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Structural Performance of Low Grade Timber Slabs

A dissertation submitted by

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Abstract

Low grade pine subject to loading exhibits a poor predictability when used in structural applications. Australia produces a large amount of low grade timber yearly which is sold at a loss due to its unreliable performance characteristics. This dissertation investigates the structural performance of slab units manufactured from low grade timber when used to form a floor slab.

Physical testing and finite element analysis modelling have been used to determine the limitations of low grade timber floor slabs. This study involved determining which of the strength and serviceability criteria governs design, along with an investigation into the performance of bugle head batten screws used to connect low grade slab units to form a floor slab. The findings of these investigations are summarised into a chart for the deflection based design of low grade timber floor slabs, and graphs describing connection performance based on various loading situations.

Investigations have concluded that utilising low grade timber in floor units increases the reliability of the product considerably. Connections can also be made that have sufficient strength to resist any forces applied between slab units.

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Nomenclature

a	Length of specimen divided by three (m)
B	Width of test specimen (m)
D	Depth of test specimen (m)
E	Modulus of Elasticity (MOE) parallel to the grain (MPa)
E^*	Characteristic short duration average MOE parallel to the grain (MPa)
$\left(f_b^{'}\right)$	Characteristic strength in bending (MPa)
$\left(f_c^{'}\right)$	Characteristic strength in compression (MPa)
$\left(f_s^{'}\right)$	Characteristic strength in shear (MPa)
$\left(f_t^{'}\right)$	Characteristic strength in tension (MPa)
G	Modulus of Rigidity (MPa)
I	Second moment of inertia (m^4)
L	Length of test specimen (m)
$M_{\max}$	Maximum bending moment (kN.m)
P_X	Load applied to test specimen at point x (kN)
δ	Central deflection of a simply supported beam (mm)
Δ_X	Specimen deflection at point x (m)
ν	Poisons ratio
ρ	Material Density (kg/m^3)
$\sigma_{\max}$	Maximum allowable stress (MPa)

Chapter 1

Introduction

1.0 Outline of the study

The study into the viability of using low grade timber floor slabs as a realistic flooring alternative in Australia has been initiated as a result of investigations into methods of making low grade timber products profitable for timber producers. The aim of this project is to investigate the structural performance of above ground low grade timber slab flooring systems with the objective of developing methods of design and construction for such systems. This will include both stress and deflection based performance studies along with slab connection methods.

1.1 Background

Hyne and Son is Australia's largest successful privately owned timber company. They are responsible for the production of structural pine building products from sustainable plantation grown timber. Timber products produced by Hyne include MGP15, MGP12, MGP10, F5 and utility grade. High grade structural timber like MGP15 is readily sold and generates higher prices than utility grade, which because of excessive knots and other faults is not a viable structural material. Hyne are seeking to develop technologies which can better utilize utility grade timber as a structural material in building applications. This research project investigates one innovative option for utilizing this low grade timber product.

Because of excessive material faults, the low grade timber is labelled as having mechanical characteristics less than F5 graded timber. Hyne can not sell this timber at a profit, hence the company seeking to develop technologies that can utilise this resource and make it profitable and sustainable.

This research on the structural performance of low grade timber slabs is intended to utilise the non structural grade product, in a manner that is safe and reliable. Currently technology is available to fabricate solid wood panels (slabs), however research is needed to investigate issues associated with the development of a timber slab flooring system. Therefore, the scope of this research will mainly focus on the structural performance of above ground timber slab flooring systems, supported by the traditional column and bearer configuration.

1.2 The problem

Australia's leading plantation pine based timber producers are continuously milling timber for use in Structural applications throughout Australia. All timber is graded according to its mechanical and visual characteristics which dictate the applications it can be utilised in and ultimately the profit that can be made from it. Currently timber is graded for usage in accordance with Table 1.

Timber that is graded less than F5 cannot be used in structural applications therefore it is sold at a loss. The aim of this project is to determine if this timber can be utilised in a manner that is practical and profitable. The current proposition for achieving this is to laminate individual pieces into a slab to achieve a degree of structural reliability and enable it to be marketed with confidence to Australian house builders.

This is a fresh idea with no previous research into the characteristics of the low grade timber used as a laminated slab. Some testing and analysis of this emerging technology is required as to determine if it is worthwhile pursuing.

Table 1 - Structural design properties of graded timber : Standards Australia (*AS1720.1 Timber Structures – Design Methods*)

Stress grade	Characteristic strength, MPa					Characteristic short duration average modulus of elasticity parallel to the grain, MPa (E)	Characteristic short duration average modulus of rigidity for beams, MPa (G)
	Bending (f'_b)	Tension parallel to grain (f'_t)		Shear in beam (f'_s)	Compression parallel to grain (f'_c)		
		Hardwood	Softwood				
F34	100	60	50	7.2	75	21500	1430
F27	80	50	40	6.1	60	18500	1230
F22	65	50	40	6.1	60	16000	1070
F17	50	30	26	4.3	40	14000	930
MGP15	**41**	-	**23**	**9.1**	**35**	**15200**	**1010**
F14	40	25	21	3.7	30	12000	800
F11	35	20	17	3.1	25	10500	700
MGP12	**28**	-	**15**	**6.5**	**29**	**12700**	**850**
F8	25	15	13	2.5	20	9100	610
F7	20	12	10	2.1	15	7900	530
MGP10	**16**	-	**8**	**5.0**	**24**	**10000**	**670**
F5	**16**	**9.7**	**8.2**	**1.8**	**12**	**6900**	**460**
F4	13	7.7	6.5	1.5	9.7	6100	410

The timber grades used in the slabs are F5 and the Machine Graded Pine grades MGP 10, MGP 12 and MGP 15. The key difference between the F grading and the MGP grading systems is the product which they are intended to resemble. The F grading system was created in America and does not accurately describe pine produced in Australia, hence the MGP grading system was developed in Australia to ensure that the label given to the timber accurately describes the timber specimen.

Pine of all grades which is used in the slabs is deemed to be low grade or Utility Grade if it contains excessive defects such as knots, resin shakes and wane. This assessment is made visually, with relatively clean timber specimens being deemed structural and defect ridden specimens being deemed low grade despite the high machine tested Strength grade assigned to the specimen.

1.3 Research objectives

The aim of this project is to investigate the structural performance of above ground low grade timber slab flooring systems with the intention of developing methods of design and construction for such systems. This will include both deflection and limiting stress based performance studies and slab connection methods. In order to achieve this, the following objectives have been created.

- Review the current use of laminated timber building technologies in other countries, to gain an understanding and appreciation of current technologies.
- Acquire timber material properties data from Hyne with the aim of using a statistically representative set of data for the prediction of the slab behaviour during testing.
- Collect structural performance data by testing prefabricated timber slabs.
- Create mathematical computer models of the above ground flooring system using Strand7 to extrapolate data on the structural requirements for this system to be viable.
- Use the results from modelling to create a design aid for the use of low grade timber slabs in floor construction.
- Investigate, create and test methods for panel connection.
- Submit an academic dissertation on the research undertaken.

1.4 Overview of the dissertation

This dissertation consists of seven chapters. Chapter 1 presents an introduction to impart an understanding of the underlying reasons for the commencement of this research, followed by a definition of the problem that is presented and the objectives of this dissertation. Chapter 2 provides an overview on the work already done that is related to this research, including past research, current technologies and relevant Australian Standards.

The main body of the dissertation starts at Chapter 3 and goes through to Chapter 6. Chapter 3 investigates the behaviour of individual low grade pine members subjected to a bending force for use in the analysis that follows in proceeding chapters. Chapter 4 investigates the behaviour of low grade pine members laminated together to form slab units. The testing in this chapter is used to get the information required for the finite element analysis modelling undertaken in the following chapter. Chapter 5 is associated with determining the limiting design criteria for low grade slab floors, comparing low grade slab floors to the current method of floor construction, and using the results of modelling to create a low grade timber floor slab design chart. Chapter 6 consists of an analysis on connection construction methods, testing of connection capacities and limitations, followed by the derivation of basic connection design criteria based on physical modelling.

Chapter 7 is the final chapter in which conclusions are drawn based on the findings of this research. Fulfilment of the set project objectives is also presented along with recommendations for future research.

Chapter 2

Literature Review

2.0 Introduction

This chapter is aimed at presenting the research that has been done into timber slab / panel construction systems. Whilst this technology has had very little investigation in Australia, MacKenzie (2009) has found that the majority of the European and Scandinavian countries have already completed extensive research in these fields and are to the stage of manufacturing pre - assembled house construction components. Most of this overseas research has been directed at roofing and wall applications and is related to three or more layers of timber glued face to face with the grain running perpendicular to that of the previous layer.

This timber panel building technology has been well researched and marketed, selling with the advantages of being acoustically superior to other materials, superior insulating properties, carbon storing capacity and structural performance. However, the single grain direction in which this research project is focused on has had no research elsewhere. The overseas timber panel manufacturers have produced a reasonable amount of company product marketing documentation, design literature, case studies and general information on cross laminated timber construction systems. However, there is no information available of a research or academic nature related to single directional slabs.

2.1 Use of glulam technology

Structural glued-laminated timber is stated as being the oldest engineered wood product (Moody and Herandez 1997). It has been stated by Lam (2001) that in Europe, North America, and Japan, glued-laminated timber is used in a wide variety of applications ranging from headers or supporting beams in residential framing to major structural elements in non residential buildings, such as girders, columns and truss members. As a result, extensive research has been conducted on the interaction between laminates and low grade timber for use in beams. Falk and Colling (1995) examined the laminating effects in beams and suggested that the apparent strength increase due to the lamination effect is a summation of separate, though interrelated, physical effects, some of which are a result of the testing procedure and others the effect of the bonding process. They also observed that un-centred defects (such as edge knots) or areas of unsymmetrical density can induce lateral bending stresses that, when combined with applied tensile stresses, reduce the measured tensile strength.

It has also been found that the lamination of timber also reinforces defects existing in a lamination by redistributing the stresses around the defect through the clear wood of adjacent laminations, thereby increasing the capacity of the cross section containing the defects (Falk and Colling 1995) . Further to this, Soltis and Rammer (1993) in their research into the shear strength of unchecked glued laminated beams has concluded that the beam shear strength decreases as beam size increases.

A publication on glued-laminated beams by (Moody and Herandez 1997) stated "Residual stresses can be locked onto wood adjacent to the glue lines during manufacture when laminations of varying moisture content are bonded together". This can result in stresses developing in service as a result of different laminations shrinking and swelling by various amounts as their moisture content changes as a result of small variations in density, growth ring orientation and grain angle. This extra stress developed by varying environments is the cause for splitting, and failure of connections and dimensional misfits within their structural application. This provides cause for tolerances to be allowed for in the design as a one percent change in dimension can be brought about by a 4 - 5 percentage point change in temperature Moody and Herandez (1997). Further to this, it has been found by Custodio et al. (2009) that the materials involved in a structural joint can also influence bond strength and durability. These material factors include the adherents, the adhesive, the design of the joint, freedom from surface contamination (including extra active contamination), stability of the adherent surface, the ability of the adhesive to wet the surface and entrapment of air / volatiles. All of these factors have a significant influence on the long term durability of the bond between laminates.

2.2 Timber material properties

In their research into the homogenised elastic properties within cross laminated timber plates, Gsell et al. (2007) state that: “timber contains a unique microstructure, which contains a strong anisotropic mechanical behaviour. Parallel to the grain, elastic stiffness parameters and material strengths are significantly higher than perpendicular (radial and tangential) to the grain". They also state that timber is a heterogeneous material with many natural defects like knots or sloping grain. Such in-homogeneities result in a high local variation of mechanical properties and stress concentrations which are taken into account in design codes such as AS1720.1 - 1997 by permitting only low admissible stresses.

One of the key features of engineered wood products noted by Lam (2001) within the manufacturing process is reconstitution of timber to form smaller pieces. This process tends to disperse natural macro defects in the wood resulting in more consistent and uniform mechanical properties, compared with those of solid sawn timber.

2.3 Current timber flooring practice

Today in Australia, timber floors comprise of a structured array of timber, including columns, bearers, joists and decking boards. Although there are many materials that can be used for the flooring surface e.g. particle board, plywood, or decking, the arrangement of bearers and joists within the supporting structure remains the same. The Australian Standard *AS1720.1* (1997) specifies the allowable deflections and stresses within a timber structure, as well as formulae to calculate appropriate timber dimensions for a specified purpose within a structure. Gsell (2007) used the properties of timber as justification for this method of timber structure assembly. One of these properties is the effectiveness of timber in seismic loading, which can be attributed to the high strength to weight ratio of timber, system redundancies and the connection ductility.

2.4 Standard floor loading and design

In a study on the current design methods in Australia, Foliente (1998) stated that the current approach to timber design is based on prescriptive or deemed to comply provisions, simplified guidelines, span tables and charts along with diagrams and figures of required construction details for simple building types and shapes. Foliente (1998) states that this should not be the case, as analysis based on first principles would be most appropriate. This includes using realistic load representations, appropriate structure types and analytical computerised models comprising of static, dynamic and stochastic analyses.

2.5 Timber element modelling

Extensive research has been done on the modelling of timber as a result of its unpredictable nature due to excessive amounts of material faults that can occur such as resin shakes, knots and wane. The type of modelling current in the year 1999 was the empirical $\frac{I_K}{I_G}$ method, as stated by Lee and Kim (1999) in their paper on the estimation of the strength properties of structural glued - laminated timber. This method accounts for the strength reducing influence of knots as a function of the second moment of area. Another approach mentioned by Lee and Kim (1999) was the transformed section method. The input value for this method consisted of beam geometry and configuration as well as allowable fibre stresses for each lamination.

They also state that most current models are based on modulus of elasticity's measured in long span tests, which means that they only account for the variability among different pieces of timber. This means that the models could not account for the variation of material properties within a given piece of timber. This information for "within-piece" variability is critical for the structural analysis techniques that require localized properties of individual elements, such as the finite element method.

2.6 Current timber slab construction practice

Multiple methods of timber slab construction are currently underway, including nailing, oversized dowel rods in undersized holes and the most common method of glue laminating, usually referred to as Glulam MacKenzie (2009). Lam (2001) states that “the mechanical and physical properties of these products depend on the interacting relationships between the quality of the resource, the manufacturing process, and the applications". According to MacKenzie (2009), Northern hemisphere solid panels are currently manufactured from slow grown spruce and pine (very tight growth rings) that are recognised as being more consistent in wood quality and stability than the faster grown exotic southern hemisphere plantation softwood and plantation hardwood resources.

2.7 Relevant Australian standards

The current Australian standard for floor design is *AS 1648 – Residential timber framed construction* (1999). This code deems the required self weight and applied load used in floor design to be based on the source of the load, the type of load, the component description and type of a structure, and the type of structural elements supporting the floor**.**

The code based design of timber structures is set out in *AS 1720.1 - Timber structure design methods* (2002). This code sets out the limit state design methods for the structural use of timber and intended use in the design or appraisal of structural elements or systems comprised of timber of wood products and of structures comprised substantially of timber.

The evaluation of the structural properties of timber is based on the standard *AS 4063* (1993). This standard sets out the procedures for evaluating structural properties of graded timber and for verifying the accuracy of specific grading techniques. This standard also specifies the requirements for resolving doubts concerning the specified design properties of particular populations of graded timber. *AS4063* (1993) is also suitable for application to both permissible stress and limit states design codes such as *AS1720.1* (2002).

2.8 Summary

Based on previous research, it can been seen that research is needed to determine the way in which glulam pine behaves when subjected to loading as a slab rather than a beam. Prior research has investigated the performance of glulam timber orientated in three or more layers with the grain direction of each layer running perpendicular to the previous layer in the timber slab wall and roofing applications. Consequently, this research will be focussed determining how single layer glue laminated slabs perform in a flooring application.

This will entail gathering data to make reliable predictions on the behaviour of slabs, inventing methods of individual slab connection to suit the application and making comparisons between a low grade timber slab floor and a traditional bearer, joist and floor board configuration of flooring. Further to this, the ability of the low grade timber floor slab construction to meet the required standards will have to be determined, along with methods of approximate analysis for the timber slabs manufactured from low grade timber in the slab flooring configuration.

Chapter 3

Individual member strength testing

3.0 Introduction

Individual low grade timber members exhibit a low level of reliability when subjected to loading, which deems them unsuitable for use in structural applications. This chapter investigates the variability in characteristics between individual low grade timber members, and uses this information as a basis for further detailed investigation on the structural performance of individual low grade timber members when used to create a laminated timber slab unit.

This initial phase of this research was aimed at determining the material characteristics of low grade timber as a basis for further analysis and modelling of the low grade timber slabs. The deflection response of low grade timber subjected to loading of a specific magnitude and distribution is critical to understanding the effectiveness of low grade timber slabs as a flooring alternative, due the deflection based criteria used in floor design.

This knowledge of the characteristics associated with low grade timber is intended to develop a model of the low grade timber slabs prior to testing. This model is required in order to approximate the load required for testing a low grade slab to the point of failure, and hence the selection of appropriate testing equipment that can handle the required forces.

Results obtained from this phase of testing will also be used to compare the characteristics of single low grade timber members, and low grade slab units comprised of twelve laminated individual low grade members when subjected to loading. This comparison will yield the suitability of low grade timber in the form of a laminated slab for use in structural flooring applications.

3.1 Methodology

The individual timber pieces were tested in a jig as shown in Figure 2. All samples tested were subjected to a four point loading. The span was taken from AS 4063 – Timber Stress Graded – In grade strength and stiffness evaluation, as 18 times the depth of the specimen (D). All specimens tested have a depth of 90 mm therefore the Test Span is 18 x 90 mm = 1620 mm. Load points were then applied at L / 3 centres as shown in Figure 1.

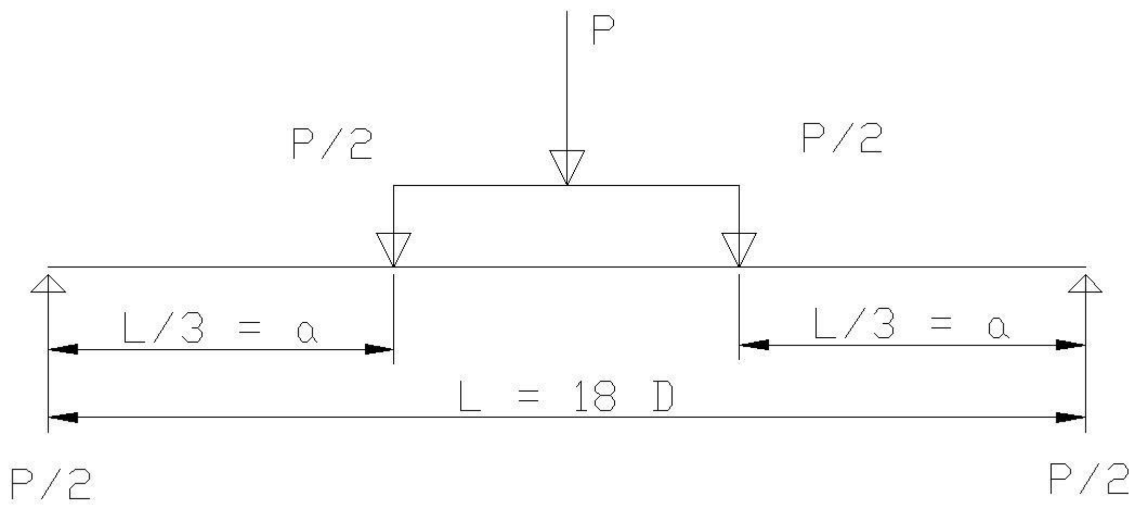


Figure 1 – Loading Setup

The load was applied using a 100 kN capacity beam with two loading points bolted onto it. Plates were used below the loading points to ensure that the load was spread sufficiently to avoid localised crushing of the timber resulting in the incorrect relationship between applied load and deflection being determined as a result of the timber crushing rather than deflecting as a result of the applied load.

Applied load and deflection was measured electronically using the System 5000 connected to a load cell and a deflection recording string port. All deflections were measured at central span via a wire connection which was looped around each individual specimen to eliminate the weakness in the timber that would be created by a nail in the centre of the specimen being tested as shown in Figure 2.

Figure 2 – Testing of an individual low grade timber member.

The supports for the loading were placed relative to the centre line of the loading rig to ensure that the jack acts on the loading rig at the centre, resulting in even forces being applied through the balanced loading contact points. A jig was then created to align the specimen with the centreline of the jack to ensure that eccentric loading was not induced during testing. This jig was then used to ensure consistency in the testing procedure.

Movement of the supports relative to the testing rig after loading was monitored via marks placed on the cement at the diagonal corners of each support to ensure that the span of the test or the alignment of the specimen relevant to the central axis of the jack would not vary from sample to sample.

Levelling of the supports was also undertaken prior to testing to ensure that the load applied would not be favoured to one point as a result of the specimen being slightly tilted in the horizontal plane. This was done by slightly elevating the required support using the threaded axis built into each support as shown in Figure 2. This was necessary in this testing due to the loading bar not being self levelling. Chains were also applied to the loading bar to ensure that when failure occurs the heavy loading bar would not fall causing injury or damage to nearby people or testing equipment.

The analysis of the test data obtained was undertaken by a Matlab code developed to read the data produced in the system 5000 format. This code was used to plot the data points obtained for each test specimen, and determine the linear portion of the load – deflection graph. The data points representing the extents of the linear region of the data were then used with equation 1 to determine the modulus of elasticity , E, of a timber sample subjected to four point loading.

$$E = \left(\frac{2\left(\frac{3a}{4L} - \left(\frac{a}{L} \right)^3 \right) L^3}{BD^3} \right) \times \left(\frac{\frac{P_2}{2} - \frac{P_1}{2}}{\Delta_2 - \Delta_1} \right) \qquad \textbf{(1)}$$

Where

B = The width of the test specimen

P_1 = The lowest load applied in the linear portion of the load deflection graph

P_2 = The highest load applied in the linear portion of the load deflection graph

Δ_1 = Deflection corresponding to P_1

Δ_2 = Deflection corresponding to P_2

3.2 Results

The individual tests proved a large variation in the force - deflection relationship which is shown in Figure 4. Testing proved that low grade pine is not reliable, as the loads and deflections for the samples tested varied considerably. Failure was also sudden and violent, with failures happening at a point of weakness within the sample such as a knot or resin shake.

The deflection at which failure occurred varied significantly due to the various modes of failure. Samples that exhibit a low failure deflection have failed in a sudden manner through a knot or resin filled shake which extends to the edge of the timber. The samples which failed after a large deflection initiated at a fault which did not extend past the edge of the timber resulting in an extenuation of the deflection to force the failure crack through the tensile edge of the sample resulting in a sudden failure at that load. The load required to cause a deflection resulting in failure was also dependent on the type of discontinuity in the timber which the failure was initiated at. An example of a failure originating from a defect is shown in Figure 3.

Figure 3 – A combination of knot and resin shake failure

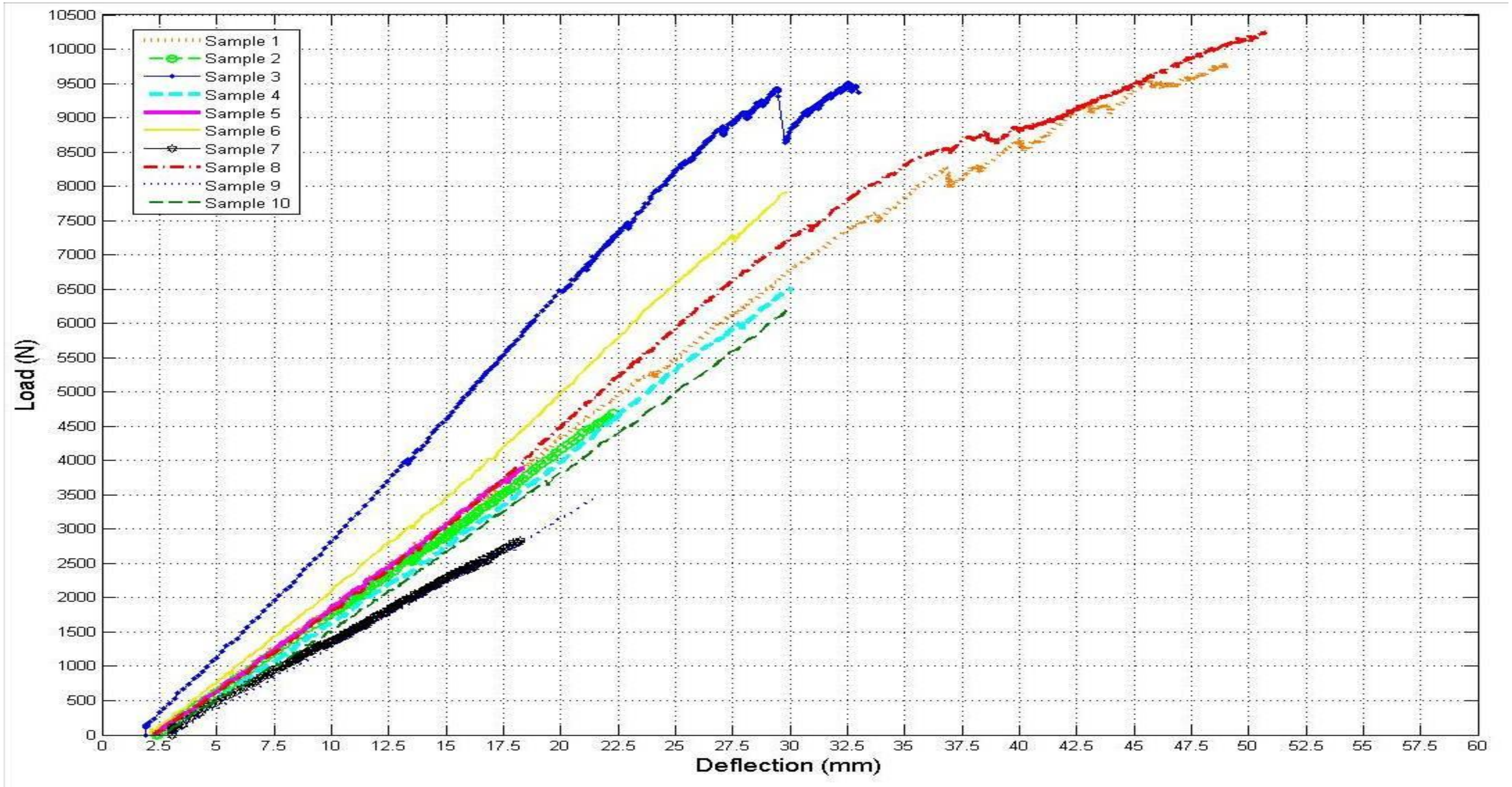


Figure 4 – Test results obtained from individual low grade timber members.

Figure 5 – Individual low grade timber members after destructive testing.

The data points obtained during the testing of each individual member yielded the modulus of elasticity values shown in Table 2. These results demonstrate the poor consistency of individual low grade timber members subjected to loading. The presence of defects within the timber is responsible for the non - uniformity in characteristics, and the range of modulus of elasticity values obtained.

Table 2 – Modulus of elasticity values obtained for each individual member.

Sample Number.	Modulus of elasticity (MPa)
1	8084.1
2	8107.4
3	12,156
4	8085.4
5	8391.9
6	9442.6
7	5973.4
8	7026.2
9	3182.4
10	6524.4
11	7928.8
Average	7445.69

3.3 Discussion

The test results prove that a defect of any size will be a vulnerable point for the initiation of failure within a low grade pine specimen. The proximity of other knots or resin shakes to a defect also influence the type of failure that occurs. Two knots in close proximity on extreme edges of the sample cause a failure line that travels in a vertical direction through the sample.

If a knot is positioned in the centre of a length of timber and another knot is located on the compressive or tensile edge, the failure will travel in a diagonal path from one knot to the other causing sudden failure once the crack reaches the knot on the extreme edge as can be seen in Figure 3.

Failures that were initiated in knots in the compressive edge of the sample travelled parallel to the clear grain to the tensile edge if no other defect was present for the failure path to connect to. A sample of failures obtained based on the location of major defects can be seen in Figure 6.

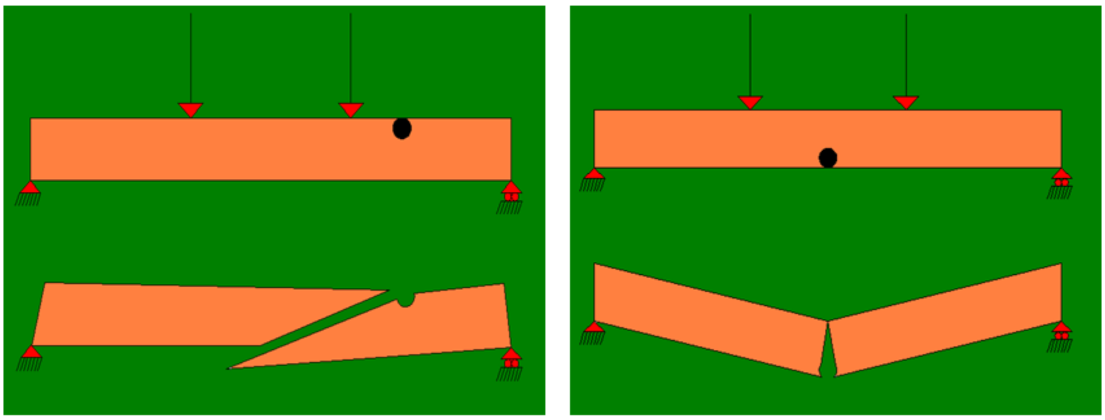


Figure 6 – Failure modes based on the location of major defects.

3.4 Conclusions

The location of the initiating point of failure is very hard to predict in low grade timber. Failure of individual low grade timber members always originates at some form of defect within the wood. The abruptness and warning given in a failure is dependent on the type of defects present and the path taken by the failure line. The length of path taken for failure to occur is dependent on the direction of the grain, the presence of any discontinuities in the grain such as resin shakes and the location of knots within the timber.

The location, and hence the magnitude of bending stresses resulting from an applied force is a critical factor in the magnitude of the load that can be applied before failure. This highlights the unpredictability of low grade timber due to the uncertainty about which defect will be the first to cause failure.

The orientation of the member under loading also has an influence on the ultimate load that can be taken. If the edge of the timber containing the most defects is place on the tensile side, the bending strength of the member will be significantly reduced. If these defects are placed on the loaded (compressive) edge the overall capacity of the member is increased due to the knots resisting compression rather than separating from the surrounding grain under tension.

Chapter 4

Low grade slab strength testing

4.0 Introduction

This chapter will focus on determining the reliability of low grade pine subjected to loading when used to form a low grade timber floor slab. This analysis will also be used to aid in the development of design criteria for floor construction using a low grade timber slab. An investigation into the structural characteristics of the slabs when subjected to floor type loading conditions will be undertaken to derive the information required for finite element analysis modelling.

The information obtained will be used to create valid models of low grade timber floor slabs in order to extrapolate the information required to create design aids for use with low grade timber slabs used as a method of floor construction.

The samples used for this testing are constructed out of 12 90 x 35 low grade timber members face laminated to form a slab unit as shown in Figure 7. The slab unit formed is 1.8 m long to allow ample span for consistency with the individual member testing and also room for supports during testing. The glue used to join individual members to create the slab unit is Purbond HB514.

The active ingredient contained within Purbond HB514 is polymeric diphenylmethane discarnate. This glue is well suited to mass construction due to the six minutes required for curing to complete. The catalyst for this glue is the moisture present within the atmosphere resulting in the glue curing completely as soon as it is exposed to the atmosphere.

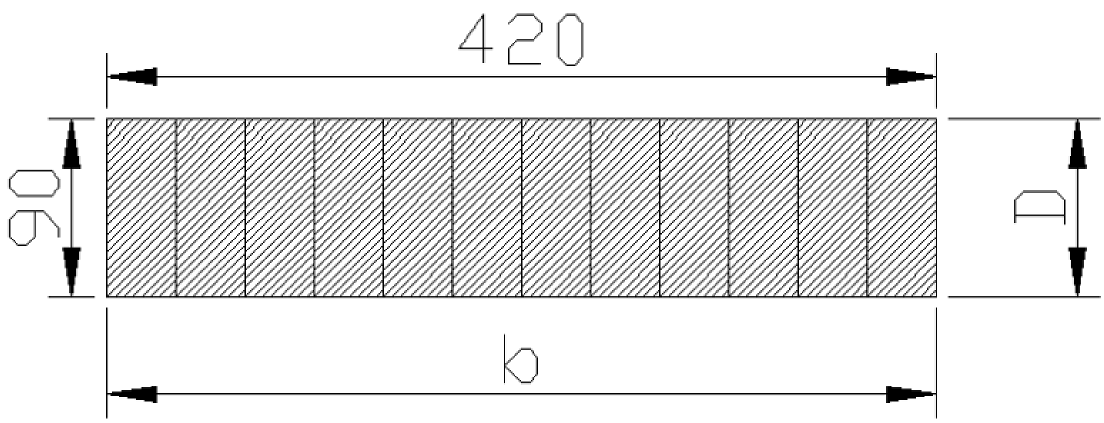


Figure 7 – Slab unit cross section

All dimensions in mm.

