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The Investigation into the Optimisation of Cross Laminated Timber Panels for use in the Australia Building Industry

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CERTIFICATION

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Abstract

This research paper will investigate the viability of using Low/Utility grade timber to construct timber beams, plate members and solid wall structures via a Cross-lamination process known as CLT. More specifically it will aim to uncover an optimum set to material specifications and dimensions for an engineered panel design.

Due the many faults and defects in the utility grade timber it is often left to be used in wood chipping and wooden pallet manufacture, still this leaves a significant amount of product in storage, costing Hyne money. As well as producing a new structurally competitive product for Hyne Timber Australia, developing a method to structurally stabilise utility grade timber will drastically reduce wastage in the wood industry as well as provide an alternative to conventional brick and mortar building.

The modelling procedure will be undertaken in the finite element modelling software package Strand 7. These models are built upon the current known data for the mechanical properties of Slash Pine. Utilising the known modulus of elasticity and the orientation of grain direction, a finite analysis can be performed, calculating stress and moment distributions and deflections under applied loading.

The data gathered from these models will then be used to draw comparisons from standard slab performance tests and the expected usage of CLT panels to help assess with further research whether the development of CLT panels from timber of sub-par quality is viable.

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Chapter 1

Introduction

1.1.0 - Research Outline

This research will investigate the viability of using Low/Utility grade timber to construct timber beams, plate members and solid wall structures via a Cross-lamination process known as CLT. More specifically it will aim to uncover an optimum set to material specifications and dimensions for an engineered beam design.

The aim for this research project is to develop a set of optimum specifications and investigate the structural performance of different CLT beam combinations, from the optimum solution to the most practical and ease of construction based on current mill specifications.

1.2.0 - Background

Hyne and Son is one of Australia's largest and the most successful privately owned timber company. They source their timber from State Forestry Pine plantations which is harvested in a sustainable manor. Hyne timber produces five different graded specimens of structural Pine with an array of different finishing treatments; these grades include MGP15, MGP12, MGP10, F5 and utility grade products.

The high grade timber produced by Hyne is readily sold to distributors for structural applications however the utility grade is deemed non-structural based on its inferior mechanical properties or visual defects such as knots, wakes and wanes which severely reduce the timber member's structural performance. For this reason utility grade timber is usually produced and processed at a loss for companies. Hyne Timber is currently investigating methods to increase the structural performance and viability of its utility grade product in order to minimize the current cost deficit.

Due the faults in the Utility grade timber it is left to be used in wood chipping and wooden pallet manufacture, still this leaves a significant amount of product in storage costing Hyne money. As well as producing a new structurally competitive product for Hyne, developing a method to structurally stabilise utility grade timber will drastically reduce wastage in the wood industry as well as provide an alternative to conventional brick and mortar building.

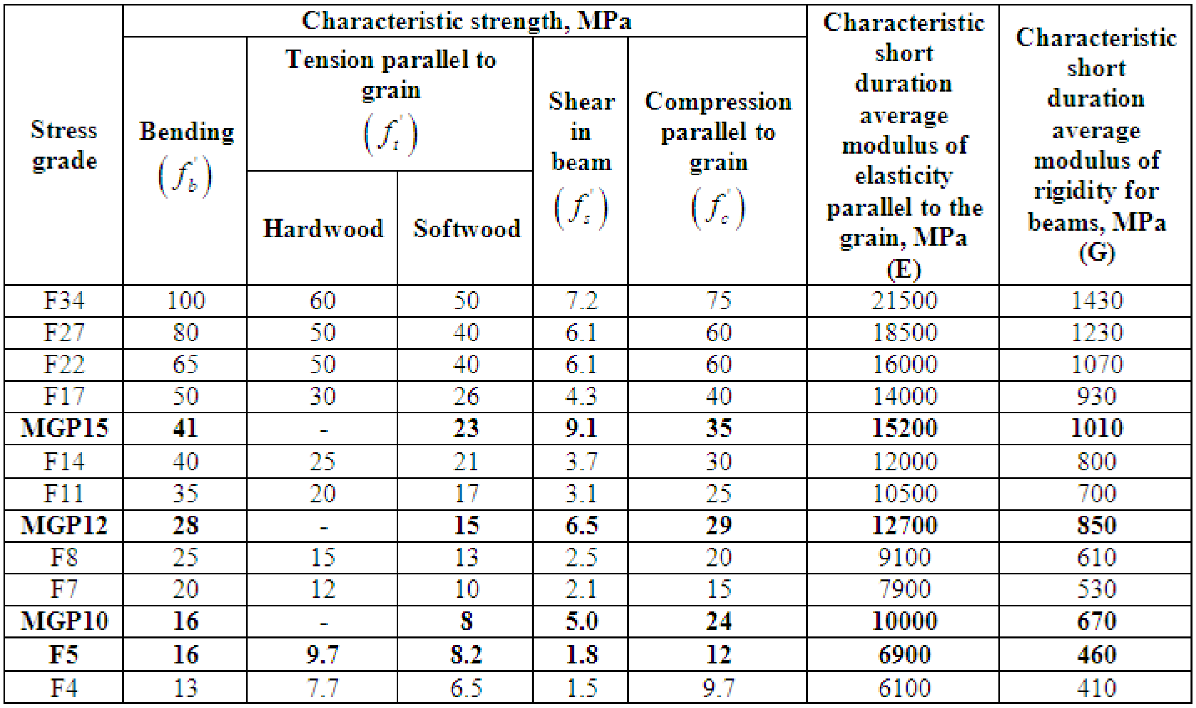
European nations are already conducting research into the viability of using Cross-Laminated timber members as the main structural components in building construction. However the companies which have dedicated time and resources to this research now have an advantage over their competitors and optimised product specifications are often patterned and considered highly valuable company secrets. This results in having limited information on products which are currently being used in the construction industry. Comparable results will need to be sourced

It is Hyne and Sons wish to develop their own CLT product independently to suite the Australian environment and the Australian construction industry.

1.3.0 - Problem Synopsis

Due to the high demand for structurally sound timber, Australia's timber industry has developed a sustainable Pine plantation and milling processes to meet the consumer requirements. However as the timber product undergoes grading through mechanical and visual means to determine what applications it can be utilised in, however much of the timber content is lost to defects such as poor growth structure. Timber which has been graded as lower then a F5 rating as per the Australian Standards *(AS1720.1 Timber Structures-Design Methods)* must be considered as a Utility grade and cannot be used in structural applications. Table 1 contains the characteristic structural design properties of the different grades of timber produced and used in Australia.

Table 1-Structural design properties of graded timber; Australian Standards (AS 1720.1 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

Nominally 50% of timber processed from each tree is considered as having utility grade properties. In some specimens however this percent can reach as high as 70% depending on the individual growing conditions.

Timber can be classed as 'Utility grade' via two processes, visual and mechanical grading. Visual grading classifies all timber that contains excessive defects such as wanes, wakes and knots as utility grade timber, this means however that relatively defect free timber with an overall high machine tested strength grade can still will still be classed as utility grade if is possesses significant localised defects.

As the utility grade timber cannot be used in structural applications it is often produced, manufacture and sold at a loss. The aim of this research is to develop a product for the Australian timber industry that will allow an avenue for viable cost recuperation as well as providing a structural alternative for otherwise near useless timber.

The idea of the Cross lamination of timber panels from defective timber to produce a new homogeneous matrix is a new initiative in Australia, even though the basic concept has been investigated in European for some time. This project will determine the most structurally sound CLT component specifications for the Australian timber industry.

1.4.0 - Safety Considerations

The main component of time dedicated to the acquisition of results will be spent theoretically modelling different CLT combinations in the finite element modelling program, Strand 7.

As a result the only safety concern for the theoretical modelling is sustaining a RSI for completing repetitive procedures. This will easily be negated by taking regular breaks.

A small amount of time will be spent conducting experimental testing on fabricated CLT panels. The Panels will be expertly fabricated by Hyne Timber in **Maryborough**, and as a result, manufacture will pose so safety concerns to this research.

Testing will be completed with the aid of USQ load testing facilities. Correct safety equipment and PPE have already been acquired and instructions on safe operating procedures for the loading equipment will be sought before testing commences.

1.5.0 - Consequential effects

The research conducted and the resulting dissertation will rely heavily on the theoretical results obtained by finite element modelling in Strand 7. As a consequence, if no significant results are produced, no accurate test specimens can be manufactured to validate results.

This would affect the major objective of the research project, which namely is to design develop and test an optimised CLT component. If for reasons unknown this occurs, Hyne Timber has specified component configurations which they believe would best meet current requirements. These specifications are based on current milling dimensions of the Maryborough Saw mill, 75 mm x 35 mm and
95 mm x 35 mm.

This would provide an avenue for theoretical modelling and the production and testing of CLT components, enabling the research to be completed.

1.6.0 - Research Objectives

The aim of this project is to investigate the structural performance of cross laminated timber panels for use as load bearing plates and develop an optimised CLT component suitable for manufacture. This investigation will study both the strength limit state of the CLT component as well as deflection performance. The following are objectives which have been outlined as critical components to the research.

- Conduct a review of the current literature on CLT panels and beams to gain an understanding and appreciation of the current technologies associated with CLT design.

- Create computer based, finite element models of different CLT combinations and orientations using Strand 7 to explore what component specifications will give the most structurally performing CLT panel.

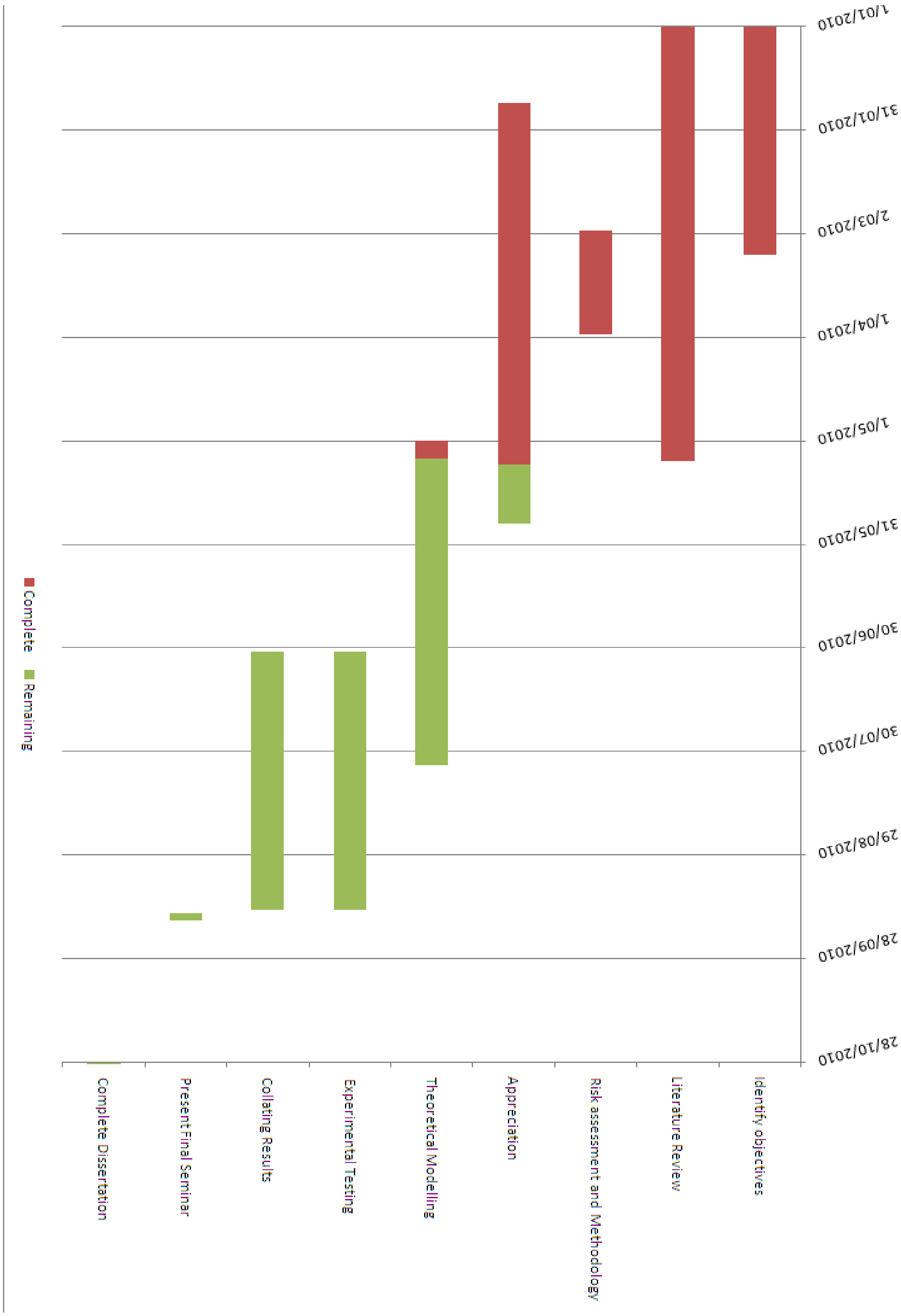
- Acquire test specimens provided by Hyne Timber. These specimens will be based on the specifications of the finite element modelling.

- Test the specimens to validate the data gathered by the theoretical modelling.

- Using both theoretical and experimental results suggest to Hyne Timber a viable CLT panel design.

1.7.0 - Time Allocation-Gantt Chart

Figure 1 - Time Allocation



Chapter 2

Literature Review

2.1.0 - Introduction

This chapter contains a brief summary of previous research that has carried out on the construction and optimisation of Cross Laminated timber products. The research and development of CLT products initially started in Switzerland in the early 1970's. As a result Europe is the world leader in CLT innovation and technologies. On the other hand Australia has only recently discovered the potential of optimising its own CLT design, in the past relying heavily on natural, old growth forests for high end structural grade timber.

The majority of overseas research has been directed at using CLT components as load bearing plates and wall panels. The general formation of these CLT components consist of 3 to 7 layers of timber, bonded together with resin with alternating layers having perpendicular grain direction.

