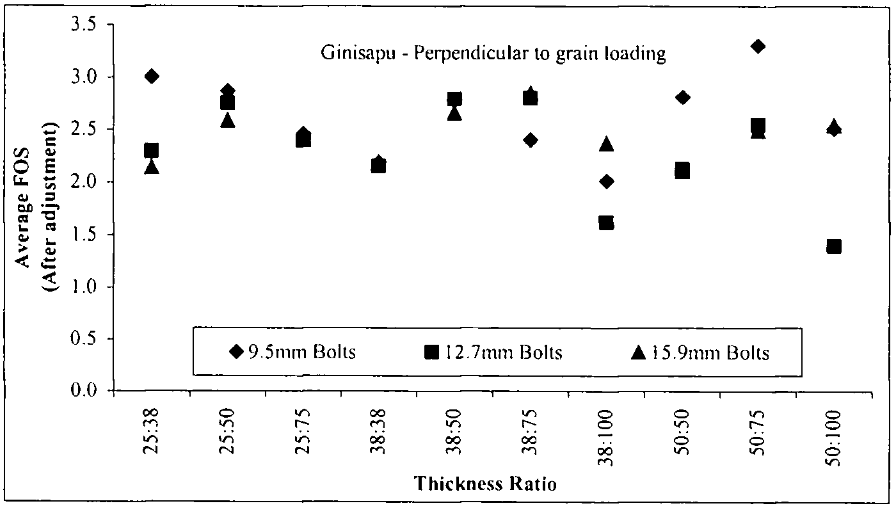


Figure 7.27: Variation of new Factors of Safety – Ginisapu – Perpendicular to grain loading

Table 7.6 shows that the new factors of safety calculated after adjusting the predicted joint strength using the adjustment factor (Equation 7.4). The average factors of safety (after adjustment) of three replicates were then plotted against the thickness ratio (Figures 7.25 to 7.27). It can be seen that, the predictions are reasonably conservative after adjusting the joint strength predicted by EYM. More than 65% of joints have the FoS within the range of 1.5 and 2.5.

It is not possible to carry out analysis by plotting the normalized joint strength versus t_2/d ratio, because lack of wide range of t_2/d for t_1/d value considered. It can be seen from Figures 3.8 to 3.10 that normalized strengths were plotted against t_2/d for several t_1/d ratios because the ratio t_1/d affect the normalized strength of the joint. In this research programme, attention was paid mainly to carry out test with a wide range of thickness ratios (side to central) because most of early researches had ignored this idea. To carry out the analysis using the normalized strength, the geometries of joints should be selected such the way that there is a wide range of central member thickness for a particular side member thickness and bolt diameter.

Chapter Eight

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORKS

Chapter 8: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORKS

8.1 CONCLUSIONS MADE FROM EMBEDMENT STRENGTH TEST SERIES

- EC 5 recommendations predict the embedment strength of local timber species reasonably well with a little discrepancy between the EC5 predictions and the experimental results.

- Difference between EC5 predictions and experimental results increase with increasing of bolt diameter for parallel to grain loading.

- Difference between EC5 predictions and experimental results decrease with increasing of bolt diameter for perpendicular to grain loading.

- Results of linear regression analysis also verify above-mentioned conclusions.

- Equation 6.1 and Equation 6.2 are proposed to be used for the determination of embedment strength of local timber species.

- Proposed new model does not have a considerable effect on either joint strength or the failure pattern of joints tested in joint strength test series.

8.2 CONCLUSIONS MADE FROM JOINT STRENGTH TEST SERIES

- European Yield Model provides more realistic design method than other empirical and analytical models, which are used to design, nailed and bolted timber joints, considering the effects of all geometric and material parameters.

- As a whole, EYM seems to be good in predicting the strength and the failure patters of joints tested.

- EYM predicted every type of failure patterns for the joints tested in this test programme.

- Every type of failure patterns were observed for the joints loaded in parallel to grain direction.

- Only failure patterns of mode 1b, mode 2 and mode 3 were observed for the joints loaded in perpendicular to grain direction.

- It seems that the EYM predictions for failure mode are reasonably good because percentage of joints, which were predicted accurately by the EYM, is close to 50%.

- The best accuracy of prediction of failure pattern is with the bearing failure of central member (mode 1b).

- Thus the EYM can be regarded as good for predicting the joints, which fails due to bearing failure than the bending failure.

- Experimental joint strengths were predicted well by EYM when thickness ratio is close to unity.

- Factor of Safety increases in considerable level when increasing the main member thickness while keeping the side member constant in thickness.

- Some of these factors of safety are too high and resulting in more conservative design.

- Although the experimental strength of the joint increases in considerable level with increasing of the thickness ratio, EYM predictions are almost same for every thickness ratio when considering a particular bolt diameter and side member thickness.

- It seems that the effect of central member thickness on the strength of joint is not critically considered by the EYM theory.

- Although the joints which have larger central member thickness were predicted to fail in mode 2 and mode 3 failure types, in which central member thickness is less critical factor, they were failed in mode 1b failure type, in which central member thickness is more critical factor.

- This behaviour was not observed by early researches. Most of early researches were conducted using unique thickness ratio (side to central) that is equal to 2.0.

- A modification factor based on the joint geometry is proposed to reduce this discrepancy between prediction and experimental results and bring the average factor of safety approximate to 2.0, which brings the factor of safety of the joint to a reasonably conservative value.

- Equation 7.4 can be used to calculate the modification factor according to the ratio of central member thickness to bolt diameter (t_2/d) and this modification factor independent from member density, member thickness and loading direction.

- After modifying the EYM predictions using the proposed modification factor, the average factor of safety is around 2.0 and thus the design has reasonably conservative factor of safety value.

8.3 RECOMMENDATIONS FOR FURTHER WORKS

- Proposed model for embedment strength (Equation 6.1 and Equation 6.2) is based on the experimental results obtained from this test series. Therefore, it is necessary to conduct a verification test programme with a wide range of parameters that affect the embedment strength to check the reliability of this proposed model and carry out necessary modifications.

- Specimens of embedment strength test were loaded in parallel and perpendicular to grain directions only. Applicability of Equation 3.25 can be further checked by conducting embedment strength tests varying the loading angle from 0^0 to 90^0.

- Only side members of the joints, in which the joints tested in perpendicular to grain direction, were subjected to the loading in perpendicular to grain direction. Therefore, it is necessary to expand the test programme as central members too are subjected to perpendicular to grain loading.

- Because of the concept of applying an adjustment factor based on joint geometry has not been proposed by earlier researchers, it is strongly recommended to carry out further investigation with wider range of joint geometry.

- Further, this research programme used lower bolt diameters and member thickness although much larger size bolts and very thick members are often used in the construction industry. Internationally, bolts of the size of more than 50mm are also used with suitable member sizes for heavy constructions. Therefore, it is required to check the applicability of EC5 recommendations to the joints made form local timber species with these larger bolts sizes too.

- Also, to develop the proposed adjustment factor, this test programme used only local timber species, which belongs to hardwood category. Therefore, it is necessary to carry out more researches with both softwood and hardwood categories to reach a reliable decision.

- This test programme was limited to the two local timber species. Because, number of species tested in this research programme is not enough to reach a reliable decision, conducting a further test programme with other timber species, in which density ranges from low to high, is required.

- It is recommended to conduct joint strength tests loading both side and central members in the directions other than parallel and perpendicular to grain.

- For future test programmes, it is necessary to select joints geometries such the way that there is a wide range of central member thickness for a particular bolt diameter and side member considered. This is required to carry out analysis plotting the normalized joint strength against the t_2/d ratio.