4.1 Methodology

The low grade timber slabs used for testing were manufactured and supplied from the Hyne Tuan sawmill. Three slabs of 3.6m length were halved to form six individual slabs for testing. E.g. sample 2 became sample 2A and sample 2B once halved. Each slab had a varying distribution of visible faults before being halved. As a result of the halving of the three samples to comply with the span requirements of AS 4063, the six tested slabs only had three variations of individual member strength grade combinations as shown in Table 3.

Table 3 – Strength grade of individual members within slab units tested.

Strength grade distribution within slab test specimens.			
Individual member	**Samples 1A and 1B**	**Samples 2A and 2B**	**Samples 3A and 3B**
1	F 5	F 5	F 5
2	F 5	MGP 10	F 5
3	MGP 10	MGP 10	MGP 12
4	F 5	MGP 12	MGP 12
5	F 5	MGP 10	MGP 10
6	MGP 12	F 5	MGP 12
7	F 5	MGP 10	F 5
8	MGP 10	MGP 10	MGP 10
9	F 5	MGP 15	F 5
10	F 5	MGP 12	MGP 10
11	MGP 12	F 5	MGP 10
12	F 5	F 5	F5

Note that the strength grading of individual members is done with a machine that determines the strength grade of the timber as it is passing through the mill. A member may be of a high strength rating such as MGP 15, but also contain a large stiff defect. A visual rating is undertaken which identifies this defect and deems the timber to be of a low grade standard due to the issues associated with defects. These defects can be seen the samples prior to testing as shown in Figure 8.

Figure 8 – Sample specimens prior to testing

All samples were loaded identically to the individual specimens as shown in Figure 1 page 17 in accordance with AS4063, with the depth of the slab units being equal to 90 mm. The orientation of supports was again calibrated to ensure that the central axis of the jack coincided with the centre of the slab to ensure even distribution of loads through both loading points, and eliminate the presence of any eccentric loading.

The loads were applied over the width of the slab at the required intervals through the use of C – section steel which had ample stiffness to apply a rigid even line load across the width of the slab. The total load applied was taken from a load cell placed directly below the axis of the jack, with deflections also being taken at the centre of the slab via a string port attached to a nail inserted in the centre of the slab. The load was applied via a hand operated jack at a constant rate. Marks were also placed at relative points to ensure the dimensions of the testing setup could be maintained for each slab sample test.

Heavy rib reinforced C section steel members were clamped to the stool tops as the supports for the slabs during loading as shown in Figure 9. The clamps were placed to eliminate the tendency of the support to roll or slide out form underneath the sample during loading. Numbers and marks were placed on all relative points of the testing setup to ensure that the test could be repeated exactly in the future if that was required. The supporting stools were located on the centreline of the testing rig to ensure that when the slab was loaded they would not slide or roll out from underneath the sample as a result of high loads creating resultant forces great enough to displace the stools from the desired location.

All testing of slabs was undertaken until multiple partial failures had occurred (*failure of individual members within the slab*) to get a good description of the patterns of loading, failure and the new reduced capacity of the slab after one initial failure.

Figure 9 – Slab testing setup.

4.2 Results

The Slabs displayed a much more predictable force - deflection characteristic as shown in Figure 11. It was noted during strength testing that if one half of the slab had on average a lower grade then the other half of the slab, than the first partial failure would occur in the weakest half of the slab as shown in Figure 10. The slabs also gave an indication of the impending failure via creaking noises leading up to a bang which indicated one partial failure within the slab. The slabs also showed elastic properties. This became obvious as the load was removed slowly, and the slabs returned to their original position. It was also noted that a defect within the timber, would fail before the laminating glue would give way as a result of the induced stresses between members of different stiffness's.

Figure 10 – Low grade slab partial failure.

The slabs were consistent within their load – deflection patterns despite the three variations of member strength grades and the six variations of fault distribution encountered within the test. The modulus of elasticity determined for each slab unit tested is shown in Table 4.

Table 4 – Modulus of elasticity of each slab sample

Slab unit number	Modulus of elasticity (MPa)
1A	8266.542
1B	8796.801
2A	8653.039
2B	9275.899
3A	9464.317
3B	8776.065
Average	8872.1104

The range of modulus of elasticity values obtained for each slab is very tight compared to the individual low grade members. The use of individual low grade timber members to form a laminated low grade slab unit also increases the average modulus of elasticity compared to the average obtained for the individual members as seen in Table 4.

The small variation in modulus of elasticity values obtained for the two samples obtained from each combination of individual members demonstrates that the unique distribution of faults within a low grade slab does have an effect on the structural performance of low grade timber slabs despite the consistency in the strength grades of the members used to construct the slab.

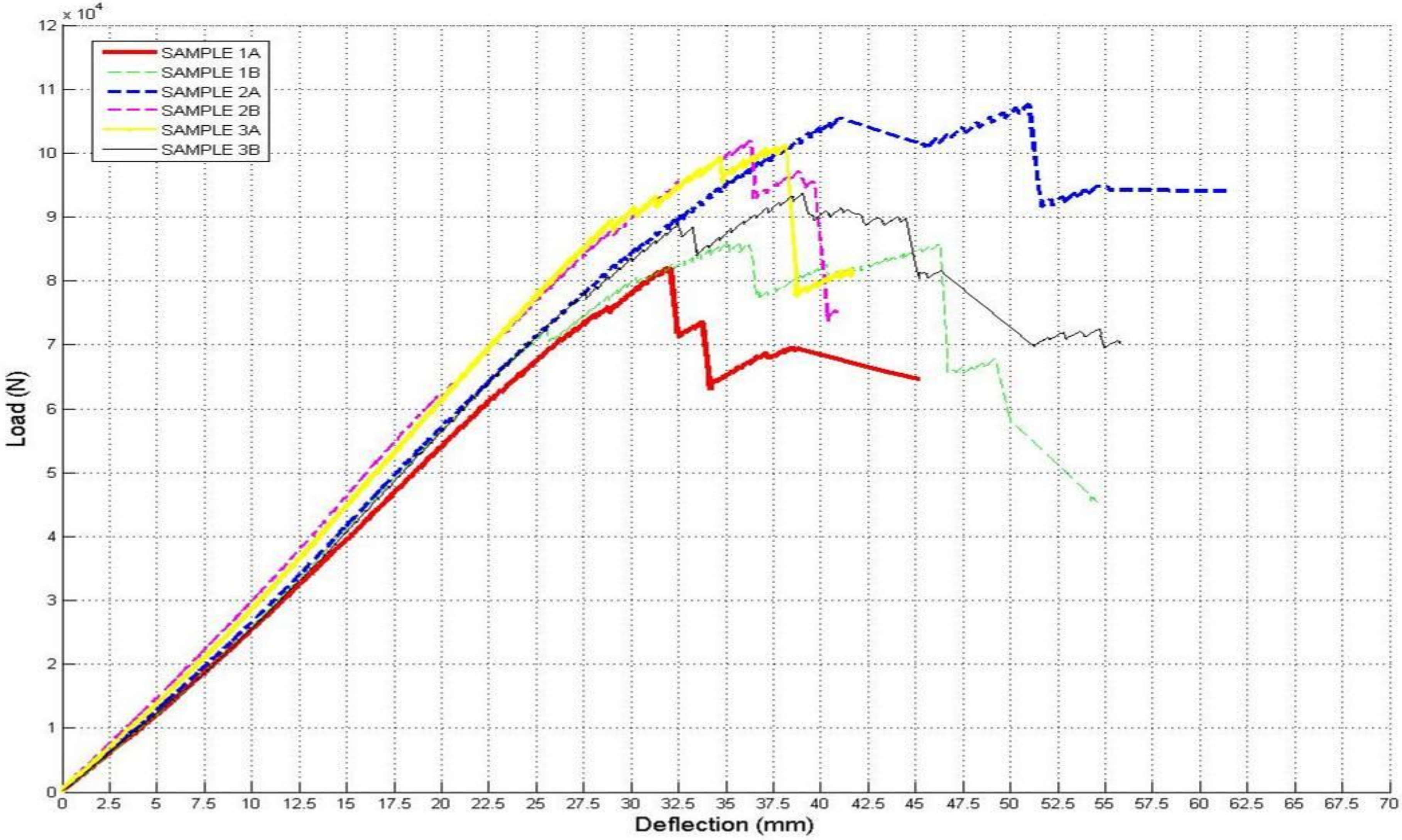


Figure 11 – Low grade timber slab test results.

4.3 Discussion

It can be seen from these results that laminating individual low grade timber lengths into a slab increase their strength and predictability as structural members due to the load sharing which arises as a result of the glue laminations. Failure during testing occurred predominantly on the outside laminates initially with internal laminates failing afterwards as the slab was reloaded to its new reduced capacity.

This type of failure is proof that the capacity of the low grade timber is increased when used in slab formation due to the defect free timber sections face laminated adjacent to a knot which increases the overall resistance to withhold the force applied. An example of the random distribution of knots and defect free sections within a slab is shown in Figure 12.

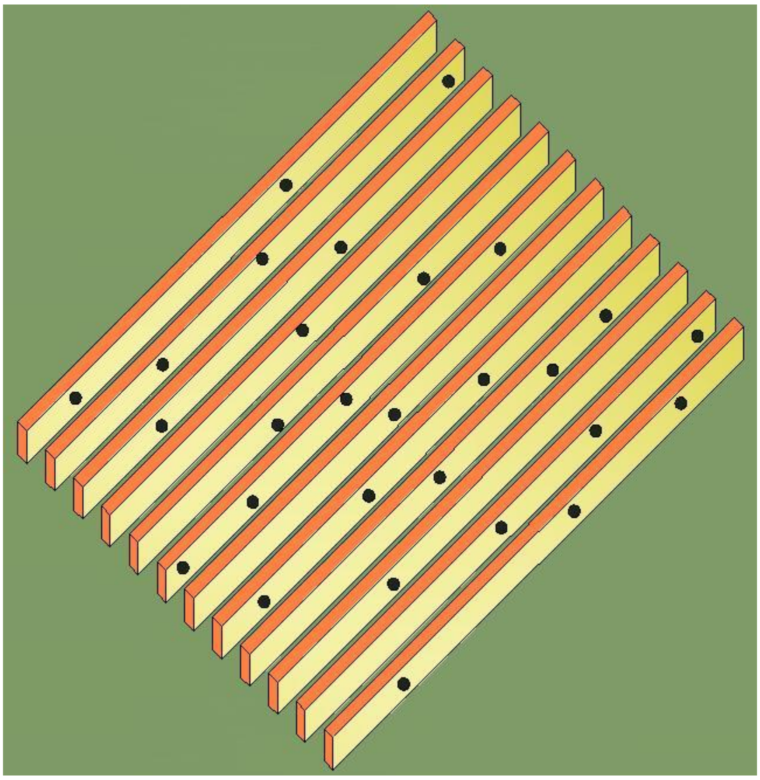


Figure 12 – Random distribution of knots and defect free sections.

If these defect free sections of timber were not laminated either side of the faulty piece of timber it would fail at a much lesser load in a sudden manner due to the absence of any strong material combined with the defect to increase the overall resistance to loading induced stresses. This type of failure within a slab would be very similar to that obtained in the individual low grade member testing due to the effective alignment of defects as shown in Figure 13.

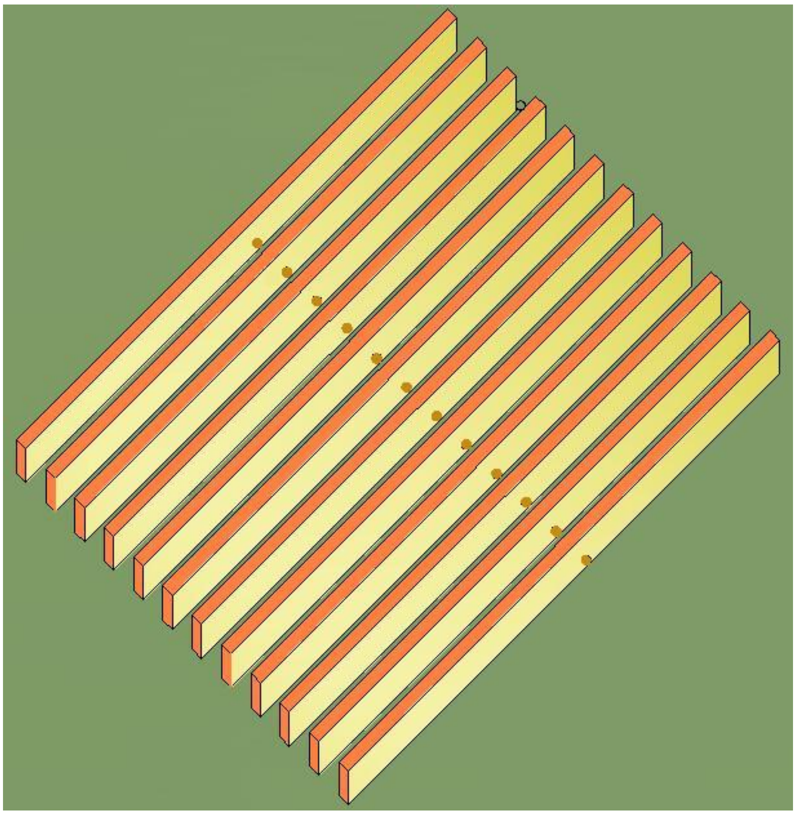


Figure 13 – Alignment of defects within a slab.

The application of the two line loads across the width of the slab has allowed an estimation of the range of total load in which the slab is likely to fail; should that value be applied in total from a combination of uniformly distributed loads and point loads. Analysis based on Strand7 modelling using the material properties determined during testing will yield further information in the consistency between the type of load applied and the deflection and stresses created as a result.

4.4 Conclusions

The randomly distributed nature of clean wood and defects within a length of timber significantly decrease the likely hood of the major defect within a piece of timber being at the same position along the length of the slab unit in all 12 individual members. Hence the load sharing between individual members is set up due to the face lamination acting as an effective strengthening agent for all defects adjacent to clear wood within the slab.

The distribution of defects randomly throughout the length of the slab results in the slab having resistance to sudden complete failure due to the load sharing setup between individual members. The testing confirmed that if one or more members within the slab failed, the overall load carrying capacity was reduced and the load was taken up by the adjacent member which had not failed.

Further reliability in strength performance would be obtained if the knots which act as discontinuities within the timber were located on the compressive edge of the slab, due to their dense composition which can resist compression but would fail under tension. This is due to the discontinuity between the grain direction of the knot resulting from the growth of a branch on the tree and the straight grain of the clear tree trunk.

The load – deflection relationship in slabs is much more predictable than the individual pieces. The highest load sustained before initial failure of the strongest slab was 107.667 kN. This partially proves that deflection limits are going to be the governing criteria due to the associated deflection. This will be validated with the use of Strand7 finite element analysis.

Failure of the low grade timber slab units is a function of the location and distribution of defects throughout each individual member. The slab will not take a bending load greater than that of the strongest individual member if they all contain a knot at the same position resulting in a sudden line failure as seen in the individual member tests.

The distribution of strength grades within the members of a slab unit can not be used as a method of determining the exact maximum load the slab can bear. Likewise, the exact modulus of elasticity associated with any combination of strength grades can not be determined. This is due to each slab unit having a unique combination of defects which in turn affect the capacity of the slab. This must be taken into consideration when designing low grade timber slab floors based on strength and serviceability criteria through the use of appropriate safety factors.

Chapter 5

Finite element analysis

5.0 Introduction

This chapter will focus on the finite element analysis modelling undertaken using Strand7 to model the performance of low grade timber slab floors. From this modelling, the limiting criteria for the use of low grade timber slabs as a flooring alternative will be established. This will be followed by a parametric study to compare the low grade floor slab characteristics to that of the standard flooring system as shown in Figure 14.

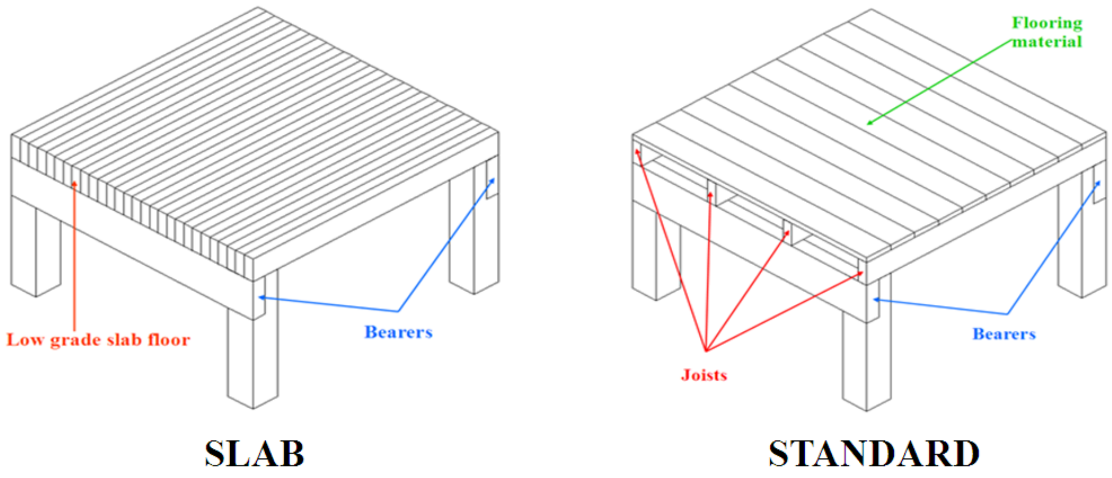


Figure 14 – Floor construction configurations

In order to understand the limitations of using low grade slabs as a flooring alternative, modelling will also be done to develop the deflection relationship between applied load and clear span. This information is required to create a design chart which defines the limitations of loading based on prescribed deflection limitations.

Parameters used in this modelling include timber material properties provided by Hyne and Timber Queensland. Pine density values used in the analysis of the low grade timber slab floor were based on properties recorded from testing undertaken at the Hyne Tuan mill as shown in Table 5.

Table 5 – Hyne Tuan mill product densities.

Hyne Tuan mill product densities (kg/m³) (untreated)						
	140x35 Dry	70 x 35 Dry	90 x 35 Dry	70 x 45 Dry	90 x 45 Dry	Average
Utility*		590	617			604
F5		557	553	552		554
M10	564	576	568	555	557	564
M12	609	625	617	596	607	611
M15	661	685	665			670

* Utility is the term used by Hyne to describe its low grade timber product.

5.1 Selection and justification of appropriate modelling parameters.

An analysis on the three major types of element which the slabs could be modelled with was performed in order to establish which type gave the most accurate depiction of the behaviour of the slab samples observed during testing. All models were made to represent slab sample 2A with a modulus of elasticity of 8653.0386 MPa. The load and deflection summary for this sample are shown in Table 6 . All three of the models were assigned the same material properties and supported as simple beams. Analysis of each model was then done to how well they replicate the physical test data.

Table 6 – Load - deflection summary for sample 2A

Slab 2A recorded test data	
Load (kN)	**Deflection (mm)**
0	0
20	7.6
40	14.5
60	21.0
80	28.2
100	37.6

The following three sections will go through and make a comparison between each of the model dimensions to justify the reasoning in the model type chosen. All models have been created with consistency in material properties, load application and restraint type in order to justify the comparison between results.

5.1.1 One dimensional beam element model

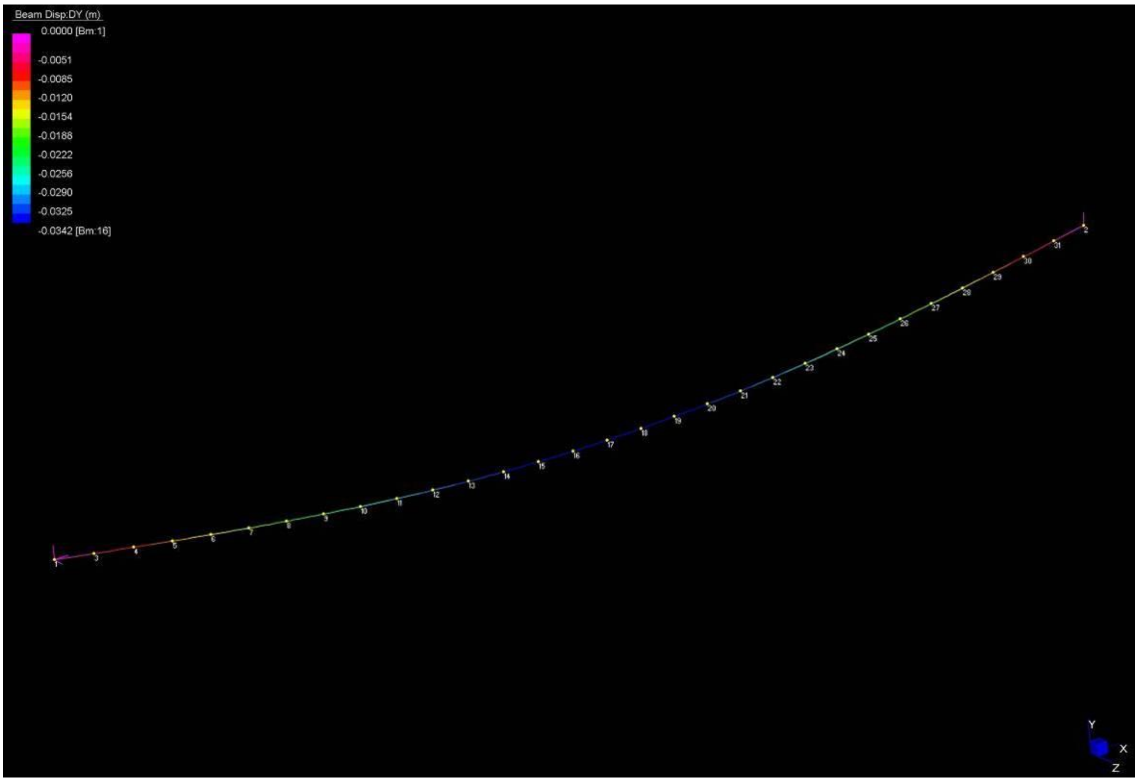


Figure 15 – A one dimensional beam element model.

The one dimensional beam model is created in Strand7 as a line element subdivided as required and supported at the nodes at each end as a simply supported beam. Material properties were then assigned in this model such as the modulus of elasticity, and the cross sectional area. The loading dimensions applied to this model were identical to that of the physical test in order to get every variable in the comparison identical. The accuracy of the result is dependent on the degree of subdivision applied, with the deflection converging to the real value as the number of subdivisions increases as shown in Table 7. The one dimensional elements do not represent an easy method of making three dimensional models of the slab in order to compare it to that of other flooring methods. This could be overcome by the use of links; however this is not a true representation of the real situation.

Table 7 – One dimensional Strand7 model convergence and comparison.

One dimensional element model convergence					
Number of Beam elements	**Deflection obtained from model (mm)**				
	20 kN Load	**40 kN Load**	**60 kN Load**	**80 kN Load**	**100 kN Load**
3	6.8	13.6	20.4	27.2	34
6	6.8	13.7	20.5	27.3	34.2
12	6.8	13.7	20.5	27.3	34.2
Physical test values	7.6	14.5	21.0	28.2	37.6
Difference to physical test values	**0.8**	**0.8**	**0.5**	**0.9**	**3.4**

This demonstrates that the minimum number of beam elements in a one dimensional model has to be greater than or equal to 6 over a 1.62 m span for convergence to occur. The difference observed in Figure 16 at loads greater than 80 kN is due to the fact that the slabs do not load and deflect in a perfectly linear fashion as seen in Figure 11. This means the model is only representative for the linear load – deflection range of the slab.

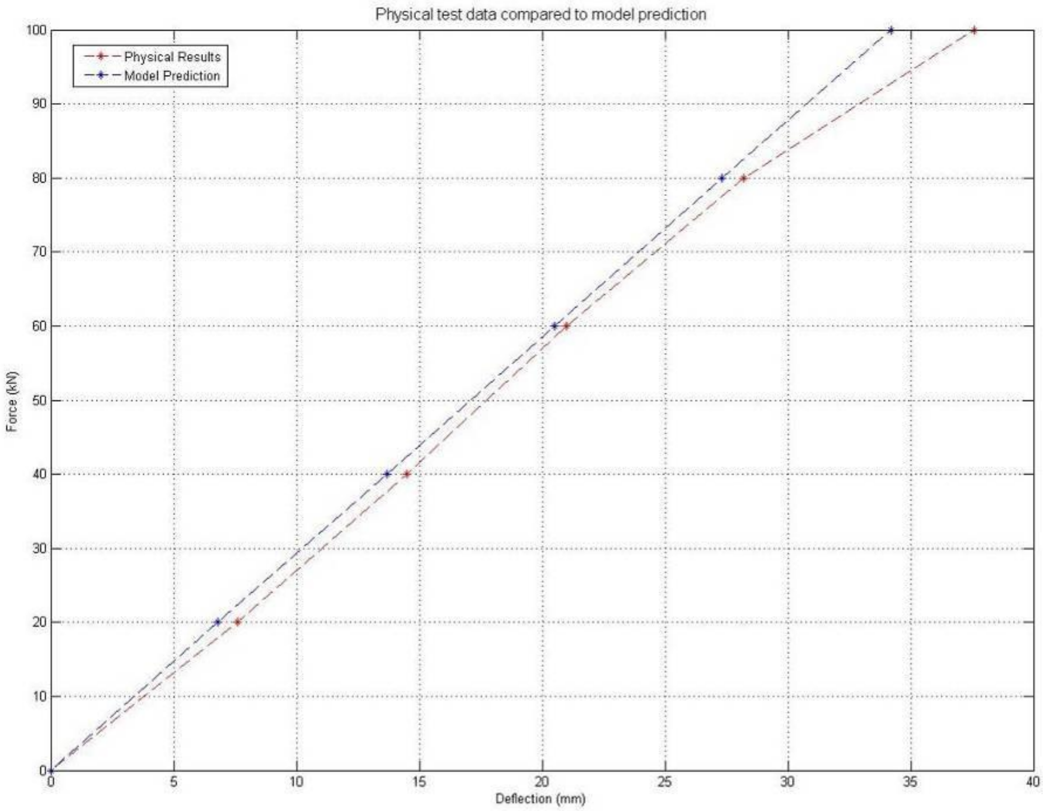


Figure 16 – Comparison between one dimensional model and physical results.

5.1.2 Two dimensional plate element model

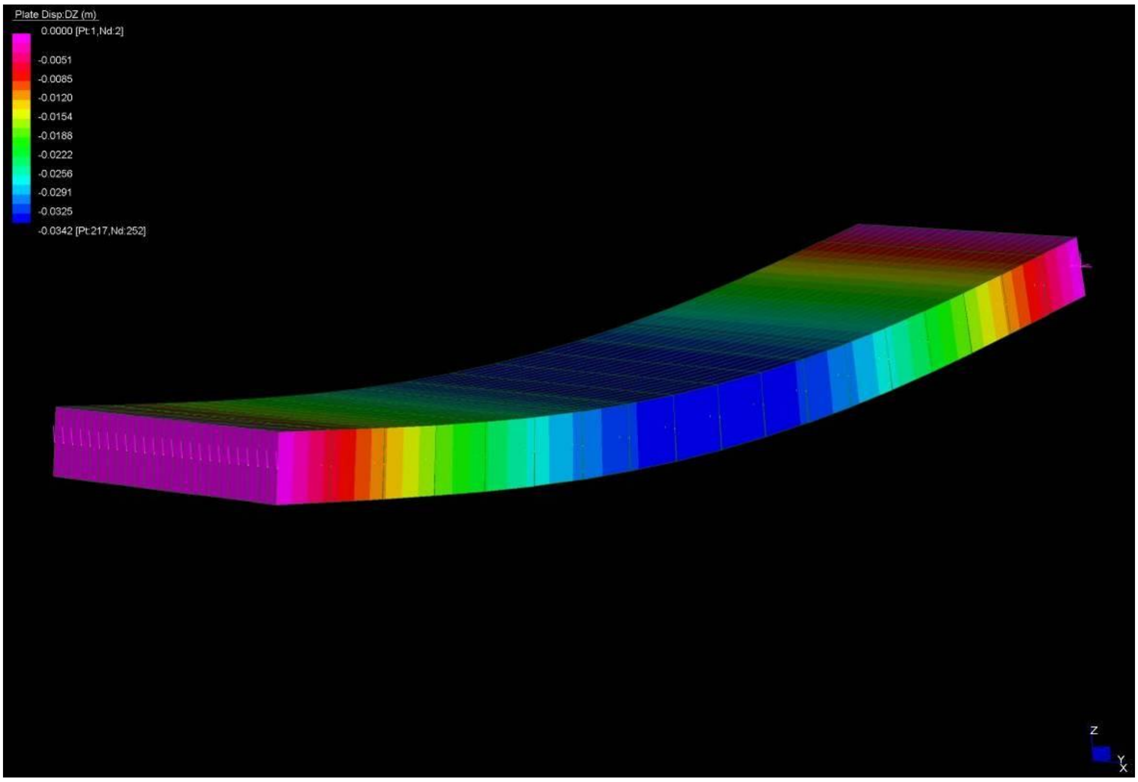


Figure 17 – A two dimensional plate element model.

The use of two dimensional plate elements to represent the beam resulted in identical results to that of the one dimensional element for each number of subdivisions. The plate was assigned a thickness of 90 mm and subdivided 24 times in the X direction, 18 times in the Y direction, with the Z direction containing only 1 element due to the two dimensional nature of the model resulting in a total of 432 plate elements. This number of plates in the model resulted in deflection values which matched the converged one dimensional model for each load case applied.

The application of the two dimensional model to three dimensional comparative models is not appropriate due to the issues associated with combining nodes in the correct relative positions. This issue arises due to the nodes being at the middle of the slab, hence the neutral axis is fixed to the supporting element rather than the tension edge. This will yield the correct relationship between the slab and the supporting element under the influence of loading. The use of links to create a three dimensional model using two dimensional elements would be sufficient to obtain correctness in the dimensions of each element and their location relative to each other. However, the issue of incorrect stresses being transferred from the slab to the supporting joist are still present due to the link being made at the neutral axis rather than the tensile face of the slab.

Minor issues also arise from the loading of the slab at the central axis rather than the top edge in the two dimensional models. The central location of the plane of nodes in the two dimensional slab models is shown in Figure 18.

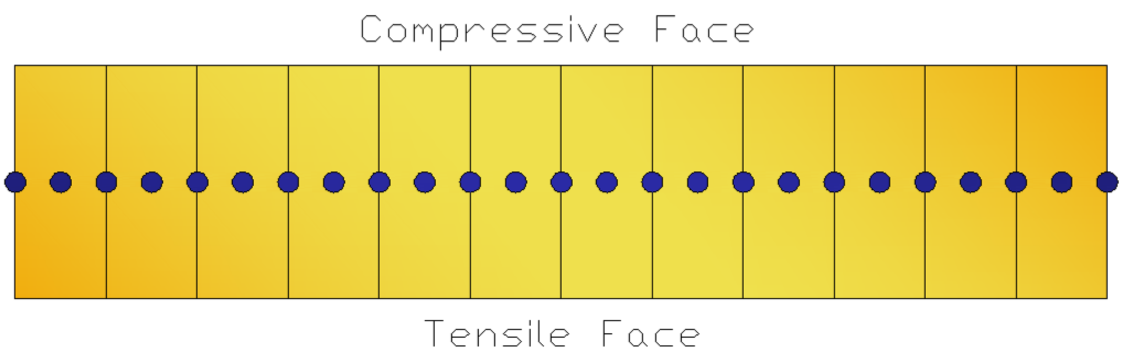


Figure 18 – Node location within a two dimensional slab model cross section

The two dimensional model lacks accuracy in the prediction of bending stresses on the tensile face of the slab. This is due to the single elements in the vertical direction which have a single stress assigned to them during analysis rather than a distribution of stresses throughout the depth of the slab as occurs in the slab during loading and modelling using three dimensional brick elements. The analysis of the slab as a flooring material needs accuracy in the modelling of working stresses to ensure that allowable stresses are not exceeded.