The Australian Timber organisation has recently started to conduct its own research into the benefits of developing an Australian CLT product. It has been noted that CLT panels possesses significant increases in structural performance over standard timber beams.

These benefits include;

- An increased Fire resistance – Building with CLT components can increase a structures fire resistance by creating large solid sections which the fire must travel through before the structure is significantly weakened. Also due the very limited cavity space available to hold oxygen in the panel, combustion is inhibited.

- Sound Proofing - Due to the solid nature of wood products and the tight bundling of individual fibres, wood possesses inherent sound absorbing mechanics. Solid CLT panels used in walls and floor plates are superior to standard construction practices at absorbing sound waves as they do no possesses hollow mid-section cavities.

- Thermal Insulation – CLT wall components offer significant improvements to thermal insulation, providing an improved barrier between 'inside' and 'outside' energy transfer rates.

2.2.0 - CLT Technology

It is stated by (Herandez and Moody, 1997) that glue laminated timber is the oldest engineered wood product in the world. It is currently used extensively in Europe, Japan and North America in a variety of applications, ranging from wall panels and floor structures in residential buildings to major load bearing beams, trusses and columns in multistorey building developments.

As a result European nations have started conducting extensive research on the optimisation of CLT design, investigating layer properties, resin types, wood species and layer orientations. Investigation into the apparent increase of strength due to lamination was conducted by Falk and Colling (1995). This research reached the conclusion that the increase of strength could be attributed to the summation of separate, physical characteristics, depending on the lamination process used to bond the CLT component and the applied testing procedures. It was also noted during these tests that the placement of defects along the component had a major influence on the measure tensile strength. Components with a significant number of un-centred edge defects, such as edge knots or wanes, produce lateral bending stresses when combined with an applied tensile load; this combined action then effectively reduces the measured tensile strength of the component. Falk and Colling (1995) also concluded that the lamination of timber reinforces the defects of the individual timber layers by redistributing the applied stress acting on the defective area to the relatively defect free wood of adjacent layers. However CLT components fall into the category of composite materials. Based on composite material theories the shear capacity of any cross sectional area is reduced as the panel or beam size increases, this has been proven to be accurate in studies carried out by Soltis (1993).

2.3.0 - Material and Elastic Properties of CLT

The material properties of CLT are dependent upon the properties of the individual timbers used in the layered structure. As the CLT component can be accurately considered as a composite material it can then be thought of having to distinct components, the reinforcing fibres (timber grains) and a binding matrix (resin). The mechanical properties of utility grade timber supplied by Hyne Timber Australia are as follows;

Utility grade timber

- Generally unspecified but below F5
- May contain defects inherit to the species of wood.
- Modular of Elasticity may vary between 6000-15000 MPa and in generally accepted as 9000MPa.

Table 2– Mechanical properties of Timber supplied by Hyne Timber,

Stress Grade	Limit Strength State, MPa			
	Bending (F'b)	Tension parallel to grain (F't)	Shear in Beams (F's)	Compression parallel to grain (F'c)
F5	16	8.2	1.8	12
MGP10	16	8.9	5.0	24
MGP12	28	15	6.5	29
MGP15	41	23	9.12	35

Accurate determination of the CLT panel stiffness properties is essential in being able to determine the structural characteristics of the complete component.

An investigation into the "...Evaluation of elastic material properties of cross – laminated timber (CLT)" by Gsell. D, *et al* (2008) concluded.

"*Due to its (timber) micro and macro structure, timber shows a strong anisotropic elastic behaviour. Parallel to the grain, moduli of elasticity are significantly higher than perpendicular to the grain structure. Furthermore, timber is a heterogeneous material with many natural defects like knots or sloped grain.*"

The mechanical properties of timber are hard to calculate at the location of a major defect. In order to create a homogeneous material out of heterogeneous material the larger defects in the timber are removed and the remaining minor defects are distributed evenly throughout the CLT component's volume. This homogenisation leaves the CLT panel with an overall combined strength, with no one point being any weaker than any other. The stiffness properties of the panel can now be accurately calculated one of two ways; either by analysing the individual layer properties using the com pond theory, Brodig and Jane (1993), or by testing sections cut from the panel using the current relevant standards,
EN 13353 (CEN 2003b), EN 13986 (CEN 2004b) and, EN 789 (CEN 2004a).

2.4.0 - Importance of Moisture Content

Research conducted by Güzlow A, *et al* (2009) on the 'Influence of wood moisture content on bending and shear stiffness of CLT panels' found that CLT components possess a very strict moisture content range, namely 12% $^{+}_{-}$ 2%. Components produced outside this range possess significantly decreased stiffness ratings. Furthermore Güzlow A, *et al* (2009) state that, "...within the hygroscopic range of timber the MoE is directly affected by a change in moisture content, and the MoE in the wood grain direction drops by 1.5% for every 1% moisture increase.

Güzlow A, *et al* (2009) outlines these effects as;

- Increased Moisture content – The principle stiffness properties drop with increasing moisture contents. However the swelling of the timber grain leads to an apparent increase in the modulus of elasticity for small service loads due to internal component friction.

- Decreased Moisture Content – Decreasing the moisture content below 10% leads to cracking of the individual timber components of the CLT panel. This relates directly to a distinct decrease in the bending stiffness perpendicular to the grain direction on the face layers. Cracking of the components also leads directly to an increase in moisture content as vapour particles are now able to be trapped and housed in the wood structure.

Not only is it important that the timber used in the component is of the right moisture content but also that the individual timber layers contain the exact same moisture content within the hygroscopic range. If the moisture content of all the individual components is not the same residual stresses will develop between adjacent layers as each layer independently shrinks or expands depending on the environmental situation. This can significantly weaken the bond strength, a major cause of joint failure and can lead to excessive cracking of the laminate. This was proven in an investigation conducted by Herandez and Moody (1997); the pair concluded that "during the manufacture of laminates, it is possible to leave residual stresses in the component by bonding layers of varying moisture contents."

2.5.0 - Resins and Bonding Agents

The selection of an appropriate bonding resin is an important process in the optimisation of the CLT component. The resin selected needs to fall into the category of a 'Prime structural adhesive' as the resin will contribute to the strength and stiffness of the wood structure for the entire lifetime duration. Faherty. K, and Williamson. T (1999) state that the use of joining timber members together through the use of an adhesive is the most effective way to apply load transfers of shear forces between adjacent timber layers. Faherty. K, and Williamson. T (1999) also state one of the most important reasons for using an adhesive is it allows the composite wood component to utilise different grades of timber, minimise the effects of defects on strength and stiffness and provide an avenue for efficient timber usage.
The pair also noted that;
"The most effective bond is obtained when grain orientation is parallel, with bond strengths in the order of the ultimate shear capacity of the wood. Through perpendicular grain orientation, the bond strength nears the ultimate shear capacity of the wood."

Two resin types are predominantly used in current industry construction overseas.

These are;
- Melamine urea formaldehyde resins
- Polyurethane resins

For glue laminated systems, MacKenzie (2009) has found the predominant resin used is Polyurethane (PUR) adhesives and many companies list this type of resin as their preferred bonding agent.
Formaldehyde resins are commonly used in the glue lamination and fibre composite

industries. The concerns with formaldehyde being a known carcinogenic have recently been alleviated with research now conclusively proving that the molecule can be changed and locked into the molecular structure with the aid of the right catalysis, leaving the resulting matrix harmless to humans.

2.6.0 - Relevant Standards

Where applicable all sizes for test specimens should be completed to the relevant Australian standards. The Current Australian standard for the design of timber based structures is outlined in detail in *AS 1720.1 – Timber Structure – Design Methods.* This section of code details the timber design limit states and appropriate modifications factors for the use in design and investigation of timber structures and structural elements.

Australian Standard code *AS 4063* details the procedures for verifying and evaluating the mechanical properties and the structural characteristics of graded timber.

Due to the Australian concept of CLT there is no relevant Australian Standards for the design and limit states of composite wood panels for use as structural elements. As a result, where needed the relevant procedures for test samples and verification will be taken with regard to European standards, where CLT design and technology is world standard.

Codes include;
EN 13353 (CEN 2003b) -
EN 13986 (CEN 2004b) -
EN 789 (CEN 2004a) -

Chapter 3

Application of Standards

3.1.0 - Important Notes

Clause 1.7 – AS 1720.1 – New Materials and Methods

These standards shall not be interpreted to prevent the use of material or of methods of design or construction not specifically referred to herein. Methods of design can be based on analytical and engineering principles, or reliable test data or both, that demonstrate the safety and serviceability of the resulting structure for the purpose intended. The classification of timbers into strength groups (clause 1.4) of their grouping for joint design (clause 4.1) shall not be interpreted as precluding the use of design data derived on the basis of authoritative research information for a particular timber product or grade of timber. Such research shall include consideration of both short-term and long term strength and stiffness properties, durability of adhesives and applicability to this standard of the data or test methods used.

***Note**: Reports containing complete information on the basis for the use of any new materials or methods of design shall be made available. It usually will be necessary to seek approval from the relevant building authority or other appropriate regulatory authority for the use of other materials and methods.*

3.2.1 - Capacity & Reduction Factors

Capacity factors are used to provide a certain element of extra safety to ensure that the members will not fail during their design life. In accordance with extracts taken from AS 1720.1 – 1997, Timber Structures, element limit states must be adhered to in accordance with limit state design methods for structural timber elements, or systems comprised of timber, or wood products and of structures comprised substantially of timber.

As CLT components currently fall under the definition of structural elements comprised substantially of timber, and there are no other appropriate applicable standards for the design of this engineered wood product, the above mentioned standard is deemed to be relevant and also must be adhered to for design purposes.

Extract from clause 2.1.2

For calculation purposes the member design capacity (ØR) of a structural member is the product of the characteristic strength of the material, the appropriate geometric properties, factors to allow for variation in strength with the environment and configuration of the element in use and a capacity factor.

The equation is expressed as follows;

$$ØM= [K_1\ K_4\ K_6\ K_9\ K1_{11}\ K_{12}]^*\ [f'_b\ Z] \qquad \text{Eqn 1}$$

Where;

Ø= Capacity Factors – (clause 2.3)

f'_b= Characteristic strength of material in bending in MPa

Z = Section modulus

K_1 - K_{12} = reduction factors based on various loading conditions and environmental effects

Capacity factors Ø, for calculating design capacities (ØR) for structural timber members and joints are listed in AS 1720.1 respectively as **Table 2.5** – '*Values of capacity factor (Ø) for calculating the design capacity (ØR) of a structural member appropriate to the type of structural material and application of the structural member*' and **Table 2.6** - '*Values of capacity factor (Ø) for calculating the design capacity (ØR) of a structural joint appropriate to the type of fastener and application of the structural joint'.* These tables are included in appendix B.

Type of structural material and applicable standards

- Glues Laminated Timber – manufactured to AS/NZ 1328

Characteristic design property to which the capacity factor, (Ø), shall be applied for calculating the design capacity, (ØR) of structural members appropriate to their application

- All Characteristic design strengths, f'_b, f'_t, f'_s, and f'_c, corresponding to Glued-Laminated, GL-grades specified in Table 7.1 of AS 1720.1

Table 3 - Extract from Tbl 2.5, AS 1720.1

All structural elements in houses and secondary structural elements in structures other than houses	Primary structural elements in structures other than houses	Primary structural elements in structures intended to fulfil an essential service or post disaster function
Ø		
.85	.70	.65

- All Characteristic design strengths, f'_p, f'_l, f'_{tp}, and f'_{sj}, corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)

Table 4 - Extract from Tbl 2.5, AS 1720.1

All structural elements in houses and secondary structural elements in structures other than houses	Primary structural elements in structures other than houses	Primary structural elements in structures intended to fulfil an essential service or post disaster function
Ø		
.80	.65	.60

3.2.2 - Reduction Factors

Reduction factors are used to negate the effects caused by the unpredictable nature of the orthotropic timber elements. These factors provide an extra factor of safety and ensure that there is still significant strength supplied by the timber element including the areas of defect. Modification factors are also used to provide extra assurance against the effects of environmental attack and long term loading situations.

These factors are;

K_1 - Effects of load duration on strength

The modification factor K_1 is used to check the strength of all structural elements for all load combinations during the effective load duration.

K_4 – Moisture conditions

Depending on the initial moisture content of the timber, the moisture at the time of loading and the environment in which the timber element will be placed, the strength capacity of the element must be modified.

For glued-laminated timber elements, appropriate values of K_4 are taken from clause 7.4.2

where it is noted that long-term creep is dependent upon size, grade, environmental conditions and surface coatings. Therefore K_4 shall be taken and assumed in all cases to be equal to 1.

K_6 – Temperature and humidity effects of strength

From AS 1720.1, For all covered timber structures under ambient conditions, no modification for strength need be made for the effects of temperature, that is K_6 =1. excepting where seasoned timber is used in structures erected in coastal regions of Queensland North of latitude 25° S, and all other regions of Australia North of latitude 16° S. for these areas the strength shall be modified by a factor of, K_6 =.90.

Further information of the effects of high atmospheric temperatures can be found in KELLOG, R.M and MEYER, R.W. *'Structural use of wood in adverse environments'*, Van NoStrand, 1982.

K_9 – Effects of strength sharing between parallel members

from clause 7.4.3 and in accordance AS 1328 *'Glued – Laminated timber construction*'; The strength sharing factor K_9, for glued - laminated timber used in parallel systems shall be taken as unity, that is K_9 =1.

K_{11} – Size factors effecting strength

AS 1328 and clause 7.4.4 – AS 1720.1 state that for glued – laminated elements, except where in grade testing demonstrates a different effect of size, the capacity shall be modified by the size factor K_{11} as outlined in the following;

- For bending K_{11} shall be taken as =1
- For compression K_{11} shall be taken as =1
- For shear K_{11} shall be taken as =1
- For tension parallel to the grain, K_{11} shall be taken as the lesser of, (150/d)^.167 or 1
- For tension perpendicular to the grain, K_{11} shall be taken as; K_{11}= (V_o/V)^.2;

Where;

V_o= 10^7 (reference volume)

V= the volume of timber stressed above 80 percent of the maximum value in tension perpendicular to the grain.