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ANNEX

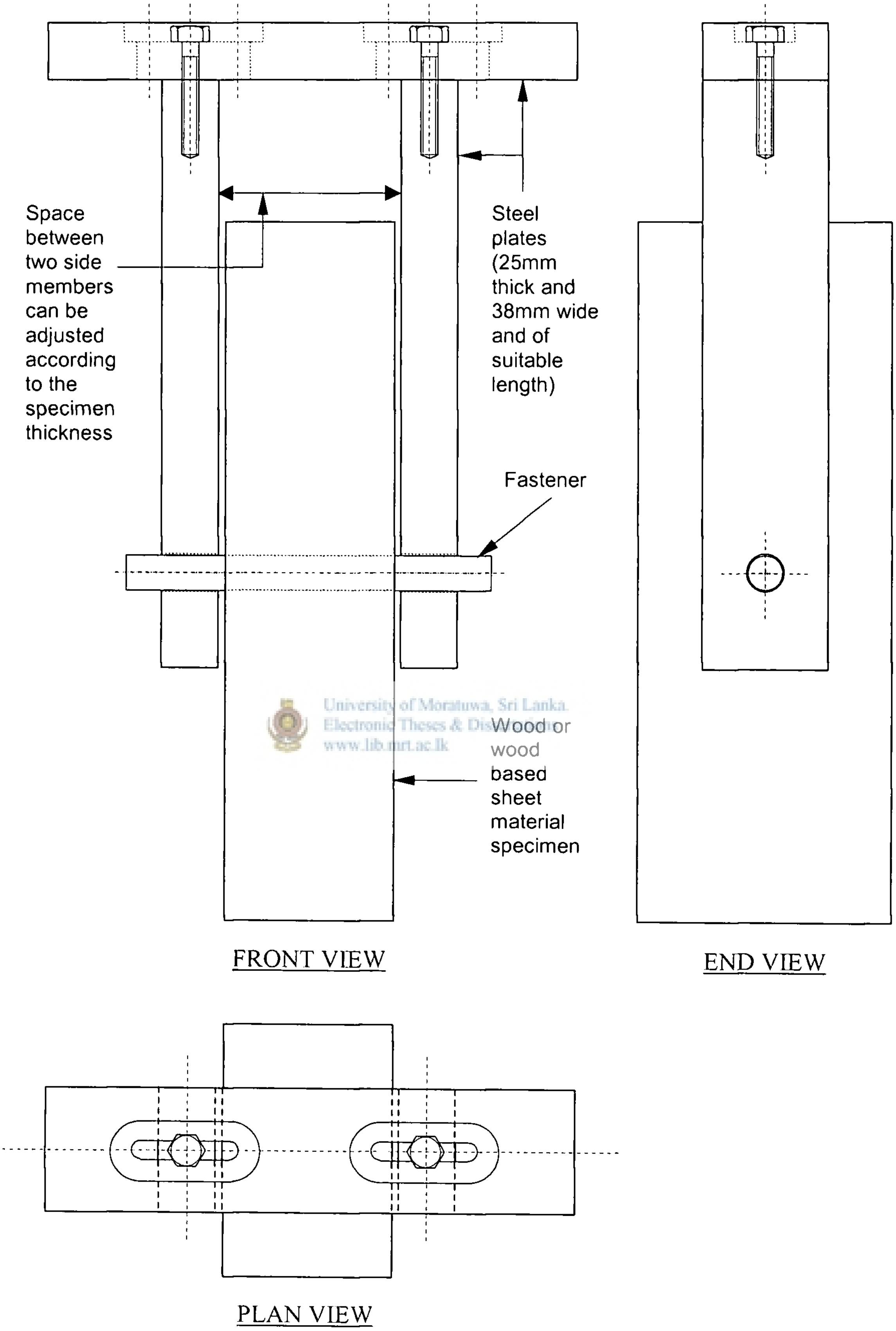


Figure A1: **Details of embedment strength test apparatus**

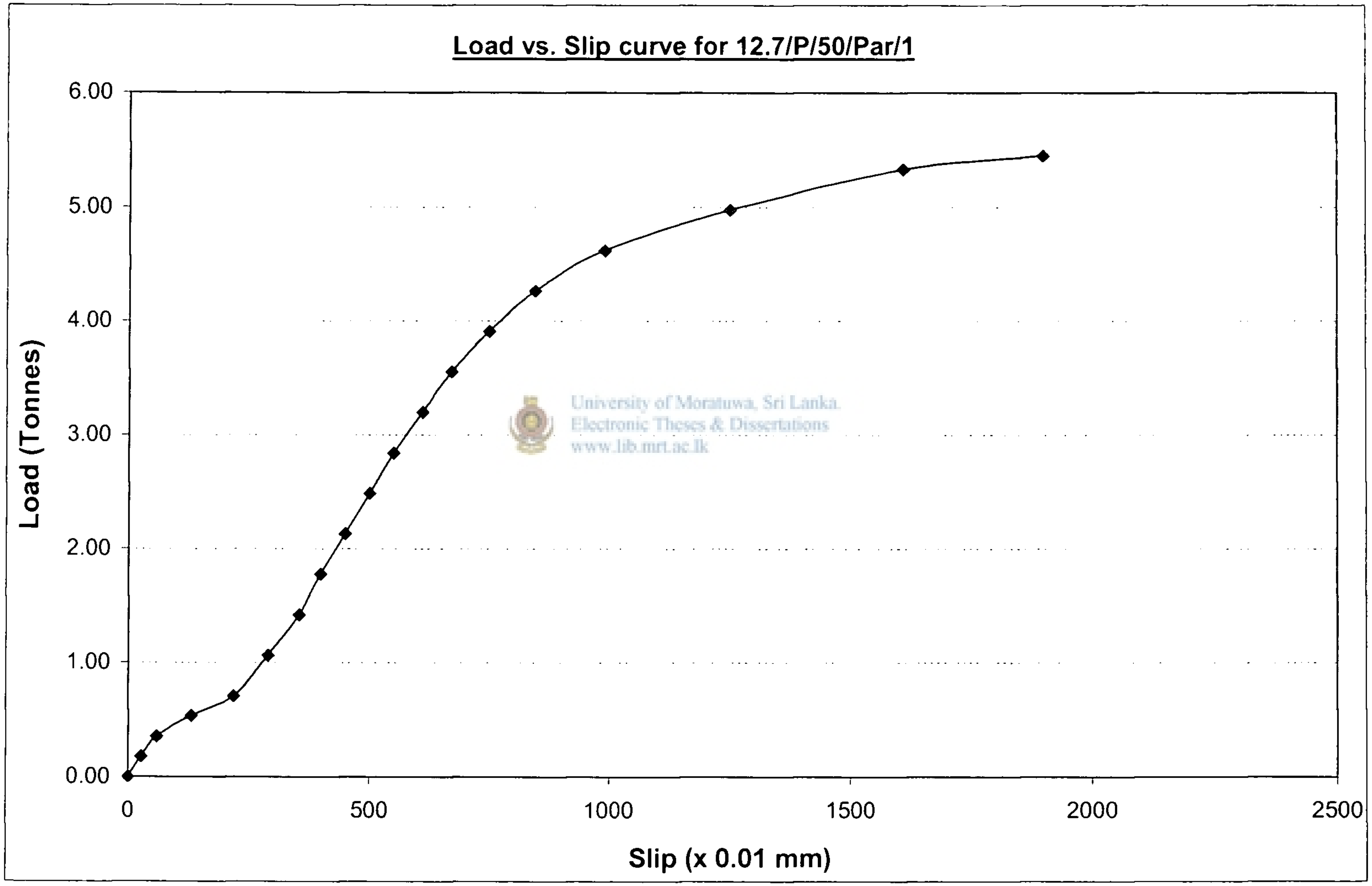
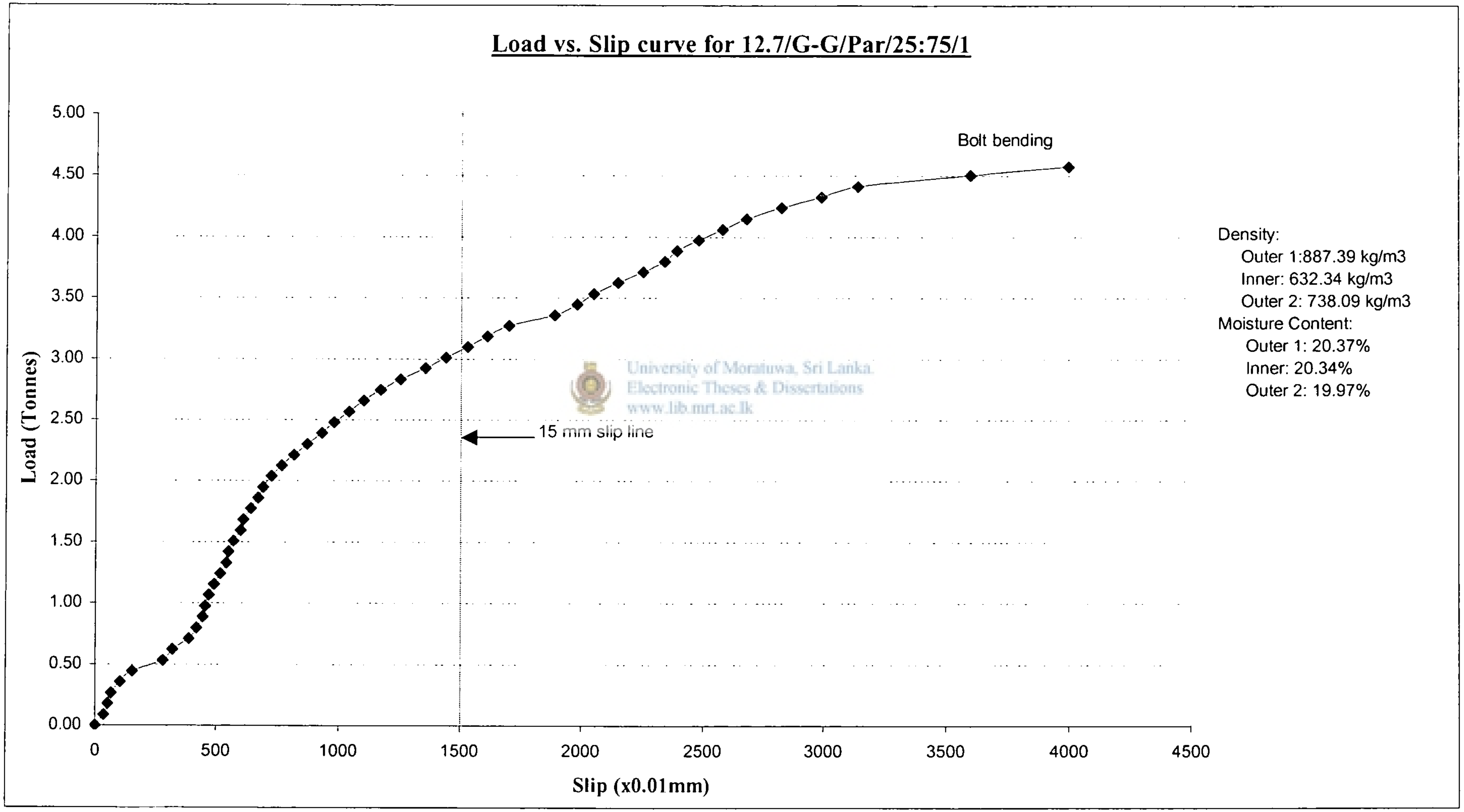