5.1.3 Three dimensional brick element model

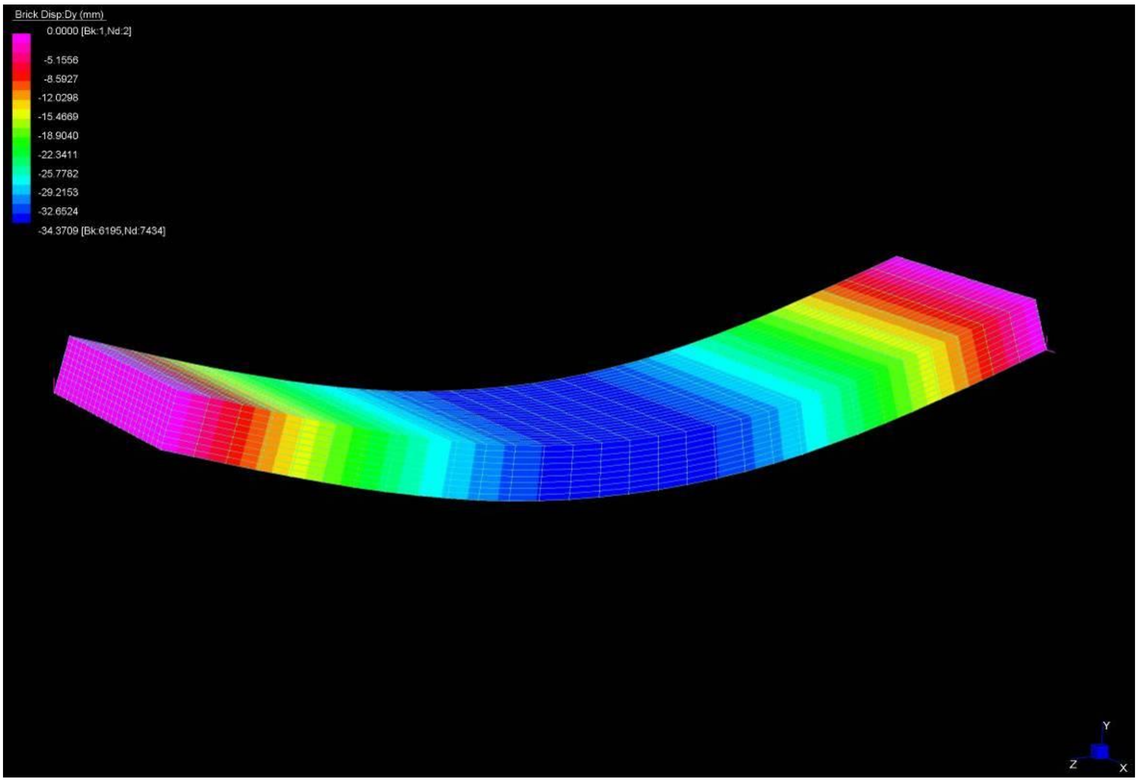


Figure 19 – A three dimensional brick element model.

The use of three dimensional modelling elements yields slightly different results to that of the two dimensional elements and one dimensional element models. It was found that a high number of bricks could be used efficiently for both convergence in results and accuracy in stress distributions created as a result of various load patterns being placed on the slab. A comparison between the three model types is shown in Table 8 to portray the difference in results obtained from each model type.

Table 8 – Strand7 model comparison

Model type	Number of elements	Deflection obtained from model (mm)				
		20 kN Load	40 kN Load	60 kN Load	80 kN Load	100 kN Load
1D Beam	**12**	6.8	13.7	20.5	27.3	34.2
2D Plate	**432**	6.8	13.7	20.5	27.3	34.2
3D Brick	**6480**	6.87	13.75	20.62	27.5	34.37
Physical Model	**1**	7.6	14.5	21.0	28.2	37.6

Modelling with three dimensional elements also results in a more accurate description of the distribution of stresses within the slab as a result of loading. This is crucial for the accurate modelling of the slabs to predict the load and span relationship which results in the allowable stress levels within the slab being exceeded.

The use of three dimensional brick elements in modelling is also preferable for the creation of three dimensional models of flooring systems. This is due to the ease at which members can be connected in a way which accurately represents the connection in the physical model, and the capability to assign unique material properties to individual brick elements as appropriate due to the arrangement of nodes as shown in Figure 20.

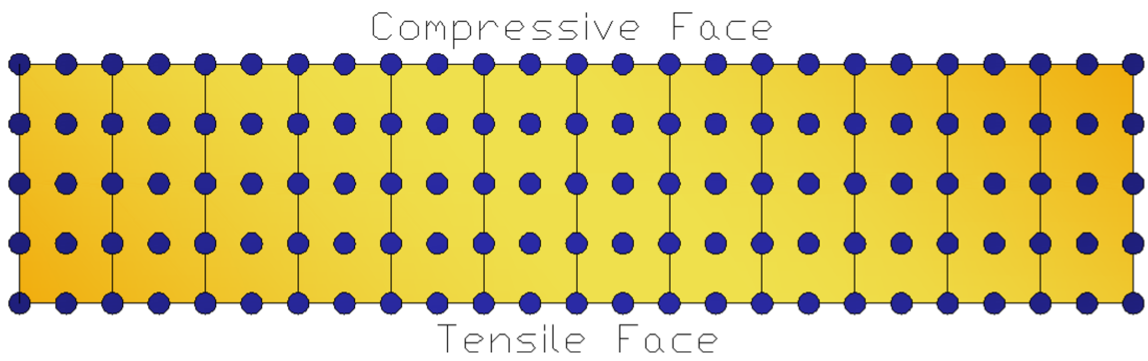


Figure 20 – Node location within a three dimensional slab model cross section.

5.1.4 Use of isotropic elements

Orthotropic elements should be used to model timber; however sufficient material information for timber in the three required directions is not available for low grade slabs due to no prior work being done in this area. The properties of pine alone could be used but this option was not taken due to the differences induced as a result of the glue laminations between pine members of varying strength grades.

Therefore the slabs were modelled as three dimensional isotropic elements due to the highest level of accuracy which was returned in the results compared to the physical test results. The modulus of elasticity used in this model was calculated using Matlab to determine the linear proportion of the load – deflection curve and calculate the modulus of elasticity based on this interpretation. This is the reason for the slight difference in the modelled slab deflection and the physical test deflection as seen in Figure 21. Note that all differences in deflection on the linear region of the graph are less than one millimetre, with the major differences between the modelled performance and the physical performance being at higher loads. This occurs where the load – deflection relationship is not linear as can be seen at the 100 kN load data points for each model in Figure 21.

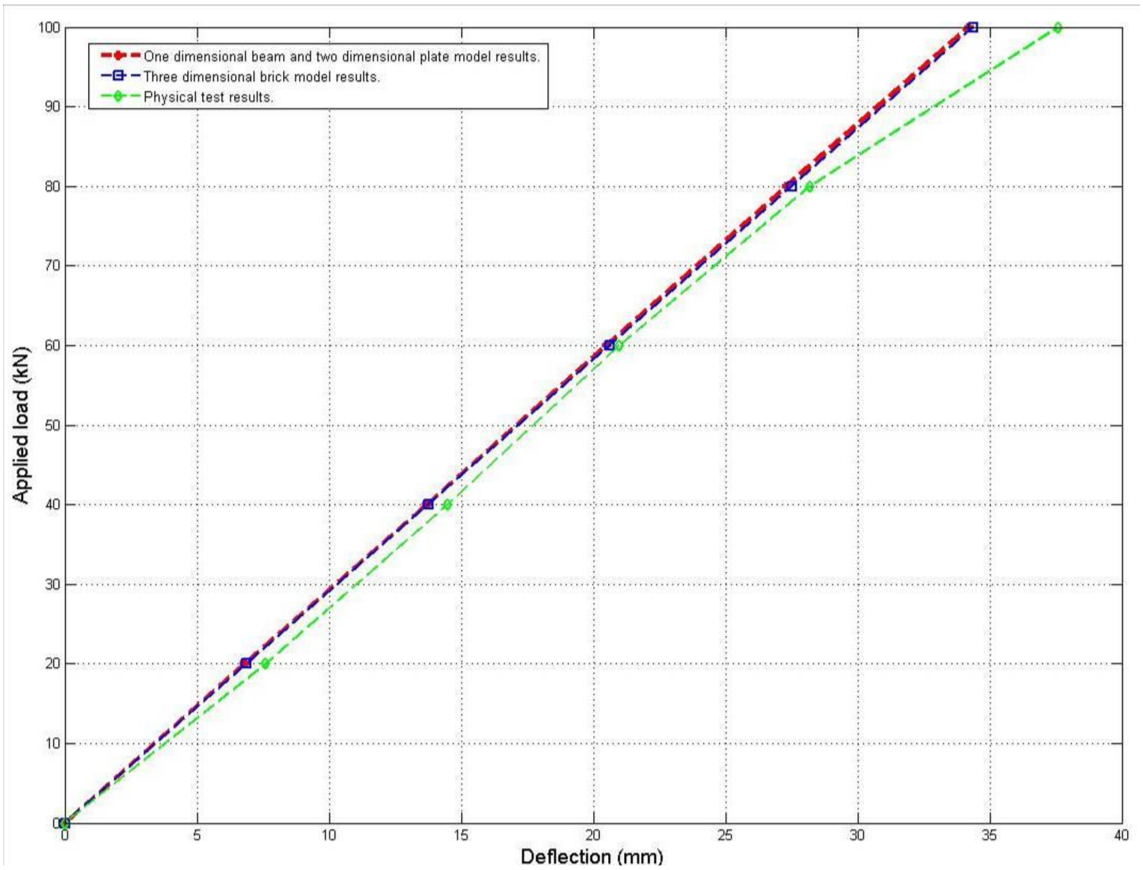


Figure 21 – Comparison of Strand7 models to physical test results.

5.1.5 Application and justification of chosen poisons ratio

The poisons ratio for all Strand7 models had to be chosen and validated due to no existing data on the poisons ratio values for low grade timber slabs. This is due to no prior investigation into the effects that glue laminations have on the poisons ratio of low grade pine.

The investigation was based around using the established three dimensional brick element model with various values of poisons ratio to determine the extents of the error within the model and design aids as a result of using a poisons ratio value which does not represent a proven value.

As the three dimensional brick elements are modelled as isotropic, one poisons ratio value was applied in all three axis. This is not a true replication of timber due to its unique properties in each of the three axis. Despite this, the results comparison between the three dimensional brick element model and the physical results prove that using a unique poisons ratio in all three directions is sufficiently accurate.

The result of varying the poisons ratio is shown in Table 9. It can be seen that there is a slight increase in the deflection value obtained from the model as the value used for poisons ratio increases. Therefore the poisons ratio value of 0.2 was chosen as the optimal value to ensure that the model results are as close to the physical test results as possible as seen in Figure 22, and design aids based on Strand7 models are an over estimate of the slabs characteristics as a slight factor of safety incorporated into the design charts.

Table 9 – Difference in model outputs for various poisons ratio values.

Load Case	Deflection recorded for a slab span of 6.0 m with varying values of poisons ratio (ν) (mm)			Maximum difference in deflection for given poisons ratio values
	ν = 0	ν = 0.1	ν = 0.2	
Self Weight	15.7	15.8	15.8	.1
1 kN/m²	29.1	29.3	29.4	.3
Self weight + 1 kN/m²	44.8	45.1	45.2	.4
Self weight + 2 kN/m²	73.8	74.4	74.5	.7
Self weight + 3 kN/m²	102.9	103.7	103.9	1
Self weight + 4 kN/m²	132.0	133	133.2	1.2
Self weight + 5 kN/m²	161.1	162.3	162.6	1.5
Self weight + 7.5 kN/m²	233.8	235.6	236.0	2.2

5.2 Methodology

The Strand7 modelling is intended to allow an accurate prediction of the low grade slabs response to loadings typically endured by floor structures. Its secondary function is to draw comparisons between the structural performances of the typical floor consisting of bearer's, joists and flooring material, and that of the low grade slab flooring system which consists only of bearers and the slab. The Strand7 finite element analysis was used to analyse the slabs based on the following two floor design criteria:

- Deflection based assessment.
- Maximum limiting stress based assessment.

The limiting stress has been determined using the stress distribution in a simple beam and the lowest load applied to cause the first partial failure within the slabs. The lowest load to cause a partial failure was taken from the test data as 75000 N. This load is transferred to its equivalent bending moment via the bending moment diagram shown in Figure 22.

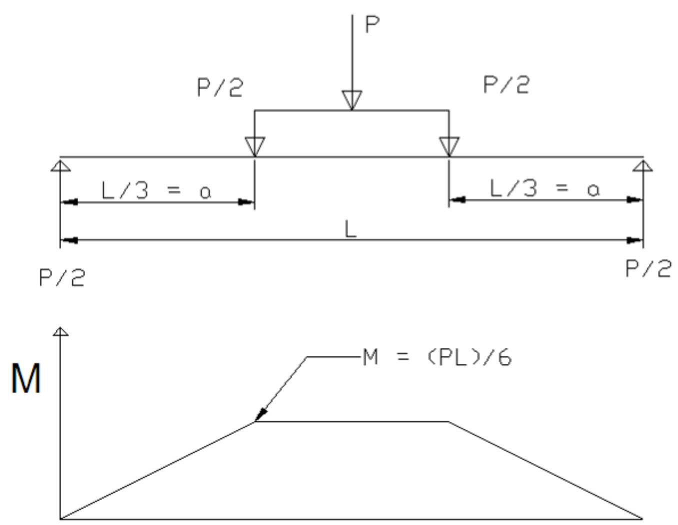


Figure 22 – Derivation of maximum moment from loading setup.

The limiting stress was then derived using beam theory to make the assumption that the stress distribution throughout the slab is linear with the positive and negative extremes at the top and bottom faces as shown in Figure 23.

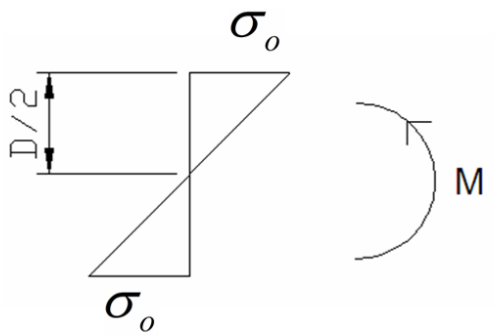


Figure 23 – Stress distribution within the slab.

Using this stress distribution and the bending moment diagram derived in Figure 22, the maximum bending stresses can be determined for the timber slab based on test results. This is done by applying the minimum P value to cause a partial failure within the weakest slab tested and the application of Equation 2.

$$\sigma_{\max} = \frac{M_{\max} \times \frac{D}{2}}{\frac{bD^3}{12}} \tag{2}$$

Longitudinal stress was created in the slab unit samples during testing; hence it will be obtained from the Strand7 models to determine the limits of loading to remain within allowable stress levels. This analysis is undertaken to determine if the strength or serviceability criteria is the critical design factor. The limiting stress value will be calculated using the preceding methodology as shown in Equations 2 – 8.

$$P = 75\ kN \tag{3}$$

$$D = .09\ m \tag{4}$$

$$L = 18D = 18 \times .090D = 1.620\ m \tag{5}$$

$$M_{\max} = \frac{PL}{6} = \frac{75 \times 1.62}{6} = 20.25\ kN.m \tag{6}$$

$$I = \frac{bD^3}{12} = \frac{.420 \times .09^3}{12} = 2.25515 \times 10^{-5} m^4 \tag{7}$$

$$\sigma_{\max} = \frac{M_{\max} \times \frac{D}{2}}{I} = \frac{20.25 \times \frac{.09}{2}}{2.25515 \times 10^{-5}} = 35,714 kN/m^2 = 35.714\ MPa \tag{8}$$

Based on these calculations the limiting longitudinal stress value is 35.714 MPa. This value will be used with the low grade slab model to determine the maximum load that may be applied to a floor slab consisting of numerous connected individual slab units. The same models will also be used to measure the floor slab deflection for the same load distribution with a varying range of intensities from the slabs response to self weight up to self weight plus 7.5 kN/m² of force over a slab of 3.6 m width and spans varying from 1.8m in multiples of 600 mm through to 6.0 m. The standard floor construction model will be used in the same way with the limiting stress in the hardwood joists taken as 80 MPa for F27 grade timber from AS1720.1 – 2002.

The results obtained from this analysis will define stress or deflection as the limiting criteria based on which is exceeded first as a result of increased loading on the floor slab.

5.2.1 Parametric study between slab and standard flooring

The parametric study between the low grade timber slab construction system and the standard bearer, joist and flooring material construction method was done in order to determine the differences in responses when loads of various magnitudes were applied to both models.

Both construction methods were modelled with identical bearers, with the difference being the slab model had only the low grade slab on the bearer, and the standard model had joists and flooring of the same material as the bearer. This was done so that the models could be compared with as few variables as possible, as any difference in material or dimensions of the bearer would yield a result of no comparative value.

The standard floor models and the slab floor models were created with a width of 3.6 m and varying floor spans for consistency between models. The load was uniformly distributed by calculating the load of 1 kN/m² over the area of the slab divided by the number of nodes in that floor area. The resulting load was then applied to each node within that area. For example the floor model 3.6 m wide and 4.8 m in span with 7408 nodes, had a total load applied to each node as shown in Equation 9. A complete list of models and applied loads used in the parametric study is given in Table 10.

$$\frac{1kN \times (3.6m \times 4.8m)}{\text{Number of nodes}} = \frac{17.28kN}{7408} = .0023326134\ kN/node \tag{9}$$

Table 10 – Model dimensions used in study with 1 kN/m² node loading values.

Model dimension (Width x Span)	Model type	Applied load (1 kN/m²)	Number of nodes	Load / node (kN)
3.6 m x 3.6 m	**slab**	12.96 kN	22,630	.00057
	standard		5,620	.00230
3.6 m x 4.2 m	**slab**	15.12 kN	26,275	.00057
	standard		6514	.00232
3.6 m x 4.8 m	**slab**	17.28 kN	29,920	.00057
	standard		7,408	.00233
3.6 m x 5.4 m	**slab**	19.44 kN	33,565	.00057
	standard		8,302	.00234
3.6 m x 6.0 m	**slab**	21.60 kN	37,210	.00058
	standard		9,196	.00234

The various load magnitudes were applied to the model by creating the following two load cases within Strand7 and then combining them and multiplying by the appropriate factor to achieve the required total load:

- Self weight (gravity)
- 1 kN/m²

This results in linear load case combinations, which are applied to the floor model allowing the predicted deflections and stresses to be recorded. Each model was run initially to record the stress in supporting members and the deflection of the floor as shown in Figure 24.

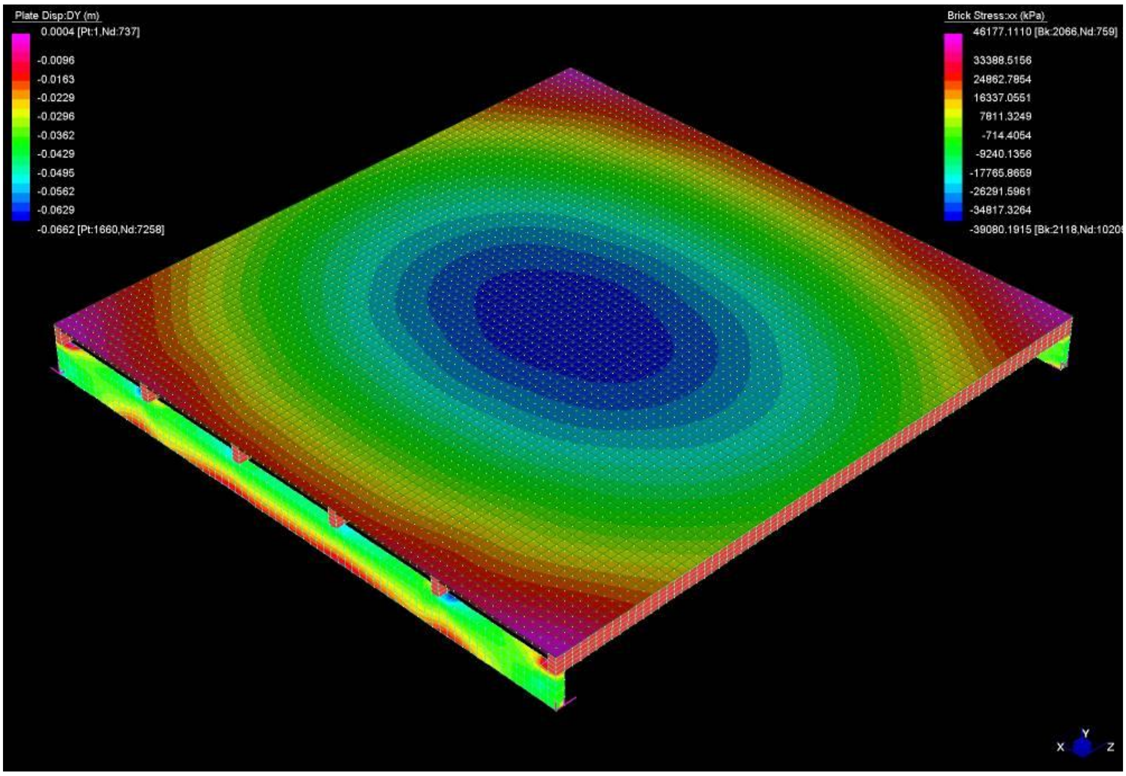


Figure 24 – Standard floor construction Strand7 model

Each model used in the parametric study was simply supported on each of the four corner nodes to allow translation in the two dimensional floor planes without allowing any vertical movement within the model as shown in Figure 25. This is realistic for a floor area supported by free standing columns as the columns will deflect inwards as a result of loads being applied to the flooring area. This restraint system has been chosen due to maximum level of deflection which will occur at the centre of the supported floor area. Restricting translation in the Z - X plane would result in tension being developed in the supporting members. The resulting deflection maximum deflections would therefore be reduced.

For the bearer in the standard and slab model, the joist in the standard model and the slab in the slab model to be simply supported, no other method of restraint can be used. This is due to the fully fixed nature of the connection between the joists / slab to the bearer in the standard and slab models respectively. The slab model was made with a full connection between the edge of the bearer and the floor slab for the entire width of the model as shown in Figure 26.

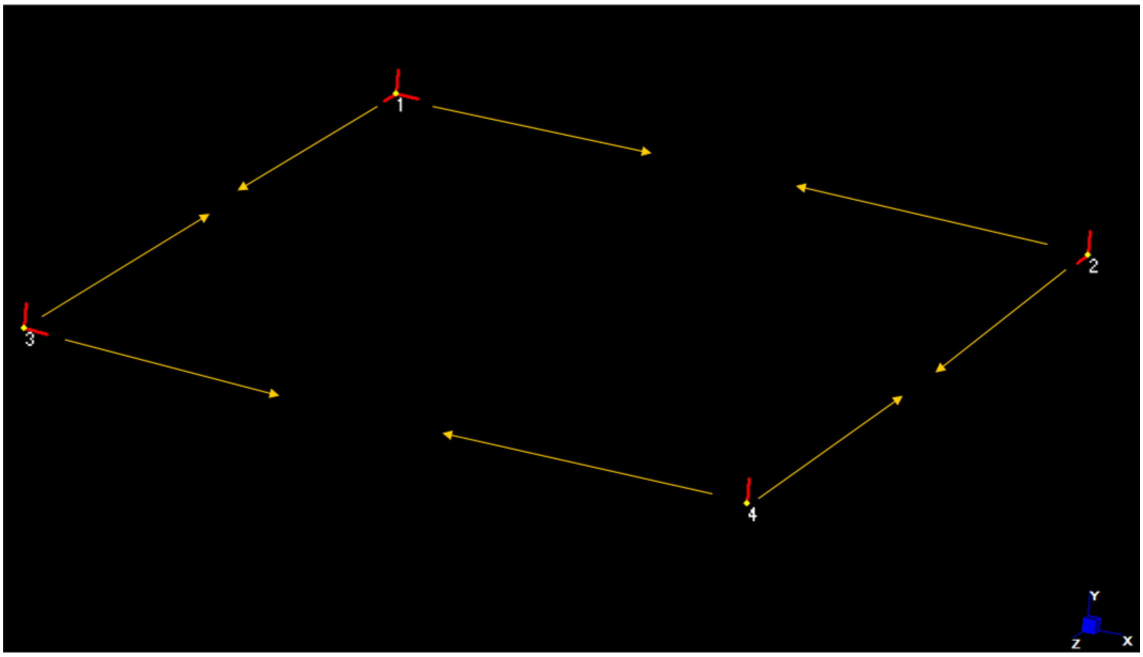


Figure 25 – Supports used in Strand7 floor models

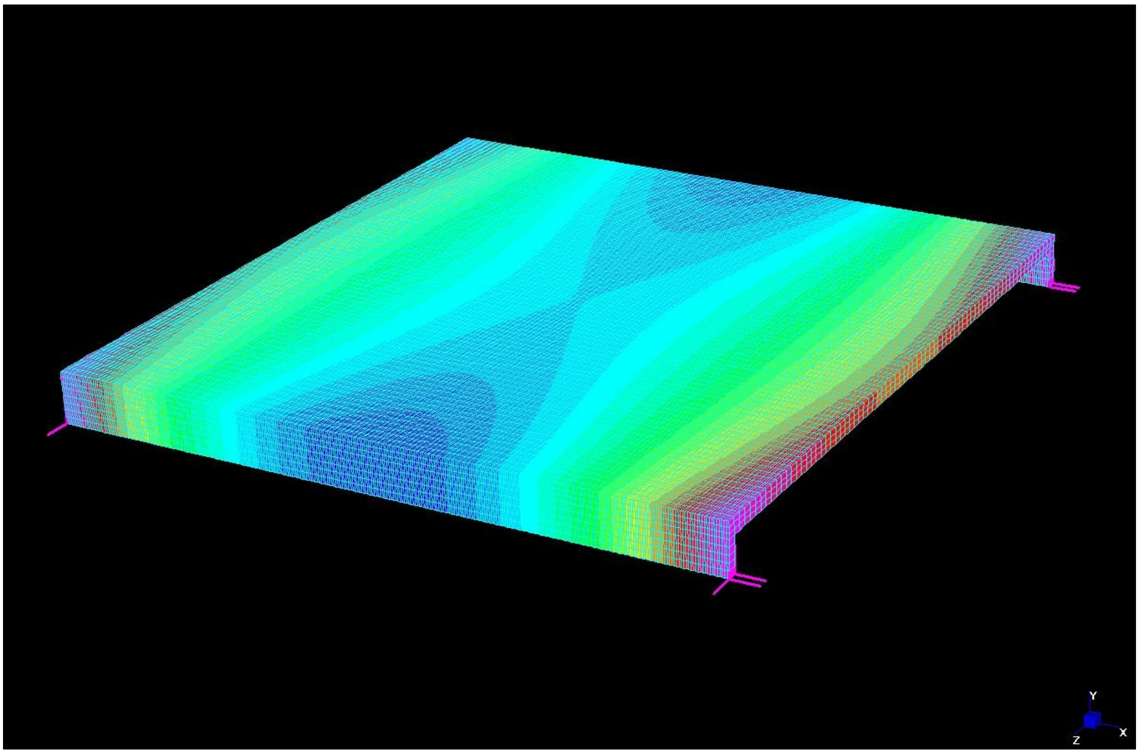


Figure 26 – Low grade timber slab floor Strand7 model

The material properties used in both models were derived from data obtained through testing, Hyne quality assurance data and spreadsheets containing hardwood tests undertaken by Timber Queensland. The material data used in each model can be seen in Table 11.

The standard floor model used in the parametric study consists of a bearer, joists and flooring material as shown in Figure 24. The low grade slab model consists of an identical bearer but the flooring material and joists are replaced by the low grade slab as shown in Figure 26.

Table 11 – Material dimensions and properties used in Strand7 models.

Member	Length (mm)	Width (mm)	Depth (mm)	Material	Modulus of Elasticity (MPa)	Density (kg/m³)	Poisons Ratio
Bearer	3600	50	200	Grey Ironbark	18702.65	1097.665	0.2
Joist	span	50	100	Grey Ironbark	18702.65	1097.665	0.2
Floor	span	3600	19	Grey Ironbark	18702.65	1097.665	0.2
Slab	span	3600	90	Low grade pine	8872.11	604	0.2

- Note that length in this table implies the span referred to in table 10 plus 100mm for the member to cover the clear span plus the width of the supporting bearers.

5.2.2 Modelling of slab performance to create design chart

To demonstrate the performance of the low grade slabs, their structural performance was modelled with Strand7 over eight spans and six separate load cases. To ensure that the chart was representative of the slab behaviour only, the bearer was removed to eliminate the deflection it adds to the system, and the associated two way bending effects. The model was simply supported at its four corners and fully supported against deflection in the vertical direction in the place of the bearers to ensure that only one way bending could occur within the model. This was done to represent a realistic support, loading and deflection situation.

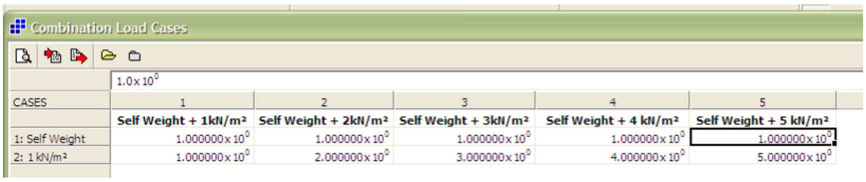
Each model was made 3.605 m wide, due to the width of the members in each slab unit of 35 mm which makes it impossible to create a slab of complete individual members 3.6 m wide exactly. The slab density was taken as 604 kg/m³ as this is the average value recorded for the low grade product produced by the Hyne Tuan mill. The following models were run to create the design chart with the loads applied for each response by the model as shown in Table 12.

Table 12 – Total load applied for each load case in Strand7 models.

Clear span (m)	Total load applied for each load case (kN).						
	Self Weight	1 kN/m²	Self Weight + 1 kN/m²	Self Weight + 2 kN/m²	Self Weight + 3 kN/m²	Self Weight + 4 kN/m²	Self Weight + 5 kN/m²
1.8	3.46	6.489	9.949	16.438	22.927	29.416	35.905
2.4	4.61	8.652	13.266	21.918	30.570	39.222	47.874
3.0	5.77	10.815	16.582	27.397	38.212	49.027	59.842
3.6	6.92	12.978	19.899	32.877	45.855	58.833	71.811
4.2	8.07	15.14	23.215	38.356	53.497	68.638	83.779
4.8	9.23	17.304	26.532	43.836	61.140	78.444	95.748
5.4	10.381	19.467	29.848	49.315	68.782	88.249	107.716
6.0	11.535	21.630	33.165	54.795	76.425	98.055	119.685

These loads were applied to the slab model by having Strand7 calculate the self weight load created by a gravitational force of -9.81 m/s/s as one separate Load case. The Uniformly Distributed Loads (UDL) were applied as a separate load case to the nodes joining brick elements that make up the slab by dividing the total force created by 1 kN/m² over the slab area by the number of nodes on the top surface of the slab as shown previously in Equation 9.

The load combination cases were applied to the model by creating load cases within Strand7 which take the self weight and combine it to the 1 kN/m² UDL multiplied by the appropriate factor to create a load case of the desired magnitude as shown in Figure 27. 1 kN/m² was used as the base value for the ease of load case creation associated with a unit value.


Combination Load Cases

1.0×10^0

CASES	1	2	3	4	5
	Self Weight + 1kN/m²	Self Weight + 2kN/m²	Self Weight + 3kN/m²	Self Weight + 4 kN/m²	Self Weight + 5 kN/m²
1: Self Weight	1.000000×10^0	1.000000×10^0	1.000000×10^0	1.000000×10^0	1.000000×10^0
2: 1 kN/m²	1.000000×10^0	2.000000×10^0	3.000000×10^0	4.000000×10^0	5.000000×10^0

Figure 27 – Strand7 load case combination screen print.

Each model was than run to analyse the deflection caused by the applied load over the given span and width, with the vertical deflection in the centre of the slab recorded. Once the load deflection lines were plotted, further lines were created to join the distinct load case results on each span. Deflection limit lines were also superimposed on the load deflection curves for each span. These lines are curved due to the variation of limiting deflection value with change in span for a set deflection limit ratio. This was done to allow interpolation of values when used in a design situation. For example taking a required load and deflection limit and using those values to solve for the maximum clear span which can be used with a low grade timber floor slab.