Note – Where a Glued – Laminated timber component is used as part of a fabricated member, the appropriate size factor to the action of the glued – laminated component should be used. That is, should a glued – laminated component be used as a tension member in a timber flange as part of a box beam, K_{11}= should be taken as a tension member, using the cross-sectional dimensions of the glued – laminated timber.

K_{12} – Stability factors for strength

Stability factors for glued – laminated timbers shall be calculated in accordance with section three of AS 1720.1, excepting the material constants ρ_b and ρ_c for beams and columns ate taken from tables 7.2(A) and 7.2(B).

AS 1720.1 – clause 1.4.3 – Changes of strength grade

the strength properties of graded timber or timber elements may alter as a consequence of subsequent processes such as longitudinal sawing, chemical treatments, re-drying processes and glued – lamination processes. Hence it may be necessary to reassess the strength properties to ensure that the graded timber or timber products still satisfy minimum design requirements.

Clause 1.4.4 – Special Provisions

Design loads for timber joints and design rules for notched beams given herein are based on the assumption that there are no loose knots, severe sloping grains, gum veins, gum or rot pockets, holes splits or any other defects in the vicinity of the joint.

All CLT components are therefore designed and evaluated with these codes and clauses in mind. All strength and capacity values are calculated and determined in accordance with AS 1720.1, section 2, 'Design Properties of Structural Timber Elements', excepting where section 7, 'Glued – Laminated Timber Construction', and AS 1328, 'Manufacture of Glued – Laminated Timber Members' specifically state otherwise. Should the capacity of joining procedure be required, AS 1720.1, section 4, 'Design Capacity of joints in Timber Structures' must be adhered to in accordance with AS 1649, 'Testing of Mechanical Fasteners and Variance of Conventional Fasteners'.

The University of Southern Queensland in conjunction with the Centre of Excellence in Engineering in Fibre Composites concludes that components can be grouped into two main categories; those that are fibre dominated and those that are resin dominated. The study reasoned that the most important ply properties, such as tensile and compressive strengths and the stiffness in the fibre direction are all fibre dominated properties. The shear properties of the composite and the properties in the directions perpendicular to the primary fibre direction are resin dominated. Fibre dominated properties are considered of primary importance to the extent that good structural design attempts to avoid any failure that is resin dominated. Therefore standards and design protocol should be focused around positioning the timber element's in the strongest configuration.

Chapter 4

Mechanical Properties

4.1.0 - Identifying Individual Matrix Element Properties

4.1.1 - Timber Properties

The mechanical properties of timber are more commonly known and reported as the material 'strength properties'. These properties include the modulus of rupture in bending and modulus of elasticity, the maximum stress parallel and perpendicular to the wood grain in compression and the maximum allowable shear stress.

The "*Wood Handbook" -Chapter 4- "Mechanical Properties of Wood*", *(Green. D et al)* outlines the nine (9) main mechanical, strength properties of wood which are used to evaluate the maximum loads in bending, impact strength, tensile strength perpendicular to the wood grain and the timber hardness.

The following material property definitions are taken from the *'Wood Handbook--Chapter 4--Mechanical Properties of Wood'***, *(Green. D et al)***

Modulus of rupture— Reflects the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit.

Work to maximum load in bending— Ability to absorb shock with some permanent deformation and more or less injury to a specimen. Work to maximum load is a measure of the combined strength and toughness of wood under bending stresses.

Compressive strength parallel to grain— Maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least dimension of less than 11.

Compressive stress perpendicular to grain— Reported as stress at proportional limit. There is no clearly defined ultimate stress for this property.

Shear strength parallel to grain— Ability to resist internal slipping of one part upon another along the grain. Values presented are average strength in radial and tangential shear planes.

Impact bending— In the impact bending test, a hammer of given weight is dropped upon a beam from successively increased heights until rupture occurs or the beam deflects152 mm (6 in.) or more. The height of the maximum drop, or the drop that causes failure, is a comparative value that represents the ability of wood to absorb shocks that cause stresses beyond the proportional limit.

Tensile strength perpendicular to grain— Resistance of wood to forces acting across the grain that tends to split member. Values presented are the average of radial and tangential observations.

Hardness— Generally defined as resistance to indentation using a modified Janka hardness test, measured by the load required to embed a 11.28-mm (0.444-in.) ball to one-half its diameter. Values presented are the average of radial and tangential penetrations.

Tensile strength parallel to grain - Maximum tensile stress sustained in direction parallel to grain. Relatively few data are available on the tensile strength of various species of clear wood parallel to grain. Table 4–7 lists average tensile strength values for a limited number of specimens of a few species. In the absence of sufficient tension test data, modulus of rupture values are sometimes substituted for tensile strength of small, clear, straight grained pieces of wood. The modulus of rupture is considered to be low or conservative estimates of tensile strength for clear specimens (this is not true for lumber).

Figure 2 – The Three Principle Axis of Wood with Respect to Grain Direction and Growth Rings

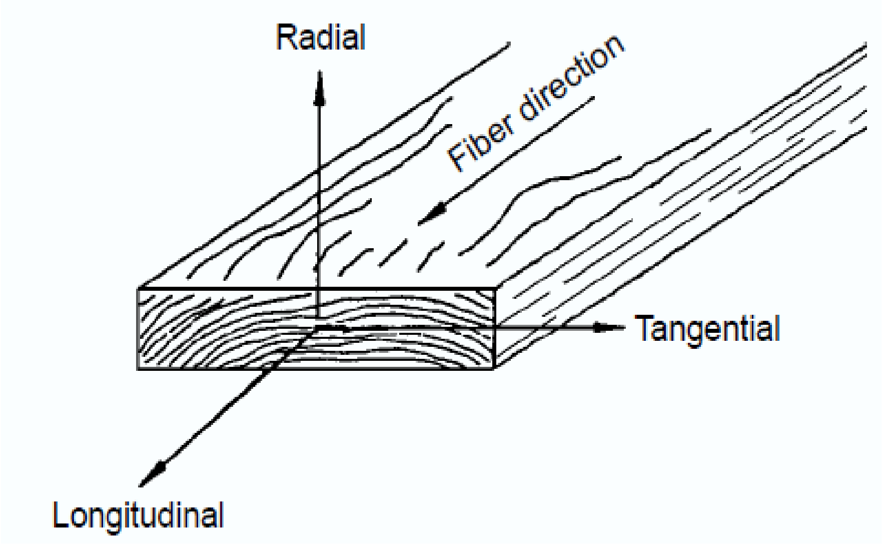
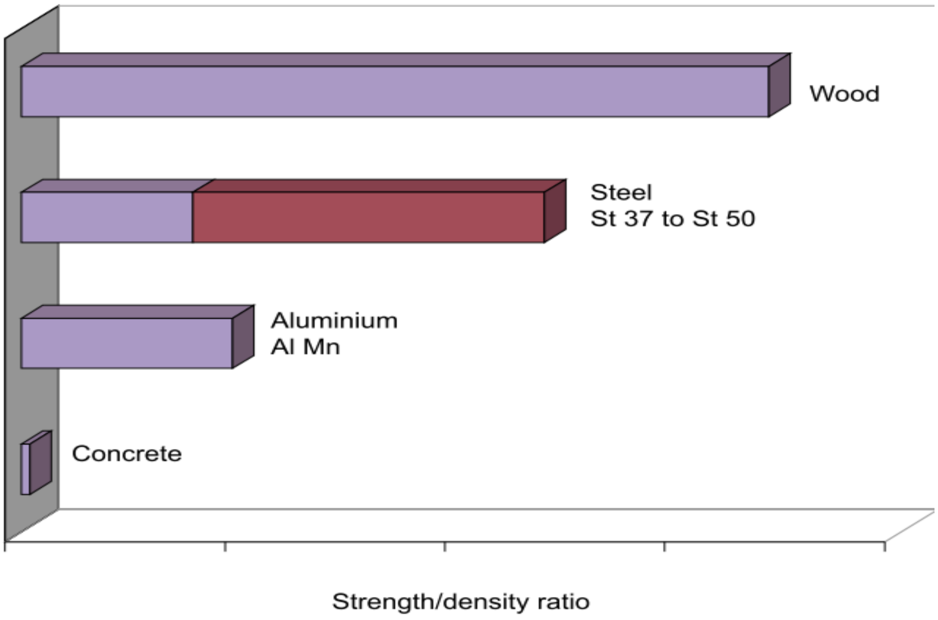


Table 5 - Slash Pine - Elastic Ratios @ 12% Moisture Content

E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L
.045	**.074**	**.055**	**.053**	**.010**

The elastic ratios of slash Pine are used to determine the modulus of elasticity of the timber in the two non primary orientations, namely the radial and tangential directions. These ratios will vary depending on the individual timber specimen and their moisture contents and density. An increase of moisture will provide an apparent increase in the modulus but only for low deflection increments, this can lead to a misinterpretation when measuring the derived stiffness properties of the member.

Figure 3 - Strength/Density Ratio of Various Construction Materials



Accurate determination of the Modulus of Elasticity of the material matrix is essential to the design of a viable CLT product. As Shown is Figure 5, wood/timber has by far the highest strength/density ratio, however in order to capitalise on the inherent strength which lies in the orientation of the timber grain, increasing the timber element's limiting factor, that is effective deflection under load is essential. The cross lamination process increases the modulus of elasticity in the secondary direction, which is the direction tangential to the primary grain direction. This method produces a reduction in the modulus in the primary direction but an increase in the secondary direction by unto 600%. As the deflection is dependent upon the resistance in the tangential and radial directions, an increase in the tangential modulus leads to a direct decrease in the elements deflection under the applied load. However due to the significant defects in the utility graded timber elements the modulus of elasticity should not be taken as the average modular for strait grained defect free timber, nor can it be accurately measured excepting by destructive mechanical means. This is due to the fact that utility grade elements may possess significant strength throughout their entity excepting in a region of defect which renders the timber non structural and unusable.

Research undertaken by Cameron Summerville, October 2009, on the 'Structural Performance of Low Grade Timber Slabs' produced a series of destructive experiments, determining the modulus of elasticity of utility grade timber elements. This experiment consisted of a random selection of 11 utility grade timber elements and subjecting them to destructive four (4) point bending tests. The average of these tests can be considered to be the average modulus for utility grade timber. Summerville (2009) was able to determine an average modulus by plotting the load - deflection data gathered for each test specimen, then determining the linear proportions that represent the extents of the linear region represented in the data. These points were then used in conjunction with the equation;

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

Eqn 2

Where;

B = The width of the test specimen

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

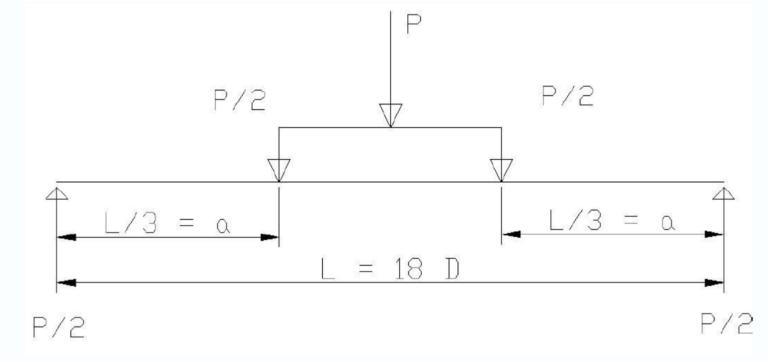
P_2 = The highest load applied in the linear portion of the load deflection graph

Δ_1= Deflection corresponding to $P1$

Δ_2 = Deflection corresponding to $P2$

And with respect to the positions given on following loading diagram;

Figure 4 - Experimental Loading Configuration



The results of Summerville's experiments have been tabulated and an average modulus calculated. These values are;

Table 6 - Experimental Data Gathered in Summerville's Experiments

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

The results obtained by Summerville (2009) can be considered as an accurate representation of the modulus of elasticity in the utility grade timber elements; however the data can be more accurately modelled by not taking into consideration the outlying data sets. By neglecting outlying data a more appropriate average is achieved. Low strength, outlying data sets can be a result of an accumulation of significant local defects such as a growth knot intercepting a localised resin shake, reducing the timber strength drastically. High strength outliers can be the result of condemned timber elements due to wanes, undesired grain slope or element bowing.

Table 7 – Modulus of Elasticity Data from Summerville's Experiment - Neglecting Outlying Data Sets

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	7730.0

When compared to Hyne Timber's generally accepted utility grade modulus of 9000MPa, the average in Table 6 is falling 14% short of the expected outcome. This is largely due to the small sample size tested by Summerville (2009) due to limiting time factors. The 100% elastic modulus from Table 8 will also be used to model effective CLT component configurations in Strand 7 as this base modulus will provide more conservative estimates on a viable cross laminated product.

Table 8 - Average Modulus of Elasticity Values for the Three Primary Grain Directions of Strait Grained, Significantly Defect Free Timber

Modulus Factor	MoE (MPa)	Direction	Modulus Factor	MoE (MPa)	Direction
125%	17125.00	Longitudinal	95%	13015.00	Longitudinal
	770.63	Tangential		585.68	Tangential
	1267.25	Radial		963.11	Radial
120%	16440.00	Longitudinal	90%	12330.00	Longitudinal
	739.80	Tangential		554.68	Tangential
	1216.56	Radial		912.42	Radial
115%	15755.00	Longitudinal	85%	11645.00	Longitudinal
	708.98	Tangential		524.03	Tangential
	1165.87	Radial		861.73	Radial
110%	15070.00	Longitudinal	80%	10960.00	Longitudinal
	678.15	Tangential		493.20	Tangential
	1115.18	Radial		811.04	Radial
105%	14385.00	Longitudinal	75%	10275.00	Longitudinal
	647.33	Tangential		462.38	Tangential
	1064.49	Radial		760.35	Radial
100%	**13700.00**	**Longitudinal**			
	616.50	**Tangential**			
	1013.80	**Radial**			

Table 9 - Average Modulus of Elasticity Values for the Three Primary Grain Directions of Utility Grade Timber - as per Summerville's Results

Modulus Factor	MoE (MPa)	Direction	Modulus Factor	MoE (MPa)	Direction
125%	9662.5	Longitudinal	95%	7343.5	Longitudinal
	434.8	Tangential		330.5	Tangential
	715.1	Radial		543.5	Radial
120%	9276.0	Longitudinal	90%	6957.0	Longitudinal
	417.42	Tangential		313.1	Tangential
	686.5	Radial		514.9	Radial
115%	8889.5	Longitudinal	85%	6570.5	Longitudinal
	400.0	Tangential		295.7	Tangential
	657.9	Radial		486.3	Radial
110%	8503.0	Longitudinal	80%	6184.0	Longitudinal
	382.6	Tangential		278.28	Tangential
	629.3	Radial		457.6	Radial
105%	8116.5	Longitudinal	75%	5797.5	Longitudinal
	365.3	Tangential		260.9	Tangential
	600.7	Radial		503.1	Radial
100%	**7730.0**	**Longitudinal**			
	347.9	**Tangential**			
	572.1	**Radial**			

The data in the above tables will be used to model the the CLT matrix in the finite element package, Strand 7.