Figure A2: Typical load-displacement curve – Embedment strength test programme



Density:
Outer 1:887.39 kg/m3
Inner: 632.34 kg/m3
Outer 2: 738.09 kg/m3
Moisture Content:
Outer 1: 20.37%
Inner: 20.34%
Outer 2: 19.97%

Figure A3: Typical load – displacement curve – Joints strength test programme

Table A1: Test results of Embedment strength tests – Parallel to grain loading

Timber species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m^3)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm^2)*
Ginisapu	9.5	25	537	17.54	40.03
			613	18.22	48.69
			480	18.00	31.52
		38	555	17.67	50.86
			593	18.48	55.26
			626	14.50	54.09
	12.7	25	527	19.11	43.31
			680	20.09	49.07
			498	16.54	30.60
		38	582	20.17	13.52
			704	17.71	45.04
			600	15.22	36.25
		50	516	17.85	36.40
			748	20.84	52.80
			614	16.56	40.34
	15.9	25	527	19.11	43.31
			680	20.09	49.07
			498	16.54	30.60
		38	582	20.17	13.52
			704	17.71	45.04
			600	15.22	36.25
		50	516	17.85	36.40
			748	20.84	52.80
			614	16.56	40.34
Kumbuk	9.5	25	918	20.93	72.40
			904	14.47	66.16
			823	15.71	49.25
		38	1016	18.92	105.39
			985	17.39	71.22
			1027	18.56	70.24
	12.7	25	927	20.98	57.90
			1019	15.50	78.31
			922	15.58	63.90
		38	861	15.79	56.75
			1025	20.30	71.14
			1005	20.77	86.57
		50	894	14.96	58.48
			928	17.56	55.24
			942	16.50	45.48
	15.9	25	927	20.98	57.90
			1019	15.50	78.31
			922	15.58	63.90
		38	861	15.79	56.75
			1025	20.30	71.14
			1005	20.77	86.57
		50	894	14.96	58.48
			928	17.56	55.24
			942	16.50	45.48

Table A1: (*Contd..*)

Timber species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m^3)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm^2)*
Hora	9.5	25	695	15.49	40.92
			686	15.96	42.00
			686	15.07	49.38
		38	727	15.63	46.39
			726	15.89	45.65
			715	15.28	48.72
	12.7	25	705	15.71	42.37
			693	16.00	41.20
			692	16.11	43.59
		38	760	15.54	49.84
			758	15.04	50.79
			748	14.78	49.29
		50	797	16.25	42.26
			827	16.18	53.78
			828	16.41	48.29
	15.9	25	705	15.71	42.37
			693	16.00	41.20
			692	16.11	43.59
		38	760	15.54	49.84
			758	15.04	50.79
			748	14.78	49.29
		50	797	16.25	42.26
			827	16.18	53.78
			828	16.41	48.29
Lunumidella	9.5	25	415	15.22	26.91
			407	14.75	32.12
			423	16.28	25.47
		38	433	15.22	30.46
			432	16.10	28.19
			526	15.49	33.14
	12.7	25	434	15.98	28.51
			409	16.09	23.93
			391	15.71	19.52
		38	410	13.95	24.71
			359	15.58	24.83
			361	14.29	50.53
		50	299	15.70	11.05
			297	15.87	10.08
			301	14.29	11.63
	15.9	25	434	15.98	28.51
			409	16.09	23.93
			391	15.71	19.52
		38	410	13.95	24.71
			359	15.58	24.83
			361	14.29	50.53
		50	299	15.70	11.05
			297	15.87	10.08
			301	14.29	11.63

Table A1: (*Contd..*)

Timber species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m^3)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm^2)*
Palu	9.5	25	1056	17.72	91.54
			1039	18.12	90.42
			1013	17.86	74.74
		38	1186	15.96	70.60
			1172	16.67	86.13
			1038	16.67	86.04
	12.7	25	1030	17.56	88.18
			1036	18.63	90.96
			1075	18.63	85.38
		38	1054	16.25	85.49
			988	16.59	70.93
			1019	16.56	77.44
		50	1123	22.18	84.58
			1100	19.92	76.74
			1109	19.91	79.67
	15.9	25	1030	17.56	88.18
			1036	18.63	90.96
			1075	18.63	85.38
		38	1054	16.25	85.49
			988	16.59	70.93
			1019	16.56	77.44
		50	1123	22.18	84.58
			1100	19.92	76.74
			1109	19.91	79.67

Table A2: Test results of Embedment strength tests – Perpendicular to grain loading

Timber Species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m³)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm²)*
Ginisapu	9.5	25	603	18.22	55.41
			534	15.46	41.75
			499	14.89	52.20
		38	562	18.45	57.89
			509	18.45	42.93
			618	15.73	54.12
	12.7	25	519	19.13	45.59
			643	19.33	50.50
			501	16.82	29.56
		38	587	20.50	23.06
			695	19.75	56.78
			606	14.58	44.33
		50	521	17.87	27.87
			732	19.48	60.54
			599	17.12	43.21
	15.9	25	553	19.90	54.99
			548	14.29	28.56
			550	16.22	26.04
		38	597	17.20	15.00
			573	18.58	34.86
			586	16.39	37.91
		50	578	16.21	36.35
			666	19.80	33.38
			608	17.20	30.71
Kumbuk	9.5	25	917	22.27	117.07
			873	15.94	89.37
			860	15.38	78.36
		38	987	17.54	96.11
			989	17.53	96.67
			1029	17.80	92.27
	12.7	25	1002	19.80	87.65
			842	15.47	102.73
			1040	16.41	146.83
		38	940	16.01	120.55
			1021	18.94	90.94
			990	19.63	69.16
		50	747	14.38	69.27
			892	17.11	90.26
			917	16.52	64.77
	15.9	25	954	21.31	52.50
			1034	18.52	64.89
			1017	18.54	75.63
		38	892	21.01	78.16
			858	16.87	57.87
			955	18.30	69.69
		50	725	14.81	56.83
			819	13.64	45.97
			818	17.14	46.65

Table A2: (*Contd..*)

Timber species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m^3)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm^2)*
Hora	9.5	25	695	15.38	42.33
			695	15.63	42.04
			702	14.93	51.15
		38	718	15.67	52.90
			711	15.77	48.23
			717	16.34	48.11
	12.7	25	715	16.37	47.67
			702	16.73	54.06
			703	15.83	60.84
		38	736	14.78	47.05
			738	15.93	47.05
			744	15.32	51.89
		50	809	16.02	56.58
			830	15.49	53.93
			823	16.36	54.53
	15.9	25	690	15.48	36.85
			687	15.28	29.21
			673	15.56	36.28
		38	707	15.79	31.71
			697	16.35	31.55
			703	16.21	31.67
		50	795	16.91	46.04
			791	17.26	44.22
			787	16.67	43.85
Lunumidella	9.5	25	413	13.33	24.51
			500	15.22	41.72
			410	16.33	12.84
		38	438	15.07	28.60
			440	14.41	30.70
			428	15.04	27.75
	12.7	25	405	16.05	24.64
			396	15.38	23.19
			404	15.67	24.35
		38	397	14.29	16.43
			362	15.22	18.11
			353	13.21	9.43
		50	291	15.45	7.22
			369	15.92	13.10
			379	13.04	14.65
	15.9	25	417	15.56	13.19
			340	15.75	8.76
			382	15.67	11.33
		38	400	15.65	18.93
			333	15.79	11.71
			344	17.86	11.10
		50	342	15.91	14.18
			369	14.08	16.05
			318	15.52	15.25