5.3 Results

Using a deflection limit of span / 250 the loads required to exceed the limit on each model type are shown in Table 13. This comparison yields results based on the average linear section of the load / deflection graphs obtained during the testing of the slabs, and hardwood material data obtained from Timber Queensland and AS1720.1 – 2002. The relationship between stress and deflection limits based on applied load is shown in Figures 28 – 21.

Table 13 – Stress and deflection limit comparison

Model	Deflection limit (mm)	Deflection based load limit (kN)	Stress limit # (MPa)	Stress based load limit (kN)	Equivalent deflection * (mm)
3.6m x 3.6m slab	14.4	42.628	35.714	373.043	126
3.6m x 3.6m standard	14.4	27.375	80	167.612	88
6.0m x 3.6m slab	24	18.068	35.714	253.993	337
6.0m x 3.6m standard	24	14.851	80	123.887	198

** Proportional linear deflection caused by the load required to meet the stress limit.*

 # Hardwood bending stress limit obtained from AS1720.1 for F27 grade timber.

Based on this modelling, the span limitations required for the stress and deflection limit to be obtained from the same load are as follows:

- 3.6 m x 3.6 m slab – Span / 28.57
- 3.6 m x 3.6 m standard – Span / 40.91
- 6.0 m x 3.6 m slab – Span / 17.80
- 6.0 m x 3.6 m standard – Span / 30.18

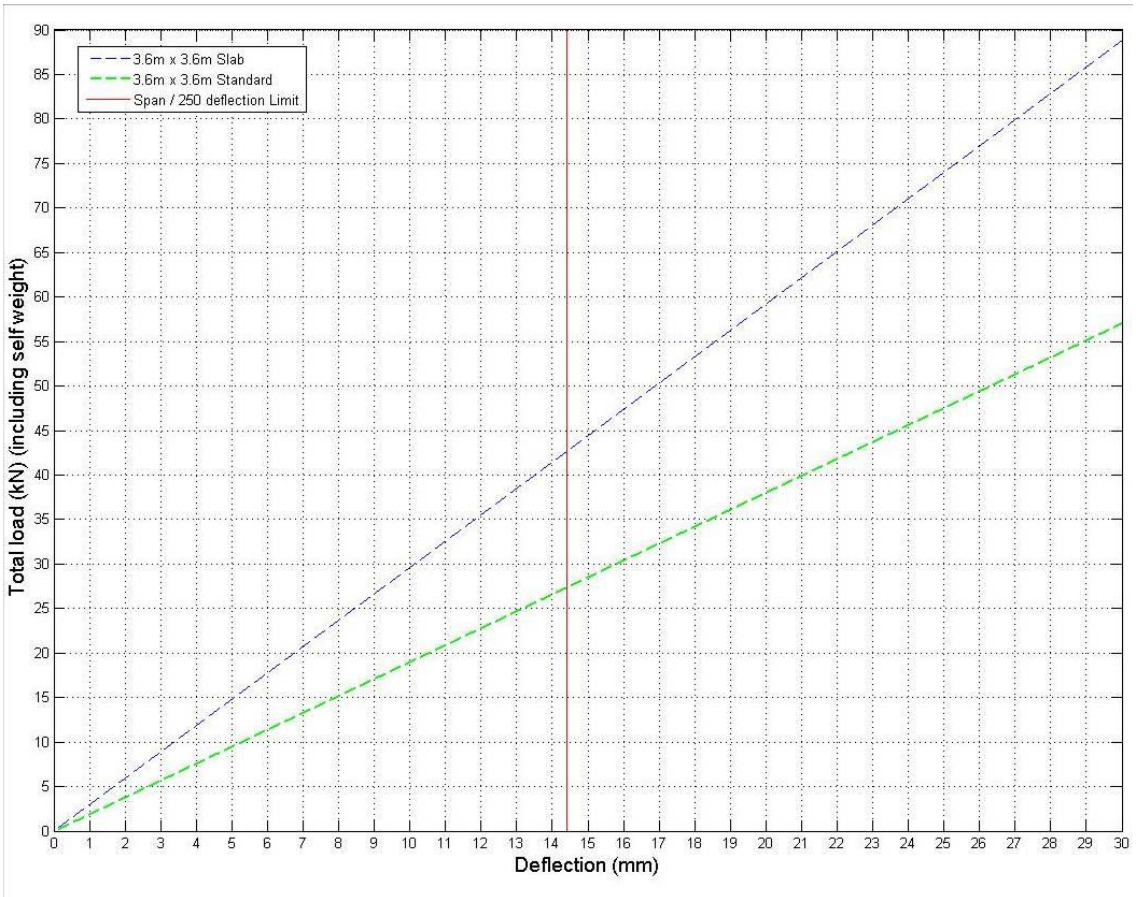


Figure 28 – 3.6m span deflection limit graph for both floor model types.

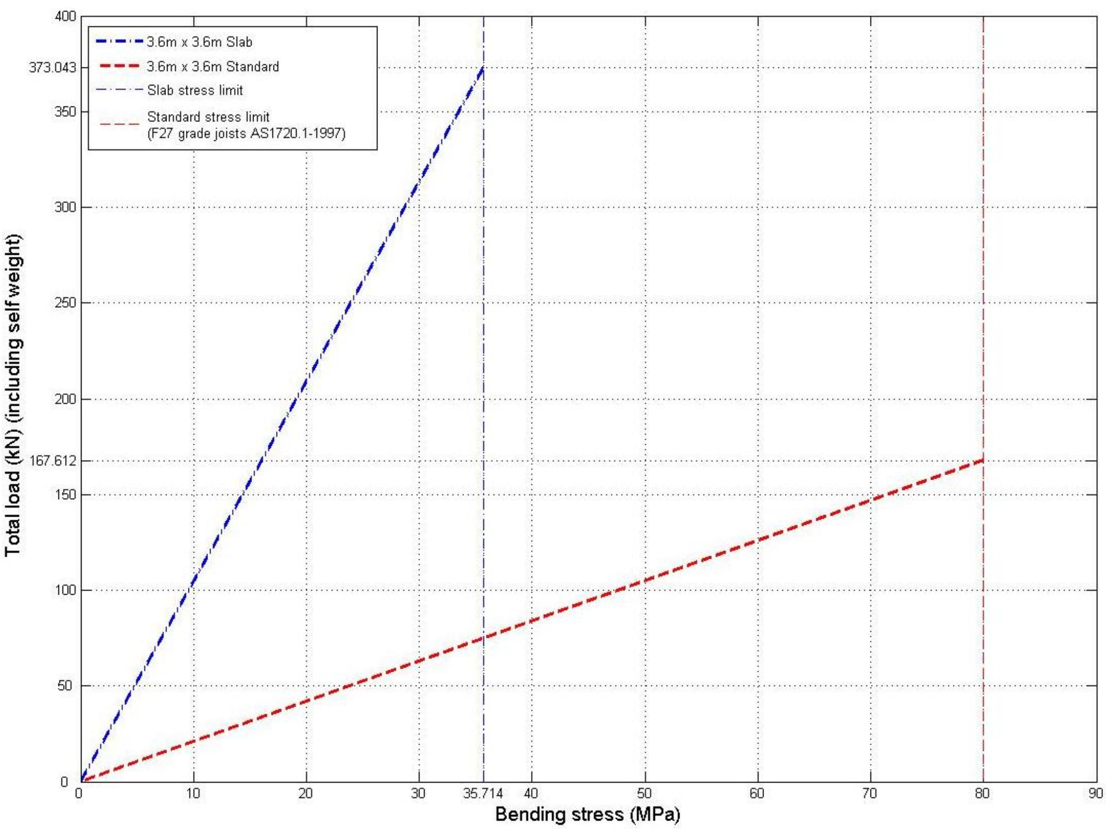


Figure 29 – 3.6m span stress limit graph for both floor model types

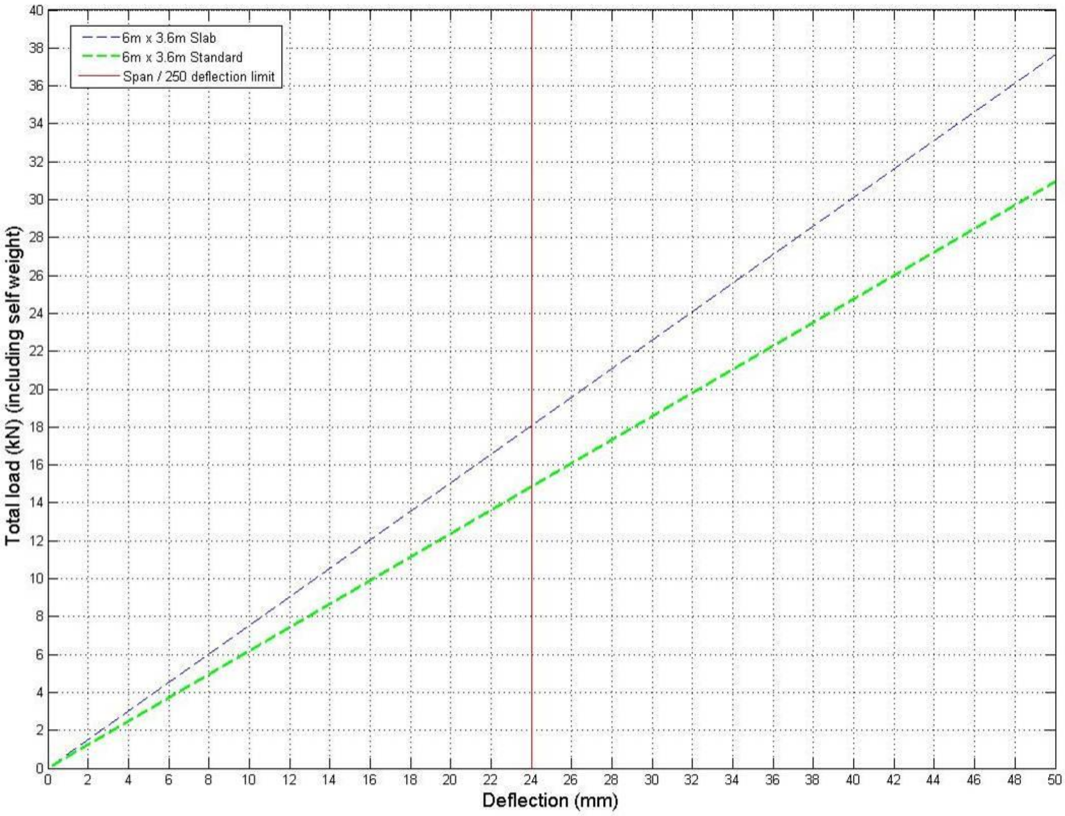


Figure 30 – 6m span deflection limit graph for both floor types

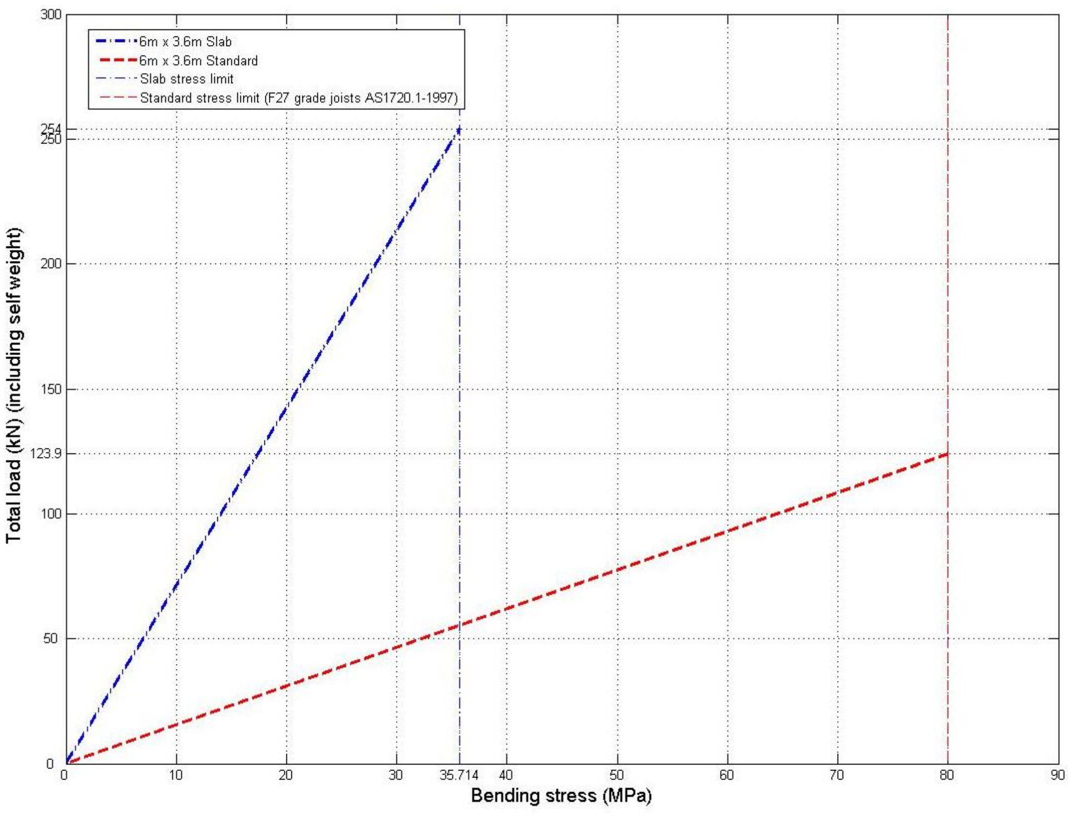


Figure 31 – 6m span stress limit graph for both floor types

5.2.3 Parametric study between slab and standard flooring

The comparison between the low grade slab floor system and the standard system yields results that show that the slab floor construction method can take a greater load than the standard method with a deflection that is significantly less as shown in the following graph. The reason for the larger total load is the self weight of the low grade slab due to the bulk of low grade timber used, compared to the skeleton structure of the standard method of floor construction.

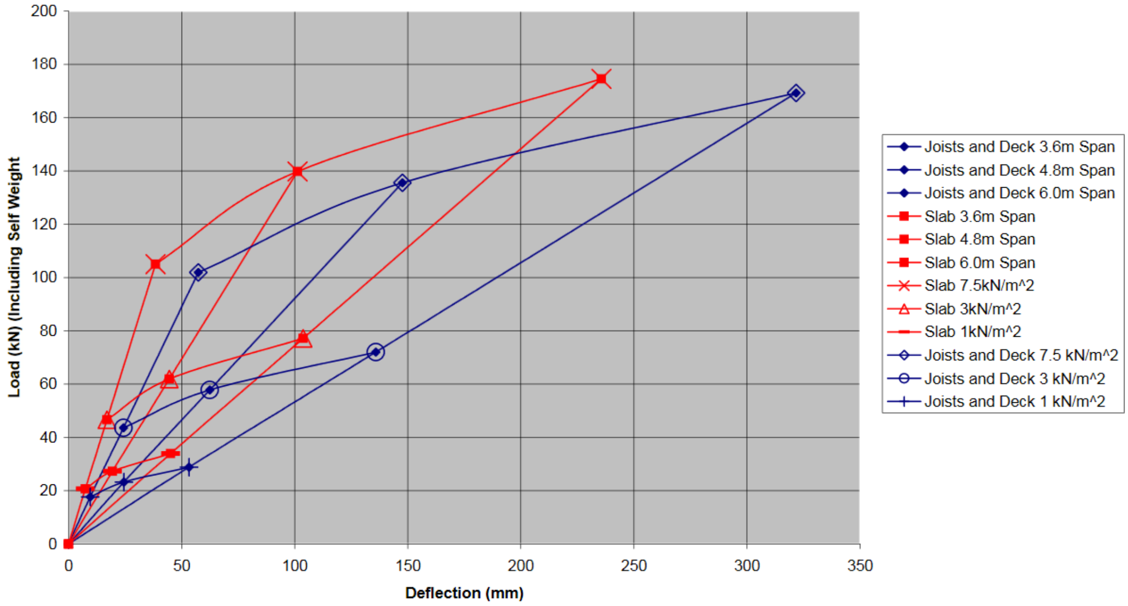


Figure 32 – Comparison between a standard and a low grade timber slab floor.

The calculation of the self weight included in the total load shows that the relationship between span and total load applied for each load case is not linear as assumed prior to modelling and analysis. It can also be seen that the deflection increases as a result of each load case within the standard model are significantly greater than that of the slab model.

5.2.4 Low grade timber slab design chart

The analysis of the low grade slab without any supporting bearer returned the deflection results shown in Table 14. This information is used with the total load information provided in Table 12 to plot the load deflection curves for slabs having a clear span range of 1.8 m – 6 m as shown in Figure 33. All deflections recorded are the maximum value obtained from the centre of the slab. Due to the deflection limits being the governing criteria no evaluation was done on the variation of stress levels within the slab as the load increases.

Table 14 – Low grade slab deflections for each load case.

Clear span (m)	**Maximum deflection for each load case (mm).**						
	Self Weight	**1 kN/m²**	**Self Weight + 1 kN/m²**	**Self Weight + 2 kN/m²**	**Self Weight + 3 kN/m²**	**Self Weight + 4 kN/m²**	**Self Weight + 5 kN/m²**
1.8	0.4	0.3	0.7	0.9	1.2	1.5	1.7
2.4	0.5	0.8	1.3	2.1	2.9	3.8	4.6
3.0	1.1	2	3.1	5.1	7.2	9.2	11.2
3.6	2.3	4.2	6.4	10.6	14.8	19	23.2
4.2	4.2	7.7	11.9	19.6	27.3	35	42.8
4.8	7.1	13	20.1	33.1	46	59	72
5.4	11.3	21	32.2	53.2	74.2	95.1	116.1
6.0	17.1	31.9	49	80.9	112.7	144.6	176.4

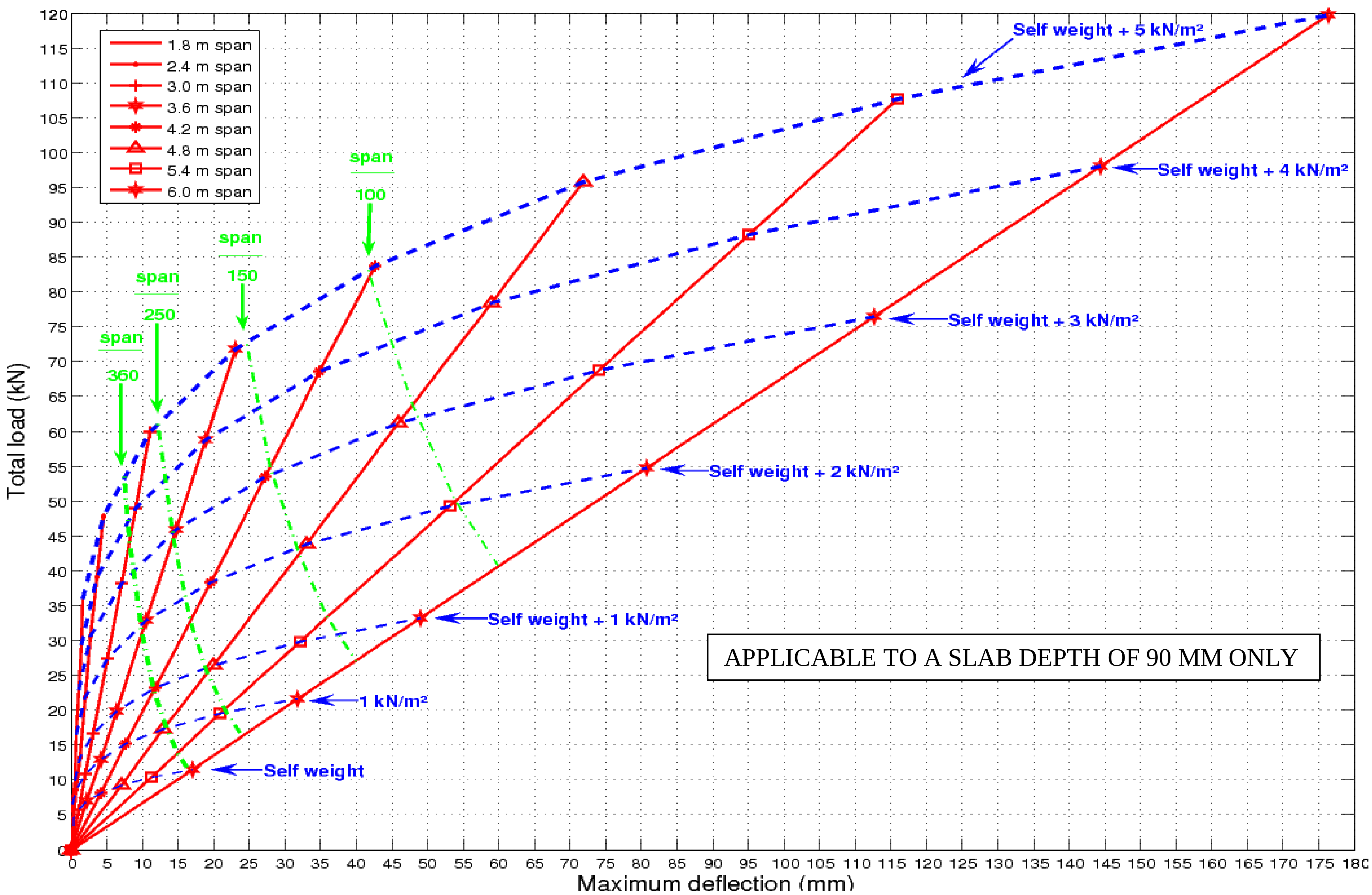


Figure 33 – Low grade timber slab design chart.

5.3 Discussion

The limiting design criteria analysis undertaken on the low grade slab demonstrates that the structural capacity of the slab is limited by the deflections induced as a result of loading. The limiting stress value applied to the low grade slabs was determined from the lowest load required to cause a partial failure in the six individual slab units tested.

Further testing of a larger sample may yield that the stress value used here is not the lowest stress which will result in a partial failure of the slab, hence further testing of the slabs should be carried out, and a factor of safety used in all calculations. The analysis of the models is linear whereas the physical test results obtained from the testing of low grade slab units is only linear in the lower load regions as can be seen in Figure 11. Therefore the values are not accurate over all portions of the load – deflection graph, but descriptive of the relationship between applied load and corresponding deflection. This can not be avoided in the linear analysis due the average modulus of elasticity used. This value was derived from the linear portion of the data obtained from the testing of individual low grade slab units.

It should also be noted that the maximum stress has been derived based on a four point loading setup which is not likely to occur in a typical floor loading situation. Therefore further testing should be undertaken which incorporates a series of point loads and uniformly distributed loads to obtain a stress limit that is the resultant of a realistic floor loading situation.

The analysis also demonstrated that the stress limit is reached in the standard floor structure at a significantly lower load than that of the slab structure. This result is valid due to the identical bearer used between the two models, and the skeleton structure of the standard construction method, which has a significantly less volume of timber resisting applied forces.

5.3.1 Parametric study between slab and standard flooring.

The parametric study between slab and standard flooring analysed the effects of different load magnitudes based on models of identical dimensions. The bearer used in both model types to support the joists and the low grade timber slab was identical. This was done to eliminate one variable in to make results comparable. In reality these bearers could be manipulated to make the deflection comparison between the model types identical.

The slab model is effectively a standard model with no spacing between the joists, and no presence of flooring material. Therefore the weight of the structure is significantly greater than that of the standard method of construction. It also results in a larger resistance to applied load which is evident in the results obtained from modelling. The larger load is partly due to the greater self weight of the structure, but the results from both models contain identical applied loads. Therefore the comparison yields that the low grade timber slab construction system can take a larger load before exceeding deflection limits than the standard method of floor construction.

5.3.2 Low grade timber slab design chart.

The low grade timber slab design chart was created using average values for the modulus of elasticity and the density of low grade pine. The density value used is the average value from a large number of tests and is therefore a representative value. The average modulus of elasticity used is the average of six tests only. The tests proved that the variance in modulus of elasticity is not large; however further testing would reveal trends which can be used to refine the model. For this reason an appropriate factor of safety should be included if using the base representative values shown in the design chart.

The modelling carried out to develop the design chart was linear. This does not represent the true load deflection characteristic of the slab; however it is a close approximation to the average deflection that can be expected for an applied load. The modelling has also been done based on the 90 mm deep slab units tested, width of 3.605 m which represents 103 individual low grade timber members within the slab. This value was used due to each individual member within the slab being 35 mm wide and the need for comparability with the standard 3.6 m wide floor used in the parametric study.

Equation 10 represents the deflection of a simply supported beam, subjected to a uniformly distributed load which can be used to describe the behaviour of the slab in one way bending.

$$\delta = \frac{5}{384} \times \frac{wL^4}{EI} \tag{10}$$

This can be used to justify that as the span increases and the same uniformly distributed load is applied, the increase in load as a function of floor area, and the increase in rigidity of the slab as result of the extra width have no effect on the total deflection at the centre of the slab.

Using Equation 10 to validate the low grade slab design chart for a load of 1 kN/m² and a clear span of 4.8 m, the deflection obtained is as shown in Equation 11. The results obtained from the linear Strand7 finite element analysis model indicate that the resultant deflection is 13mm as can be seen in Table 14.

$$\delta = \frac{5}{384} \times \frac{(1 \times 3.605) \times 4.8^4}{8872.11 \left(\frac{3.605 \times .09^3}{12} \right)} = 12.82 \ mm \tag{11}$$

Applying this equation for a slab of 20 m width, it can be seen via Equation 12 that the difference in central deflection is the same; therefore the design chart can be used for any required span subjected to a uniformly distributed load with accuracy.

$$\delta = \frac{5}{384} \times \frac{(1 \times 20) \times 4.8^4}{8872.11 \left(\frac{20 \times .09^3}{12} \right)} = 12.82 \ mm \tag{12}$$

The difference in deflection between theoretical values and the value obtained from this particular model are .18 mm different. This is most likely due to the effect of the poisons ratio value of 0.2 used in all models. Convergence within the finite element analysis model is present and therefore the model values represent the best approximation to the deflection based on the material specific properties used in the model.

5.4 Conclusions

Comparative models of the standard and the slab flooring system have shown that the low grade timber floor slabs can perform better than the standard floor, as equivalent loading on top of the self weight causes a considerably greater deflection in the standard floor than it does in the slab. The slab has proven to perform better than the standard floor construction method in both stress and deflection based analyses.

The results are reliant on a lot of variables which could be manipulated to make the standard flooring method perform better than the slab, however this would only happen if the joists were spaced more closely than that of standard practice. If a model were created like this the results would be effectively converging on that of the slab floor, i.e. joists with zero spacing on a bearer are the same as a slab.

The isotropic brick elements used to model the flooring systems has been proven to be adequate despite the single direction modulus of elasticity and poisons ratio value that do not accurately depict the real structure. Tests models were run between Strand7 and the standard single slab units with results within 0.5 mm of the recorded deflections. Theoretical results also yield a value which is within 0.5 mm of the model.

The low grade slab design chart accurately describes the structural limitations of using low grade timber as a one way floor slab based on the six sample slabs tested. This development provides a reasonably safe method of designing a floor that is required to exceed the capacity of the standard method of floor construction over set spans.

The design of appropriate bearers to support the weight of the slab and the applied load shown in the design chart can also be undertaken based on the total load values presented. This implies that two way bending will be present within the slab if the deflection within the supporting bearer is significant. Further research into the performance of slabs subjected to two way bending is required to determine the exact capabilities of a low grade timber floor slab in this situation.

The elimination of the extra floor depth associated with the joists required to support flooring material in standard floor construction is a major advantage of using low grade slabs for above ground flooring applications. The extra head room created allows better use of space for installation of essential services without compromising structural integrity or ceiling height.

Chapter 6

Connections

6.0 Introduction

This section is aimed at developing connection methods and investigating the performance of connections between low grade timber slab units acting as a floor slab. Research of this nature has not been undertaken previously due to the fact that this is the first work which investigates the effectiveness of using low grade slab units as a flooring alternative. The development of a suitable connection method involves the development of multiple conceptual prototypes, with the process of elimination based on required characteristics.

The major force that will be present in the joint is a shear force due to the differential deflection that occurs as a result of differences in the stiffness of each individual slab unit, and separation of slab units that could occur if the slab is subjected to a tensile force perpendicular to the direction of the laminates.

The aim of the connection strength in all directions is to exceed that of the strength of the glue that is laminating the timber pieces together into a slab, and also exceed the strength of the timber itself when subjected to any force which the connection is expected to withstand.

This presents a challenge as the strength of individual members in bending, shear and tension has been proven to be highly variable. Therefore the analysis has to be done based on the expected load range that will be applied to the slab which will not cause deflections greater than the given design maximums.

Moisture related effects on joint performance have been taken into consideration, however a full analysis of the effects of moisture on low grade timber floor slabs is outside the scope of this research work. This needs to be given a more detailed analysis in future research work related to the appropriateness of low grade timber slab units used in floor construction.

6.1 Methodology

Initial investigation on slab unit connection required a determination of the most appropriate connection method. To do this, a range of ideas were established and weighted to show the most appropriate one in terms of:

- Connection suitability to resist shear - **A**
- Connection suitability to resist tension perpendicular to the laminates - **B**
- Ease of manufacture and construction - **C**
- Envisaged cost of materials + manufacture + transport + construction - **D**
- Time taken to manufacture, transport and construct - **E**

6.1.1 Connection methods evaluation

Multiple ideas were created, and investigated on their merit in the factors listed in section 6.1. Many methods of forming a connection to resist a single force were thought of, however only those that could meet the two criteria in some capacity were used for further analysis to pick the most suitable prototype to construct and test. The selected ideas included:-

- **IDEA 1 -** A single high grade timber plank jointed into the face of the connecting slabs
- **IDEA 2 -** A plank spanning the length of the slab with nails or screws driven directly into each member.
- **IDEA 3 -** A large dovetail block fixed into a pre-cut joint in the slabs
- **IDEA 4 –** 140 mm deep laminates on the outside edges of each slab with bolts connecting them together underneath the slab.

- **IDEA 5 -** Bugle Head batten screws skewed into the slabs and counter sunk below the surface.

Reference: See Appendix F for diagrams of each of these ideas.

6.1.2 Selection using weighted decision matrix

The conceptual connection ideas were evaluated to determine which best met all of the requirements of a slab unit connection. This was done using a weighted decision matrix as shown in Table 15. Each of the ideas was compared with each of the criteria which have to be met by a connection in order to be practical and effective. Numbers were used as the weighting factor with five representing an excellent fit to the criteria, and one representing a very poor fit to the criteria. The score of each idea was than determined by summing each of the criteria ratings for each idea to get a total score for each idea.

From this evaluation it can be seen that the bugle head batten screw concept made an excellent fit to all required criteria, followed by the spanning plank concept which did not fit all the criteria to the same extent. Based on this decision making, the bugle head batten screw concept been perused.

Table 15 – Connection method evaluation matrix

IDEA	**Criteria Rating**					
	A	**B**	**C**	**D**	**E**	**Total**
1	1	1	5	4	3	**9**
2	3	5	5	3	3	**19**
3	2	3	1	1	2	**9**
4	4	3	1	2	2	**12**
5	5	5	5	5	5	**25**

6.1.3 Bugle head batten screw testing methodology

The aim of the connections investigation is to establish a method of joining two adjacent slabs that is stronger than the glue itself, and the low grade timber.

The method of constructing the joint involved marking the centre of the second laminate in from the edge of the slab unit and drilling a countersinking hole so that the heads of the screws were just below the surface of the slab, and would penetrate to the depth shown in Figure 34 .

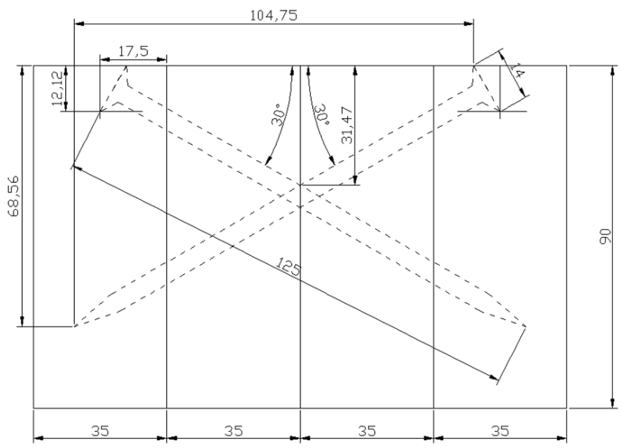


Figure 34 – Cross section of chosen connection method

A 4 mm pilot hole was then drilled at 30 degrees to the horizontal into the slab to guide the screws in at the correct angle. The pilot hole did not extend through the edge of the slab unit. The two main purposes of this starter hole were to ensure the correct angle was achieved and a looser level of friction was present in the slab which the screw was being driven from to ensure that all screws pulled the slabs together to their greatest capacity. After the pilot holes had been created, 125 mm bugle head batten screws were driven into the holes and through into the adjacent slab as shown in Figure 35. Bench clamps were applied over the span of the slab to ensure that the screws pulled tight and formed a bond between the slabs equal to the screws capacity.