4.1.2 - Resin Properties

Selection of an appropriate bonding resin is significantly important as the strength of the CLT component relies on an effective bond between the timber elements. Due to the negligible thickness of the bonding resin layer, the surface area in contact with the timber element becomes the critical factor and the maximum surface area for bonding layers should be utilised.

Due to the layer thinness the axial compressive strength of the resin is not a major contributing factor, as compression loads will be carried by the timber. Instead the shear resistance of the resin and the axial strain due to deformation as a result of applied loading will factor more predominately.

The deformation due to deflections under applied loading will not only create stress throughout the timber layers but also through the layers of the bonding resin. It is a critical requirement of the bonding resin that it is able to 'flex' with the low timber modulus or possesses an allowable strain limit that exceeds that of the timber. The critical component in the selection of an appropriate resin is that the bond layer of the resin between the adjacent timber layers must NOT fail before the sounding timber elements.

Resin absorption is considered to have no effect on the mechanical properties of the timber. This assumption is made on the grounds that it is neither possible nor viable to accurately ascertain how far the resin absorption will penetrate into the timber elements, nor the effect that this will have on the timber strength properties. The complications in absorption arise from not being able to accurately and with certainty determine the initial surface properties of the timber elements. Superficial surface defects may allow for increased absorption, while not affecting the timber strength, thus making any reasonable estimates difficult. Also local, surface moisture content would need to be strictly monitored. Exceptionally hot or humid periods would cause differentials in the absorption rates, further complicating calculations and predictability.

The absorption of the resin into the timber grain through the pressure that would be applied by the gluing clamps can effectively be considered as a form of resin impregnation. As can be proven in current research, the vast majority of composites formed by resin impregnation create a stronger, ridged, more durable matrix. By not considering the mechanical effects of resin absorption the resulting models will produce conservative data sets for analysis. Some suitable resins include;

PUR Bond 514

Adhesive systems for engineered wood products

Uses – A durable construction adhesive suitable for the bonding of most construction materials.

PUR Bond 530

Adhesive systems for engineered wood products

Uses – A durable construction adhesive suitable for the bonding of most construction materials.

Sikadur -30

Adhesive for bonding reinforcement

Uses – adhesive for bonding reinforcement, particularly in structural strengthening of brick and timber.

Sika – SuperGrip 30 minutes

Fast curing premium polyurethane construction adhesive

Uses – A versatile transparent polyurethane adhesive, suitable for construction and the bonding of timber and MDF, stone, marble, glass and metals.

4.1.3 – Poisson's Ratio

Poisson's ratio is the ratio of the transverse to the axial strain under load deformation; the deformation perpendicular to the direction of the load is proportional to the deformation parallel to the direction of the load. The Poisson's ratios vary within individual timber specimens of the same species depending on the timber's moisture content and specific gravity.

Table 10 - Slash Pine - Poisson's Ratios @ 12% Moisture Content

v_{LR}	v_{LT}	v_{RT}	v_{TR}
.392	.444	.447	.387

However the data represented in is only true for strait, relatively defect free slash pine elements. The Poisson's ratios for timber members less than that of an F5 grade can be assumed to be that of the above mentioned values excepting at the area of significant defect. In the immediate region of a significant defect the mechanical properties of the element are not calculable, and the effects of this on a possible change in deformation ratios are currently unknown.

The timber elements to be used in the finite element modelling of the cross laminated members are to reflect the material properties of the Hyne Timber Australia Milling Plant's 'Utility Grade' product. As most of the timber classed as utility grade product is a result of timber lengths having areas of significant defect and not poor quality of the entire element, the average Poisson's ratio for slash pine can still be applied to the utility grade product, so long as it is still within the specified moisture content for the given ratios. A change in moisture content will reveal a change in ratios as the internal pressure between the wood grain increases or decrease as the grain swells and shrinks. Should the moisture content rise the deformation ratio will also increase, proportionally as the moisture content decreases so too does the ratio.

4.2.0 - Conclusion

The correct modelling of the mechanical properties of the timber element are essential in creating a accurate CLT model to allow a viability analysis into developing a serviceable product.

The properties of the utility grade timber are somewhat less than that of the average defect free slash pine element. But due to the nature of cross lamination and the minimisation of defects due to restriction in the amount of defect present in any given cross section, the strength properties for average, defect free slash pine can be used. However data gathered via means of destructive testing has yield strength properties for utility grade timber and the average properties for defects. This data set will also be modelled to provide a conservative estimate to a CLT product.

The only significance of the resin properties is in its ability to provide a strong, durable and reliable bond between the adjacent timber layers. Due to the minimal cross sectional area of the resin layers, it is assumed that they provide no recordable increase in strength in their own right to the resulting material matrix. The matrix properties of the CLT component will be calculated using the mechanical properties of the Slash pine. It will be assumed that the resin only supplies a physical bond between the two adjacent timber layers and the resin properties supply no significant increase in strength to the resin - timber matrix, nor does the resin affect the mechanical properties of the timber.

Chapter 5

Finite Element Modelling

5.1.0 - Introduction

This chapter will focus on the accurate finite element modelling of the CLT matrix in the software package known as Strand 7. From this modelling assumptions and recommendations will be drawn up regarding the viability of processing utility grade timber into CLT components and assessing whether the developed product has any significant increase in performance over current constructions applications.

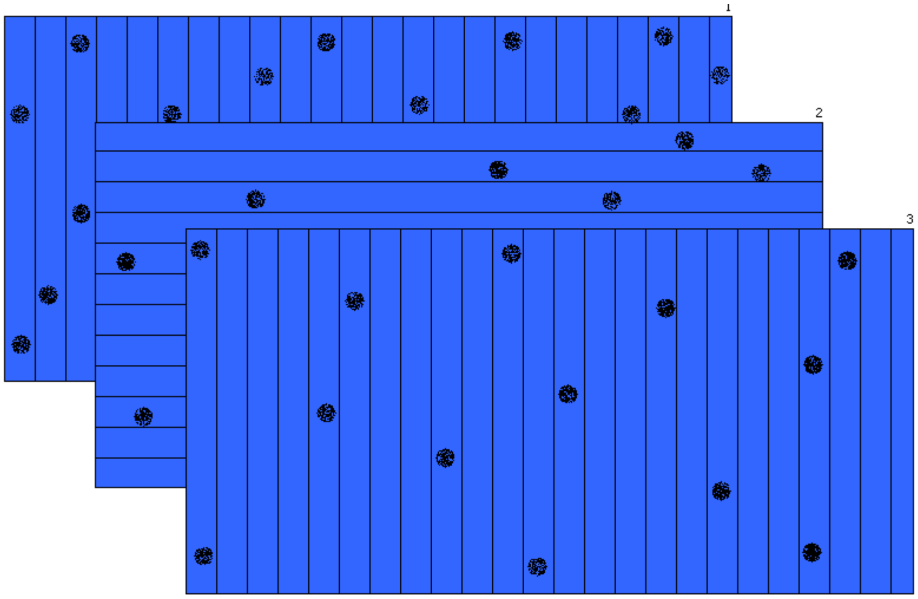
Strand 7 is a powerful finite element modelling package, it is able to accurately measure and calculate stress, strains, deflections, shear forces, bending moments and deformations under an applied load. More significantly it is capable of calculating the resulting CLT matrix's mechanical strength properties accurately and effectively. This is essential in providing initial data that would otherwise need to be gathered through tedious hand calculations or by destructive testing on models.

5.2.0 - Strand 7 – Data Inputs

5.2.1 - Initial Modelling Assumptions

Infinitely thin layers of bonding resin theoretically exist between the timber layers. Modelling these layers within the material matrix is difficult as the interaction between the resin is highly dependent upon the individual properties used in any given layer of any given product. The models used to analyse the viability of a CLT product are formed on three (3) main assumptions. The first sets of models assume that the timber layers and not affected by the bonding resin used, subsequently the resin properties are not used in the calculation of the stiffness matrices and the subsequent material matrix properties. The second assumption is that the bonding resin used poses no change to the mechanical properties of the timber due to surface absorption by the timber element. The third assumption is that through the process of cross lamination and the gluing of multiple timber element together the effects of defects are significantly reduced and although the strength properties of the newly formed matrix may not be equal to that of a strait, defect free sample of Slash Pine, the resulting matrix strength properties will provide sufficient data for initial viability tests.

Figure 5 - Pictorial Representation of Defect Distribution



5.2.2 - Modelling Parameters

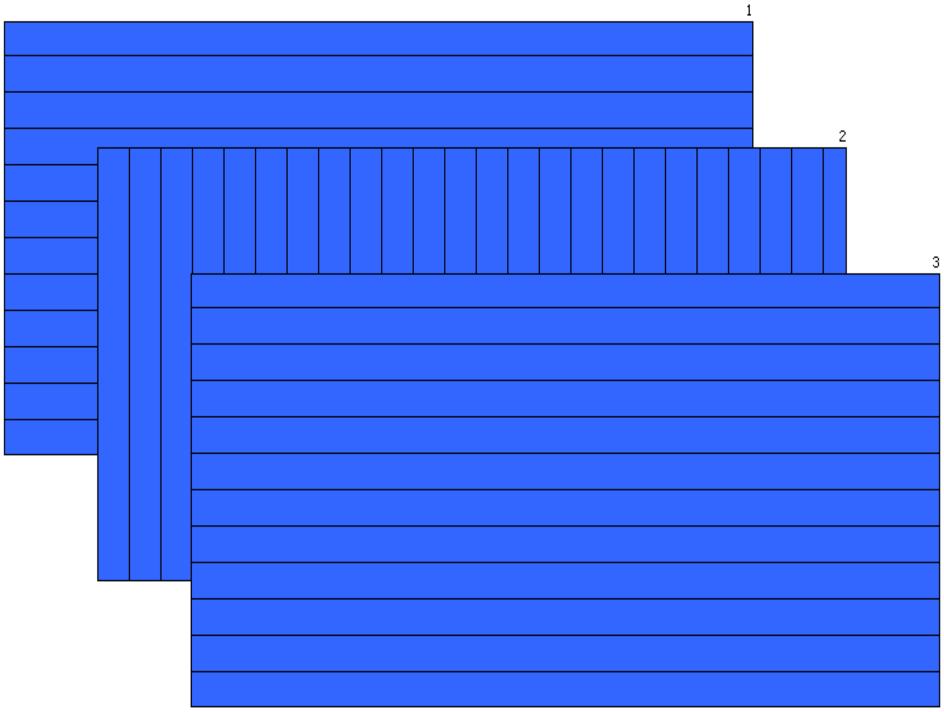
The models produced in Strand 7 are subject to the normal loading parameters which would influence their intended use, namely as slabs and load bearing wall panels. As load bearing wall panels are being covered in a separate research objective, the models produced in Strand will be limited to load bearing slabs.

Models produced will rely on the mechanical data inputs of the two materials that make up the CLT matrix, this data is published in the previous chapter. However due to the bonding resin contributing no significant strength to the matrix, the resin’s mechanical properties are neglected. Strand 7 requires the data inputs of; modulus of elasticity, modulus of rigidity and Poisson's ratios in the primary and secondary directions, as well as the orientation of the grain direction. These inputs are saved in Strand under the allocated material type for later access and use.

Models are composed of 861 individual elements, creating a 900 x 1800 mm two dimensional panel face. These panel dimensions were selected bearing in mind that future viability assessments would need to produce sizable yet suitable experimental test subjects to later fully validate the conclusions reached based on the theoretical finite element models. The 2D panel face is selected and defined as a ply element, which is essential in modelling the cross lamination effect. During the 'definition stage' of the ply element the prompted inputs of; layer thickness, layer orientation, number of layers and material type are required by Strand 7 for future calculations. With these data inputs the 2D elements are able to be successfully formulated into a 3D panel element. Strand 7 is able to model the ply, laminate element in 1, 2 or 3 dimensions, however the 3 dimensional element is by far most accurate way to perform a theoretical analysis on the newly formed ply, cross laminate element. One dimensional element modelling should not be used in any case as the line element produced does not nor can it take into consideration the changed mechanical properties of the ply elements that run perpendicular to the line modelled. One dimensional line analysis can only be used for fully homogeneous materials like steel and glass.

The effects of cross lamination can be modelled in two dimensions, with the addition of a depth component to the line model the 2D model can now accurately calculate the effects of differing layer orientations. However due to the nature of 2D element modelling of non homogeneous materials, every 2D model produced from any given section of the laminate panel would yield different results, leading to an infinite amount of sections required to complete an analysis. The 3D modelling of the laminate provides the most accurate and decisive data of element stress distribution, moment and deflection distribution and ultimately failure.

Figure 6 - 3 Ply, Cross Lamination, Layer Formulation & Orientation



5.2.3 - Use of Isotropic Elements

Timber elements should be considered as being an orthotropic material and not isotropic. An orthotropic material can be described as any material which has the different materials properties or strengths in different orthogonal directions, where as an isotropic material has uniform strength properties in all directions of the element. Data does not currently exist on the orthotropic nature of ‘Utility grade’ timber, nor will it be feasible to conduct tests on the timber to determine these values due to the unpredictable nature of the defects within each individual timber element. For this reason the mechanical properties of clear, strait grained slash pine were used to model the individual orthotropic layers. These properties can only be used if the assumption is made that the resin layers between the timbers do not significantly contribute to the resulting matrix strength.