Table A2: (*Contd..*)

Timber species	Bolt Diameter, d *(mm)*	Member Thickness, t *(mm)*	Density, ρ *(kg/m^3)*	Moisture Content *(%)*	Embedment Strength, f_h *(N/mm^2)*
Palu	9.5	25	1057	17.83	112.57
			1064	17.91	96.78
			1026	17.79	105.07
		38	1011	17.10	92.56
			1063	16.58	73.59
			1162	14.38	73.59
	12.7	25	1008	16.96	99.89
			1003	19.14	88.98
			1018	18.18	95.25
		38	993	15.34	83.19
			1043	16.15	76.16
			1006	15.38	81.89
		50	1054	20.00	82.34
			1087	18.97	77.30
			1062	19.25	75.62
	15.9	25	1043	17.60	81.07
			1060	18.52	76.37
			1067	18.35	80.88
		38	1120	16.41	82.08
			1079	16.27	87.61
			1055	15.66	70.14
		50	1174	21.63	72.48
			1053	21.27	68.09
			1134	18.25	69.51

Table A3: Test results of Joint strength tests – Kumbuk parallel to grain loading, 9.5mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
9.5/K-K/Par/25:38/1	25	38	1.44	3.79	2.63	15.62	984	1.23	3.19	2.00	2	1b	2.60	1.63
9.5/K-K/Par/25:38/2			1.40	3.68	2.63	18.11	958	1.23	2.83	2.35	2	1b	2.30	1.91
9.5/K-K/Par/25:38/3			1.50	3.79	2.53	17.17	881	1.20	3.10	2.24	2	1b	2.57	1.86
9.5/K-K/Par/25:50/1		50	2.00	5.05	2.53	15.92	986	1.20	4.15	3.67	2	2	3.45	3.05
9.5/K-K/Par/25:50/2			1.88	4.95	2.63	15.90	968	1.23	4.20	3.06	2	1b	3.42	2.49
9.5/K-K/Par/25:50/3			1.88	4.95	2.63	15.71	963	1.23	4.01	2.91	2	1b	3.27	2.37
9.5/K-K/Par/25:75/1		75	3.13	7.89	2.53	17.22	879	1.20	5.66	4.40	2	1a	4.70	3.65
9.5/K-K/Par/25:75/2			3.08	7.79	2.53	16.35	895	1.20	6.01	3.84	2	1a	4.99	3.19
9.5/K-K/Par/25:75/3			3.08	7.79	2.53	16.58	891	1.20	5.93	2.94	2	1a	4.92	2.44
9.5/K-K/Par/38:38/1	38	38	1.03	3.79	3.68	18.96	984	1.40	2.48	2.13	3	2	1.77	1.52
9.5/K-K/Par/38:38/2			1.00	3.37	3.37	17.01	1022	1.40	3.27	2.26	3	1b	2.33	1.61
9.5/K-K/Par/38:38/3			1.03	3.68	3.58	17.24	989	1.40	3.27	2.35	3	1b	2.33	1.68
9.5/K-K/Par/38:50/1		50	1.50	5.05	3.37	17.44	936	1.40	4.06	3.07	3	3	2.90	2.19
9.5/K-K/Par/38:50/2			1.34	4.95	3.68	17.79	910	1.40	4.50	2.76	3	1b	3.21	1.97
9.5/K-K/Par/38:50/3			1.39	5.26	3.79	20.18	951	1.40	4.68	3.18	3	1b	3.34	2.27
9.5/K-K/Par/38:75/1		75	2.11	7.79	3.68	16.97	898	1.40	5.48	4.20	3	1a	3.91	3.00
9.5/K-K/Par/38:75/2			2.11	7.79	3.68	16.85	904	1.40	6.01	3.24	3	3	4.29	2.31
9.5/K-K/Par/38:75/3			2.18	7.79	3.58	17.28	897	1.40	4.66	2.29	3	1b	3.32	1.63
9.5/K-K/Par/38:100/1		100	3.23	10.53	3.26	16.58	987	1.39	6.01	3.22	2	3	4.34	2.32
9.5/K-K/Par/38:100/2			2.88	10.32	3.58	17.18	927	1.40	5.56	3.41	3	1a	3.97	2.43
9.5/K-K/Par/38:100/3			3.09	10.42	3.37	17.14	860	1.40	6.19	4.71	3	1b	4.42	3.36
9.5/K-K/Par/50:50/1	50	50	1.07	5.05	4.74	16.99	823	1.40	3.89	2.52	3	2	2.78	1.80
9.5/K-K/Par/50:50/2			1.00	4.95	4.95	17.34	825	1.40	4.19	3.35	3	1b	2.99	2.39
9.5/K-K/Par/50:50/3			1.00	4.95	4.95	17.96	851	1.40	4.33	3.03	3	1b	3.09	2.16
9.5/K-K/Par/50:75/1		75	1.59	7.68	4.84	16.37	813	1.40	5.39	4.00	3	1b	3.85	2.85
9.5/K-K/Par/50:75/2			1.57	7.79	4.95	17.69	860	1.40	5.48	3.88	3	1b	3.91	2.77
9.5/K-K/Par/50:75/3			1.50	7.89	5.26	24.19	962	1.40	5.12	3.18	3	1b	3.65	2.27
9.5/K-K/Par/50:100/1		100	2.22	10.53	4.74	13.73	773	1.40	7.15	3.42	3	1a	5.10	2.44
9.5/K-K/Par/50:100/2			2.25	10.42	4.63	17.24	910	1.40	7.24	4.32	3	3	5.16	3.08
9.5/K-K/Par/50:100/3			2.00	10.53	5.26	26.48	980	1.40	8.29	2.74	3	1b	5.91	1.95

** Average of three members*

Table A4: Test results of Joint strength tests – Kumbuk parallel to grain loading, 12.7mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
12.7/K-K/Par/25:38/1	25	38	1.52	2.99	1.97	27.59	980	1.96	4.04	3.32	2	1b	2.07	1.70
12.7/K-K/Par/25:38/2			1.40	2.76	1.97	27.76	1081	1.96	2.91	1.77	2	1b	1.49	0.90
12.7/K-K/Par/25:38/3			1.52	2.99	1.97	31.17	1020	1.96	4.15	3.25	2	1b	2.12	1.66
12.7/K-K/Par/25:50/1		50	2.04	3.86	1.89	35.62	1086	1.93	4.15	4.89	2	2	2.15	2.53
12.7/K-K/Par/25:50/2			1.96	3.86	1.97	29.17	1036	1.96	5.65	4.27	2	1b	2.89	2.18
12.7/K-K/Par/25:50/3			1.92	3.78	1.97	25.43	1022	1.96	6.10	4.50	2	1b	3.12	2.30
12.7/K-K/Par/25:75/1		75	2.96	5.83	1.97	25.84	1003	1.96	7.27	3.57	2	2	3.72	1.83
12.7/K-K/Par/25:75/2			3.08	5.83	1.89	26.14	1019	1.93	6.35	3.08	2	2	3.28	1.59
12.7/K-K/Par/25:75/3			2.92	5.75	1.97	23.67	1015	1.96	7.17	4.58	2	1b	3.67	2.34
12.7/K-K/Par/38:38/1	38	38	1.00	2.83	2.83	19.80	1001	2.26	3.36	3.00	2	1b	1.49	1.33
12.7/K-K/Par/38:38/2			1.00	2.52	2.52	17.00	989	2.01	2.91	2.17	1b	1b	1.45	1.08
12.7/K-K/Par/38:38/3			1.06	2.76	2.60	17.86	995	2.17	4.15	3.17	2	1b	1.92	1.46
12.7/K-K/Par/38:50/1		50	1.44	3.62	2.52	18.45	1010	2.14	6.10	4.88	2	2	2.85	2.28
12.7/K-K/Par/38:50/2			1.53	3.62	2.36	15.47	918	2.08	5.24	3.57	2	2	2.52	1.72
12.7/K-K/Par/38:50/3			1.47	3.70	2.52	15.27	952	2.14	6.25	4.58	2	2	2.92	2.14
12.7/K-K/Par/38:75/1		75	2.24	5.83	2.60	18.41	1012	2.17	8.47	6.50	2	2	3.91	3.00
12.7/K-K/Par/38:75/2			2.24	5.83	2.60	16.99	939	2.17	5.68	2.75	2	2	2.62	1.27
12.7/K-K/Par/38:75/3			2.35	5.75	2.44	20.12	970	2.11	7.66	4.88	2	2	3.63	2.31
12.7/K-K/Par/38:100/1		100	3.03	7.64	2.52	18.48	948	2.14	6.54	4.08	2	2	3.06	1.91
12.7/K-K/Par/38:100/2			3.06	7.72	2.52	17.26	914	2.14	7.98	2.67	2	2	3.73	1.25
12.7/K-K/Par/38:100/3			2.62	7.64	2.91	25.12	994	2.29	6.15	4.08	2	2	2.68	1.78
12.7/K-K/Par/50:50/1	50	50	1.05	3.39	3.23	16.05	907	2.43	5.84	4.00	2	1b	2.41	1.65
12.7/K-K/Par/50:50/2			1.07	3.70	3.46	16.41	763	2.53	5.68	1.67	2	1b	2.24	0.66
12.7/K-K/Par/50:50/3			1.06	3.94	3.70	22.33	954	2.56	5.75	3.21	3	1b	2.25	1.26
12.7/K-K/Par/50:75/1		75	1.55	5.75	3.70	16.38	917	2.56	6.97	3.87	3	2	2.73	1.51
12.7/K-K/Par/50:75/2			1.63	5.91	3.62	14.72	866	2.56	7.40	2.50	3	1b	2.90	0.98
12.7/K-K/Par/50:75/3			1.61	5.83	3.62	14.41	929	2.56	10.18	5.50	3	2	3.98	2.15
12.7/K-K/Par/50:100/1		100	2.13	7.72	3.62	16.30	782	2.56	9.81	2.96	3	2	3.84	1.16
12.7/K-K/Par/50:100/2			2.09	7.72	3.70	16.05	891	2.56	10.32	2.50	3	2	4.04	0.98
12.7/K-K/Par/50:100/3			2.09	7.72	3.70	14.59	921	2.56	10.00	3.33	3	2	3.91	1.30