Figure 35 – Arrangement of bugle head batten screws.

The method used to ensure that all screws entered at the correct angle was to cut a waste piece of pine at 30 degrees, and use this surface to run the drill into the countersinking hole at the set angle as shown in Figure 36. This initial hole angle was then used as a guide to complete the clearance hole which only ran from the starting slab to the interface between slab units. This helped to ensure that the screws embedded in the adjacent slab unit to their maximum capacity.

Figure 36 – Creating the correct angle for the screw joint.

Screws were driven into at 200 mm centres from both sides of the joint into the opposing slab. The joint lines were staggered so that one screw was passing into the opposing slab at every 100 mm throughout the length of the slab as shown in Figure 37.

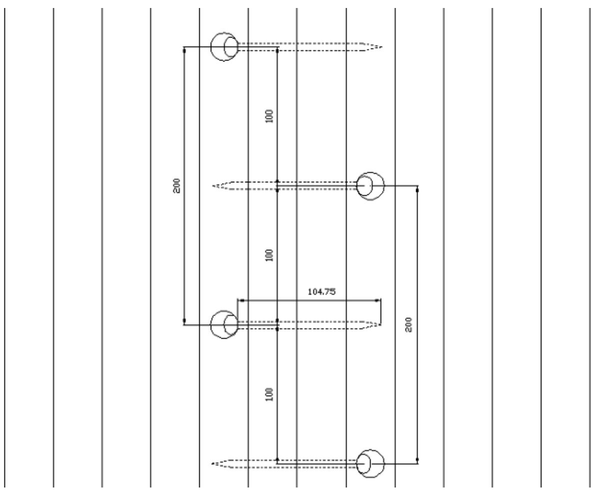


Figure 37 – Plan view of chosen connection system

6.1.3.1 Two slab bending test

To do this the initial test was two slabs joined together with 14G 125 mm bugle head batten screws skewed into the slabs at 200 mm centres from both slabs into the adjacent slab as shown in Figure 37.

Once the slabs were connected, they were arranged under the testing rig to meet the dimensions of testing as used in previous individual sample and slab tests. Heavy duty "I" beams and Square sections were used to get the required heights and spans so that the appropriate loading support conditions were met. Figure 38 depicts the testing setup applied.

The system 5000 was then connected with two string ports and a load cell, to measure the applied load, and the deflections of the slab being loaded, and the slab which was connected to the loaded slab with no load applied, to obtain a measurement in the difference in deflection, or deflection passed through the connection as load was applied.

Figure 38 – Loading setup for two slab bending test.

6.1.3.2 Three slab shear and bending test

The three slab connection test consisted of three individual slab units joined at the edges using the connection method shown in Figure 34 and Figure 37. In order to apply the loads at the required intervals over the width of one slab, heavy duty solid steel sections were cut to 420 mm lengths to apply a line load over the width of the centre slab only. A heavy duty steel section was used to ensure that zero deflection occurred within the line load bar resulting in an even distribution of applied force across the distribution of the slab.

The supports were setup to provide a vertical restraint at the ends of the outside slabs only, with the centre slab being free to push down through between the other two if a shear failure happened before the bending failure. To do this heavy C sections were placed on a long supporting beam so that the inside ends of the heavy C sections were supporting the laminate on the outside slabs that is adjacent to the centre slab. This was done to initiate a shear failure along the connection between the centre slab and each of the outside slabs, should the shear be the first failure mode to occur.

Bench clamps and G clamps were also provided at appropriate points within the test setup to avoid the displacement of any of the supporting structure during loading. Specifically, they were aimed at lateral displacement of supports and the inwards rolling of the C sections that was likely to occur as the load on the slabs was increased.

The heavy duty yellow stools shown in Figure 39 were used to create a testing surface level to the besser bricks used sit the testing supports on the far side of the slab. This was done by raising the supporting surface of each stool via its threaded plate configuration until the levels of all four supporting members were identical.

Deflections were measured at the centre of the middle slab which has the load applied and the centre of the outside slab which is situated at the left hand side of the centre slab as shown in Figure 39. This was done to record the difference in deflection between the loaded central slab and the connected outside slabs. The total load applied was also measured via a load cell placed at the connection between the jack and the spreader bar. This ensured that a measure of the total load transferred from the spreader bar into the two heavy duty steel sections used as loading points was obtained accurately. To ensure that the load applied by the two loading points was even, the centre of the slab area was placed directly in line with the axis of the jack, and the loading points spaced at identical distances from the centre of the slab to match the loading setup used in the strength testing of individual low grade slab units.

Figure 39 – Loading setup used on three slab test shear and bending test.

6.1.3.3 Batten screw shear capacity testing

Due to the batten screws passing though a shear plane in the connection between slab units, testing was undertaken on the capacity of screws in shear in order to determine the total contribution each screw could have within a joint resisting shear. This test was done by creating two pieces of plate steel with a hole drilled through them slightly larger than the diameter of the screws to be tested. This was done so that the screws could be inserted though the two holes without the creation of excessive heat which may change the material properties of the screws. The two plates were used to act as a material for the materials testing system machine to grip, and also for the precise shear plane created between the plates when a screw was placed through the hole in both plates.

Waste materials from previous testing were used to create two blocks of timber which could be used to hold the screw in the correct position for shear failure to occur above the thread in each test specimen. The secondary purpose of the timber was to create a tension within the screw that is identical to that of a screw driven into pine, as the combination of tension, compression and shear forces is present within the batten screw connections between slab units. This ensures that the result obtained is as realistic as possible to that of the expected shear capacity of screws when used in a low grade timber connection.

Shear capacity testing of each sample was than measured using the materials testing system machine. Each sample was inserted through the two steel plates tightened with the timber blocks. An electric drill with a slipping clutch mechanism was used to ensure that the each screw was tightened to the same value of torque within low grade timber block. The screw inserted into the shear testing rig appeared as shown in Figure 40.

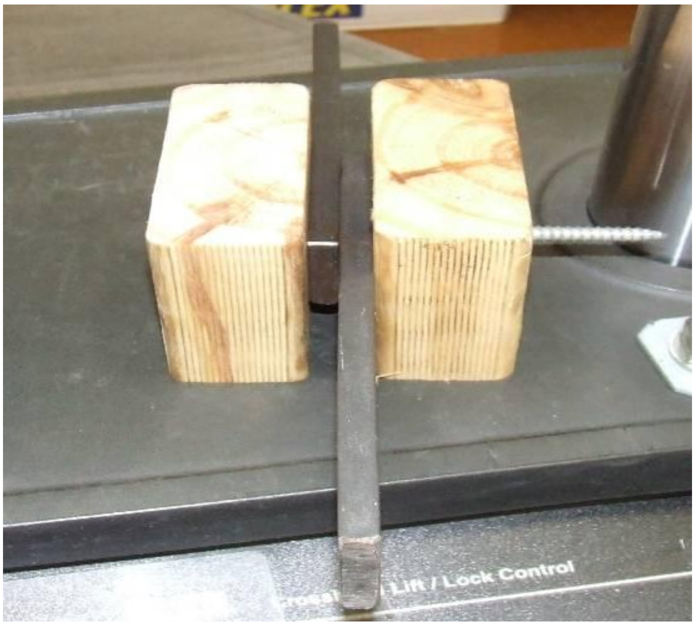


Figure 40 – Batten screw shear testing rig

The testing rig was then inserted into the testing machine. This was done by placing the steel plates in the grip jaws as shown in Figure 41. The tests were then initiated with a data logger recording the axial tension and deflection within the shear plane of each screw up to the point of shear failure. This data was then retrieved from the electronic data base and analysed for the required information.

Figure 41 – MTS machine used for testing the bugle head batten screws

6.1.3.4 Individual member shear capacity testing

This experiment was done with the intention of determining the capacity of a single member within a slab subjected to a pure shear force. This was done by loading one individual member and supporting the members adjacent to it as shown in Figure 42 to prevent deflection within the slab and create a shear loading condition along each glue lamination joint.

Figure 42 – Supports used in the individual member shear tests

The load was then applied through a steel section with a width less then 35 mm along the individual member to be tested. Supports were placed to ensure that only the individual member being loaded could be displaced vertically as shown in Figure 43. The heavy duty steel sections used for the three slab tests were also clamped on top of the slab unit at each end to ensure that transverse bending could not occur as result of the vertical deflection restraint systems placed and the magnitude of the load to be applied. Besser bricks were used to support the two custom made deflection supports depicted in Figure 43. These supports were placed at one third intervals under the slab to prevent any deflection that is created as a result of the force applied and still allow the member being loaded to fail in shear as intended.

Figure 43 – Setting up the individual member shear capacity test.

The span used in this test was not relevant due the shear strength over the length of the slab being measured rather than the bending strength. The supports restraining the members adjacent to the member being loaded from vertical displacement were provided at the same distance apart as the bending tests. This was done for consistency with previous tests, and a known length over which the shear force was being applied to the glue laminations.

6.1.3.5 Three slab pure shear test

This test was undertaken to provide information on the capacity of a bugle head batten screw joint between two slabs as a function of the number of screws within the joint per meter. This test was done using three slabs joined together at adjacent faces as shown in Figure 44.

The restraint system applied was devised to allow only shear failure of the centre loaded slab along the connection lines to occur. This was done by creating vertical deflection restraints at the ends of the slab identical to that used in the three slab shear and bending combination test. Additional supports in the centre thirds of the span were also provided to prevent bending as a result of the load applied. These were pieces of waste timber cut to length and placed on besser bricks on the unloaded side of the joint lines as shown in Figure 45. A solid steel member was also placed across the ends of the slab to prevent transverse bending moments developing as a result of the vertical deflection as shown in Figure 44.

Figure 44 – Testing setup used for the three slab pure shear test.

Screws were then placed in each slab at even intervals to provide consistency in the failure and test results. Initially four screws were placed in each joint connecting adjacent faces totalling eight screws resisting the shear force applied. Each joint consisted of two screws driven from the centre slab into the outside slab and two screws driven from the outside slab into the centre slab. This was done to ensure that there was a balance between the number of screws subjected to a combination of tension and shear and a combination of compression and shear. Load was the only factor to be recorded due to the deflection of the slab being restrained by supports. This was done using a load cell in the same manner as the individual member shear capacity test.

This test was then repeated with six screws in each joint connecting adjacent faces. To keep the results consistent the centre slab was staggered horizontally to ensure that the screws went into fresh timber rather than same hole or areas within the vicinity of the screw joint used in the previous test. This was done to develop the required relationship between the number of screws used in a joint per meter and the total load capacity of the joint per meter.

Figure 45 – Supports used in three slab pure shear test.

6.2 Results

The results obtained from the various tests undertaken prove that the 125mm bugle head batten screw is a very effective means of creating a connection between slab units to resist the forces applied in a standard floor loading situations. The two and three slab tests undertaken were aimed at determining the effectiveness of the screw connection in bending, shear and a combination of bending and shear. The results obtained have shown the joint design required to exceed the strength of the slab units, and the spacing of screws required per meter to resist a load of given magnitude per metre of slab unit.

The bugle head batten screw connections appeared as shown in Figure 46 prior to destructive testing. This consistency in the construction of connections has yielded results which correlate well between separate test types. This will be expanded on further in the discussion section.

Figure 46 – Bugle head batten screw connection prior to testing.

6.2.1 Two slab bending test

The results obtained from the two slab bending test indicate that the connection method has sufficient performance to prevent differential separation of slabs during a loading situation. The results show that the spacing and orientation of batten screws used is sufficient to take an applied load greater than that of the capacity within a single slab.

The bending load transferred through the connection into the free slab was not large enough to cause any failure within the free slab. The loaded slab did fail in an identical manner to the individual low grade sample units testing. All failures within the loaded slab were partial and generally occurred at discontinuities within the wood structure such as knots and resin shakes as show in Figure 47.

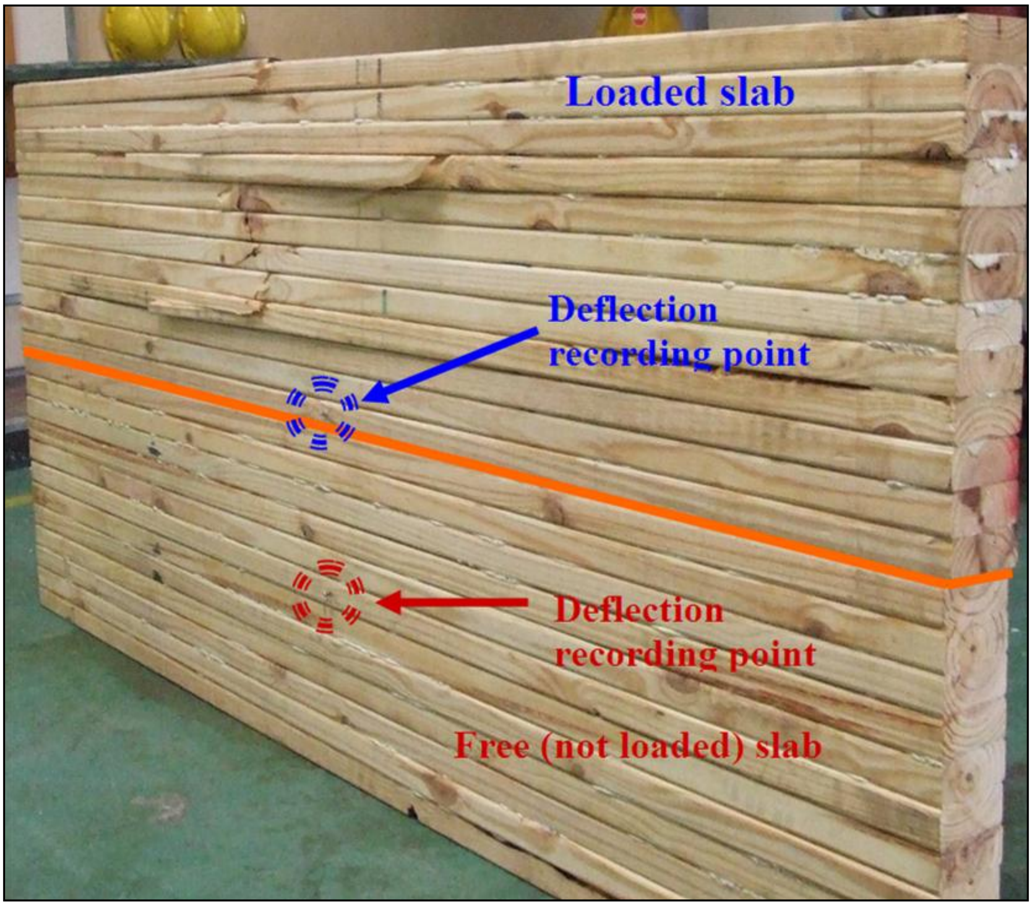


Figure 47 – Two slab test samples after failure.

The consistency in deflection between the loaded and free slab units demonstrate that the connection is capable of transferring the load between slab units without any differential deflection occurring at the connection line. At the maximum load taken by the loaded slab, the difference in deflection between the connection laminate of the free slab and the middle of the loaded slab was 13 mm.

A visual inspection of the deflection difference between slab units during testing confirmed that the connection worked perfectly as intended. The two slab test also demonstrated the slabs ability to return to a position of zero deflection after the load is removed despite the partial failure of members within the loaded slab. From this particular test it can be seen that the maximum load taken by two connected slab units prior to any partial failures is 95 kN. This is taken from the small discontinuity shown in Figure 48.

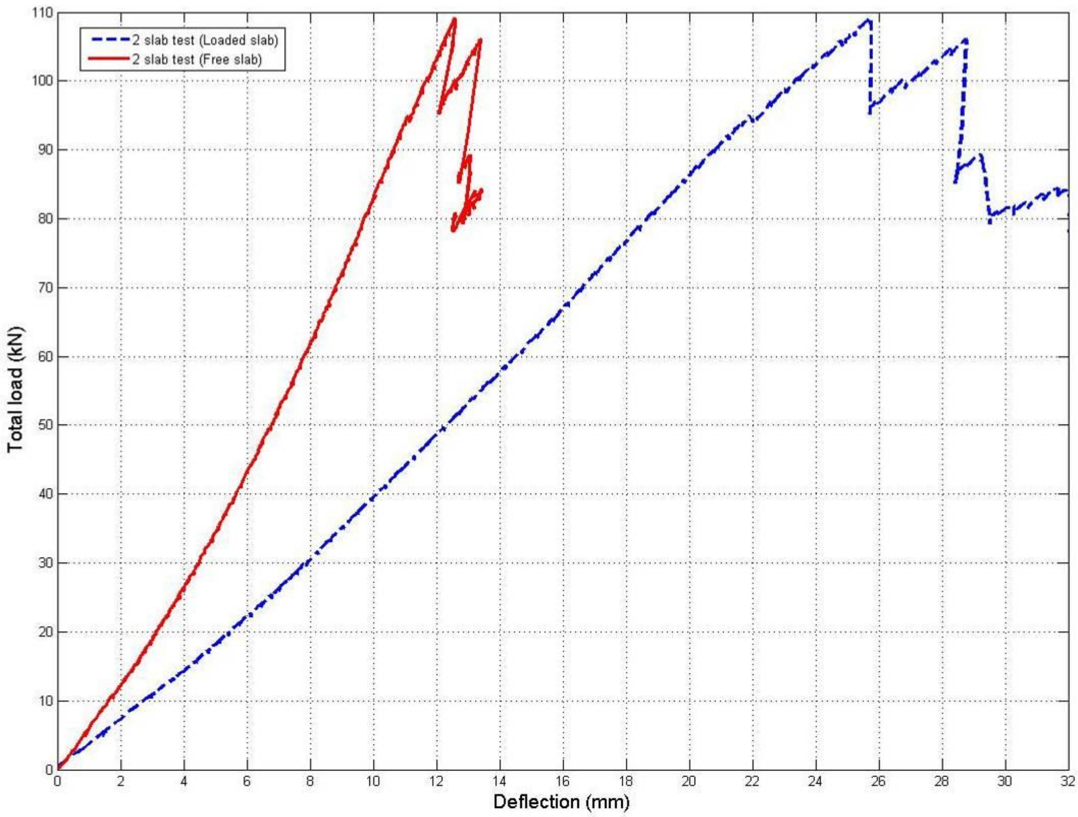


Figure 48 – Load vs deflection curves for the two slab bending test.

6.2.2 Three slab shear and bending test

The three slab shear and bending test provided a situation which allowed the middle slab to be subjected to a shear force along the join lines and also deflect between the supports. No restraint to rotation was provided at the supports so that a central deflection which is comparable to previous slab tests could be obtained. As a result of this, a bending moment was developed in the transverse direction resulting in the sudden bending failure shown in Figure 49.

This failure occurred solely along the glue lamination joint between the loading points, and in a combination of the glue lamination joint and a defect within in the timber between the loading points and the vertical deflection restraint provided to the two outside slabs. The individual member that the failure occurred in came from the central axis of the tree as can bee seen in the direction of the end grain which is circular around the central pith.

Figure 49 – Failure mode for three slab shear and bending test.

The load deflection relationship obtained between the central loaded slab and the free outside slabs also proves that the connection was ample in preventing differential deflection and shear failure along the join line up to a load of 81 kN. Minimal warning signs presented themselves prior to the violent bending failure that resulted from a bending moment developing along the axis perpendicular to the direction of the individual members.

The deflection experienced in the unloaded slabs in the three slab shear and bending test was much greater than that of the two slab bending test as seen in Figure 50. This is due to the symmetrical nature of the loading in the three slab test compared to that of the two slab test.

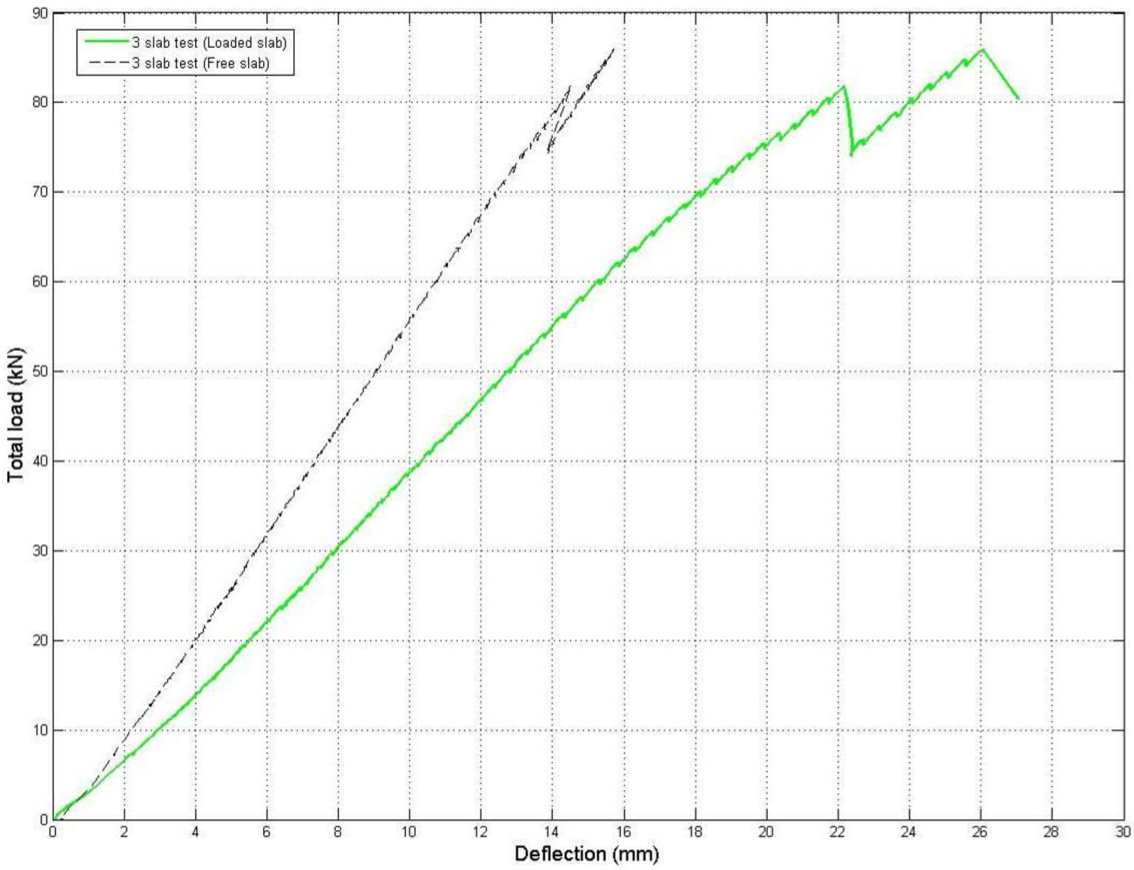


Figure 50 – Load vs deflection curve for three slab shear and bending test.

6.2.3 Batten screw shear capacity testing

The shear capacity testing of the screws was used to determine the capacity of a single screw in a timber joints subjected to a shear force. All test samples failed above the thread as intended so that the shear area could be accurately determined. The shear capacity obtained exceeded 1.6 kN in all specimens as shown in Figure 51. The friction developed between the two metal plates that form the shear plane contributed to the total force required to cause the screws to fail in shear. The test procedure used for each specimen was very consistent as a result of the simple testing setup and machinery used and the consistency of steel.

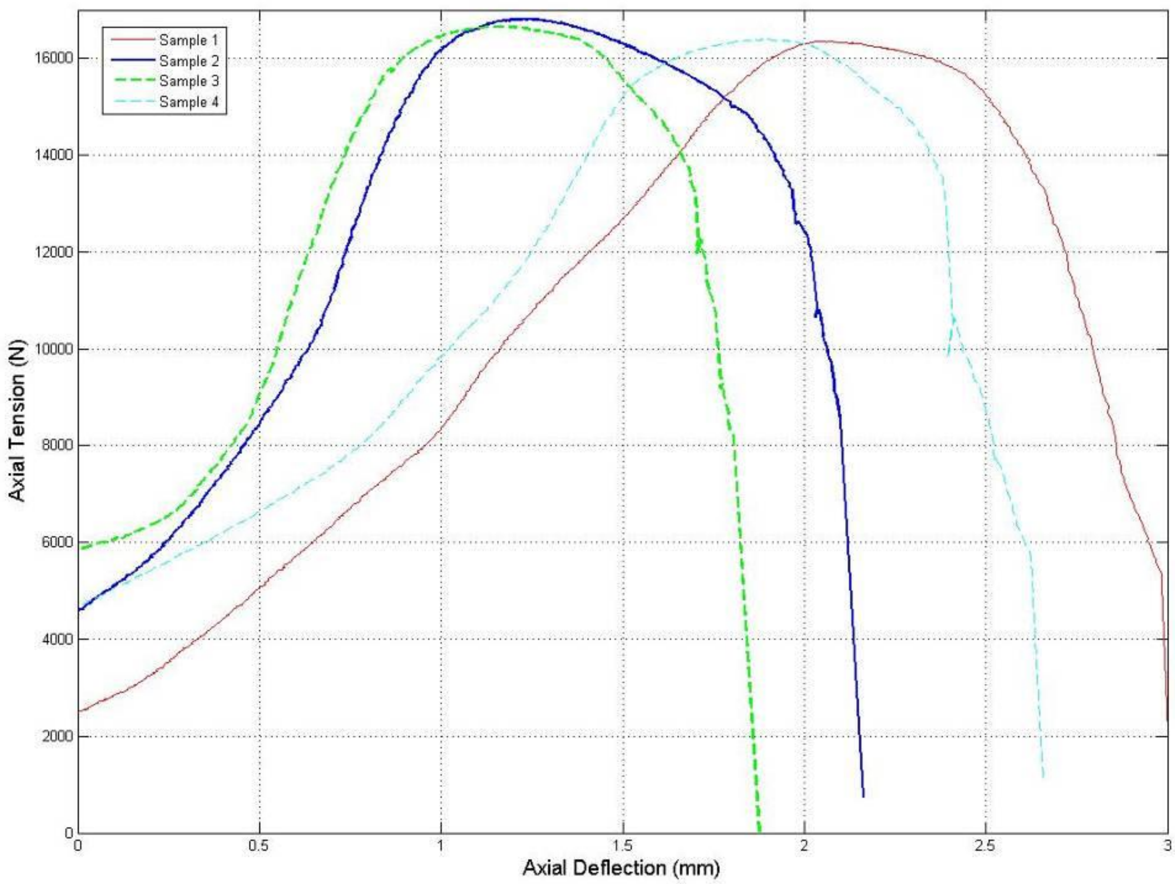


Figure 51 – Batten screw shear test results.

6.2.4 Individual member shear capacity testing

The testing of individual members within a low grade slab element was done in order to determine the strength of the glue lamination joints. This information is required to determine the limiting criteria for the design of connections. A connection with strength in shear greater than that of the laminations is greater then the strength required due to the slab failing in shear before the connection between slab units.

This test returned range of results which demonstrated that the low grade timber will fail due to the crushing force in some cases before the glue lamination will fail in shear. This is due to the orientation of the growth rings within the cross section of the timber member. The angle of the growth rings within the cross section of the individual member is determined by the location within the log from which it has been cut as shown in Figure 52.

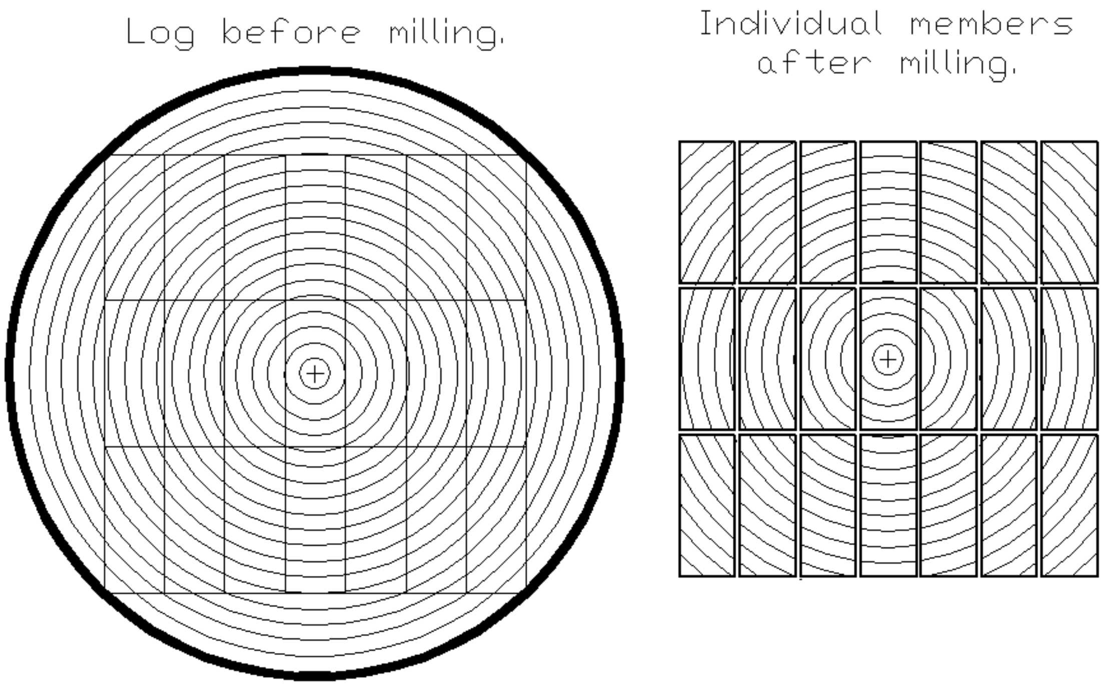


Figure 52 – Cross section growth rings within individual members.

Test results revealed that timber samples with growth ring grain in directions other than vertical failed at a load much lower than that of the sample containing the growth ring that was mostly vertical as can be seen in Figure 53. The only specimen that failed in shear along the glue lamination joint as intended was specimen 4 which has a mainly vertical growth ring direcion. Hence this test has been used to derive the strength of the glue lamination subjected to a shear force.

Figure 53 – Shear failure along the glue lamination.

All other members with angled grain failed through crushing of the timber as a result of the load applied along the member to create shear failure. All timber crushing failures occurred as a result of apparent shear forces developing along the growth rings that have a tangential angle within the proximity of 30 to 60 degrees. This result demonstrates that the majority of the low grade timber specimens are weaker than the actual glue when subjected to a shear loading situation. The relationship between grain direction and failure load cannot be quantified with a strong correlation due to the variability induced by the presence of defects throughout the length of the timber. Testing has shown that samples with symmetry about the Y axis of an individual member cross section are more likely to fail in shear along the glue lamination lines rather than crushing or shear within the individual member.

The results of the individual member shear testing shown in Figure 54 demonstrate the high variability in peak load that can be taken by an individual member subjected to a shear force. All forces for this testing were recorded via a load cell connected to the System 5000 which was recording the data regular intervals. These intervals represent the dimensionless incremental counter values used on the X - axis shown in Figure 54. This approach was taken due to the fact that no deflections could be recorded as a result of the supports creating the shear loading situation.

The load taken to create a pure shear failure along the glue lamination lines either side of the member was recorded as 221.61 kN. The rise and fall within the test plots is due to the load decreasing slightly during the elevation of the jack pump handle ready for the next stroke.