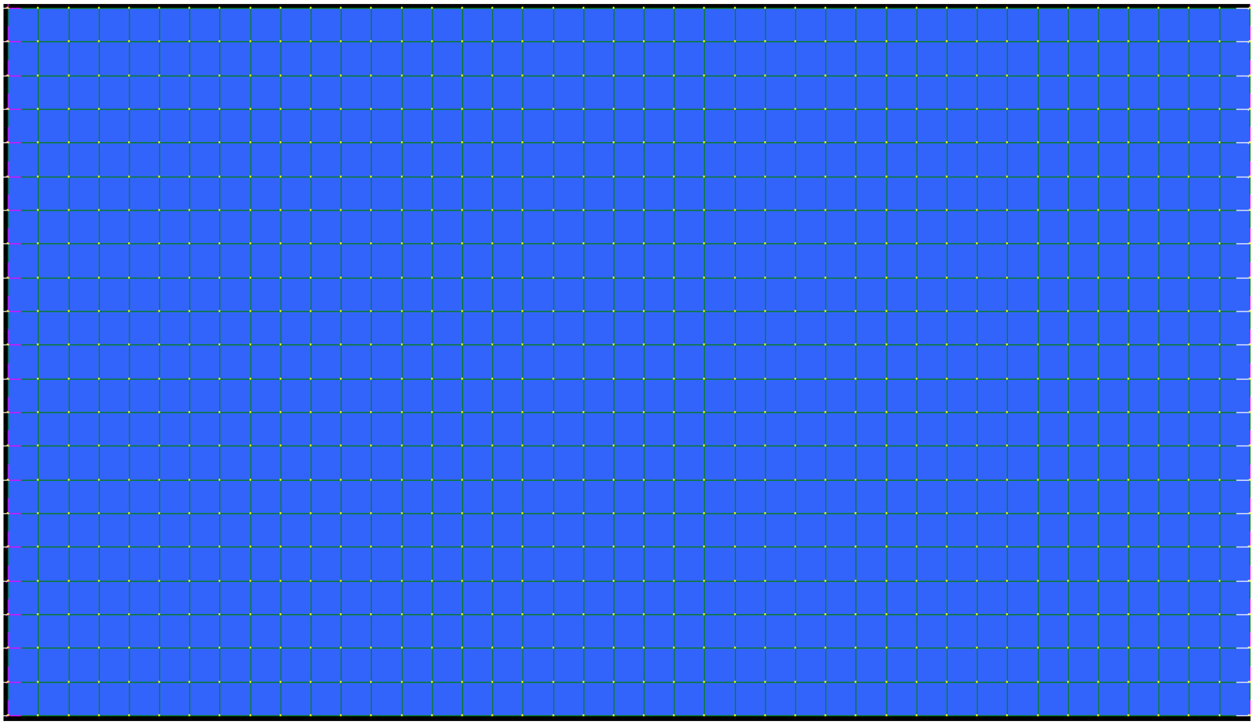
The panel elements could be modelled as 3 dimensional isotropic elements, however problems do arise when the orthotropic, timber elements are cross laminated to form the CLT panel. There is currently insufficient data on the effects of stress distribution across the face of the layers which run perpendicular to the principle direction; as timber elements are non-isotropic, they possess significant reductions in their mechanical properties in both perpendicular directions from the principle grain orientation. Due to the non homogenous properties of the CLT panel and the assumption that the bonding resin does not increase the material matrix strength, a clear conclusion cannot be reached as to whether first ply failure will occur at the extreme fibres or whether it will occur on the outer most perpendicular layers. This analysis of failure falls outside the scope of this initial viability assessment and will not be covered in this dissertation. Due to this reason the models will be designed with orthotropic layer properties but analysed as an isotropic element. However due to a significant change in mechanical properties in both the tangential and radial directions, classifying timber as an isotropic material and modelling it as such will result in bias results and not allow for a full assessment on the viability and utility of CLT elements made from utility grade timber.

5.3.0 - Loading

As the model has been formulated into a ply, laminate element and will be analysed as such it is important that the correct loading be applied to the model. Strand 7 uses the location of 'nodes' and an X, Y, Z coordinate scheme to determine where a force starts and in what direction it acts. Nodes are automatically formulated at the vertices of the individual elements which make up the panel. Strand 7 also uses the nodes a reference point for measuring deflection, moment and changes in stress distributions. The models produced have a total of 924 nodes which are located on the top free face of the laminate.

Due to the nature of the laminate panel and its intended future uses it will be loaded with a global pressure. This loading type falls within the standard load definitions for wall, floor and load bearing panels as outlined in the AUSTRALIAN STANDARDS Appendix B.

Figure 7 - Laminate Top Surface – Node Locations



The placement of the reference nodes is important to the accurate calculation of the stress distributions. Placement of the nodes must be on one of the laminates free surfaces, that is the top or bottom face. This is due to the location of the maximum compression and tensile strain limits on these faces, parallel to the principle fibre direction. As the element is loaded it deforms creating compression on the top face and a tension zone on the bottom face. Between the two zones lies the neutral. Along this the stress distribution is zero; therefore placing the reference nodes here will not yield any results.

Figure 8 - Stress Conditions

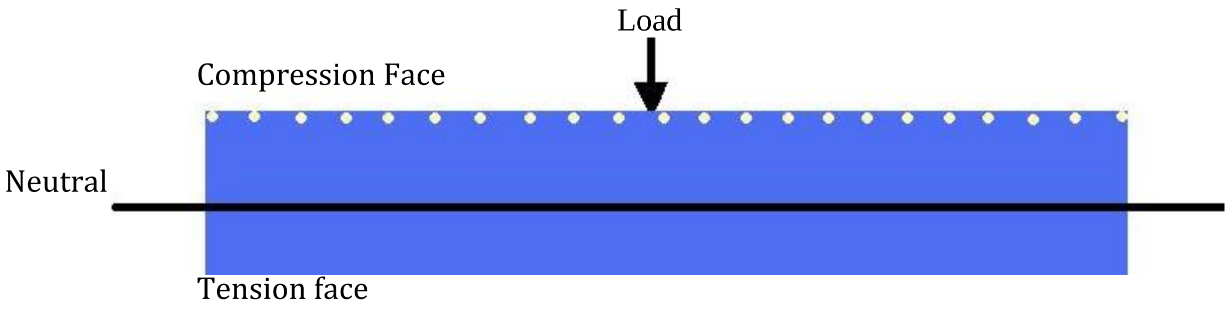


Figure 9 - Stress Distribution

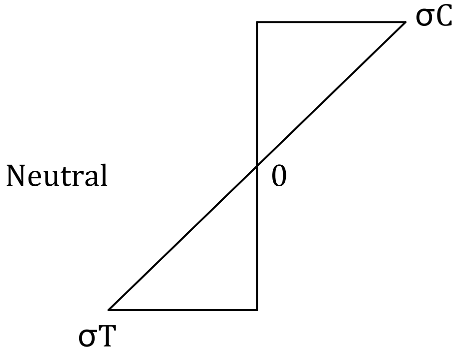


Figure 9 depicts the standard stress distribution which will be used to model the orthotropic nature of the CLT panels

The failure stress distribution at the extreme fibres can be calculated by multiplying the characteristic modulus of elasticity by the ultimate failure strain, this gives the stress limit for first ply failure.

$$\sigma = E * \varepsilon$$ Eqn 3

Where; ε is equal to the ultimate failure strain in either compression or tension.

First however the new modulus of elasticity for the ply matrix must be calculated. Due to the cross lamination of the ply and the orthotropic properties of timber, the modulus changes between the alternating layers, resulting in a reduction in stiffness in the primary direction but an increase in the tangential direction which directly correlates to an increase in deflection resistance. The combined matrix modulus of elasticity was obtained from the results outputs from Strand 7.

However if the strain in the element does not exceed the allowable failure limit, the maximum applied stress can be calculated by multiplying the induced moment under loading by the section modulus.

$$\sigma = M * Z$$ Eqn 4

Where;

$$Z = \frac{y}{I}$$ Eqn 5

And;

y= the depth from the neutral to the extreme stress fibres

I= second moment of area

Accurate determination using these methods however, can only be achieved if the element is modelled with simple supports; this allows for the maximum mid-span moment and importantly the mid-span deflections to be accurately calculated. The simple support restricts the element's displacement from the point of origin while still allowing maximum rotational effects under loading.

Figure 10 - Figure of Initial Support Conditions

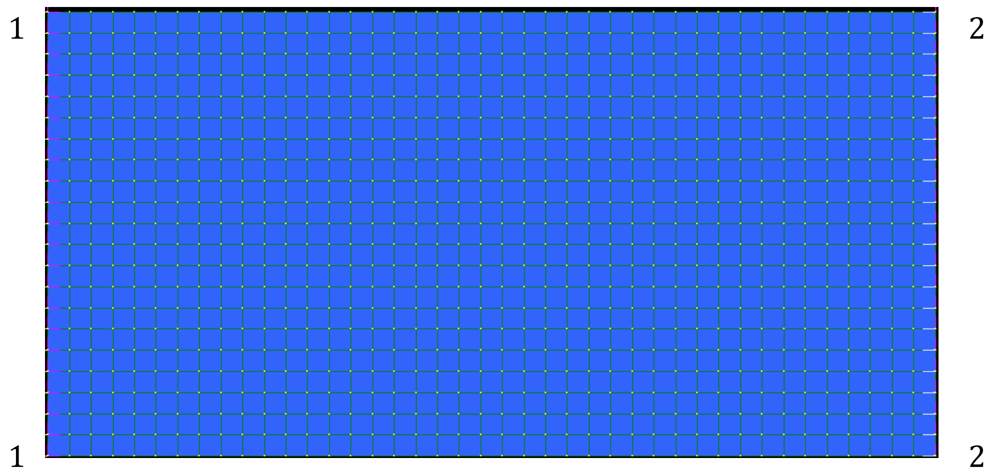


Table 11 - Support Conditions as Modelled in Strand 7

Direction	1 (Pin)	2 (Roller)
Displacement		
X	Fixed	Free
Y	Fixed	Fixed
Z	Fixed	Fixed
Rotation		
X	Fixed	Fixed
Y	Free	Free
Z	Fixed	Fixed

The above table lists the support conditions with respect to the three primary axis.
Note: Ends ‘1’ & ‘2’ taken with respect to figure 10

As the load on the panel increases so too does the compressive, tensile and shearing forces within the element until the point where the element fails and ruptures. For panels made from wood, failure usually occurs within the compression zone, followed by ultimate failure on the extreme tension face. The maximum compressive or tensile stress in the fibres at fracture is referred to as the Modulus of Rupture and although it is not a direct measurement of the stress of the fibres at failure it is proportional to it and can be used for design purposes. The modulus of rupture can be considered as a direct measurement of the bending strength of the panel.

5.4.0 - Dimension Influences on Strength and Stiffness

An understanding of the ratios between an increase in panel strength and the reduction in deflection and the increase or decrease in panel dimensions is important in the optimisation of the CLT component. In understanding how these relationships can affect the outcome of any given configuration, it is important to first understand how they affect the panel. However the following can only be proven to hold true for solid elements of the same material, it will be investigated further to conclude whether these basic guidelines can be used in the simple analysis of CLT members.

The bending strength of a rectangular beam or panel which is loaded and analysed on simple supports varies inversely as the span increases. That is, if the span was to be doubled, the effective strength of the element would be halved. The deflection of a beam also varies with the cube of the effective span, should the span be doubled the deflection would be increased by 2^3=6 times greater, and should the span be trebled 3^3= 27 times greater.

The ultimate bending strength of the panel increases directly as the width increases, with all other variable being kept constant. For instance if a 300mm panel can carry a 5 kPa pressure, a 600mm panel of the same configuration would be able to carry a 10 kPa pressure. The width of any given panel also varies inversely with the deflection under an applied load. Should the width be halved, the resulting deflection under the same load would be effectively doubled and vice versa, should the width be doubled the resulting deflection would be halved.

The depth of the panel however plays the greatest roll in increasing the bending strength and limiting deflection. The strength of the panel will increase with the square of its depth; that is, should the depth be doubled the bending strength would effectively be increased by four times. Therefore if an imaginary panel 150 mm deep could carry a load of 5kN, a panel of the same width and effective span but 300 mm deep could carry a load of 20 kN.

The depth of a panel also varies inversely with the deflection under an applied load. That is, halving the depth of the panel increases the deflection eight times. Thus if a panel 150 mm thick deflected 2mm under a 5kN applied load, the same beam with a reduced depth of 75 mm under the same lode would deflect by 16 mm.

The depth of the panel element is dependent upon the amount of layers specified during the creation of the ply. Conventional designs which are already successfully marketed commercially overseas consist of 3, 5 or 7 layers. As the number of layers increase so too does the panel depth and a reduction in deflection under applied loading.

Second moment of area;

$$I = \frac{bD^3}{12}$$

Eqn 6

Where the limiting deflection equation is;

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

Eqn 7

As can be seen in the above equations, as the depth of the slab, D increases so too does the second moment of area, I. The second moment of area along with the effective span, L are the most influential variables in limiting deflection, as can be seen in equation #3.

Graphical representations of this relationship can be seen in figure 11 and figure 12. Figure 11 depicts the cubic relationship between the increase in depth and the significant increase in the second moment of area. The second graph depicts the inverse, cubic relationship between the reduction of a slab’s deflection under an applied load and an increase in the slab depth. This proves that there is a point of feasibility where an increase in D to further reduce deflection can no longer be considered viable, once this stage is reached it is the responsibility of the engineer to alter the remaining variables; effective span, effective load and the material modulus to meet deflection requirements.