* *Average of three members*

Table A5: Test results of Joint strength tests – Kumbuk parallel to grain loading, 15.9mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
15.9/K-K/Par/25:38/1	25	38	1.50	2.26	1.51	18.33	942	2.71	4.01	3.18	2	1a	1.48	1.17
15.9/K-K/Par/25:38/2			1.57	2.26	1.45	16.70	932	2.69	2.91	2.00	2	1b	1.08	0.74
15.9/K-K/Par/25:38/3			1.50	2.26	1.51	19.28	827	2.71	4.53	3.26	2	1b	1.67	1.20
15.9/K-K/Par/25:50/1		50	1.88	2.83	1.51	19.92	964	2.71	6.04	4.76	2	1a	2.23	1.76
15.9/K-K/Par/25:50/2			1.92	2.89	1.51	16.29	961	2.71	4.52	3.40	2	1a	1.67	1.26
15.9/K-K/Par/25:50/3			1.96	2.83	1.45	16.92	888	2.69	6.40	4.18	2	1a	2.38	1.55
15.9/K-K/Par/25:75/1		75	3.22	4.65	1.45	17.99	932	2.69	6.90	4.65	2	2	2.56	1.73
15.9/K-K/Par/25:75/2			3.13	4.72	1.51	17.74	908	2.71	7.12	4.20	2	1a	2.63	1.55
15.9/K-K/Par/25:75/3			3.13	4.72	1.51	20.97	933	2.71	7.27	4.76	2	1a	2.68	1.76
15.9/K-K/Par/38:38/1	38	38	1.06	2.26	2.14	19.82	1000	2.73	4.37	3.41	1b	1b	1.60	1.25
15.9/K-K/Par/38:38/2			1.00	2.26	2.26	17.85	974	2.73	3.35	2.20	1b	1b	1.23	0.81
15.9/K-K/Par/38:38/3			1.03	2.26	2.20	18.95	963	2.73	3.59	2.47	1b	1b	1.32	0.91
15.9/K-K/Par/38:50/1		50	1.55	3.21	2.08	21.51	1073	2.93	6.50	3.29	2	1b	2.22	1.12
15.9/K-K/Par/38:50/2			1.42	3.21	2.26	22.17	913	3.02	6.35	4.87	2	1b	2.10	1.61
15.9/K-K/Par/38:50/3			1.29	2.83	2.20	18.46	890	2.99	5.71	4.59	2	1b	1.91	1.54
15.9/K-K/Par/38:75/1		75	2.24	4.65	2.08	23.34	1077	2.93	8.20	5.06	2	2	2.80	1.73
15.9/K-K/Par/38:75/2			2.08	4.72	2.26	20.23	974	3.02	10.93	8.73	2	2	3.62	2.89
15.9/K-K/Par/38:75/3			2.08	4.72	2.26	23.74	974	3.02	11.23	5.88	2	2	3.72	1.95
15.9/K-K/Par/38:100/1		100	2.75	6.23	2.26	18.06	943	3.02	10.47	7.06	2	2	3.46	2.34
15.9/K-K/Par/38:100/2			2.97	6.16	2.08	16.15	927	2.93	8.20	4.27	2	2	2.80	1.46
15.9/K-K/Par/38:100/3			2.91	6.23	2.14	17.68	935	2.96	8.20	6.35	2	2	2.77	2.15
15.9/K-K/Par/50:50/1	50	50	1.00	3.21	3.21	43.25	1168	3.60	5.83	4.41	2	1b	1.62	1.23
15.9/K-K/Par/50:50/2			1.00	3.27	3.27	31.86	1100	3.64	7.50	5.27	2	1b	2.06	1.45
15.9/K-K/Par/50:50/3			1.02	3.21	3.14	31.33	1115	3.55	6.02	5.00	2	1b	1.69	1.41
15.9/K-K/Par/50:75/1		75	1.45	4.65	3.21	30.73	1158	3.60	8.79	5.88	2	2	2.44	1.64
15.9/K-K/Par/50:75/2			1.47	4.72	3.21	37.81	1113	3.60	8.58	6.33	2	2	2.39	1.76
15.9/K-K/Par/50:75/3			1.45	4.65	3.21	31.25	1120	3.60	10.68	5.00	2	2	2.97	1.39
15.9/K-K/Par/50:100/1		100	1.96	6.29	3.21	28.01	1165	3.60	13.24	9.65	2	2	3.68	2.68
15.9/K-K/Par/50:100/2			1.92	6.29	3.27	26.23	976	3.64	14.53	10.93	2	3	3.99	3.00
15.9/K-K/Par/50:100/3			1.98	6.23	3.14	24.76	1053	3.55	12.71	10.71	2	1b	3.58	3.01