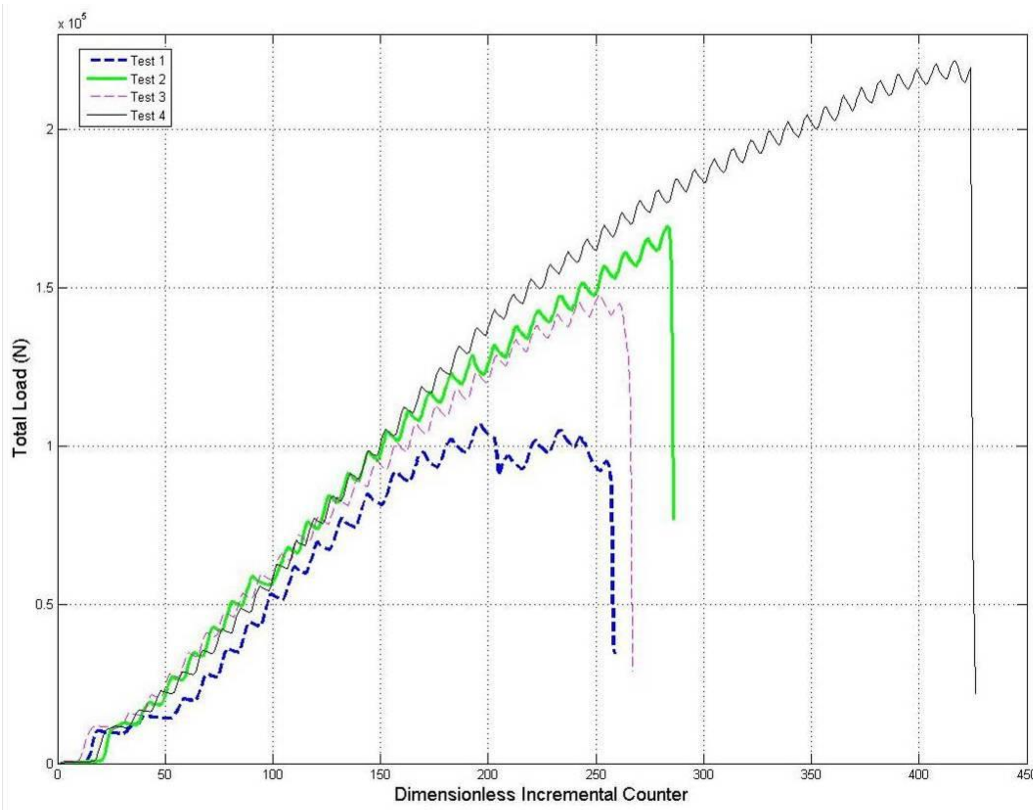


Figure 54 – Individual member shear capacity test results.

6.2.5 Three slab pure shear test

This test was undertaken to determine the shear capacity of a loaded slab unit connected between two free slab units based on the number of screws in the connection. The results obtained from the two tests undertaken reveal a similar loading pattern and two separate peak loads which is information required from this experiment.

Testing also revealed that screws will fail in shear sooner then they will pull out of the timber they have been inserted into. The shear plane for each failure was at the point were the screw passed from the clearance hole into the solid timber when they were inserted. This is shown within the inset picture of the screws in Figure 55. The screws that have not failed in shear demonstrate a point of contra flexion which indicates the position where shear failure is going to occur as a result of the loaded slab deflecting downwards between the two outside loaded slabs.

Figure 55 – Failure of connection in shear.

All connections were made in accordance with the steps set out in the methodology section with the number of screws in each joint reduced and kept to an even number. The graph shows the results for one connection line either side of the middle loaded slab with four screws used in the first test and then six to develop the relationship.

This resulted in a total of 8 screws connecting the loaded slabs to the free slabs taking a peak load of 49.722 kN and a total of 12 screws taking 71.556 kN over a loaded length of 1.62 m. The symmetry in the placement of screws and the loading of the slab show a linear relationship between the number of screws and the maximum shear load which can be taken by the slab. This will be further analysed in the discussion section. The similarity in loading behaviour based on the number of screws inserted can be seen in Figure 56.

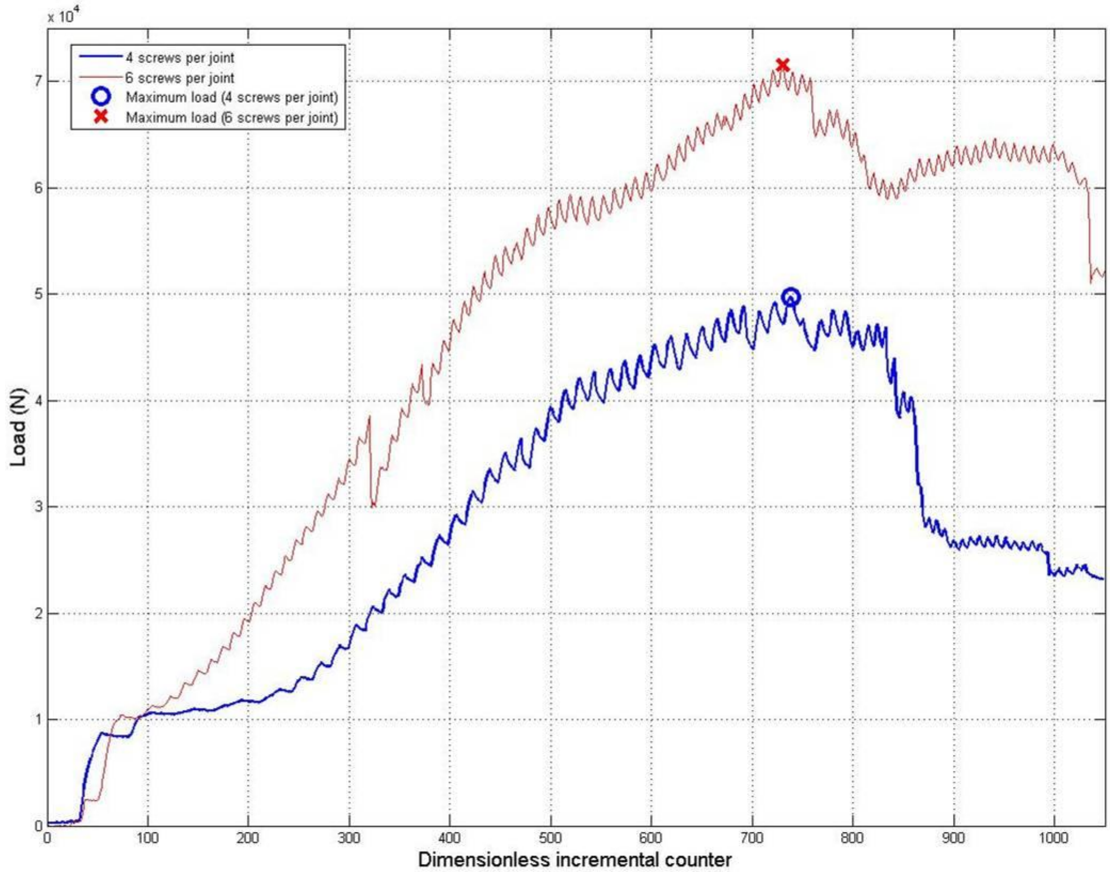


Figure 56 – Test results from three slab pure shear test.

6.3 Discussion

The results obtained from the testing of bugle head batten screws used to connect slab units has revealed consistencies in the performance of the connection in a variety of loading situations. Within the Two and Three slab testing of the connections performance under pure bending and a combination of bending a shear, it was seen that the connections created with the batten screws are much stronger than the strength of the low grade timber when subjected to the applied forces.

This resulted in a requirement to determine the exact capacity of the batten screw joints with a varying number of screws applied in each joint. This is due to the complexity in analysing the connection theoretically. Analysis could determine only the force component applied to each screw, and the combination of forces carried by a screw in the connection depending on its orientation relative to the loaded and free slabs. The complexities an analysing this connection arose form the lack of information on the pull out capacity of a single screw embedded in low grade pine, and the ability of a single screw to resist shear forces. A sample of screws was tested in shear only to determine their capacity in shear to quantify the capacity of a joint subjected to pure shear alone based on the assumption that shear failure will occur prior to the screw pulling out of the adjacent low grade slab.

Consideration given to the combination of forces carried by a screw revealed that the screw driven from the free slab into the loaded slab would undergo a combination of tension and shear whilst the screw driven from the loaded slab into the free slab would undergo a combination compression and shear when forces were applied to the loaded slab as shown in Figure 57. Therefore the number of screws driven from the loaded slab into the free slab and vice versa had to be even in order for the joint to be balanced. This balance ensures that the number of screws undergoing tension and shear is equal to the number of screws experiencing compression and shear.

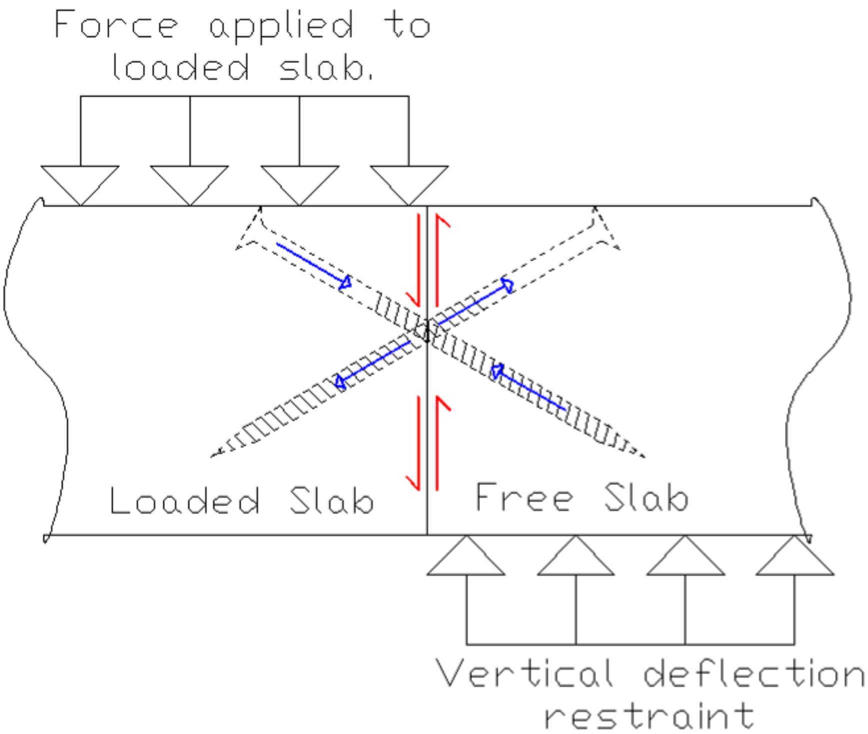


Figure 57 – Forces present within a batten screw connection.

If an odd number of screws was used in a connection it would result in more screws undertaking one of the combinations of forces than the other combination of forces which is dependent on their orientation relative to the loaded and free slabs. The simplifying assumptions of shear occurring before pull out capacity was reached, and the balance of tension and compression forces within each screw used in a loaded joint created from batten screws was then confirmed to be correct in the analysis of connection combining three slab units subjected to pure shear. Further analysis on the performance of the joint in various situations will be presented in the following sections.

6.3.1 Combined actions testing.

The combination of results obtained from two slab bending test and the three slab combined shear and bending test revealed that the load deflection characteristic for the loaded slab in each experiment was identical from a load of 0 kN through to 35 kN where the load deflection characteristics of the two tests begin to diverge. This is due to the slabs having a slightly different stiffness which resulted in differing deflections in the higher load range, and the onset of two way bending in the three slab test.

It can also be sent that the free slab in the combined shear and bending test deflected further for an equivalent load than that of the two slab pure bending test. This is not the expected outcome due to the combined stiffness of the three slab units being greater than the two slab units. This result is most likely due to the fact that the outside edge of the loaded slab in the two slab unit test deflected further than the inside edge due to the presence of the connected free slab. In the three slab unit test the loaded slab deflected by an even amount on both connected edges due to the presence of a connected free slab on each side. Hence the overall deflection experienced by the free slabs in the combined shear and bending test is greater than the deflection within free slab of the two slab unit pure bending test as a result of the balance created by only having a slab unit connected either side of the loaded slab unit as shown in Figure 58 .

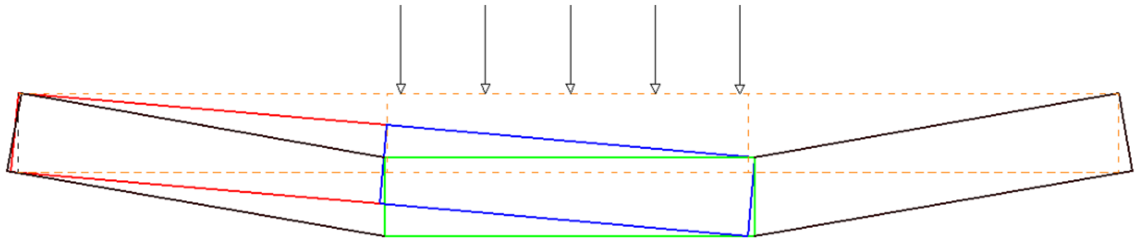


Figure 58 – Mid span deflection cross sections

Figure 59 describes the characteristics of each test undertaken to determine the ability of the batten screw connection to withstand a variety of applied forces. The three slab shear and bending test failed at a lower load than the two slab test due to induced bending stresses perpendicular to the direction of the individual members within the slab units. This could have been avoided however providing restraints to prevent this would also provide restraints to rotation about the supports which would limit the central deflection reading and make it non comparable to the two slab pure bending test.

The point of divergence between the two slab test loaded slab and the three slab test loaded slab shown in Figure 59 represents the point where two way bending within the slab was initiated due to the configuration of the supports which was intended to allow both shear and bending to occur within the slab unit connection.

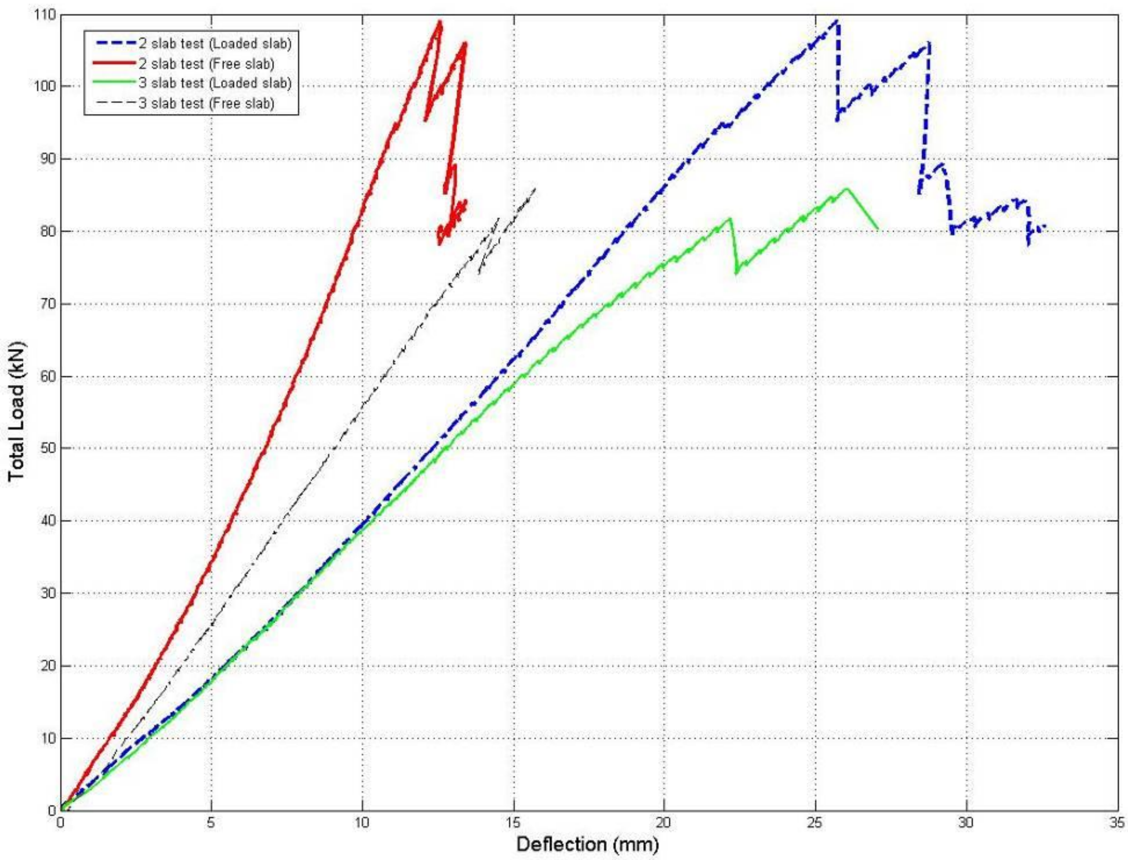


Figure 59 – Results comparison between two and three slab test.

6.3.2 Batten screw shear capacity testing

The testing of the batten screws used for the connection in shear revealed that they are very consistent in resisting shear force. The shear area tested was that perpendicular to the screws longitudinal axis which is not the exact shear area present within the low grade slab unit connections due to the screws being skewed at 30° to the horizontal plane. Each of the four samples tested exceeded a capacity of 16000 N over this shear area, resulting in the shear capacity of the screw as shown in equation 13.

$$\text{Shear Capacity} = \frac{\text{Force}}{\text{Area}} = \frac{16000}{\frac{\pi \times D^2}{4}} = \frac{16000}{\frac{\pi \times 5^2}{4}} = 815 N/mm^2 \quad \textbf{(13)}$$

The total capacity of an individual screw in a low grade timber slab unit connection can be found by multiplying the capacity found in Equation 14 by the shear area of a screw skewed at 30° to the horizontal. The shear area is determined in accordance with equation 14.

$$Area = \pi \times \frac{\frac{5}{\cos(30)}}{2} \times \frac{5}{2} = 22.6725 mm^2 \quad \textbf{(14)}$$

Therefore the shear capacity of a 14G 125 mm bugle head batten screw skewed at 30 degrees to the horizontal plane is:

22.6725 x 815 = 18478 N.

This value is representative of the number of screws that could be used in a slab to allow shear failure, and was used to create physical models that would fail at low loads to develop relationships between load and failure based on physical testing.

6.3.3 Individual member shear capacity testing

The results obtained from the test to determine the capacity of the glue lamination joints in shear showed that the member subjected to the shear force required a straight and vertical growth ring orientation. Test results varied quite significantly due to the different growth ring orientations which appear to determine if the timber will fail as a result of the shear force applied before the glue lamination joint will fail. An example of an individual member failing prior to the glue lamination joint failing in shear is shown in Figure 60. In this example the low grade timber defects have contributed to the failure which further reduces the timbers capacity to resist a load intended to create shear failure along the glue lamination lines.

Figure 60 – Failure due to curved end grain.

Only one single test did create the desired failure due to the selection of the most appropriate member to load as the trend became visible throughout the testing process. This member failed at a peak load of 221.6 kN. Therefore the shear capacity of a single glue lamination line per meter length of slab is given in Equation 15.

$$\left(\frac{221611}{2}\right) \div 1.62 = 68398 N/m \tag{15}$$

It is understood that this value is not representative due to it being obtained from one single successful test. It is the value which results in most low grade timber samples failing due to crushing prior to a clean shear failure along the glue lamination lines. Therefore this result is indicative of the required shear strength to be exceeded by the connection if the shear load applied to any portion of the slab is to exceed this value.

6.3.4 Three slab pure shear test.

The three slab pure shear test was used to develop a relationship between the number of screws in a connection, and the total shear force that connection can withstand. Based on the testing of individual screw specimens, the force required to shear one screw inserted in the connection at the set angle is 18.478 kN.

Neglecting any other possible failure modes such as the timber splitting around the joint or the screw pulling out of the low grade timber, the initial connection tested in shear contained four screws in each joint line to ensure failure happened within the slab at a load within the proximity of 18.478 x 4 = 73.912 kN per connection line. This value approximates to 73.912 / 1.62 = 45.6 kN per meter length of slab.

All connections had to have an even number of screws inserted from each direction for consistency with other test results. Therefore values of four and six screws per connection line were chosen as the most appropriate connections to establish the relationship between the number of screws and the total applied load.

Testing revealed that the relationship between the number of screws inserted into the connection and the total force required for the connection to fail in shear is a linear as shown in Figure 61. The data points in this graph are derived from the maximum force values obtained in section 6.2.5. As can be seen in this graph, the abundance of variables present within low grade timber appears to have little effect on the consistency of results obtained.

The results obtained were converted into units per meter length of slab for ease of interpretation and design based on Figure 61. This chart is intended for a slab loaded between two free slabs to create a shear loading on the joint. Therefore the total number of screws required per connection should be halved to ensure that the distribution of screws within the two connection lines is even.

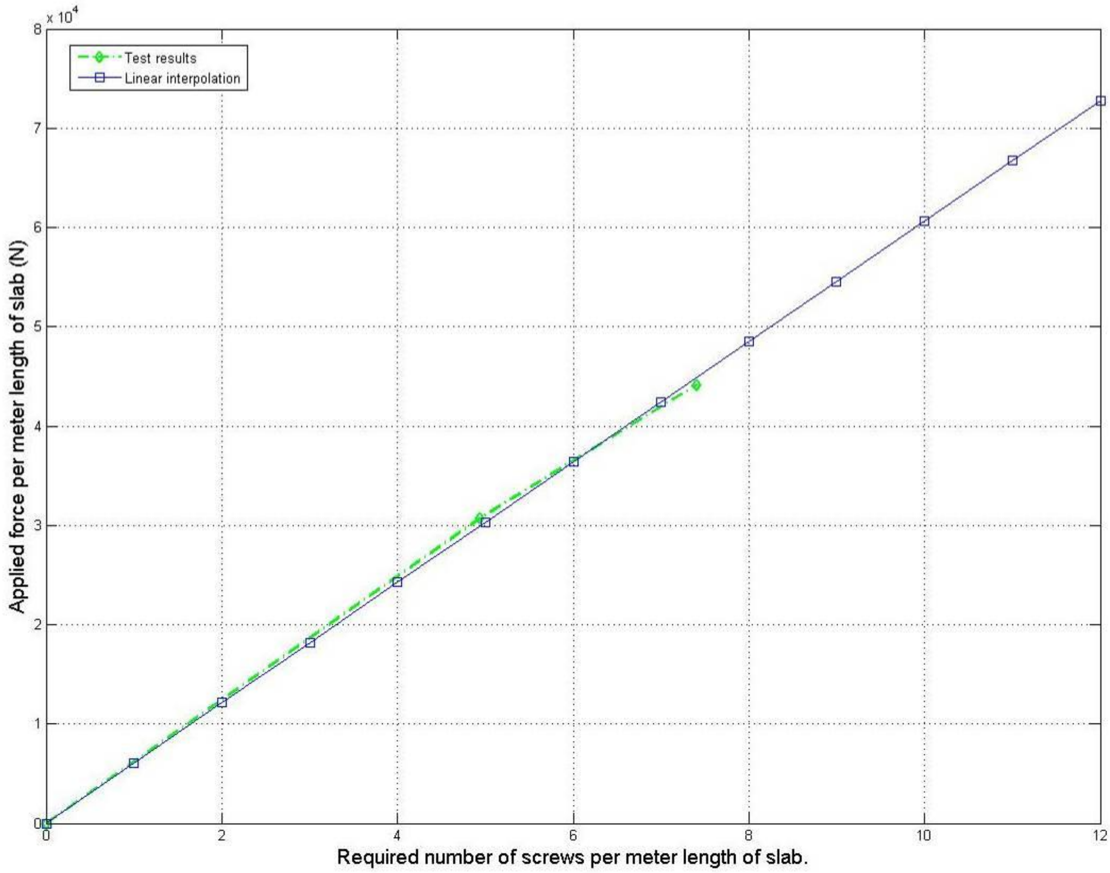


Figure 61 – Floor slab connections design chart.

A variety of failure modes occurred within the connection under shear, with the shear failure of individual screws being the main failure mechanism. The other source of weakness in the connection subjected to shear is the timber splitting through the counter sunk hole resulting in an effective shear failure.

Inspection of screws that did not fail fully in shear showed signs of a point of contra flexion developing at the interface between slab units. This would later be the point where shear failure occurred if more of the total load applied was distributed onto that screw. The reason for some screws not shearing off completely is the composition of the low grade timber surrounding the area where the screw in question is located, which allows local crushing around the screw, or splitting of the timber which houses the screw in position.

The pull out capacity of the batten screws was not exceeded in any connection test undertaken which indicates that shear is the major contributing factor in the strength of the joint. The relationship between the screws in a combination of tension and shear, and a combination of compression and shear requires a more detailed analysis in order to get a complete data set which fully describes the characteristics of a bugle head batten screw used as a connection alternative between low grade slab units.

The loading situation on a floor slab is not definite and can arise in a number of different manners dependent on the floor usage. The requirement for a floor to reach a set un - supported span will result in the bending force always being present within connections, and shear forces of considerable magnitude when large point loads such as piano legs are supported by low grade timber slabs.

6.4 Conclusions

Connections comprised of skewed 14G 125 mm bugle head batten screws can be made to exceed the capacity of the slab subjected to bending or shear. The design aid created for constructing appropriate connections between slab units presents a method of creating a connection with ample capacity to resist any force which is within the capacity range of the slab units themselves.

Although this is adequate for construction, it is based only on physical test results which show that the screws will fail in shear before the pull out capacity is reached. The shear capacity of a skewed bugle head batten screw is a function of the angle that it is inserted at, and hence the area of the elliptical shear plane created. The variation of the shear capacity within a screw subjected to a combination of shear and tensile / compressive forces is not fully understood, however analysis of the joint has revealed that this situation is present within a connection between slab units. Further analysis on this type of connection needs to be undertaken to develop a suitable theoretical method of calculating the required spacing and orientation of screws in order to exceed the predicted forces between individual slab units.

Investigation on connections between slab units has also shown that the direction of the growth rings in each individual member affect the ability of the slab to take loads in a two way bending situation. The direction of growth rings also contributes significantly to the capacity of a slab unit subjected to shear forces. The variability of the timber properties within a low grade timber slab also effect connection performance and should be investigated completely for use with theoretical connection design.

Chapter 7

Conclusions

7.0 Summary

This research project has investigated the structural performance of low grade timber laminated into slab units to be used as a flooring system. A full analysis from the behaviour of individual members and slab units through to the performance of slab units connected to form a floor slab has been investigated with the intention of determining the limitations of using low grade timber slabs in flooring applications.

A combination of analysed test results and modelling revealed that the critical limiting factor associated with low grade timber slabs used in a flooring application is deflection. A full analysis of various loading situations and clear floor spans has been undertaken to develop a deflection based design chart for low grade timber slabs applied to flooring applications.

The testing of connections between individual slab units has proven that a connection can be made which exceeds the strength of the slab in any combination of forces applied. Further testing and analysis provided a simplified method of joint design based on the load applied per meter length of the slab.

7.1 Achievement of project objectives

The following objectives have been addressed:

Reviewing the current use of laminated timber building technologies in other countries, to gain an understanding and appreciation of current technologies.

A literature review has been undertaken to examine prior work done on different facades of timber floor slabs which are created from individual laminated low grade timber members. Due to this paper being the first on the use of low grade timber being used in slabs as a flooring alternative, no literature has been found which can be used as a comparison to my findings.

Extensive work has been undertaken in the use of timber bulk timber laminated into a cross laminated product consisting of three or more layers, and the effects that timber quality and using glue lamination has on the over length of a structure comprised of such materials. Although it is clear that a sufficient amount of work has been done in the use of bulk timber members to act as structural elements based on company product marketing literature, research papers are not able to be interpreted due to the abundance of Scandinavian and German dialect used to compose these papers. Further information the various aspects of using laminated low grade timber as a floor slab alternative can be found in Chapter 2.

Acquisition of timber material properties data from Hyne with the aim of using a statistically representative set of data for the prediction of the slab behaviour during testing.

The timber material properties that are a valid sample for the source of the low grade timber used in the slab was obtained from Hyne for use in modelling the behaviour of low grade timber slab floors subjected to loading. Evidence of this can be seen in Table 5 and Appendix D. Extra information has also been obtained from Timber Queensland from a large database on the properties of Australian hardwoods which was used for the Grey Ironbark properties in the Strand7 parametric modelling shown in chapter 5.

Collect structural performance data by testing prefabricated timber slabs.

The characteristics of single low grade timber members and laminated low grade timber slabs were determined as a result of the testing work shown in Chapters 3 and 4. The major difference observed between the low grade timber members and the slab units comprising of low grade timber is the increase in consistency of the load deflection relationship.

The numerical results obtained and the observations taken from the behaviour of both forms of low grade timber display the fact that the glue used in the lamination of individual members to form low grade slab units is responsible for creating a load sharing system around areas of defects within individual members. This results in a significantly decreased variation in the load – deflection characteristics observed in the low grade timber slab units compared to that of individual low grade timber members.

Create mathematical computer models of the above ground flooring system using Strand7 to extrapolate data on the structural requirements for this system to be viable.

Chapter 5 focussed on the selection of appropriate modelling parameters, and the creation and use of Strand7 finite element analysis computer models to analyse the limitations of using low grade timber slabs as a flooring alternative. Results from this modelling highlighted that serviceability is the governing criteria in the design of floor slabs constructed out of low grade timber.

Multiple span and load comparisons were also undertaken for a low grade slab model and a standard flooring model in order to determine if the performance of the low grade slab units used a flooring method are viable compared to that of the current standard construction. This analysis was taken from a structural performance view point and concluded that the low grade slab has a greater weight than the standard flooring system, however the deflection response to all loading and span situations is less than that of the standard floor constructed out of bearers, joists and a flooring material.

Use the results from modelling to create a design aid for the use of low grade timber slabs in floor construction.

The structural characteristics of low grade timber floor slabs were obtained in Chapter 4. This information was incorporated in a range of Strand7 models as described in Chapter 5. These models were then used to collected load and maximum deflection data points over various spans with consistent loads applied. The result is a deflection based design chart for 90 mm deep floor slabs subjected to a variety of different load cases.

Due to deflection being the limiting criteria in the design of low grade timber floor slabs, deflections limit lines are superimposed on the chart so that it can be interpreted in accordance with the required deflection limit used in design.

Investigate, create and test methods for panel connection.

The investigation of connections subjected to the forces which occur between slab units is evident in module 6. Investigations revealed that it is possible to create a connection that exceeds the strength of both the low grade timber and the glue lamination lines between individual slab unit members. Investigations have also determined that there is a linear relationship between the number of bugle head batten screws in a joint, and the total shear force which the connection can withstand. Simplification of the connection and the use of this physical test has resulted in the creation of a connection design chart which can be used to determine the minimum number of screws required to resist a total shear applied load.

7.2 Major findings

As a result of the research work undertaken, the following major findings have been established:

- Low grade timber members subjected to loading are highly unpredictable due to the presence of excessive defects within the timber
- Low grade timber laminated into floor slab units results in a product which is very predictable when a load is applied, with a much smaller variation in results than that of individual members

- Extra head room is created as a result of the joists and flooring material being replaced by the slab.
- Low grade timber slabs are capable of taking loads with reliability that are typically endured by flooring systems when the span is within the determined limits.
- Low grade timber slabs compare favourably to the standard floor construction method of bearers joists and flooring materials based on the smaller deflection obtained from the low grade slab model. The disadvantage is the increased weight of the structure due to the bulk of timber used.
- Connections can be made between slab units which are sufficient to endure the loads that low grade timber slabs are capable of carrying. This allows floors of any desired width to be created from a group of low grade slab units placed side by side which acts as one single slab.

7.3 Future Work

The findings resulting from this research highlight several areas that are crucial to floor design and require further investigation. These factors have not been considered in this research paper with the exception of connection design which was given some simplified investigation to derive a set of proven realistic criterion for the connection of low grade slab units.

Further analysis of the connection method is required to fully understand the behaviour of low grade slab unit connections which is complex and still not understood in a comprehensive manner.

It is recommended that the following items be given detailed investigation in order to determine the commercial viability of using low grade timber slabs as a flooring alternative in Australia.

- Natural frequency
- Creep effects
- Moisture related effects on slab performance
- Further investigation on connection design between slab units
- Cost comparison
- Effects of two way bending

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Appendix A

Project Specification

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **Cameron James Clifford Summerville**

TOPIC: Structural Performance of Low Grade Timber Slabs

SUPERVISORS: Associate Professor Karu Karunasena

SPONSORSHIP: Hyne Timber
Faculty of Engineering and Surveying

PROJECT AIM: To investigate the structural performance of above ground Low Grade Timber Slab flooring systems and develop design criteria for slabs as a flooring alternative.

PROGRAMME: **(Issue B, 28th September 2009)**

1. Research the current use of laminated timber building technologies in other countries.

2. Obtain timber material properties data from Hyne to obtain statistically representative data related to low grade timber.

3. Collect structural performance data by testing prefabricated Low Grade Timber Slabs.

4. Create a mathematical computer model of the above ground flooring system using Strand7 to extrapolate data on the structural requirements for this system to be viable.