Figure 11 - Cubic Increase in Second Moment of Area as Ply Depth Increases

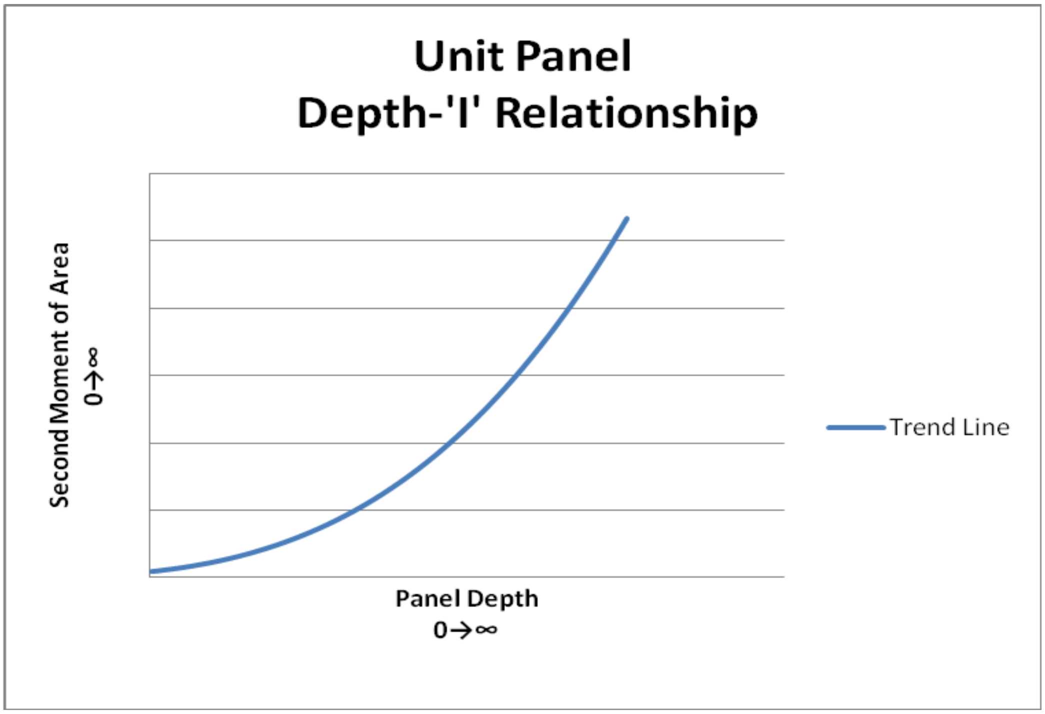
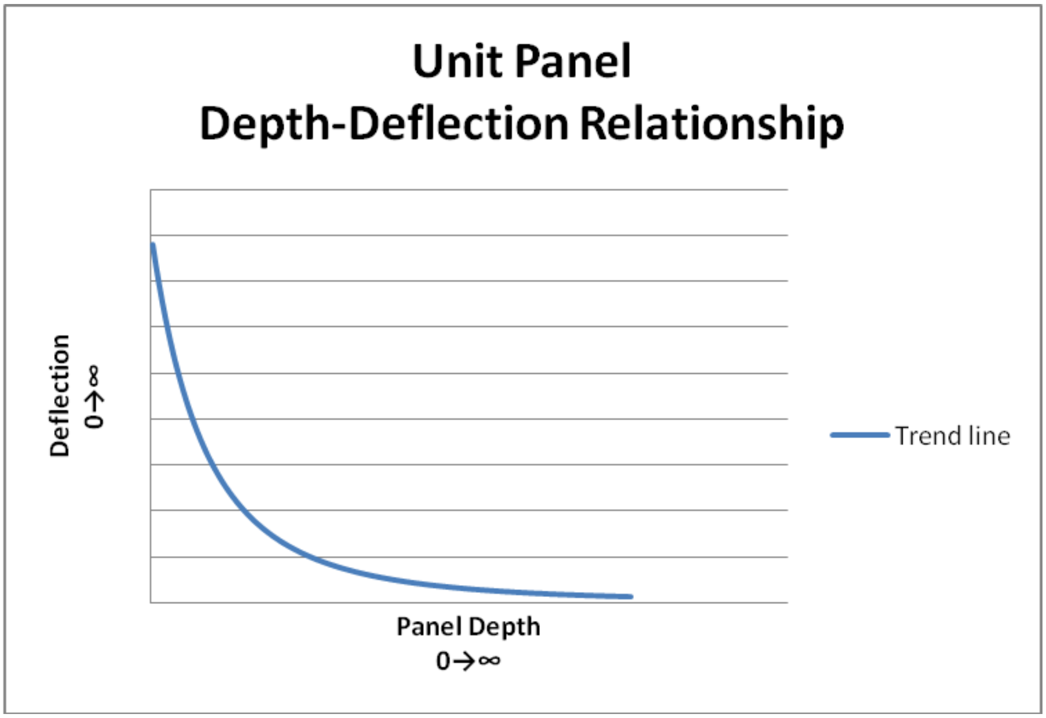


Figure 12 - Decrease in Deflection as Panel Depth Increases



Chapter 6

Results

6.1.0 - Combined Matrix Properties

Table 12 - CLT Component Strength Properties, as computed by Strand 7

Number of layers	**3**	**5**	**7**
Layer thickness	33 mm	33 mm	33 mm
Ply thickness	99 mm	165 mm	231 mm
Strength Properties			
Ex	9407.23 MPa	8529.46 MPa	8153.07 MPa
Ey	5014.12 MPa	5893.33 MPa	6270.078 MPa
Gxy	726.1 MPa	726.1 MPa	726.1 MPa
ν xy	.05499	.04679	.04398
ν yx	.02931	.03233	.03382
σ max C	56.1 MPa	56.1 MPa	56.1 MPa
τ max shear	11.6 MPa	11.6 MPa	11.6 MPa
ε C @ failure Axial compression	.00409	.00409	.00409
ε T @ failure @ extreme fibre (MoR)	.00818	.00818	.00818

Note the failure strains are constant and independent of the thickness and number of layers in each ply. This is because the components cannot be classed as a true composite where the resin and fibre combine, both contributing their strength properties to create an entirely new entity. Instead the resin acts as a bonding agent between layers and the timber element retain their original strength properties. This becomes important later during the analysis of stress distributions and the theoretical failure load for each panel designed.

Models produced in Strand 7 were designed to represent CLT component comprised of 3, 5 and 7 ply, Utility Pine and solid slash pine elements of corresponding thicknesses. These models were then used to calculate theoretical strength properties for each individual model and compare theoretical performance results between the CLT components and their solid pine counter parts. Early, preliminary results show that theoretical CLT components perform far superior to their solid pine counter parts.

Note: Once again it is important to highlight that these results are based on theoretical models produced by Strand 7. As a result they have no actual credibility backed by experimental results; instead they rely on inferences drawn from results gained from the testing of clear, strait grained, timber specimens and from glued – laminated components.

Results gathered focus primarily on the increase in stiffness of the tuned CLT components and consequently the resulting decrease in panel deflection. Analysing this decrease between CLT and conventional slabs is critical in being able to determine the viability of the manufactured products. For the purpose of this research and the analysis of the results produced, the multi-ply elements will be regarded as an assembly of orthotropic plies. However a far simpler yet still effective analysis of results can be carried out if the elements were considered as transversely isotropic (anisotropic); that is, the properties of the individual timber elements in the tangential direction are equal to the strength properties in the radial direction. For transversely isotropic elements, the relationship between the stresses and strains for timber relative to the principle longitudinal axis has 5 independent stress-strain constants which can be calculated by;

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{22} \\ \gamma_{12} \end{Bmatrix} = \begin{pmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & \frac{-\nu_{21}}{E_{22}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & \frac{-\nu_{23}}{E_{22}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{-\nu_{23}}{E_{22}} & \frac{1}{E_{22}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2(1+\nu_{23})}{E_{22}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{12}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \qquad \text{Eqn 8}$$

Which can be further simplified if a two dimensional stress state is assumed. However note that using a plane stress state is only able to formulate an approximation of actual behaviour of the CLT component and does not model the component in the CLT element's thickness direction (plane direction – Z or the radial direction). This two dimensional stress state equates to;

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} = \begin{pmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \gamma_{12} \end{Bmatrix} \qquad \text{Eqn 9}$$

It should be notes also that as the matrix is symmetrical, the ratio between longitudinal Poisson's ratio and elastic modulus (ν_{12}/E_{11}) and the corresponding tangential counterparts are equal.

That is;

$$\frac{-\nu_{21}}{E_{22}} = \frac{-\nu_{12}}{E_{11}} \qquad \text{Eqn 10}$$

These equations were used to calculate the theoretical maximum stress for the ply components, including the maximum shear stresses which the core can support. These results are discussed later.

Working backwards from the stress state matrices it is possible to determine without the aid of computer simulations, the modulus of the ply components in both the primary and tangential directions. The modulus of stiffness in both directions is of primary importance to the strength of the CLT component and in creating a structurally stable, construction element.

6.2.0 - Deflection

Deflection limits could be argued as the most important aspect of slab design. A slab may be strong enough to withstand the effects of an applied load, however if the slab exceeds the required deflection limits it will be deemed to have failed the design requirements.

In accordance with AS 1170, section 7, clause 7.3, *'Serviceability limit sates'*, when considering a serviceability limit state, it shall be confirmed that;

$$\delta <= \delta_t \qquad \text{Eqn. 11}$$

Where;

δ = The value of the serviceability parameter determined on the basis of design action combinations.

δ_t = The limiting value of the serviceability parameter.

And where clause 7.3 notes;

The limiting factor of the serviceability parameter should be determined based on accepted information, unless specific limits are specified for the particular structure being designed. Guidance on acceptable serviceability limits for typical situations are given in appendix C of AS 1170.

Table 13 - Extract from AS 1170, Appendix C, Table C1, 'Suggested Serviceability Limit State Criteria'

Element	Phenomenon Controlled	Serviceability Parameter	Element Response
Floors and floor supports			
Beams where line-of-sight is along invert	Sag	Mid-span Deflection	Span/500
Beams where line-of-sight is across the soffit	Sag	Mid-span Deflection	Span/250
flooring	Ripple	Mid-span Deflection	Span/300
Floor joists/beams	Sag	Mid-span Deflection	Span/300
Normal floor systems	Noticeable sag	Mid-span Deflection	Span/400
Specialist floor systems	Noticeable sag	Mid-span Deflection	Span/600
floors-supporting masonry walls	Wall cracking	Mid-span Deflection	Span/500
Floors-supporting plaster lined walls	Cracks in lining	Mid-span Deflection	Span/300

In order to calculate deflection, Strand 7 uses a system of inter-lamina stiffness matrices to determine the individual reactions at each node. Similarly the slab deflection equation can be used to determine the mid-span deflection values.

$$L_{ef}/d = k_3\, k_4 \left[\frac{(\Delta/L_{ef})\, E}{F_{d\,ef}} \right]^{2/3} \qquad \text{Eqn 12}$$

Where;

L_{ef}/d = The deflection limit selected in accordance with clause 2.4.2 and the deflection (Δ) is taken on the center-line between the supports used to determine L_{ef}.

L_{ef} = The effective span

k_3 = 1.0 for one-way, simply supported slabs

k_4 = The deflection constant, which for simply supported slabs is; $k_4 = 1.6$

$F_{d\ ef}$ = The effective design load, per unit area, taken as;

For total deflection; $F_{d\ ef} = (1+k_{cs})g + (\psi_s+k_{cs}\ \psi_l)q$ Eqn 13

$k_{cs} = .8$

And where ψ_s and ψ_s are taken from AS 1170.1, Table 4.1, *'Short-term, Long-term & Combination Load Factors'*

Table 14 - Extract from AS 1170, Table 4.1, 'Short-term, Long-term & Combination load factors'

Character of imposed actions	Short-term factor (ψ_s)	Long-term factor (ψ_l)	Combination factor (ψ_c)
Distributed imposed actions, Q			
Floors			
Residential & domestic	0.7	0.4	0.4
Offices	0.7	0.4	0.4
Parking	0.7	0.4	0.4
Retail	0.7	0.4	0.4
Storage	1.0	0.6	0.6
Other	1.0	0.6	0.6
Roofs			
Roofs used for floor type activities (see AS 1170.1)	0.7	0.4	0.4
All other roofs	0.7	0.0	0.0
Concentrated imposed actions (including balustrades), Q			
Floors	1.0	0.6	As for distributed floor actions
Floors of domestic housing	1.0	0.4	
roofs used for floor type activities	1.0	0.6	
all other roofs	1.0	0.0	0.0
Balustrades	1.0	0.0	0.0
Long-term installed machinery, tare weight	1.0	1.0	1.2

The following table below gives a comparison between the deflection of a theoretical CLT components and a theoretical solid pine element of the same thickness. These values are calculated using the above mentioned formula for the limiting deflection criteria. As can be seen in each theoretical case the CLT components outperforms its solid pine counterpart in both short-term and long-term deflection limits. With the difference in deflection between the CLT panels and the solid pine panels rising exponentially as the number of layers increase. This increase in deflection resistance effectively means that he panels are able to bear more load per unit area, or theoretically are able to span greater effective lengths.