**Average of three members*

Table A6: Test results of Joint strength tests – Ginisapu parallel to grain loading, 9.5mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
9.5/G-G/Par/25:38/1	25	38	1.58	4.00	2.53	21.61	670	0.95	2.70	2.11	2	1b	2.84	2.22
9.5/G-G/Par/25:38/2			1.81	4.00	2.21	18.35	754	0.91	2.13	1.80	2	1b	2.34	1.98
9.5/G-G/Par/25:38/3			1.73	4.00	2.32	18.16	618	0.92	2.48	1.86	2	1b	2.68	2.01
9.5/G-G/Par/25:50/1		50	2.23	5.16	2.32	22.86	698	0.92	2.96	2.21	2	2	3.20	2.39
9.5/G-G/Par/25:50/2			1.77	4.84	2.74	19.78	697	0.98	2.96	2.48	2	1b	3.01	2.52
9.5/G-G/Par/25:50/3			2.33	5.16	2.21	19.39	696	0.91	2.92	2.18	2	1b	3.21	2.39
9.5/G-G/Par/25:75/1		75	3.52	7.79	2.21	27.62	743	0.91	4.42	3.73	2	1a	4.85	4.09
9.5/G-G/Par/25:75/2			3.41	7.89	2.32	26.20	805	0.92	5.69	3.53	2	1a	6.16	3.82
9.5/G-G/Par/25:75/3			3.41	7.89	2.32	28.37	802	0.92	5.75	3.60	2	1a	6.22	3.90
9.5/G-G/Par/38:38/1	38	38	1.00	4.00	4.00	26.19	732	1.19	2.21	1.72	3	2	1.86	1.45
9.5/G-G/Par/38:38/2			1.00	4.00	4.00	20.71	900	1.19	2.66	2.12	3	1b	2.24	1.78
9.5/G-G/Par/38:38/3			1.00	4.00	4.00	27.77	784	1.19	2.27	1.69	3	1b	1.91	1.42
9.5/G-G/Par/38:50/1		50	1.29	5.16	4.00	23.26	661	1.19	2.34	2.02	3	3	1.97	1.70
9.5/G-G/Par/38:50/2			1.32	5.26	4.00	19.98	740	1.19	4.59	2.55	3	1b	3.86	2.15
9.5/G-G/Par/38:50/3			1.35	5.26	3.89	28.99	830	1.18	4.01	3.08	2	1b	3.39	2.60
9.5/G-G/Par/38:75/1		75	2.00	7.79	3.89	39.93	802	1.18	4.91	2.95	2	1a	4.15	2.49
9.5/G-G/Par/38:75/2			2.03	7.89	3.89	41.77	845	1.18	5.39	3.23	2	3	4.56	2.73
9.5/G-G/Par/38:75/3			2.03	7.89	3.89	32.89	847	1.18	5.32	3.61	2	1b	4.50	3.05
9.5/G-G/Par/38:100/1		100	2.61	10.42	4.00	34.84	817	1.19	6.54	5.00	3	3	5.51	4.21
9.5/G-G/Par/38:100/2			2.70	10.53	3.89	37.04	804	1.18	5.18	2.95	2	1a	4.38	2.49
9.5/G-G/Par/38:100/3			2.70	10.53	3.89	33.30	810	1.18	5.48	3.14	2	1b	4.63	2.66
9.5/G-G/Par/50:50/1	50	50	1.00	5.16	5.16	41.75	752	1.19	2.39	1.82	3	2	2.01	1.53
9.5/G-G/Par/50:50/2			1.00	5.16	5.16	18.43	693	1.19	3.10	1.78	3	1b	2.61	1.50
9.5/G-G/Par/50:50/3			1.00	5.26	5.26	37.16	904	1.19	4.06	3.32	3	1b	3.42	2.79
9.5/G-G/Par/50:75/1		75	1.50	7.89	5.26	48.90	918	1.19	4.59	2.36	3	1b	3.86	1.99
9.5/G-G/Par/50:75/2			1.53	7.89	5.16	35.45	844	1.19	5.48	4.10	3	1b	4.61	3.45
9.5/G-G/Par/50:75/3			1.53	7.89	5.16	36.05	895	1.19	4.77	3.08	3	1b	4.02	2.59
9.5/G-G/Par/50:100/1		100	2.04	10.53	5.16	32.58	730	1.19	4.86	1.82	3	1a	4.09	1.53
9.5/G-G/Par/50:100/2			2.00	10.53	5.26	30.84	791	1.19	5.75	2.20	3	3	4.84	1.85
9.5/G-G/Par/50:100/3			2.04	10.53	5.16	25.09	821	1.19	7.24	5.18	3	1b	6.09	4.36

**Average of three members*

Table A7: Test results of Joint strength tests – Ginisapu parallel to grain loading, 12.7mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
12.7/G-G/Par/25:38/1	25	38	1.50	2.60	1.73	20.46	668	1.49	1.79	1.40	1b	1b	1.20	0.94
12.7/G-G/Par/25:38/2			1.48	2.68	1.81	19.62	723	1.53	1.42	1.15	1b	1b	0.93	0.75
12.7/G-G/Par/25:38/3			1.55	2.68	1.73	18.97	724	1.53	1.67	1.11	1b	1b	1.09	0.72
12.7/G-G/Par/25:50/1		50	2.09	3.78	1.81	20.96	692	1.57	3.33	2.38	2	2	2.12	1.51
12.7/G-G/Par/25:50/2			2.09	3.78	1.81	19.53	691	1.57	3.47	3.14	2	1b	2.21	2.00
12.7/G-G/Par/25:50/3			2.18	3.78	1.73	19.90	827	1.56	3.35	2.72	2	1b	2.14	1.74
12.7/G-G/Par/25:75/1		75	3.18	5.51	1.73	20.23	753	1.56	4.58	4.04	2	2	2.93	2.59
12.7/G-G/Par/25:75/2			3.13	5.67	1.81	20.66	661	1.57	4.27	3.46	2	2	2.72	2.20
12.7/G-G/Par/25:75/3			3.60	5.67	1.57	19.00	687	1.55	4.95	3.54	2	1b	3.20	2.29
12.7/G-G/Par/38:38/1	38	38	1.03	2.68	2.60	20.46	576	1.53	2.25	1.88	1b	1b	1.47	1.23
12.7/G-G/Par/38:38/2			1.09	2.91	2.68	20.33	595	1.67	2.09	1.82	1b	1b	1.25	1.09
12.7/G-G/Par/38:38/3			1.00	2.68	2.68	19.76	594	1.53	1.75	0.37	1b	1b	1.14	0.24
12.7/G-G/Par/38:50/1		50	1.53	3.86	2.52	21.29	621	1.70	3.82	3.24	2	2	2.25	1.91
12.7/G-G/Par/38:50/2			1.50	3.78	2.52	19.61	674	1.70	4.38	4.04	2	2	2.58	2.38
12.7/G-G/Par/38:50/3			1.41	3.78	2.68	19.99	670	1.74	3.72	2.93	2	2	2.14	1.69
12.7/G-G/Par/38:75/1		75	2.00	5.35	2.68	22.95	587	1.74	4.73	3.88	2	2	2.72	2.23
12.7/G-G/Par/38:75/2			2.12	5.67	2.68	19.73	605	1.74	4.54	3.41	2	2	2.61	1.96
12.7/G-G/Par/38:75/3			2.12	5.67	2.68	19.56	616	1.74	4.52	3.22	2	2	2.60	1.85
12.7/G-G/Par/38:100/1		100	3.06	7.72	2.52	20.89	617	1.70	4.68	2.95	2	2	2.75	1.74
12.7/G-G/Par/38:100/2			2.88	7.72	2.68	21.20	666	1.74	6.07	4.95	2	2	3.50	2.85
12.7/G-G/Par/38:100/3			2.88	7.72	2.68	21.05	653	1.74	7.12	4.00	2	2	4.10	2.30
12.7/G-G/Par/50:50/1	50	50	1.00	3.78	3.78	23.19	686	2.05	2.57	2.19	2	1b	1.26	1.07
12.7/G-G/Par/50:50/2			1.00	3.78	3.78	23.22	813	2.05	3.82	3.00	2	1b	1.87	1.47
12.7/G-G/Par/50:50/3			1.02	3.78	3.70	20.96	759	2.02	3.93	2.86	2	1b	1.94	1.41
12.7/G-G/Par/50:75/1		75	1.53	5.67	3.70	21.81	677	2.02	5.68	3.40	2	2	2.81	1.68
12.7/G-G/Par/50:75/2			1.53	5.67	3.70	21.05	781	2.02	4.56	3.15	2	1b	2.25	1.56
12.7/G-G/Par/50:75/3			1.53	5.67	3.70	20.35	696	2.02	5.10	3.28	2	2	2.52	1.62
12.7/G-G/Par/50:100/1		100	2.09	7.72	3.70	25.83	744	2.02	7.35	2.84	2	2	3.63	1.40
12.7/G-G/Par/50:100/2			2.09	7.72	3.70	21.24	695	2.02	7.94	2.50	2	2	3.93	1.24
12.7/G-G/Par/50:100/3			2.09	7.72	3.70	20.68	634	2.02	6.47	4.12	2	2	3.20	2.04