5. Use the results from modelling to create a design aid for the use of Low Grade Timber Slabs in Floor Construction.

6. Investigate, create and test methods for panel connection.

7. Submit an academic dissertation on the research.

AGREED: __________________(student) _________________(supervisor)

Date____/____/_______ Date____/____/_______

Appendix B

OH&S - Work Permit

SWP 001

FACULTY OF ENGINEERING & SURVEYING

WORK PERMIT

Permit No: 1111

This form is to be used where a Standard Work or Operating Procedure (SWP/SOP) indicates that a permit is required to use Engineering and Surveying facilities and equipment.

APPLICATION

Name of Applicant: Cameron Summerville

I wish to apply for approval to use the Faculty of Engineering and Surveying equipment and facilities:

Work Area / Location: Z4 Instron Area

(Work area staff must be consulted BEFORE using any facilities)

Equipment / Process: Elasticity testing of timber Slab

Relevant SWPs: – For Unit / Project: –

From (Start): 8:00 AM/PM Date: 01/08/09

To (Permit Expires): 8:00 AM/PM Date: 01/12/09

I certify that I have read and understand the requirements of the Standard Work Procedure applicable to this permit. I agree to comply with those requirements and any special precautions/instructions listed below.

Signature: Summerville **Date :** 26/09/09

APPROVAL

(To be completed by Work Area Manager/Supervisor)

Special Precautions/Instructions: Safety footwear & hardhat to be worn in Instron Area.

ALL WORK AREAS AND EQUIPMENT MUST BE CLEANED AFTER USE.

The above applicant has shown to me that he/she is competent to carry out the procedure and/or operate the equipment specified in this work permit. The Permit is granted for the period stated above.

Name: Daniel Eisike **Date:** 26/08/09

Position : Technical officer **Signature:** Daniel Eisike

THIS PERMIT MAY BE REVOKED AT ANY TIME.

Appendix C

OH&S – Purbond 514 MSDS

Purbond
Adhesive systems for engineered wood

*** MATERIAL SAFETY DATA SHEET ***

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NUMBER	142-941A
PRODUCT NAME	PURBOND ® HB 514 adhesive
Manufacturer	Purbond Inc. P.O. Box 8039 Tacoma, Washington 98418 USA Emergency Telephone: CHEMTREC: 800-424-9300 (24 hours) CHEMTREC International: 703-527-3887 (call collect)

2. COMPOSITION/INFORMATION ON INGREDIENTS

CHEMICAL FAMILY Isocyanate Adhesive

COMPONENT	CAS NUMBER	CONCENTRATION (% by weight)
Polymeric Diphenylmethane diisocyanate	9016-87-9	60 - 100

3. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

WARNING.
Respiratory irritant.
EYE IRRITANT.
RESPIRATORY SENSITIZER.
SKIN SENSITIZER.
Not readily biodegradable.
Brown Liquid Negligible odor

EYE	Will cause eye irritation.
SKIN CONTACT	Repeated and/or prolonged contact may cause irritation and skin sensitization.
INHALATION	Vapors and/or aerosols may cause irritation. May cause allergic respiratory reaction.

INGESTION	Low oral toxicity.

4. FIRST-AID MEASURES

EYE	Immediate medical attention is not required. Irrigate with eyewash solution or clean water until pain is relieved.
SKIN CONTACT	Immediate medical attention is not required. Wash skin with soap and water. Remove grossly contaminated clothing, including shoes, and launder before re-use. Discard shoes.
INHALATION	Immediate medical attention is not required. Remove to fresh air. If breathing is difficult, give oxygen. If breathing has stopped, give artificial respiration. Get medical attention.
INGESTION	Immediate medical attention is not required. Treat symptomatically and supportively.

5. FIREFIGHTING MEASURES

AUTOIGNITION	483°C
FLASH POINT	>200°C (Pensky-Martens Closed Tester)
EXTINGUISHING MEDIA	CO2; Dry Chemical; Foam
SPECIAL FIREFIGHTING PROCEDURES	Fire fighters should be equipped with self-contained breathing apparatus to protect against potentially toxic and irritating fumes.; Cool exposed equipment with water spray.
FIRE & EXPLOSION HAZARDS	Combustion will evolve toxic and irritant vapors.
HAZARDOUS COMBUSTION PRODUCTS	Decomposes upon heating to release toxic fumes of nitrogen oxides, carbon monoxide, carbon dioxide, and hydrogen cyanide.
LOWER EXPLOSION LIMIT (%)	Not applicable
UPPER EXPLOSION LIMIT (%)	Not applicable

6. ACCIDENTAL RELEASE MEASURES

SPILL AND LEAK PROCEDURES	Absorb spillages onto sand, earth or any suitable absorbent material. Sweep up and shovel into waste drums.

For safety and environmental precautions, please review entire Material Safety Data Sheet for necessary information.

7. HANDLING AND STORAGE

STORAGE TEMPERATURE	Ambient.
HANDLING/STORAGE	Store at room temperature. Product contains hazardous volatile ingredients which could accumulate in the unvented headspace of drums or bulk storage vessels. Open drums in ventilated area. Avoid breathing vapors.
SENSITIVITY TO STATIC ELECTRICITY	No
SPECIAL SENSITIVITY	Keep away from moisture.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

VENTILATION REQUIREMENTS	Provide local exhaust ventilation system to meet published exposure limits.
EYE PROTECTION REQUIREMENTS	Safety glasses, goggles or face shield to protect against splashing. Personal eye protection should conform to EN 166.
GLOVE REQUIREMENTS	Gloves are recommended due to possible irritation. Gloves should conform to EN 374.
CLOTHING REQUIREMENTS	Appropriate protective clothing and equipment is recommended to minimize skin contact with this substance.
CHANGE/REMOVAL OF CLOTHING	Remove contaminated clothing and launder before reuse.
WASH REQUIREMENTS	Wash before eating, drinking, or using toilet facilities.
RESPIRATOR REQUIREMENTS	Respiratory protection required if the exposure level is unknown or has been measured and found to exceed the published exposure limits. Self-contained breathing apparatus with a full facepiece operated in pressure-demand or other positive pressure mode.

9. PHYSICAL AND CHEMICAL PROPERTIES

PURE SUBSTANCE OR MIXTURE	Mixture
PHYSICAL FORM	Liquid
COLOR	Brown
ODOR	Negligible
ODOR THRESHOLD	Not available
PH AS IS	Not applicable
pH IN (1%) SOLUTION	Not applicable
OXIDIZING PROPERTIES	Not applicable
BOILING POINT	Not applicable
MELTING/FREEZING POINT	Not applicable
SOLUBILITY IN WATER	Insoluble
PARTITION COEFFICIENT (n-octanol/water)	Not applicable
VISCOSITY	6000mPas
SPECIFIC GRAVITY (WATER=1)	1.1
BULK DENSITY	Not available
EVAPORATION RATE	Not applicable
VAPOR PRESSURE (mmHg)	Not applicable
VAPOR DENSITY (air = 1)	Not applicable
VOLATILES	<1%
VOLATILE ORGANIC COMPOUNDS	<10g/liter
AUTOIGNITION	483°C
FLASH POINT	>200°C (Pensky-Martens Closed Tester)

10. STABILITY AND REACTIVITY

STABILITY	Stable
CONDITIONS TO AVOID	Avoid moisture contamination.

HAZARDOUS DECOMPOSITION PRODUCTS	Decomposes upon heating to release toxic fumes of nitrogen oxides, carbon monoxide, carbon dioxide, and hydrogen cyanide.

11. TOXICOLOGICAL INFORMATION

ROUTE OF ENTRY Inhalation; Skin Contact

CARCINOGEN	IARC (group)	NTP	OSHA Substance Specific Regulation
COMPONENT			
There is no evidence that this product poses a carcinogenic risk under normal conditions of handling and use.	N	No	Not Listed

CHRONIC (LONG TERM) EFFECTS OF EXPOSURE}

EFFECTS OF CHRONIC EXPOSURE	Although this product has not been tested for chronic effects it is judged as having a low order of toxicity based on component information. Use of good industrial hygiene practices is recommended.
TARGET ORGANS	Respiratory system; Skin
RESPIRATORY SENSITIZATION	Sensitizer. May cause allergic reaction.
SKIN SENSITIZATION	Sensitizer. May cause allergic reaction.

PRODUCT TOXICOLOGY

PRODUCT INFORMATION Not established.

COMPONENT	ORAL TOXICITY	NOTES ON ORAL TOXICITY
Polymeric Diphenylmethane diisocyanate	Oral LD50:Rat>15000mg/kg	Irritant and may cause nausea and vomiting.

COMPONENT	DERMAL TOXICITY	NOTES ON DERMAL TOXICITY
Polymeric Diphenylmethane diisocyanate	Dermal LD50:Rabbit>5000mg/kg	Repeated and/or prolonged contact may cause skin sensitization. Irritating to the skin.

COMPONENT	INHALATION TOXICITY	NOTES ON INHALATION TOXICITY
Polymeric Diphenylmethane diisocyanate	Inhalation LC50 (4hr):Rat490mg/m3	Exposure to high concentrations may produce lung damage. Extremely toxic. Respiratory sensitizer. Respiratory irritant. Symptoms may develop after several hours. Symptoms may include irritation to the eyes, nose, throat and lungs, possibly combined with dryness of the throat, tightness of chest and

difficulty in breathing.

COMPONENT	NOTES ON EYE IRRITATION
Polymeric Diphenylmethane diisocyanate	Will cause eye irritation.

12. ECOLOGICAL INFORMATION

POTENTIAL EFFECT ON ENVIRONMENT	Not readily biodegradable.
POTENTIAL TO BIOACCUMULATE	The product has low potential for bioaccumulation.
AQUATIC TOXICITY	None Established

13. DISPOSAL CONSIDERATIONS

WASTE DISPOSAL METHODS	Waste disposal should be in accordance with existing Community,National and local regulations.
EMPTY CONTAINER WARNINGS	Empty containers may contain product residue; follow MSDS and label warnings even after they have been emptied.

14. TRANSPORTATION INFORMATION

This section provided for general information only.
FOR NON-BULK SHIPMENTS.
FOR MORE COMPLETE TRANSPORTATION REGULATORY INFORMATION PLEASE REFER TO THE SHIPPING DOCUMENTS ACCOMPANYING THE SHIPMENT OF THIS PRODUCT.

DOT CLASSIFICATION Not applicable.

The information provided herein may not include the impact of additional regulatory requirements (eg, for materials meeting the definition of a hazardous waste under RCRA, hazardous substances under CERCLA, and/of marine pollutants under CWA or other similar federal, state or local laws) or any associated exceptions or exemptions under regulations applicable to the transport of this material.

15. REGULATORY INFORMATION

USA

TSCA — This product is manufactured in compliance with all provisions of the Toxic Substances Control Act, 15 U.S.C. 2601 et. seq.

SARA - Section 313 (Superfund Amendments and Reauthorization Act of 1986 - 40CFR 372)

	CAS NUMBER	CONCENTRATION (% by weight)
Polymeric diphenylmethane diisocyanate	9016-87-9	61.00000

CALIFORNIA PROPOSITION 65
WARNING: This product contains the following chemicals that are known to the State of California to cause cancer, birth defects or other reproductive harm.
Unless a concentration is specified in Section 2 of the MSDS, the below chemical/s are present in trace amounts.

COMPONENT	CAS NUMBER
None reportable.	

16. OTHER INFORMATION

HMIS® Hazard Ratings
HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings are not required on MSDSs by OSHA's 29 CFR 1910.1200, we choose to provide them as a service to our customers using HMIS®. These ratings are to be used only with a fully implemented HMIS® program. To deal adequately with the safe handling of this material, all the information contained in this MSDS must be considered.

NPCA recommends that employers must determine appropriate PPE for the actual conditions under which this product is used in their workplace. For information on PPE codes, consult the HMIS® Implementation Manual.

HMIS® is a registered trademark of the National Paint and Coatings Association (NPCA).

Health	Flammability	Reactivity
2	1	1

RECOMMENDED USE	Adhesive
MSDS DATE	17-April-2006
FOR INFORMATION CONTACT:	Purbond Inc. P.O. Box 8039 Tacoma, Washington 98418 USA Tel: 1-800-585-6390 Fax: 1-866-585-7122

ADDITIONAL INFORMATION: The information given and the recommendations made herein apply to our product(s) alone and are not combined with other product(s). Such are based on our research and on data from other reliable sources and are believed to be accurate. No guaranty of accuracy is made. It is the purchaser's responsibility before using any product to verify this data under their own operating conditions and to determine whether the product is suitable for their purposes.

Appendix D

Hyne Tuan mill material property data.

Hyne Timber - Tuan Mill	February 2009

Report on the Structural Properties of Tuan Framing Products

Report Period: 1st February 2009 to 28th February 2009	Report Date: 3/3/09

Basis of Structural Properties	AS 1720 - Timber Structures Part 1: Design Methods
Basis of Testing	AS/NZS 4063 - Timber-Stress Graded - In-Grade strength and stiffness evaluation

Mean Modulus of Elasticity - Bending

Product			Sampling Rate	Sample Statistics (Non-parametric)			MOE Actual : Design (%)	Statistical Confidence (%) that Design Values are met	Design MOE Values (GPa)
Type	Section Size	Grade		No.	Mean MOE (GPa)	COV MOE (%)			
Solid	90 x 35	F5	1/1500	37	8.61	29%	125%	100.0%	6.9
Solid	90 x 35	MGP10	1/1500	73	10.37	29%	104%	85.1%	10
Solid	90 x 35	MGP12	1/1500	60	13.68	25%	108%	98.8%	12.7
Solid	90 x 35	MGP15	1/1500	24	17.41	15%	104%	90.3%	16.7
				483	Weighted Result		**110%**	**97.0%**	
						Target	> 94%	>50%	

5% Modulus of Rupture - Bending

Product			Sampling Rate	Sample Statistics (Log-Normal)			MOR Actual : Design (%)	Statistical Confidence (%) that Design Values are met	Design MOR Values (MPa)
Type	Section Size	Grade		No.	5%ile MOR (MPa)	COV MOR (%)			
Solid	90 x 35	F5	1/1500	37	21.4	35%	134%	99.6%	16
Solid	90 x 35	MGP10	1/1500	73	24.3	36%	152%	100.0%	16
Solid	90 x 35	MGP12	1/1500	60	33.5	31%	120%	99.4%	28
Solid	90 x 35	MGP15	1/1500	24	52.8	22%	129%	99.9%	41
				483	Weighted Result		**148%**	**99.9%**	
						Target	> 91%	>75%	

Table 5 – Hyne Tuan mill product densities.

Hyne Tuan Mill Product Density (kg/m³) (Untreated)						
	140x35 Dry	70 x 35 Dry	90 x 35 Dry	70 x 45 Dry	90 x 45 Dry	Average
Utility*		590	617			604
F5		557	553	552		554
M10	564	576	568	555	557	564
M12	609	625	617	596	607	611
M15	661	685	665			670

* Utility is the term used by Hyne to describe its low grade timber product.

Appendix E

Timber Queensland Grey Ironbark test data.

Grey Ironbark Test data from Timber Queensland

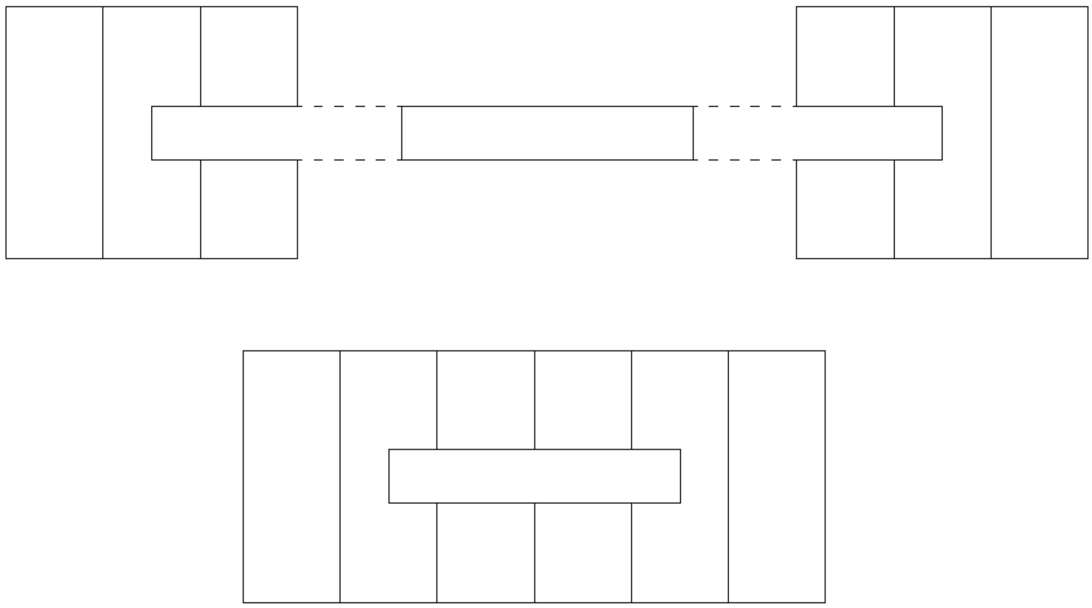
No	Species	Visual Grading	MOE (GPa)	MOR (GPa)	Moisture Content (%)	Density (kg/m³)
0577	GRI	R	17.29	91.85	green	1135
0722	GRI	R	19.11	97.62	green	1099
0573	GRI	27	16.11	85.06	green	1130
0574	GRI	27	16.23	79.04	green	1136
0575	GRI	27	17.27	72.44	green	1134
0576	GRI	27	15.79	83.36	green	1114
0716	GRI	27	19.94	98.47	green	1130
0718	GRI	27	18.09	109.75	green	1060
0719	GRI	27	17.86	102.66	green	1073
0721	GRI	27	19.86	106.66	green	1121
1119	GRI	27	19.65	102.61	green	1064
1120	GRI	27	19.91	104.20	green	1071
0499	GRI	R	19.46	92.77	green	1128
0497	GRI	27	21.13	94.11	green	1120
0720	GRI	27	20.71	112.80	green	1092
0496	GRI	27	-	112.54	green	1143
0717	GRI	27	-	106.72	green	1105
1119	GRI	34	14.65	105.77	15	972
1120	GRI	34	25.00	127.73	14	1072
0577	GRI	34	17.78	53.42	16	1162
0722	GRI	34	19.74	135.20	17	1100
0721	GRI	R	19.61	109.54	14	1090
0573	GRI	34	14.56	75.70	16	1092
0574	GRI	34	16.54	93.84	16	1098
0575	GRI	34	15.43	78.92	14	1096
0716	GRI	34	19.99	131.57	16	1092
0718	GRI	34	20.23	120.63	16	1074
0717	GRI	34	16.77	90.71	17	1074
0719	GRI	34	18.11	71.43	20	1082
0720	GRI	R	15.85	93.36	15	1079
0497	GRI	34	21.10	103.29	15	1153
0496	GRI	34	20.46	111.52	15	1177
0576	GRI	34	14.79	90.60	16	1076
0414	GRI	27	22.84	117.26	green	1135
0608	GRI	27	19.39	113.00	green	1124
0653	GRI	27	19.89	101.46	green	1185
0660	GRI	27	23.74	113.67	green	1171
0661	GRI	27	23.33	114.94	green	1164
0666	GRI	27	22.28	106.90	green	1127
0860	GRI	R	19.55	96.20	green	1204
0654	GRI	27	21.23	98.04	green	1170
0856	GRI	R	20.35	114.59	green	1133
0862	GRI	27	17.86	60.80	green	1216
1093	GRI	R	7.06	25.12	green	1194
1091	GRI	22	12.67	64.52	green	1148
0412	GRI	27	23.18	118.93	green	1135
0853	GRI	R	17.10	72.94	green	1231
0655	GRI	27	21.82	105.95	green	1169
0413	GRI	27	22.54	120.14	green	1110
0657	GRI	27	21.53	110.04	green	1191
0662	GRI	27	22.39	114.96	green	1168

0667	GRI	27	23.51	108.79	green	1185
0410	GRI	R	21.66	116.82	green	1127
0411	GRI	27	21.30	118.65	green	1137
0663	GRI	27	20.06	115.40	green	1150
0857	GRI	27	19.83	116.65	green	1221
0418	GRI	R	21.86	116.16	green	1120
0419	GRI	R	22.56	110.31	green	1140
0604	GRI	27	20.61	102.55	green	1147
0605	GRI	27	19.34	96.52	green	1119
0606	GRI	27	19.85	100.55	green	1145
0607	GRI	27	20.78	104.52	green	1125
0609	GRI	27	17.27	94.33	green	1121
0656	GRI	27	21.00	115.15	green	1140
0664	GRI	27	25.07	123.11	green	1141
0665	GRI	27	22.02	126.51	green	1187
0849	GRI	27	20.02	118.19	green	1192
0850	GRI	27	20.10	100.30	green	1210
0851	GRI	27	15.87	95.62	green	1206
0859	GRI	27	19.43	114.10	green	1228
0603	GRI	27	15.45	101.30	green	1170
0658	GRI	27	17.12	113.05	green	1187
0659	GRI	27	20.70	115.65	green	1195
0409	GRI	27	23.06	118.88	green	1131
0602	GRI	27	21.30	102.97	green	1150
0852	GRI	R	19.77	105.05	green	1204
1092	GRI	R	11.76	32.77	green	1156
1089	GRI	22	12.97	78.47	green	1212
1090	GRI	22	13.64	83.81	green	1156
1096	GRI	27	14.14	81.25	green	1145
1088	GRI	R	14.84	87.91	green	1172
1094	GRI	27	12.99	77.44	green	1183
1095	GRI	27	13.99	72.16	green	1189
1097	GRI	27	12.47	71.91	green	1162
1098	GRI	27	11.20	67.16	green	1178
0859	GRI	R	20.99	90.70	12	1187
1089	GRI	43	13.59	57.05	10	1100
0853	GRI	R	21.83	131.25	12	1263
0418	GRI	R	23.15	123.07	11	1131
1095	GRI	43	4.52	13.18	11	1089
0656	GRI	43	24.48	100.87	13	1126
0852	GRI	43	25.64	137.68	12	1212
0664	GRI	34	21.47	96.99	14	1075
0411	GRI	34	23.68	106.81	11	1088
1094	GRI	R	13.90	66.87	14	1111
1090	GRI	34	14.48	62.53	11	1112
0851	GRI	43	15.55	139.13	13	1213
0666	GRI	R	21.24	80.55	12	1099
0654	GRI	34	23.69	127.47	12	1107
0413	GRI	34	21.90	105.59	12	1033
0412	GRI	43	26.83	155.72	11	1121
0603	GRI	43	24.26	127.09	13	1138
0606	GRI	43	26.62	154.21	14	1152
0659	GRI	43	25.57	155.30	12	1143
0849	GRI	43	23.33	136.18	13	1186

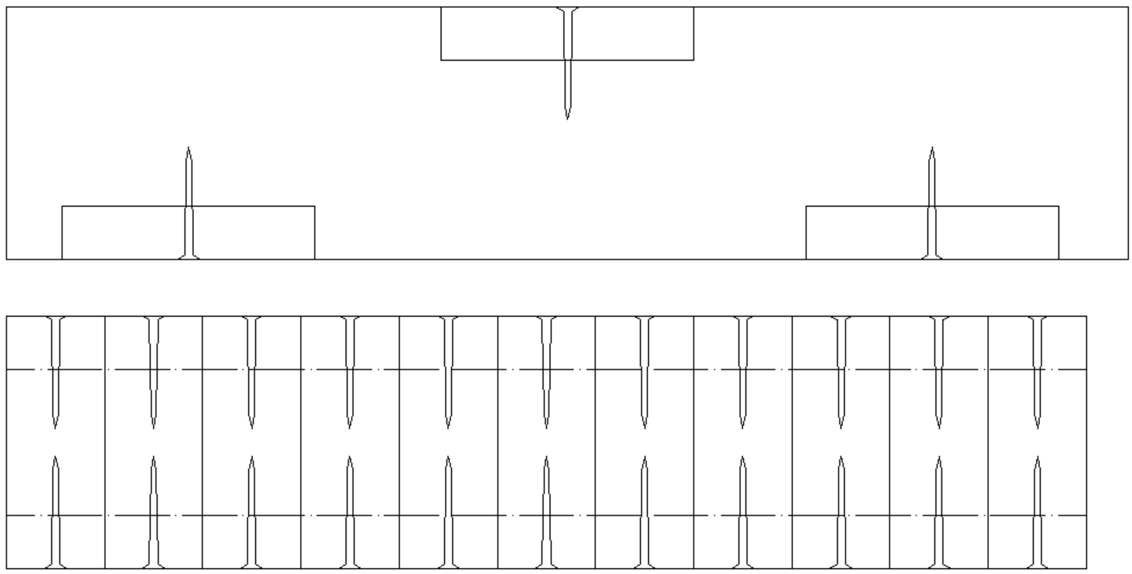
0419	GRI	43	25.54	119.32	12	1118
0604	GRI	43	24.94	135.75	12	1134
0605	GRI	43	26.40	143.27	13	1127
0608	GRI	43	26.21	137.32	12	1142
0661	GRI	43	23.46	149.96	12	1153
0665	GRI	43	-	123.60	12	1086
0667	GRI	43	20.24	116.39	13	889
0860	GRI	43	24.04	113.93	12	1227
0862	GRI	43	21.19	90.31	12	1162
1097	GRI	43	14.16	76.03	10	1078
0856	GRI	43	20.87	141.39	12	1151
0857	GRI	43	20.78	95.69	11	1209
1088	GRI	R	16.59	70.20	10	1085
0410	GRI	34	24.19	65.64	13	1089
0655	GRI	34	22.95	63.50	15	1139
0850	GRI	R	9.44	18.25	12	1079
0609	GRI	43	24.27	118.75	15	1149
0653	GRI	34	25.09	136.56	13	1080
0663	GRI	27	19.79	61.47	15	1085
0409	GRI	34	20.76	37.25	13	1103
0660	GRI	34	24.48	123.49	11	1104
0607	GRI	27	24.00	137.36	13	1079
0662	GRI	27	25.85	100.04	12	1109
1091	GRI	43	12.41	56.27	11	1047
0414	GRI	R	22.65	123.23	13	1033
0602	GRI	43	22.31	149.60	11	1089
0657	GRI	R	24.02	129.55	12	1114
0658	GRI	43	25.12	151.03	15	1138
1098	GRI	43	13.54	60.93	10	1102
1096	GRI	R	16.33	78.57	10	1066
1093	GRI	43	15.90	63.54	11	1029
1093	GRI	R	9.51	38.66	10	1069

Appendix F

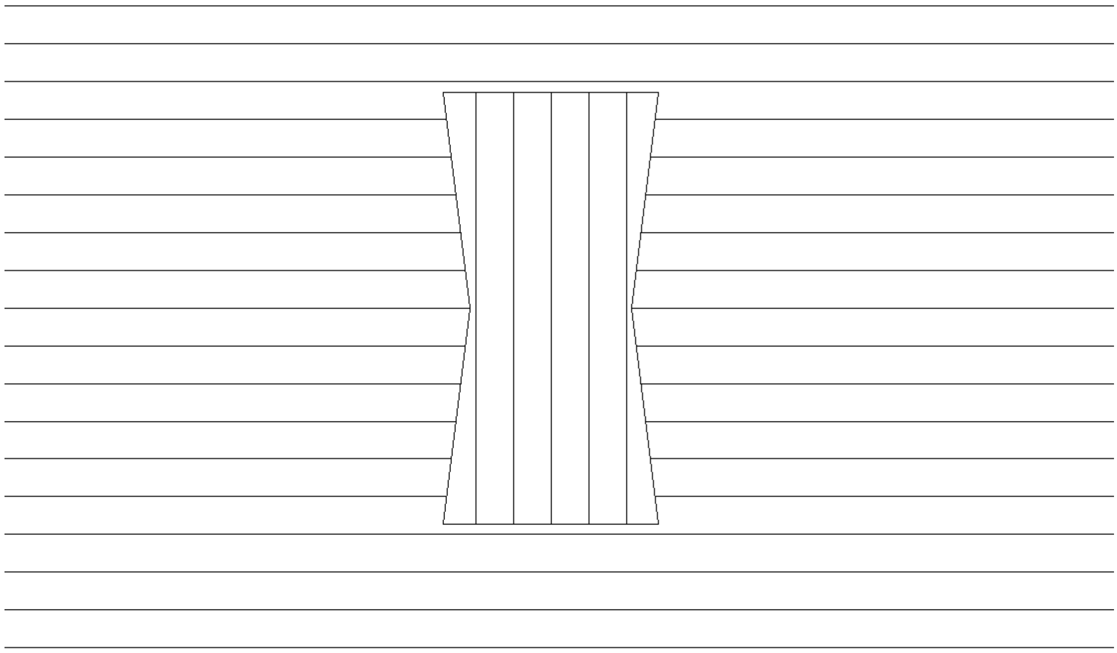
Slab unit connection ideas.