Table 15 - Comparison of Deflection Values between a Solid Slash Pine Element and a CLT Component

Span	Deflection limits		Solid Pine deflection values			CLT deflection values		
	Short-term	Long-term	Thickness (mm)			Thickness (ply)		
(mm)	Span/250	Span/500	99	165	231	3	5	7
1000	4.00	2	1.84	0.4	0.14	1.38	0.28	0.1
1100	4.40	2.2	2.69	0.58	0.21	2.02	0.41	0.15
1200	4.80	2.4	3.81	0.82	0.3	2.86	0.59	0.21
1300	5.20	2.6	5.25	1.13	0.41	3.93	0.81	0.29
1400	5.60	2.8	7.06	1.52	0.56	5.29	1.09	0.39
1500	6.00	3	9.3	2.01	0.73	6.97	1.43	0.51
1600	6.40	3.2	12.04	2.6	0.95	9.03	1.86	0.66
1700	6.80	3.4	15.34	3.31	1.21	11.5	2.37	0.85
1800	7.20	3.6	19.28	4.16	1.52	14.46	2.97	1.06
1900	7.60	3.8	23.93	5.17	1.88	17.95	3.69	1.32
2000	8.00	4	29.39	6.35	2.31	22.04	4.53	1.62
2100	8.40	4.2	35.72	7.72	2.81	26.79	5.51	1.97
2200	8.80	4.4	43.02	9.29	3.39	32.27	6.64	2.37
2300	9.20	4.6	51.4	11.1	4.05	38.55	7.93	2.83
2400	9.60	4.8	60.93	13.16	4.8	45.7	9.4	3.36
2500	10.00	5	71.74	15.5	5.65	53.81	11.07	3.95
2600	10.40	5.2	83.93	18.13	6.61	62.95	12.95	4.62
2700	10.80	5.4	97.6	21.08	7.68	73.2	15.06	5.38
2800	11.20	5.6	112.89	24.38	8.89	84.67	17.42	6.22
2900	11.60	5.8	129.9	28.06	10.23	97.42	20.04	7.16
3000	12.00	6	148.76	32.13	11.71	111.57	22.95	8.2
3100	12.40	6.2	169.61	36.64	13.35	127.21	26.17	9.35
3200	12.80	6.4	192.58	41.6	15.16	144.44	29.71	10.61
3300	13.20	6.6	217.81	47.05	17.15	163.35	33.6	12
3400	13.60	6.8	245.43	53.01	19.32	184.07	37.87	13.52
3500	14.00	7	275.6	59.53	21.69	206.7	42.52	15.19
3600	14.40	7.2	308.48	66.63	24.28	231.36	47.59	17
3700	14.80	7.4	344.21	74.35	27.1	258.16	53.11	18.97
3800	15.20	7.6	382.96	82.72	30.15	287.22	59.08	21.1
3900	15.60	7.8	424.89	91.78	33.45	318.66	65.55	23.41
4000	16.00	8	470.17	101.56	37.01	352.63	72.54	25.91

These results when compared to those generated by the Strand 7 analysis vary between 1% and 15%. This is due to Strand having to use mathematical approximations on nodes where the implicit equation sets do not yield appropriate results. Strand 7 analysis also shows an exponential decrease in deflection as the number of layers in the CLT component increases, proving beyond a doubt that the multi-layered components do outperform conventional solid timber members.

Table 16 - Strand 7 Deflection Values for a given 10 kPa Load

Span (mm)	**Strand 7 CLT deflection values (mm)**		
	3 Ply	5 Ply	7 Ply
1800	15.3342	1.0902	.5796

Analysis of these results begins to shed light on one of the main questions investigated by this research paper, that is; why do currently marketed overseas products only consist of 3, 5, and 7 layers? The answer to this question was discovered while analysing the deflection limits between the different layer combinations while considering the increased stiffness of the CLT panels as more layers are added.

By themselves the number of layers in any given CLT component does not directly add any significant strength increase to the resulting matrix, except the added strength that accompanies an increase in depth. For example, a theoretical panel comprised of 7 layers, each layer 33 mm thick equalling a total thickness of 231 mm behaves almost exactly the same as a 3 ply panel consisting of layers which are 77 mm thick (total thickness equals 231 mm).

From equation 12;

$$L_{ef}/d = k_3\, k_4 \left[\frac{(\Delta/L_{ef})\, E}{F_{d\,ef}} \right]^{2/3}$$

For a 3 ply component;

$d = 77$ mm $D = 231$ mm
$E = 13700$ MPa $F_{d\ eff} = .1$ MPa
$K_3 = 1.0$ $K_4 = 1.6$
$L_{ef} = 1800$ mm

Total Mid-span deflection
$\Delta = 1.13$ mm

For a 7 ply component;

$d = 33$ mm $D = 231$ mm
$E = 13700$ MPa $F_{d\ eff} = .1$ MPa
$K_3 = 1.0$ $K_4 = 1.6$
$L_{ef} = 1800$ mm

Total Mid-span deflection
$\Delta = 1.06$ mm

The difference between the two theoretical deflections is less than .1 mm, with a difference of approximately 6%. it would seem therefore that there is no distinct advantage to creating components with an excessive amount of layers. The same result can be achieved with fewer layers of greater individual thickness. It was than concluded that the sole reason behind international marketers creating panels of differing layer numbers is to achieve the desired panel depth without having to occur expensive changes to their current milling specifications. Mills would produce timber elements of set sizes to meet the current demand of the building industry and changes to their milling process is not worth the expense for an emerging product that makes up such a small percentage of the industry.

Figure 13 - Deflection for a 3 Ply CLT Element under a 10 kPa Load

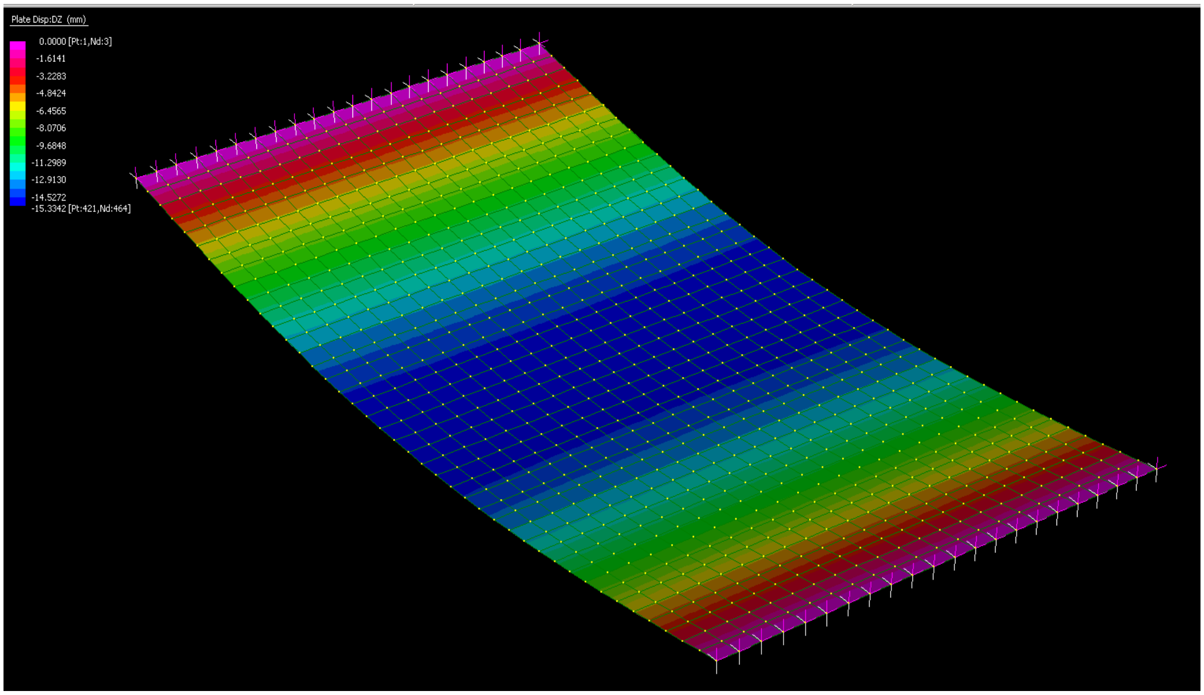


Figure 14 - Deflection for a Solid Slash Pine Panel of an Equivalent Thickness to a 3 Ply CLT Element under the same Load

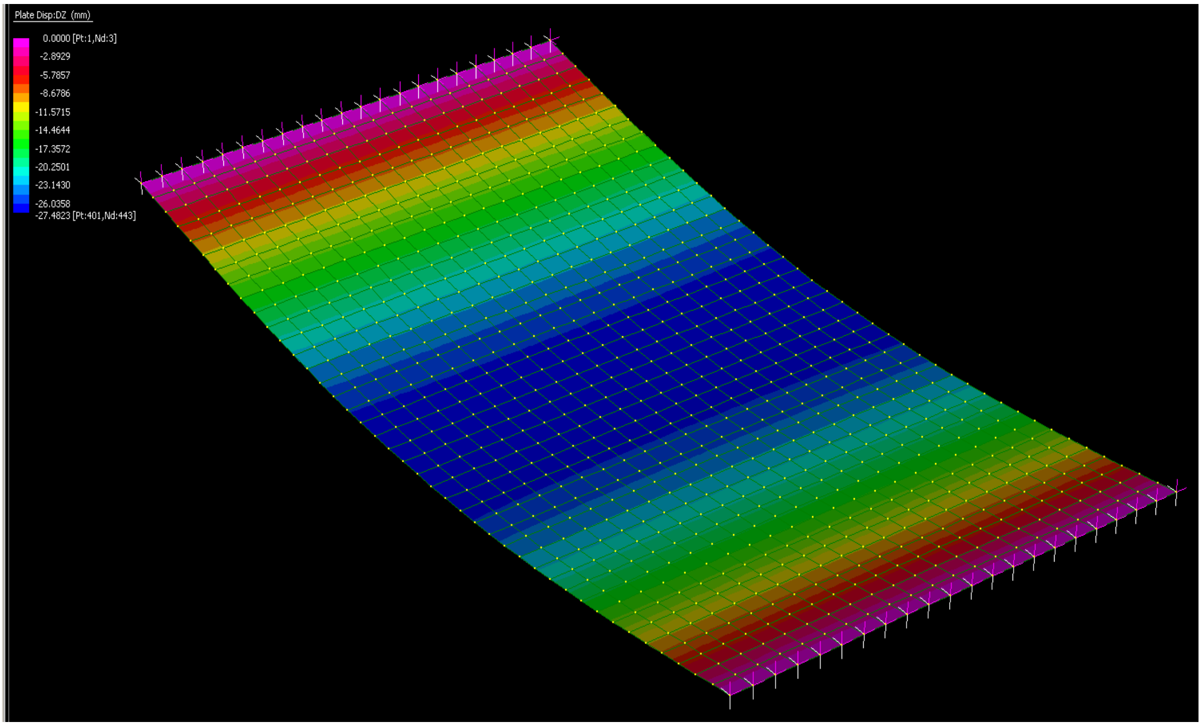


Figure 15 - Deflection for a 5 Ply CLT Element under a given 10 kPa Load

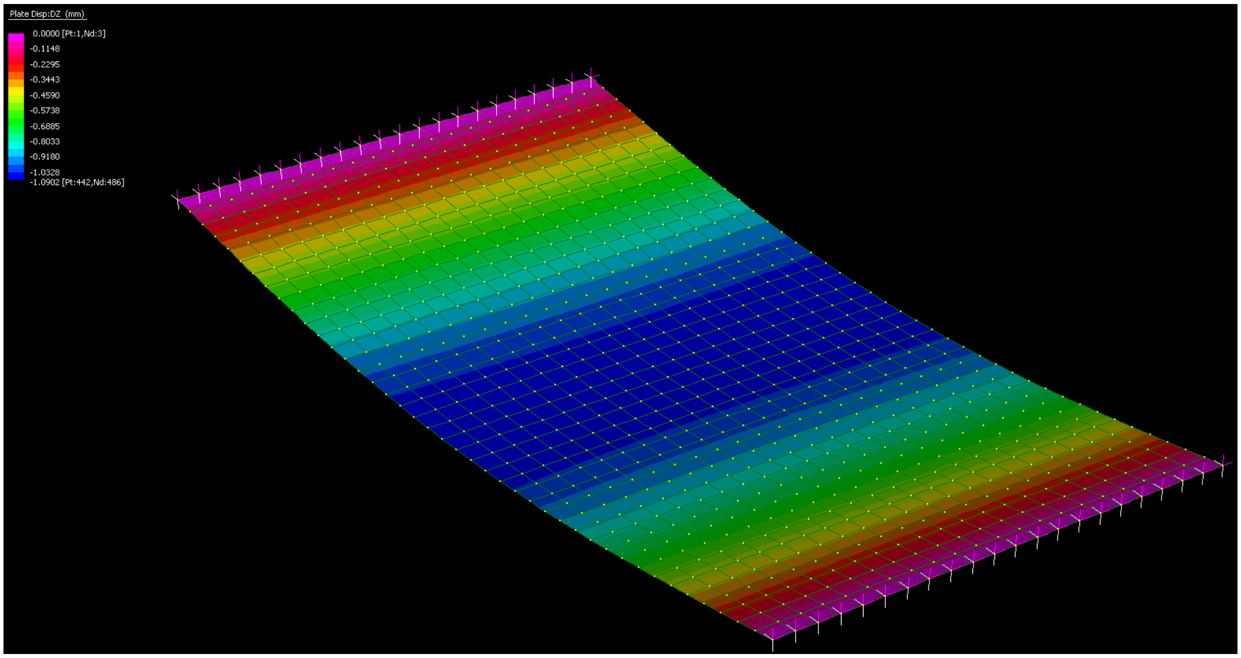
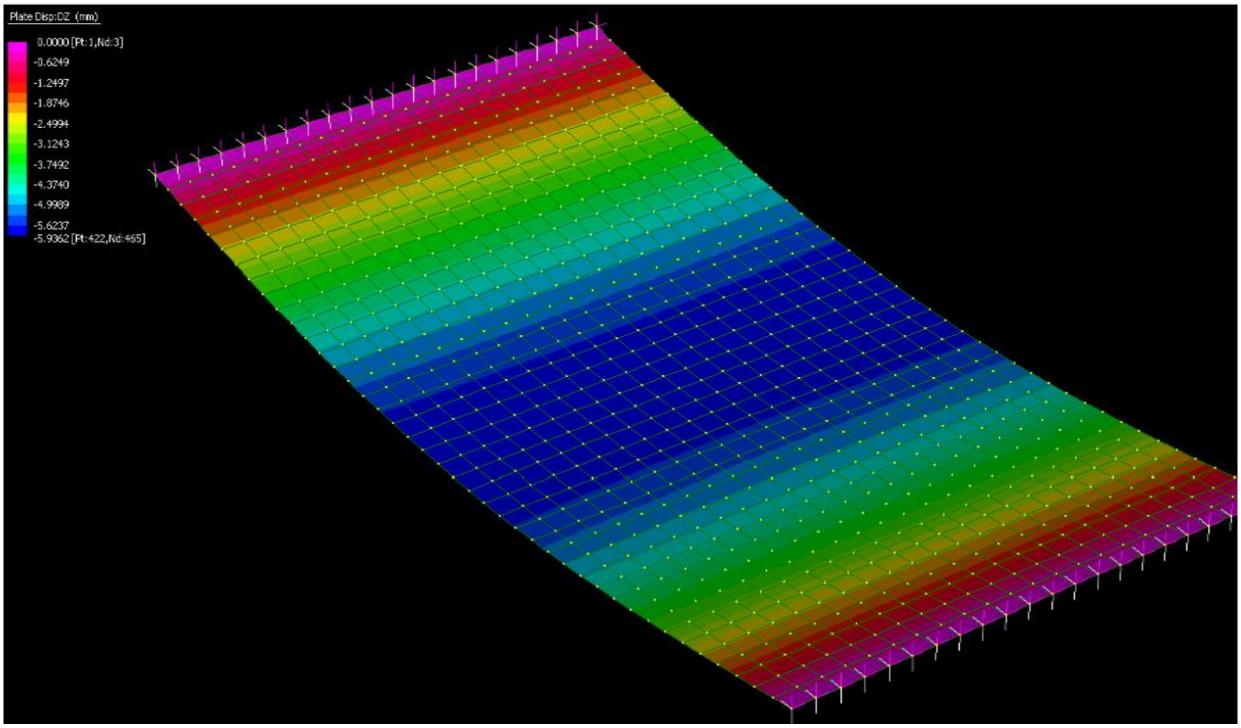