**Average of three members*

Table A8: Test results of Joint strength tests – Ginisapu parallel to grain loading, 15.9mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
15.9/G-G/Par/25:38/1	25	38	1.67	2.20	1.32	27.31	723	1.90	3.10	2.84	1b	1a	1.63	1.49
15.9/G-G/Par/25:38/2			1.80	2.26	1.26	20.26	902	1.96	2.33	1.86	1b	1b	1.19	0.95
15.9/G-G/Par/25:38/3			1.67	2.20	1.32	25.62	797	1.90	3.20	2.56	1b	1b	1.68	1.34
15.9/G-G/Par/25:50/1		50	2.40	3.02	1.26	23.36	739	2.18	3.54	3.27	1a	1a	1.63	1.50
15.9/G-G/Par/25:50/2			2.40	3.02	1.26	18.58	762	2.18	4.01	3.12	1a	1a	1.84	1.43
15.9/G-G/Par/25:50/3			2.45	3.08	1.26	19.98	741	2.18	3.57	2.89	1a	1a	1.64	1.33
15.9/G-G/Par/25:75/1		75	3.65	4.59	1.26	30.31	738	2.18	3.80	3.46	1a	2	1.75	1.59
15.9/G-G/Par/25:75/2			3.65	4.59	1.26	19.31	760	2.18	3.57	3.07	1a	1a	1.64	1.41
15.9/G-G/Par/25:75/3			2.96	4.65	1.57	20.22	768	2.26	6.19	4.96	2	1a	2.74	2.20
15.9/G-G/Par/38:38/1	38	38	1.03	2.26	2.20	37.37	960	1.96	3.01	2.92	1b	1b	1.54	1.49
15.9/G-G/Par/38:38/2			1.03	2.20	2.14	27.51	862	1.90	2.55	2.21	1b	1b	1.34	1.16
15.9/G-G/Par/38:38/3			1.03	2.20	2.14	29.06	862	1.90	3.57	2.82	1b	1b	1.88	1.48
15.9/G-G/Par/38:50/1		50	1.33	3.02	2.26	45.18	893	2.42	4.86	4.37	2	1b	2.01	1.81
15.9/G-G/Par/38:50/2			1.33	3.02	2.26	25.88	908	2.42	3.50	2.69	2	1b	1.45	1.11
15.9/G-G/Par/38:50/3			1.40	3.08	2.20	26.31	908	2.40	4.45	3.85	2	1b	1.85	1.60
15.9/G-G/Par/38:75/1		75	2.14	4.72	2.20	41.54	951	2.40	8.20	6.75	2	2	3.41	2.81
15.9/G-G/Par/38:75/2			2.11	4.65	2.20	18.43	885	2.40	6.97	6.07	2	2	2.90	2.53
15.9/G-G/Par/38:75/3			2.09	4.59	2.20	20.75	816	2.40	7.40	4.69	2	2	3.08	1.95
15.9/G-G/Par/38:100/1		100	2.71	5.97	2.20	31.86	848	2.40	7.42	5.00	2	2	3.09	2.08
15.9/G-G/Par/38:100/2			2.71	5.97	2.20	22.90	969	2.40	8.20	5.83	2	2	3.41	2.43
15.9/G-G/Par/38:100/3			2.71	5.97	2.20	20.42	940	2.40	8.56	5.76	2	2	3.56	2.40
15.9/G-G/Par/50:50/1	50	50	1.09	3.02	2.77	35.60	897	2.60	4.88	3.95	2	1b	1.88	1.52
15.9/G-G/Par/50:50/2			1.00	3.02	3.02	21.11	835	2.61	3.33	2.85	1b	1b	1.28	1.09
15.9/G-G/Par/50:50/3			1.09	3.02	2.77	29.21	948	2.60	4.45	3.90	2	1b	1.71	1.50
15.9/G-G/Par/50:75/1		75	1.65	4.97	3.02	35.40	905	2.70	7.62	5.46	2	2	2.82	2.02
15.9/G-G/Par/50:75/2			1.54	4.65	3.02	23.52	886	2.70	7.69	5.81	2	2	2.85	2.15
15.9/G-G/Par/50:75/3			1.54	4.65	3.02	21.81	828	2.70	7.19	5.00	2	2	2.66	1.85
15.9/G-G/Par/50:100/1		100	2.02	5.97	2.96	40.36	859	2.67	8.56	6.34	2	2	3.20	2.37
15.9/G-G/Par/50:100/2			1.98	5.97	3.02	20.84	926	2.70	7.76	5.60	2	3	2.87	2.07
15.9/G-G/Par/50:100/3			2.16	5.97	2.77	22.98	791	2.60	6.97	4.85	2	1b	2.68	1.87

**Average of three members*

Table A9: Test results of Joint strength tests – Ginisapu perpendicular to grain loading, 9.5mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m³)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
9.5/G-G/Per/25:38/1	25	38	1.52	4.00	2.63	14.32	589	0.90	3.43	2.38	2	1b	3.81	2.64
9.5/G-G/Per/25:38/2			1.52	4.00	2.63	16.70	588	0.90	3.69	2.38	2	1b	4.09	2.64
9.5/G-G/Per/25:38/3			1.52	4.00	2.63	16.41	585	0.90	3.61	3.37	2	1b	4.01	3.74
9.5/G-G/Per/25:50/1		50	1.96	5.16	2.63	15.32	638	0.90	4.54	2.35	2	2	5.04	2.61
9.5/G-G/Per/25:50/2			1.92	5.05	2.63	16.78	572	0.90	4.23	3.00	2	1b	4.69	3.33
9.5/G-G/Per/25:50/3			1.92	5.05	2.63	16.93	606	0.90	4.23	3.40	2	1b	4.69	3.77
9.5/G-G/Per/25:75/1		75	2.96	7.79	2.63	15.32	556	0.90	4.27	2.96	2	1a	4.74	3.28
9.5/G-G/Per/25:75/2			2.96	7.79	2.63	16.45	560	0.90	5.00	3.62	2	1a	5.55	4.02
9.5/G-G/Per/25:75/3			2.96	7.79	2.63	17.19	579	0.90	4.52	2.70	2	1a	5.02	3.00
9.5/G-G/Per/38:38/1	38	38	1.00	4.00	4.00	16.29	589	1.08	3.55	2.85	3	2	3.28	2.64
9.5/G-G/Per/38:38/2			1.00	4.00	4.00	16.02	567	1.08	2.89	1.92	3	1b	2.67	1.78
9.5/G-G/Per/38:38/3			1.00	4.00	4.00	18.34	582	1.08	2.68	2.33	3	1b	2.48	2.15
9.5/G-G/Per/38:50/1		50	1.29	5.16	4.00	16.05	576	1.08	5.00	3.92	3	3	4.62	3.63
9.5/G-G/Per/38:50/2			1.29	5.16	4.00	16.74	622	1.08	3.78	2.42	3	1b	3.50	2.24
9.5/G-G/Per/38:50/3			1.26	5.05	4.00	17.52	615	1.08	4.83	3.87	3	1b	4.47	3.58
9.5/G-G/Per/38:75/1		75	1.95	7.79	4.00	16.78	578	1.08	4.74	3.38	3	1a	4.38	3.13
9.5/G-G/Per/38:75/2			1.95	7.79	4.00	18.34	561	1.08	4.71	2.81	3	3	4.36	2.60
9.5/G-G/Per/38:75/3			1.92	7.68	4.00	17.07	562	1.08	5.37	4.67	3	1b	4.97	4.32
9.5/G-G/Per/38:100/1		100	2.63	10.53	4.00	14.89	551	1.08	6.46	3.46	3	3	5.97	3.20
9.5/G-G/Per/38:100/2			2.63	10.53	4.00	16.70	549	1.08	5.70	3.46	3	1a	5.27	3.20
9.5/G-G/Per/38:100/3			2.70	10.53	3.89	17.23	602	1.08	5.90	3.67	3	1b	5.46	3.39
9.5/G-G/Per/50:50/1	50	50	1.00	5.26	5.26	16.05	629	1.08	4.06	3.23	3	2	3.75	2.99
9.5/G-G/Per/50:50/2			1.00	5.26	5.26	17.11	627	1.08	4.44	3.77	3	1b	4.11	3.49
9.5/G-G/Per/50:50/3			1.00	5.16	5.16	17.82	635	1.08	3.98	3.43	3	1b	3.68	3.17
9.5/G-G/Per/50:75/1		75	1.51	7.79	5.16	15.07	621	1.08	5.39	4.77	3	1b	4.98	4.41
9.5/G-G/Per/50:75/2			1.51	7.79	5.16	17.22	651	1.08	5.33	4.85	3	1b	4.93	4.49
9.5/G-G/Per/50:75/3			1.51	7.79	5.16	18.03	665	1.08	5.56	5.33	3	1b	5.14	4.93
9.5/G-G/Per/50:100/1		100	2.04	10.53	5.16	16.11	645	1.08	7.92	5.08	3	1a	7.32	4.70
9.5/G-G/Per/50:100/2			2.00	10.53	5.26	17.65	655	1.08	7.76	4.15	3	3	7.18	3.84
9.5/G-G/Per/50:100/3			2.04	10.53	5.16	18.27	672	1.08	7.01	4.00	3	1b	6.48	3.70