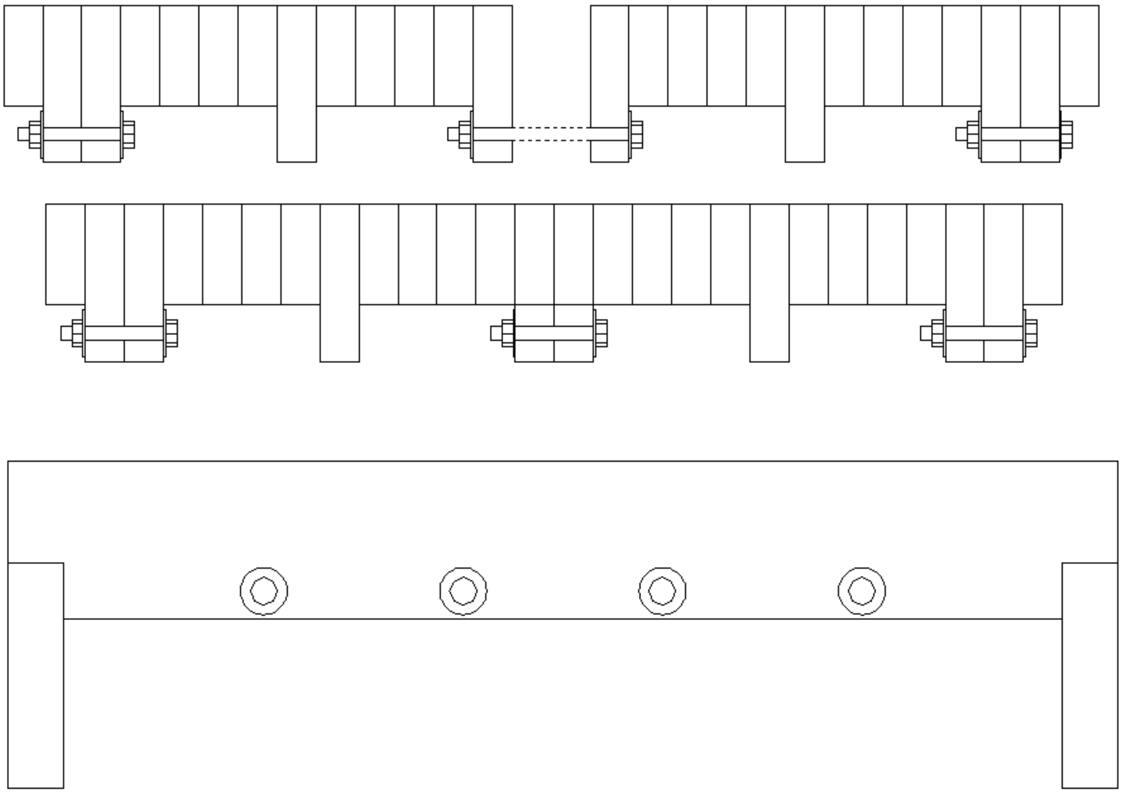
IDEA 1 – Single high grade timber plank face jointed into adjacent slab units



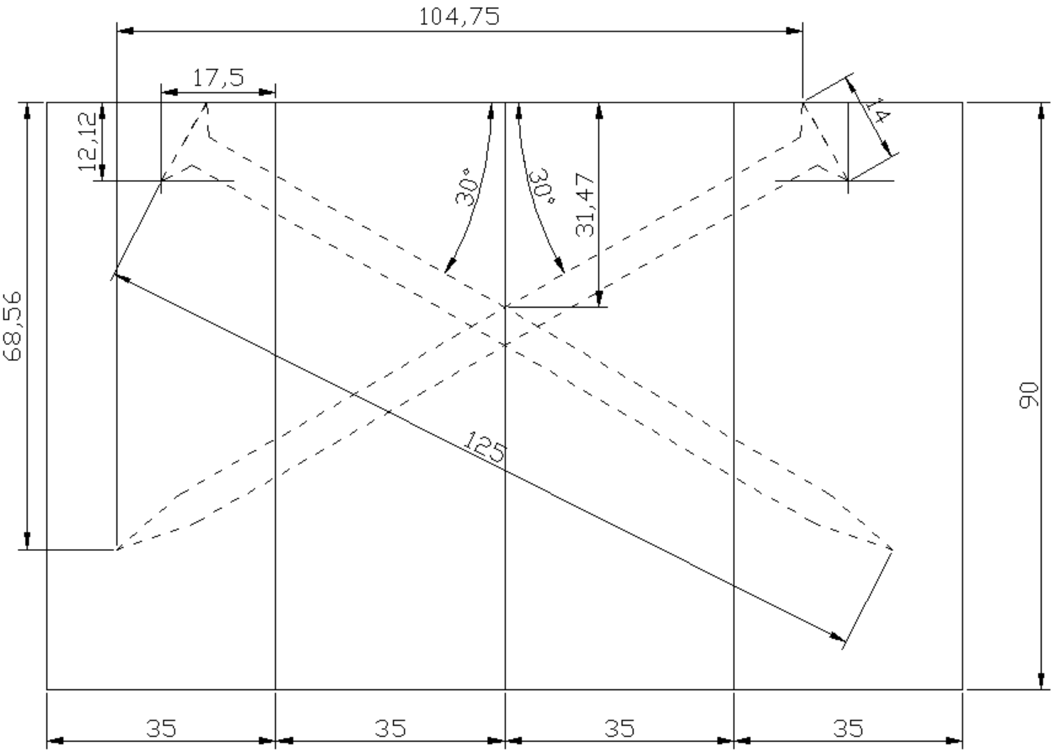
IDEA 2 – A plank spanning the length of the slab with nails or screws driven directly into each member

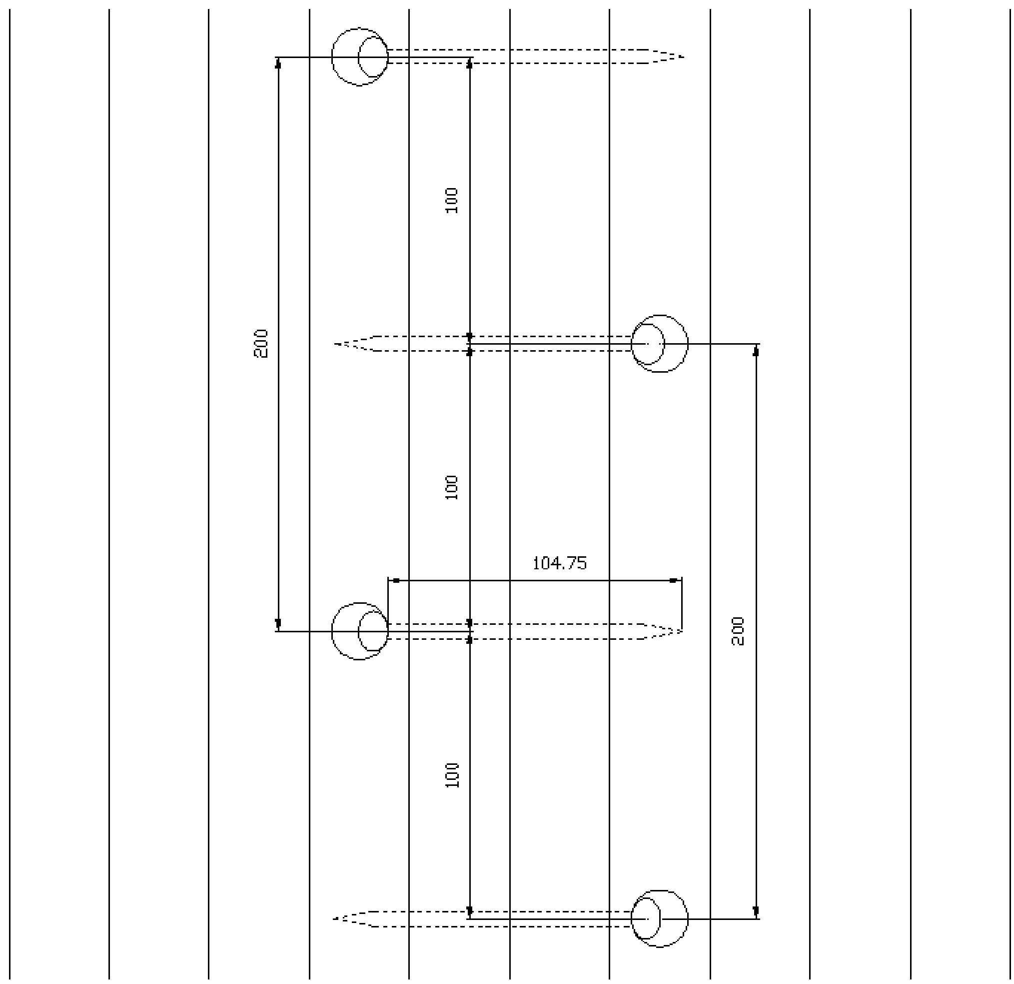


IDEA 3 – A large dovetail block fixed into a pre-cut joint in the slabs.



IDEA 4 – 140 mm deep laminates on the outside edges of each slab unit with bolts connecting them together underneath the slab





IDEA 5 – Bugle head batten screws skewed into the slabs and counter sunk below the surface.

Appendix G

Matlab code used to analyse recorded data

G.1 – Matlab code used to plot test results.

```
clear
clc
format short g

% timber sample properties

B = 35*12;
D = 90;
L = 1620;
a = L/3
n = (((3*a)/(4*L))-((a/L)^3))

%_______________________________________________________________________


Sample_n = xlsread('CAMERON - S1A')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E1 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))


hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'r')
hold on

%_______________________________________________________________________

Sample_n = xlsread('CAMERON - S1B')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E2 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))


hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'g')
hold on
```

```
%_____________________________________________________________________


Sample_n = xlsread('CAMERON - S2A')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E3 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))


hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'b')
hold on

%_____________________________________________________________________

Sample_n = xlsread('CAMERON - S2B')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E4 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))

hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'm')
hold on


%_____________________________________________________________________



Sample_n = xlsread('CAMERON - S3A')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));
```

```
D_diff = D2-D1;

E5 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))


hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'y')
hold on

%___________________________________________________________________________

Sample_n = xlsread('CAMERON - S3B')
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E6 = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))


hold on
plot(Sample_n(:,3),(Sample_n(:,4)*1000), 'k')
hold on

%___________________________________________________________________________
_____

ylabel('Load (N)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Timber Slab Test Results','fontsize',14)
h = legend('SAMPLE 1A','SAMPLE 1B','SAMPLE 2A','SAMPLE 2B','SAMPLE
3A','SAMPLE 3B',2);
grid on

Average = (E1+E2+E3+E4+E5+E6)/6
```

G.2 – Matlab code used to calculate Modulus of Elasticity

```
clear
clc
format short g

% timber sample properties

B = 35*12;
D = 90;
L = 1620;
a = L/3
n = (((3*a)/(4*L))-((a/L)^3))

%_______________________________________________________________________


alpha = 1;
while alpha <12

document = uigetfile('*.xls','Open data file');
Sample_n = xlsread(document)
display(document)
N = size(Sample_n(:,3));

P2 = (Sample_n(floor((N(1,1)-(N(1,1)/2))),5));
P1 = (Sample_n(floor((0+(N(1,1)/9))),5));

P_diff = P2/2-P1/2;

D2 = (Sample_n(floor((N(1,1)-N(1,1)/2)),3));
D1 = (Sample_n(floor((0+N(1,1)/9)),3));

D_diff = D2-D1;

E = (((2*n*L.^3)/(B*D.^3))* (P_diff/D_diff))

LOBF = [P2, P1;D2,D1];
figure('Position',get(0,'ScreenSize'))
plot(LOBF(2,:),LOBF(1,:),'b-*','markersize', 20,'linewidth', 2)
hold on
plot(Sample_n(:,3),Sample_n(:,5), 'r')
hold on

x_coord = Sample_n(N(1,1),3)/2;
y_coord = Sample_n(N(1,1),5)/2;

text(x_coord,y_coord,num2str(E),'fontsize', 16,'fontweight', 'bold')


ylabel('Load (N)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Test Results Analysis','fontsize',14)
h = legend('Modulus of Elasticity (MPa)',document,2);
grid on
%print('-djpeg100',document)
pause

alpha = alpha + 1
end
```

G.3 – Matlab code used to plot design chart

```
clear;
clc;
LOAD_DATA =
[0,3.460399412,6.489,9.949399412,16.43839941,22.92739941,29.41639941,3
5.90539941;%,52.12789941;

0,4.613865883,8.652,13.26586588,21.91786588,30.56986588,39.22186588,47
.87386588;%,69.50386588;

0,5.767332354,10.815,16.58233235,27.39733235,38.21233235,49.02733235,5
9.84233235;%,86.87983235;

0,6.920798825,12.978,19.89879882,32.87679882,45.85479882,58.83279882,7
1.81079882;%,104.2557988;

0,8.074265296,15.141,23.2152653,38.3562653,53.4972653,68.6382653,83.77
92653;%,121.6317653;

0,9.227731766,17.304,26.53173177,43.83573177,61.13973177,78.44373177,9
5.74773177;%,139.0077318;

0,10.38119824,19.467,29.84819824,49.31519824,68.78219824,88.24919824,1
07.7161982;%,156.3836982;

0,11.53466471,21.63,33.16466471,54.79466471,76.42466471,98.05466471,11
9.6846647]%,173.7596647]

DEFLECTION_DATA = [0,0,0,0,0,0,0,0;
                   0.4,0.5,1.1,2.3,4.2,7.1,11.3,17.1;
                   0.3,0.8,2,4.2,7.7,13,21,31.9;
                   0.7,1.3,3.1,6.4,11.9,20.1,32.2,49;
                   0.9,2.1,5.1,10.6,19.6,33.1,53.2,80.9;
                   1.2,2.9,7.2,14.8,27.3,46,74.2,112.7;
                   1.5,3.8,9.2,19,35,59,95.1,144.6;
                   1.7,4.6,11.2,23.2,42.8,72,116.1,176.4;]
                   %2.4,6.7,16.3,33.6,62.1,104.5,168.5,256.1]
for i = 1:8
plot(DEFLECTION_DATA(:,i),LOAD_DATA(i,:),'-r*')
hold on
end

for i = 1:8
plot(DEFLECTION_DATA(i,:),LOAD_DATA(:,i),'-b')
hold on
end

for n = 1:8
gradient(1,n) = LOAD_DATA(n,8)/DEFLECTION_DATA(8,n);
hold on
end
gradient

Lmark = 1;
for L = 1800:600:6000
    %xLon400(1,Lmark)= L/400;
    xLon360(1,Lmark) = L/360;
    %xLon300(1,Lmark) = L/300;
    xLon250(1,Lmark) = L/250;
    %xLon200(1,Lmark) = L/200;
    xLon150(1,Lmark) = L/150;
    xLon100(1,Lmark) = L/100;
    Lmark = Lmark + 1;
end
```

```
%xLon = [xLon400;xLon350;xLon300;xLon250;xLon200;xLon150;xLon100]
xLon = [xLon360;xLon250;xLon150;xLon100]


g_mark = 1;%2;
for column_mark = 1:8
for row_mark = 1:4

        yLon(row_mark,column_mark) = xLon(row_mark,column_mark) *
gradient(1,g_mark);
end
g_mark = g_mark + 1;
end




yLon
for xplot = 1:8
    for yplot = 1:4

        %if yLon(yplot,xplot) < LOAD_DATA(yplot,xplot)+60
        %xplot(yplot,xplot) = xLon(yplot,xplot)
        %yplot(yplot,xplot) = yLon(yplot,xplot)
        %plot(xLon(yplot,xplot),yLon(yplot,xplot),'-g*')
        plot(xLon(yplot,:),yLon(yplot,:),'-g*')

        hold on

      %  end
    end
end


ylim([0 120])
grid on
ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Load / Deflection Limit Graphs for LOW GRADE
SLAB','fontsize',14)
```

G.4 – Matlab code used to plot stress limit graphs

```
clear
clc
SPAN_1 = 3600;
SPAN_2 = 6000;

%______________________DEFLECTIONS____________________________________
_____
Stress_Lim_SLAB = [35714,35714];
Stress_Lim_NORM = [80000,80000]
%_______________3.6 m x 3.6 m Slab____________________________________

Load_One_t =
[0,7.889,12.96,20.849,33.809,46.769,59.729,72.689,105.089];;
Stress_One_t =
[0,701.8559,1247.9872,1949.8431,3197.8302,4445.8174,5693.8045,6941.791
7,10061.7596];

plot(Stress_One_t, Load_One_t,'b--*')

hold on
%_______________3.6 m x 3.6 m
Standard____________________________________

Load_Two_t =
[0,4.696,12.96,17.656,30.616,43.576,56.536,69.496,101.896];
Stress_Two_t =
[0,1833.6946,6240.0804,8073.77550,14313.8554,20553.9358,26794.0162,330
34.0966,48634.2976];

Drawing_Limit = [0,max(Load_One_t)];

plot(Stress_Two_t, Load_Two_t,'m--*');
hold on

plot(Stress_Lim_SLAB,Drawing_Limit,'b');

hold on

plot(Stress_Lim_NORM,Drawing_Limit,'m');

hold on

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Stress (kPa)','fontsize',14)
title ('Timber Flooring Stress Limits 3.6m span','fontsize',14)
h = legend('3.6m x 3.6m Slab','3.6m x 3.6m Standard','Stress
Limit',2);
grid on


figure



%_______________6 m x 3.6 m Slab____________________________________

Load_One_s =
[0,12.503,21.6,34.103,55.703,77.303,98.903,120.503,174.503];
```

```
Stress_One_s =
[0,1671.3984,3048.7292,4720.1276,7768.8569,10817.5861,13866.3153,16915
.0445,24536.8676];

plot(Stress_One_s, Load_One_s,'b--*')

hold on
%_______________6 m x 3.6 m
Standard____________________________________

Load_Two_s =
[0,7.2387,21.6,28.8387,50.4387,72.0387,93.6387,115.2387,169.2387];
Stress_Two_s =
[0,4102.7515,14024.84,18125.2787,32149.0627,46173.9029,60198.7431,7422
3.5834,109285.6839];

Drawing_Limit = [0,max(Load_One_s)];

plot(Stress_Two_s, Load_Two_s,'m--*')

hold on

plot(Stress_Lim_SLAB,Drawing_Limit,'b')

hold on

plot(Stress_Lim_NORM,Drawing_Limit,'m')

hold on

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Stress (kPa)','fontsize',14)
title ('Timber Flooring Stress Limits for 6m span','fontsize',14)
h = legend('6m x 3.6m Slab','6m x 3.6m Standard','Stress Limit',2);
grid on


%_____________COMPARISON OF STRESSES ON STANDARD FLOORING
SETUP___________%

figure

%Load Case 1
%STRESS_COMPARISONa = [Stress_Two_s(1),Stress_Two_t(1)]
%LOAD_COMPARISONa = [Load_Two_s(1),Load_Two_t(1)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--*')
%hold on

%Load Case 1
STRESS_COMPARISONa = [Stress_Two_s(2),Stress_Two_t(2)];
LOAD_COMPARISONa = [Load_Two_s(2),Load_Two_t(2)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--*')
if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
        CASE ='Slab Stress Limit'
          UNKNOWN_SPAN_LC1js = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                                (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
```

```
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC1,'bd')
            SLAB_LENGTH_LC1 = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC1 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end

hold on

%Load Case 2
STRESS_COMPARISONa = [Stress_Two_s(3),Stress_Two_t(3)];
LOAD_COMPARISONa = [Load_Two_s(3),Load_Two_t(3)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--*')
if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC2 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC2,'gd')
            SLAB_LENGTH_LC2js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC2 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on


%Load Case 3
STRESS_COMPARISONa = [Stress_Two_s(4),Stress_Two_t(4)];
LOAD_COMPARISONa = [Load_Two_s(4),Load_Two_t(4)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--*')
if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC3 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC3,'cd')
            SLAB_LENGTH_LC3js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC3 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 4
STRESS_COMPARISONa = [Stress_Two_s(5),Stress_Two_t(5)];
LOAD_COMPARISONa = [Load_Two_s(5),Load_Two_t(5)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'m--*')
if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC4 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC4,'md')
```

```
            SLAB_LENGTH_LC6js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC6 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 5
STRESS_COMPARISONa = [Stress_Two_s(6),Stress_Two_t(6)];
LOAD_COMPARISONa = [Load_Two_s(6),Load_Two_t(6)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--o')
if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC5 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC5,'rd')
            SLAB_LENGTH_LC5js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC5 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on


%Load Case 6
STRESS_COMPARISONa = [Stress_Two_s(7),Stress_Two_t(7)];
LOAD_COMPARISONa = [Load_Two_s(7),Load_Two_t(7)];

plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--o')

if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC6 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_NORM(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC6,'bd')
            SLAB_LENGTH_LC6js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC6 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end

hold on


%Load Case 7
STRESS_COMPARISONa = [Stress_Two_s(8),Stress_Two_t(8)];
LOAD_COMPARISONa = [Load_Two_s(8),Load_Two_t(8)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--o')

if STRESS_COMPARISONa(2) < Stress_Lim_NORM(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_NORM(1)
          UNKNOWN_SPAN_LC7 = (((LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))/(STRESS_COMPARISONa(1)-STRESS_COMPARISONa(2)))...
```

```
             *(Stress_Lim_NORM(1) - STRESS_COMPARISONa(2)))+
LOAD_COMPARISONa(2);
        hold on
         plot(Stress_Lim_NORM(1),UNKNOWN_SPAN_LC7,'gd')
         SLAB_LENGTH_LC7js = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC7 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end


        %LOAD_COMPARISONa(2) = SPAN_1;
        %LOAD_COMPARISONa(1) = SPAN_2;
end
hold on
%Load Case 1
%STRESS_COMPARISONa = [Stress_Two_s(9),Stress_Two_t(9)]
%LOAD_COMPARISONa = [Load_Two_s(9),Load_Two_t(9)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--o')
%hold on

plot(Stress_Lim_SLAB,Drawing_Limit,'r')
hold on
plot(Stress_Lim_NORM,Drawing_Limit,'b')

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Stress (kPa)','fontsize',14)
title ('Comparison Between Standard 3.6m and 6m span for each Load
Case','fontsize',14)
h = legend('Gravity','1kN/m^2','Gravity + 1kN/m^2','Gravity +
2kN/m^2','Gravity + 3kN/m^2'...
    ,'Gravity + 4kN/m^2','Gravity + 5kN/m^2','Limiting Stress',2);
grid on


%______________COMPARISON OF STRESSES ON SLAB FLOORING
SETUP___________%

figure

%Load Case 1
%STRESS_COMPARISONa = [Stress_One_s(1),Stress_One_t(1)]
%LOAD_COMPARISONa = [Load_One_s(1),Load_One_t(1)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--*')
%hold on
%Load Case 1
STRESS_COMPARISONa = [Stress_One_s(2),Stress_One_t(2)];
LOAD_COMPARISONa = [Load_One_s(2),Load_One_t(2)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--*')

if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC1 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                           (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC1,'bd')
            SLAB_LENGTH_LC1ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC1 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
```

```
end

hold on

%Load Case 2
STRESS_COMPARISONa = [Stress_One_s(3),Stress_One_t(3)];
LOAD_COMPARISONa = [Load_One_s(3),Load_One_t(3)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--*')
if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC2 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC2,'gd')
            SLAB_LENGTH_LC2ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC2 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 3
STRESS_COMPARISONa = [Stress_One_s(4),Stress_One_t(4)];
LOAD_COMPARISONa = [Load_One_s(4),Load_One_t(4)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--*')
if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC3 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC3,'cd')
            SLAB_LENGTH_LC3ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC3 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 4
STRESS_COMPARISONa = [Stress_One_s(5),Stress_One_t(5)];
LOAD_COMPARISONa = [Load_One_s(5),Load_One_t(5)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'m--*')
if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC4 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC4,'md')
            SLAB_LENGTH_LC4ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC4 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on
```

```
%Load Case 5
STRESS_COMPARISONa = [Stress_One_s(6),Stress_One_t(6)];
LOAD_COMPARISONa = [Load_One_s(6),Load_One_t(6)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--o')

if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC5 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC5,'rd')
            SLAB_LENGTH_LC5ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC5 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on


%Load Case 6
STRESS_COMPARISONa = [Stress_One_s(7),Stress_One_t(7)];
LOAD_COMPARISONa = [Load_One_s(7),Load_One_t(7)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--o')
if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC6 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC6,'bd')
            SLAB_LENGTH_LC6ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC6 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 7
STRESS_COMPARISONa = [Stress_One_s(8),Stress_One_t(8)];
LOAD_COMPARISONa = [Load_One_s(8),Load_One_t(8)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--o')

if STRESS_COMPARISONa(2) < Stress_Lim_SLAB(1)
    if STRESS_COMPARISONa(1) > Stress_Lim_SLAB(1)
          UNKNOWN_SPAN_LC7 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Stress_Lim_SLAB(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Stress_Lim_SLAB(1),UNKNOWN_SPAN_LC7,'bd')
            SLAB_LENGTH_LC7ss = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC7 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on
```

```
%Load Case 1
%STRESS_COMPARISONa = [Stress_Two_s(9),Stress_Two_t(9)]
%LOAD_COMPARISONa = [Load_Two_s(9),Load_Two_t(9)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--o')
%hold on

plot(Stress_Lim_NORM,Drawing_Limit,'r')
hold on
plot(Stress_Lim_SLAB,Drawing_Limit,'b')

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Stress (kPa)','fontsize',14)
title ('Comparison Between Slabs of 3.6m and 6m span for each Load
Case','fontsize',14)
h = legend('Gravity','1kN/m^2','Gravity + 1kN/m^2','Gravity +
2kN/m^2','Gravity + 3kN/m^2'...
    ,'Gravity + 4kN/m^2','Gravity + 5kN/m^2','Limiting Stress',2);
grid on
```

G.5 – Matlab code used to plot deflection limit graphs

```
clear
clc
SPAN_1 = 3600;
SPAN_2 = 6000;
%______________________DEFLECTIONS____________________________________
_____
Deflection_Lim_3p6 = [12,12];
%________________3.6 m x 3.6 m Slab____________________________________

Load_One_t =
[0,7.889,12.96,20.849,33.809,46.769,59.729,72.689,105.089];
Deflection_One_t = [0,2.5,4.4,6.9,11.3,15.7,20.1,24.5,35.5];

plot(Deflection_One_t, Load_One_t,'b--*')

hold on
%_______________3.6 m x 3.6 m
Standard____________________________________

Load_Two_t =
[0,4.696,12.96,17.656,30.616,43.576,56.536,69.496,101.896];
Deflection_Two_t = [0,2.1,6.9,9.0,15.8,22.7,29.5,36.4,53.6];

Drawing_Limit = [0,max(Load_One_t)];

plot(Deflection_Two_t, Load_Two_t,'m--*')
hold on

plot(Deflection_Lim_3p6,Drawing_Limit,'r')

hold on

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Timber Flooring Deflection Limits 3.6m span','fontsize',14)
h = legend('3.6m x 3.6m Slab','3.6m x 3.6m Standard','Deflection
Limit',2);
grid on


figure


Deflection_Lim_6 = [15,15];

%_______________6 m x 3.6 m Slab____________________________________

Load_One_s =
[0,12.503,21.6,34.103,55.703,77.303,98.903,120.503,174.503];
Deflection_One_s = [0,15.8,28.8,44.6,73.4,102.2,131,159.8,231.8];

plot(Deflection_One_s, Load_One_s,'b--*')

hold on
%_______________6 m x 3.6 m
Standard____________________________________

Load_Two_s =
[0,7.2387,21.6,28.8387,50.4387,72.0387,93.6387,115.2387,169.2387];
```

```
Deflection_Two_s = [0,10.4,35.1,45.4,80.5,115.6,150.7,185.8,273.5];

Drawing_Limit = [0,max(Load_One_s)];

plot(Deflection_Two_s, Load_Two_s,'m--*')
hold on

plot(Deflection_Lim_6,Drawing_Limit,'r')

hold on

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Timber Flooring Deflection Limits for 6m span','fontsize',14)
h = legend('6m x 3.6m Slab','6m x 3.6m Standard','Deflection
Limit',2);
grid on

%_____________COMPARISON OF Deflections ON STANDARD FLOORING
SETUP___________%

figure

%Load Case 1
%STRESS_COMPARISONa = [Deflection_Two_s(1),Deflection_Two_t(1)]
%LOAD_COMPARISONa = [Load_Two_s(1),Load_Two_t(1)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--*')
%hold on

%Load Case 1
STRESS_COMPARISONa = [Deflection_Two_s(2),Deflection_Two_t(2)];
LOAD_COMPARISONa = [Load_Two_s(2),Load_Two_t(2)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC1 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                           (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC1,'bd')
            SLAB_LENGTH_LC1jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC1 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 2
STRESS_COMPARISONa = [Deflection_Two_s(3),Deflection_Two_t(3)];
LOAD_COMPARISONa = [Load_Two_s(3),Load_Two_t(3)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC2 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                           (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC2,'gd')
```

```
            SLAB_LENGTH_LC2jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC2 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 3
STRESS_COMPARISONa = [Deflection_Two_s(4),Deflection_Two_t(4)];
LOAD_COMPARISONa = [Load_Two_s(4),Load_Two_t(4)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC3 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC3,'cd')
            SLAB_LENGTH_LC3jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC3 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 4
STRESS_COMPARISONa = [Deflection_Two_s(5),Deflection_Two_t(5)];
LOAD_COMPARISONa = [Load_Two_s(5),Load_Two_t(5)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'m--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC4 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC4,'md')
            SLAB_LENGTH_LC4jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC4 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 5
STRESS_COMPARISONa = [Deflection_Two_s(6),Deflection_Two_t(6)];
LOAD_COMPARISONa = [Load_Two_s(6),Load_Two_t(6)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC5 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC5,'rd')
            SLAB_LENGTH_LC5jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC5 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
```

```
    end
end
hold on

%Load Case 6
STRESS_COMPARISONa = [Deflection_Two_s(7),Deflection_Two_t(7)];
LOAD_COMPARISONa = [Load_Two_s(7),Load_Two_t(7)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC6 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2)
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC6,'bd')
            SLAB_LENGTH_LC6jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC6 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 7
STRESS_COMPARISONa = [Deflection_Two_s(8),Deflection_Two_t(8)];
LOAD_COMPARISONa = [Load_Two_s(8),Load_Two_t(8)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC7 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC7,'gd')
            SLAB_LENGTH_LC7jd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC7 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on
%Load Case 1
%STRESS_COMPARISONa = [Deflection_Two_s(9),Deflection_Two_t(9)]
%LOAD_COMPARISONa = [Load_Two_s(9),Load_Two_t(9)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--o')
%hold on

plot(Deflection_Lim_6,Drawing_Limit,'r')
hold on
plot(Deflection_Lim_3p6,Drawing_Limit,'b')

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Comparison Between Standard 3.6m and 6m span for each Load
Case','fontsize',14)
h = legend('Gravity','1kN/m^2','Gravity + 1kN/m^2','Gravity +
2kN/m^2','Gravity + 3kN/m^2'...
    ,'Gravity + 4kN/m^2','Gravity + 5kN/m^2','Limiting Deflection',2);
grid on
figure
```

```
%Limit_Lengths =
[SLAB_LENGTH_LC1jd,SLAB_LENGTH_LC2jd,SLAB_LENGTH_LC3jd,SLAB_LENGTH_LC4
jd,SLAB_LENGTH_LC5jd,SLAB_LENGTH_LC6jd,SLAB_LENGTH_LC7jd]
plot([4298.4,3.9956],[Load_Two_s(3),Load_Two_s(4)])

%______________COMPARISON OF Deflections ON SLAB FLOORING
SETUP___________%

figure

%Load Case 1
%STRESS_COMPARISONa = [Deflection_One_s(1),Deflection_One_t(1)]
%LOAD_COMPARISONa = [Load_One_s(1),Load_One_t(1)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--*')
%hold on

%Load Case 1
STRESS_COMPARISONa = [Deflection_One_s(2),Deflection_One_t(2)];
LOAD_COMPARISONa = [Load_One_s(2),Load_One_t(2)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC1 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC1,'bd')
            SLAB_LENGTH_LC1sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC1 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 2
STRESS_COMPARISONa = [Deflection_One_s(3),Deflection_One_t(3)];
LOAD_COMPARISONa = [Load_One_s(3),Load_One_t(3)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC2 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC2,'gd')
            SLAB_LENGTH_LC2sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC2 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 3
STRESS_COMPARISONa = [Deflection_One_s(4),Deflection_One_t(4)];
LOAD_COMPARISONa = [Load_One_s(4),Load_One_t(4)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
```

```
          UNKNOWN_SPAN_LC3 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC3,'cd')
            SLAB_LENGTH_LC3sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC3 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 4
STRESS_COMPARISONa = [Deflection_One_s(5),Deflection_One_t(5)];
LOAD_COMPARISONa = [Load_One_s(5),Load_One_t(5)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'m--*')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC4 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC4,'md')
            SLAB_LENGTH_LC4sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC4 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 5
STRESS_COMPARISONa = [Deflection_One_s(6),Deflection_One_t(6)];
LOAD_COMPARISONa = [Load_One_s(6),Load_One_t(6)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'r--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC5 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC5,'rd')
            SLAB_LENGTH_LC5sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC5 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 6
STRESS_COMPARISONa = [Deflection_One_s(7),Deflection_One_t(7)];
LOAD_COMPARISONa = [Load_One_s(7),Load_One_t(7)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'b--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC6 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
```

```
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC6,'bd')
            SLAB_LENGTH_LC6sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC6 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on

%Load Case 7
STRESS_COMPARISONa = [Deflection_One_s(8),Deflection_One_t(8)];
LOAD_COMPARISONa = [Load_One_s(8),Load_One_t(8)];
plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'g--o')
if STRESS_COMPARISONa(2) < Deflection_Lim_6(1)
    if STRESS_COMPARISONa(1) > Deflection_Lim_6(1)
          UNKNOWN_SPAN_LC7 = ( ( (LOAD_COMPARISONa(1) -
LOAD_COMPARISONa(2))* (Deflection_Lim_6(1) -
STRESS_COMPARISONa(2)))/...
                          (STRESS_COMPARISONa(1)-
STRESS_COMPARISONa(2)) ) + LOAD_COMPARISONa(2);
        hold on
            plot(Deflection_Lim_6(1),UNKNOWN_SPAN_LC7,'gd')
            SLAB_LENGTH_LC7sd = (((SPAN_2-SPAN_1)*(UNKNOWN_SPAN_LC7 -
LOAD_COMPARISONa(2)))/...
             (LOAD_COMPARISONa(1) - LOAD_COMPARISONa(2))) + SPAN_1
    end
end
hold on
%Load Case 1
%STRESS_COMPARISONa = [Deflection_Two_s(9),Deflection_Two_t(9)]
%LOAD_COMPARISONa = [Load_Two_s(9),Load_Two_t(9)]
%plot(STRESS_COMPARISONa, LOAD_COMPARISONa,'c--o')
%hold on

plot(Deflection_Lim_6,Drawing_Limit,'r')
hold on
plot(Deflection_Lim_3p6,Drawing_Limit,'b')

ylabel('Total Load (kN) (Including Self Weight)','fontsize',14)
xlabel('Deflection (mm)','fontsize',14)
title ('Comparison Between Slabs of 3.6m and 6m span for each Load
Case','fontsize',14)
h = legend('Gravity','1kN/m^2','Gravity + 1kN/m^2','Gravity +
2kN/m^2','Gravity + 3kN/m^2'...
    ,'Gravity + 4kN/m^2','Gravity + 5kN/m^2','Limiting Deflection',2);
grid on
figure

plot([SLAB_LENGTH_LC1sd,SLAB_LENGTH_LC2sd,SLAB_LENGTH_LC3sd,SLAB_LENGT
H_LC4sd],...
    [Load_One_s(2),Load_One_s(3),Load_One_s(4),Load_One_s(5)])
```