**Average of three members*

Table A10: Test results of Joint strength tests – Ginisapu perpendicular to grain loading, 12.7mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m³)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
12.7/G-G/Per/25:38/1	25	38	1.52	2.99	1.97	17.31	623	1.44	3.43	2.73	2	1b	2.38	1.89
12.7/G-G/Per/25:38/2			1.48	2.91	1.97	17.09	613	1.44	3.35	2.93	2	1b	2.32	2.03
12.7/G-G/Per/25:38/3			1.52	2.99	1.97	19.68	625	1.44	3.33	2.88	2	1b	2.31	2.00
12.7/G-G/Per/25:50/1		50	1.96	3.86	1.97	16.86	652	1.44	4.98	3.67	2	2	3.45	2.55
12.7/G-G/Per/25:50/2			2.00	3.94	1.97	17.74	710	1.44	5.00	3.93	2	1b	3.47	2.73
12.7/G-G/Per/25:50/3			2.00	3.94	1.97	21.32	667	1.44	4.91	4.19	2	1b	3.41	2.91
12.7/G-G/Per/25:75/1		75	3.00	5.91	1.97	18.28	638	1.44	4.78	4.23	2	2	3.32	2.93
12.7/G-G/Per/25:75/2			3.00	5.91	1.97	17.57	639	1.44	5.54	3.80	2	2	3.84	2.64
12.7/G-G/Per/25:75/3			3.00	5.91	1.97	22.39	605	1.44	5.50	4.58	2	1b	3.81	3.18
12.7/G-G/Per/38:38/1	38	38	1.00	2.99	2.99	18.41	603	1.66	3.29	2.93	2	1b	1.99	1.77
12.7/G-G/Per/38:38/2			1.00	2.99	2.99	17.87	595	1.66	3.73	3.33	2	1b	2.25	2.01
12.7/G-G/Per/38:38/3			1.00	2.99	2.99	19.77	602	1.66	3.20	3.00	2	1b	1.93	1.81
12.7/G-G/Per/38:50/1		50	1.32	3.94	2.99	19.48	652	1.66	5.41	4.47	2	2	3.27	2.70
12.7/G-G/Per/38:50/2			1.29	3.86	2.99	19.15	648	1.66	5.07	5.00	2	2	3.06	3.02
12.7/G-G/Per/38:50/3			1.32	3.94	2.99	21.01	633	1.66	4.76	4.27	2	2	2.87	2.58
12.7/G-G/Per/38:75/1		75	1.95	5.83	2.99	19.24	638	1.66	7.00	5.57	2	2	4.23	3.36
12.7/G-G/Per/38:75/2			1.97	5.91	2.99	18.75	651	1.66	6.25	5.40	2	2	3.77	3.26
12.7/G-G/Per/38:75/3			1.97	5.91	2.99	21.82	656	1.66	6.58	5.92	2	2	3.97	3.57
12.7/G-G/Per/38:100/1		100	2.63	7.87	2.99	19.47	674	1.66		2.67	2	2		1.61
12.7/G-G/Per/38:100/2			2.63	7.87	2.99	19.37	630	1.66		5.33	2	2		3.22
12.7/G-G/Per/38:100/3			2.63	7.87	2.99	20.57	689	1.66		3.31	2	2		2.00
12.7/G-G/Per/50:50/1	50	50	1.00	3.94	3.94	20.21	663	1.92	3.67	3.30	2	1b	1.91	1.72
12.7/G-G/Per/50:50/2			1.02	3.94	3.86	19.95	706	1.90	5.56	4.47	2	1b	2.93	2.35
12.7/G-G/Per/50:50/3			1.00	3.94	3.94	21.69	667	1.92	4.87	4.35	2	1b	2.53	2.26
12.7/G-G/Per/50:75/1		75	1.50	5.91	3.94	22.71	646	1.92	7.21	6.27	2	2	3.75	3.26
12.7/G-G/Per/50:75/2			1.50	5.91	3.94	19.16	618	1.92	7.17	6.47	2	1b	3.73	3.36
12.7/G-G/Per/50:75/3			1.50	5.91	3.94	22.19	647	1.92	5.71	5.15	2	2	2.97	2.68
12.7/G-G/Per/50:100/1		100	2.00	7.87	3.94	20.22	627	1.92	5.92	3.53	2	2	3.08	1.84
12.7/G-G/Per/50:100/2			2.00	7.87	3.94	18.70	619	1.92	7.27	3.57	2	2	3.78	1.86
12.7/G-G/Per/50:100/3			2.02	7.95	3.94	21.15	661	1.92	9.30	4.27	2	2	4.84	2.22

**Average of three members*

Table A11: Test results of Joint strength tests – Ginisapu perpendicular to grain loading, 15.9mm bolt diameter

Specimen Identification No.	t_1 *(mm)*	t_2 *(mm)*	t_2/t_1	t_2/d	t_1/d	Moisture Content* *(%)*	Density* *(kg/m^3)*	Failure Load *(Tonnes)*			Failure Mode		Factor of Safety	
								EYM	Ult.	Yield	EYM	Exp.	Ult.	Yield
15.9/G-G/Per/25:38/1	25	38	1.52	2.39	1.57	13.12	637	2.01	3.94	3.00	2	1a	1.96	1.49
15.9/G-G/Per/25:38/2			1.52	2.39	1.57	17.99	593	2.01	3.84	3.57	2	1b	1.91	1.78
15.9/G-G/Per/25:38/3			1.52	2.39	1.57	16.66	611	2.01	4.00	3.40	2	1b	1.99	1.69
15.9/G-G/Per/25:50/1		50	2.00	3.14	1.57	13.18	650	2.01	5.37	4.95	2	1a	2.67	2.46
15.9/G-G/Per/25:50/2			2.08	3.14	1.51	17.92	656	2.00	6.00	4.67	2	1a	3.00	2.33
15.9/G-G/Per/25:50/3			1.96	3.08	1.57	16.54	639	2.01	4.83	4.15	2	1a	2.40	2.07
15.9/G-G/Per/25:75/1		75	3.00	4.72	1.57	13.29	627	2.01	5.00	4.00	2	2	2.49	1.99
15.9/G-G/Per/25:75/2			3.08	4.65	1.51	17.44	625	2.00	6.15	5.48	2	1a	3.07	2.74
15.9/G-G/Per/25:75/3			3.00	4.72	1.57	16.28	627	2.01	6.67	6.25	2	1a	3.32	3.11
15.9/G-G/Per/38:38/1	38	38	1.00	2.39	2.39	13.52	593	2.07	4.50	3.57	1b	1b	2.18	1.73
15.9/G-G/Per/38:38/2			1.03	2.39	2.33	16.80	606	2.07	4.50	3.57	1b	1b	2.18	1.73
15.9/G-G/Per/38:38/3			1.00	2.39	2.39	15.97	564	2.07	4.46	3.35	1b	1b	2.16	1.62
15.9/G-G/Per/38:50/1		50	1.32	3.14	2.39	13.42	627	2.19	4.80	4.48	2	1b	2.19	2.04
15.9/G-G/Per/38:50/2			1.35	3.14	2.33	18.08	650	2.17	5.96	5.29	2	1b	2.74	2.44
15.9/G-G/Per/38:50/3			1.32	3.14	2.39	16.57	616	2.19	7.54	5.70	2	1b	3.44	2.60
15.9/G-G/Per/38:75/1		75	1.97	4.72	2.39	12.43	641	2.19	7.33	6.10	2	2	3.35	2.78
15.9/G-G/Per/38:75/2			2.03	4.72	2.33	17.82	602	2.17	7.17	6.71	2	2	3.30	3.09
15.9/G-G/Per/38:75/3			1.97	4.72	2.39	16.28	604	2.19	9.00	7.50	2	2	4.11	3.42
15.9/G-G/Per/38:100/1		100	2.63	6.29	2.39	13.17	642	2.19	10.03	7.00	2	2	4.58	3.20
15.9/G-G/Per/38:100/2			2.78	6.29	2.26	17.98	614	2.15	9.50	5.48	2	2	4.41	2.54
15.9/G-G/Per/38:100/3			2.63	6.29	2.39	16.19	602	2.19	11.04	7.00	2	2	5.04	3.20
15.9/G-G/Per/50:50/1	50	50	1.00	3.14	3.14	12.57	646	2.45	3.78	3.52	2	1b	1.54	1.43
15.9/G-G/Per/50:50/2			1.00	3.14	3.14	18.86	675	2.45	6.31	5.48	2	1b	2.57	2.23
15.9/G-G/Per/50:50/3			1.00	3.14	3.14	14.93	634	2.45	5.39	4.80	2	1b	2.20	1.96
15.9/G-G/Per/50:75/1		75	1.48	4.65	3.14	11.55	596	2.45	8.50	6.62	2	2	3.46	2.70
15.9/G-G/Per/50:75/2			1.50	4.72	3.14	18.41	633	2.45	7.44	6.48	2	2	3.03	2.64
15.9/G-G/Per/50:75/3			1.50	4.72	3.14	15.95	626	2.45	8.02	6.80	2	2	3.27	2.77
15.9/G-G/Per/50:100/1		100	2.00	6.29	3.14	12.44	616	2.45	10.55	7.24	2	2	4.30	2.95
15.9/G-G/Per/50:100/2			2.00	6.29	3.14	18.00	585	2.45	9.50	6.95	2	3	3.87	2.83
15.9/G-G/Per/50:100/3			2.00	6.29	3.14	15.74	579	2.45	9.69	9.30	2	1b	3.95	3.79

**Average of three members*