Figure 16 - Deflection for a solid Slash Pine Panel, Equivalent in Thickness to a 5 ply CLT Component Under the same Applied Load

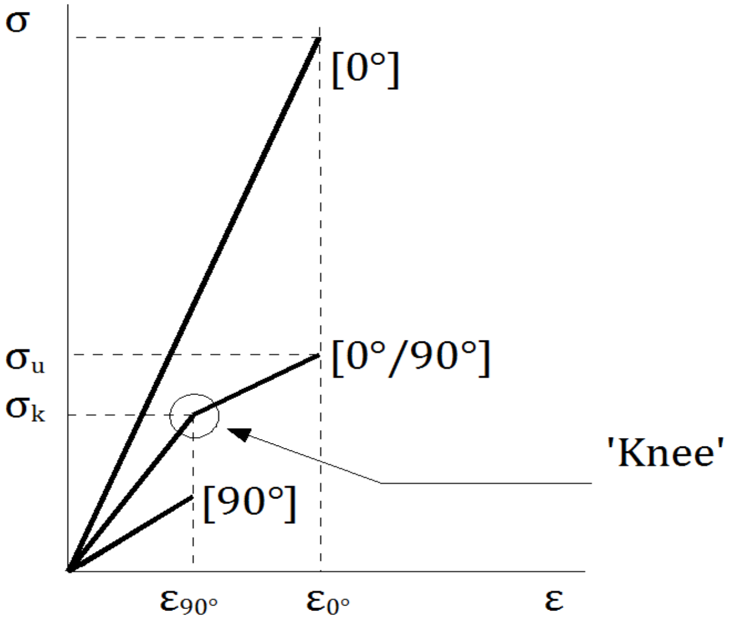


6.4.0 - The Tuning of Modulus of Elasticity

Unlike metals and most alloys, it is not likely that a CLT component will exhibit gross yielding at the point of failure, yet the CLT components do not behave like traditional brittle materials. Experiments carried out by USQ in conjunction with the CEEFC proved that under a static load many laminates show non-linear characteristics attributed to sequential ply failure. Tests which were previously carried out showed that the tensile strain curve of a [0°, 90°, 90°, 0°] laminate could be approximated by a bilinear curve. The joint study concluded that the point at the intersection of the two linear regions represented the failure of the ply layers which were oriented 90° to the primary fibre direction. However the ultimate failure of the laminate occurred at the fracture strain of the extreme most fibres in the primary direction. The study also concluded that the change in slope of the stress-strain curve after the 'knee' could also be reasonably predicted by assuming that all the plies orientated in the perpendicular direction have failed and can no longer contribute to the strength or modulus of the resulting matrix.

Figure 17 - Approximated Laminate Bilinear Curve

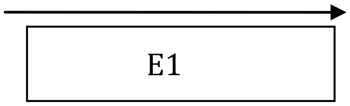
(Taken from figure 4.5, *'Mechanics and Technology of Fibre Composites'*)



Although previously stated that the number of layers in any component does not add any strength to the resulting matrix except to add depth to the panel, the number of layers in these models do in fact add some small portion of strength to the resulting element. This is due to the thickness of the layers which make up the entity of the component all being the same size. The more layers in the component the more 'tuned' the component becomes. As the CLT components are always going to be comprised of an odd number of timber layers to ensure that the extreme layers on the compression and tension faces both run in the same direction for maximum strength, there will always be a difference in the elastic modulus between the primary longitudinal direction and the secondary longitudinal direction, or in other words the tangential direction.

Consider a solid timber element, no matter how thick the element is cut, the tangential/longitudinal modulus of elasticity ratio is always kept constant, that is 100% of E_L and E_T are present in each direction. Now consider a CLT component comprised of three timber layers, the resulting matrix now consists of 2/3 of the modulus contributing to the primary fibre direction and 1/3 contributing to the tangential fibre direction. Giving resulting matrix specifications of;

Figure 18 -Solid Wood Element

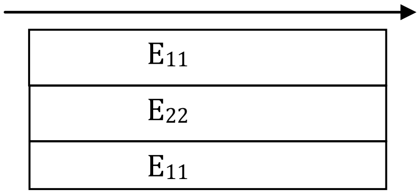


Longitudinal fibre direction

E_L/E_T=.0445

E_L= 13700 MPa

Figure 19 -3 Ply CLT Element



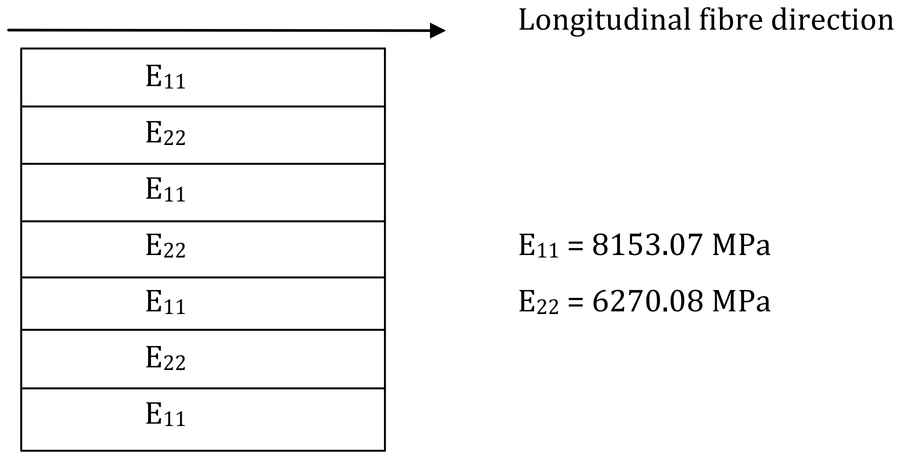
Longitudinal fibre direction

E_{11} = 9047.23 MPa

E_{22} = 5014.12 MPa

If now a 7 ply component was considered of any thickness and assuming the initial and final timber layers have grain orientations in the primary direction; of the seven layers, four would contribute to the CLT component's major strength properties in the primary direction and the three perpendicular layers would contribute their strength properties to the tangential direction.

Figure 20 - 7 Ply CLT Element



E_{11} = 8153.07 MPa

E_{22} = 6270.08 MPa

As can be seen in the above representations, increasing the number of layers perpendicular to the longitudinal by one (solid pine element ---> 3 ply CLT component) increases the stiffness in the tangential direction of the panel by approximately 8 times. Adding two more perpendicular layers (3 ply component ---> 7 ply component) furthers increases the stiffness in the secondary direction by 1.25.

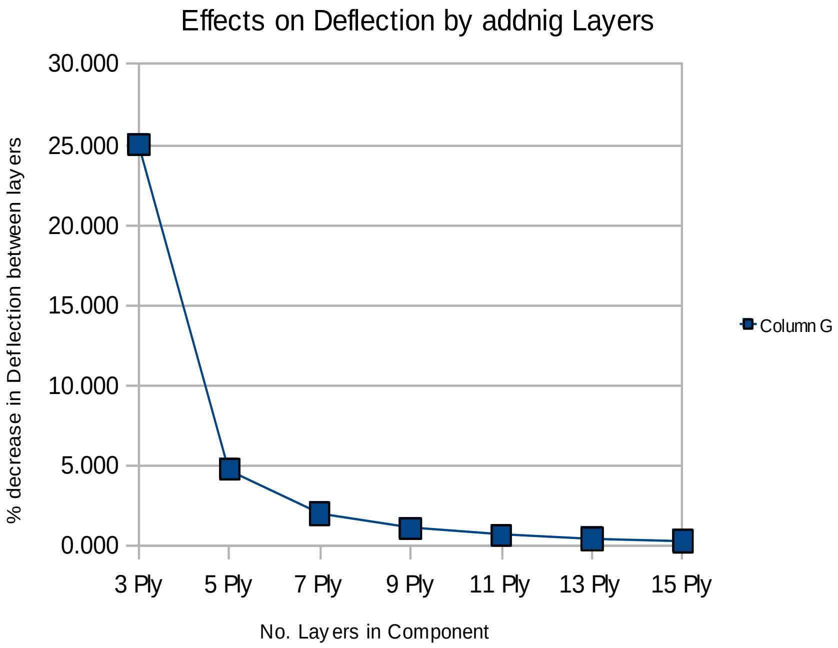
This difference in tangential stiffness between the CLT components with low layer counts and those with subsequently higher layer counts is effectively equal to a decrease in deflection. So the question was asked, to what degree does the addition of extra layers really effect the deflection of the engineered panel design and after how many layers does adding an extra perpendicular layer become impractical?

Firstly the difference was analysed using the adapted panel deflection theory mentioned earlier in this chapter. These results were obtained by analysing panels of 3, 5 and 7 ply thicknesses, calculating the theoretical defection values and analysing the differences.

Table 17 - Theoretical Deflections for CLT Components of Differing Thicknesses

	Thickness (mm)				Deflection decrease Between Layers (%)
	99	165	231	297	
Ply Layers	Deflection Values (mm)				
3 Ply	14.46	3.12	1.14	0.54	-
5 Ply	13.77	2.97	1.08	0.51	4.762
7 Ply	13.50	2.92	1.06	0.50	2.000
9 Ply	13.35	2.88	1.05	0.49	1.099
11 Ply	13.25	2.86	1.04	0.49	0.694
13 Ply	13.19	2.85	1.04	0.49	0.478
15 Ply	13.15	2.84	1.03	0.49	0.350

Figure 21 - % Decrease in Deflection by Adding an Additional Perpendicular Layer.



As can be seen in the above table, the percentage of deflection decrease between layers drops significantly after 9 plies have been assembled. This symbolise that the increase in deflection resistance caused by the high modulus of elasticity of the layers orientated perpendicular to the principle fibre direction of the component does have limitations. Components consisting of 9 and even 7 plies seem to possess sufficiently tuned mechanical properties in both primary and secondary directions that the adding of an additional layer will result in more effort and cost then what would be returned in performance by the CLT component.

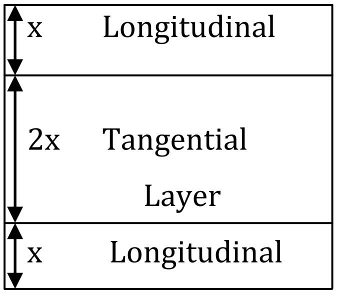
From these results the conclusion was reached that any further analysis of CLT components above 9 plies was no longer necessary. Instead focus was redirected to the thought and analysis of components that possess individual layers of differing thickness.

6.5.0 - Possible Combinations

As stated in the above section, the more 'tuned' the CLT component becomes the more structurally stable it is. For this reason CLT components with approximately equal modulus in both primary and secondary directions were analysed. In order for this process to work there must be an equal volume of timber running in the components longitudinal direction as there is running in the tangential direction. Before this analysis was conducted it was reasoned that all and any trial thicknesses should be considered and as a result it is recognised that not all component selections would be a feasible thickness for construction.

These components consisted of an odd number of layers to still allow the extreme fibres at the compression and tension faces to run in the main longitudinal direction for maximum strength. However as the volume of timber orientated with it's grain running in the primary axis direction is equal to the volume in the tangential direction the theoretical components could be all modelled on a 3 layered CLT configuration. Increasing the thickness of the timber layer which runs tangentially to the longitudinal axis of the CLT component eliminates the need to incorporate additional layers to 'tune' the CLT element. Reducing the number of layers in any given component also reduces the time of manufacture and the number of components that need bonding. Also reducing the number of layers that are needed to be bonded to form the component reduces the possibility of unexpected resin failure along the bond surface, as this region is susceptible to excessive surface defects prior to bonding as well as areas of inclusion and micro defects within the resin itself as it cures.

Figure 22 - Component of Equal Timber Volumes in both Main Directions



These models produced will be modelled around the same parameters as the previous components which had equal layer thicknesses. These new components with the equally 'tuned' ratios will also be modelled to the same thickness of the previous ply components to ensure that an accurate, theoretical analysis can be carried out and the data gathered, used as a comparison between the two data sets. Early hypotheses in the modelling process expected the deflection in the panels under the influence of the applied load to be less than that of the CLT components which process multiple layers of equal thickness. As well a providing a decrease in deflection, it is also theorised that extra stress will be present at the extreme fibres under the same applied load due to the decrease in the longitudinal modulus of elasticity. To further explain, even though the modulus for the entire component has decreased, the failure strain of the timber elements at the extreme fibres of the CLT component are still equal to that of a regular, single timber element. So modelling the maximum stress equates to;

$$\sigma_{max} = E \times \varepsilon_{failure} \qquad \text{Eqn 13}$$

As the modulus E, decreases, σ_{max} must also decreases.

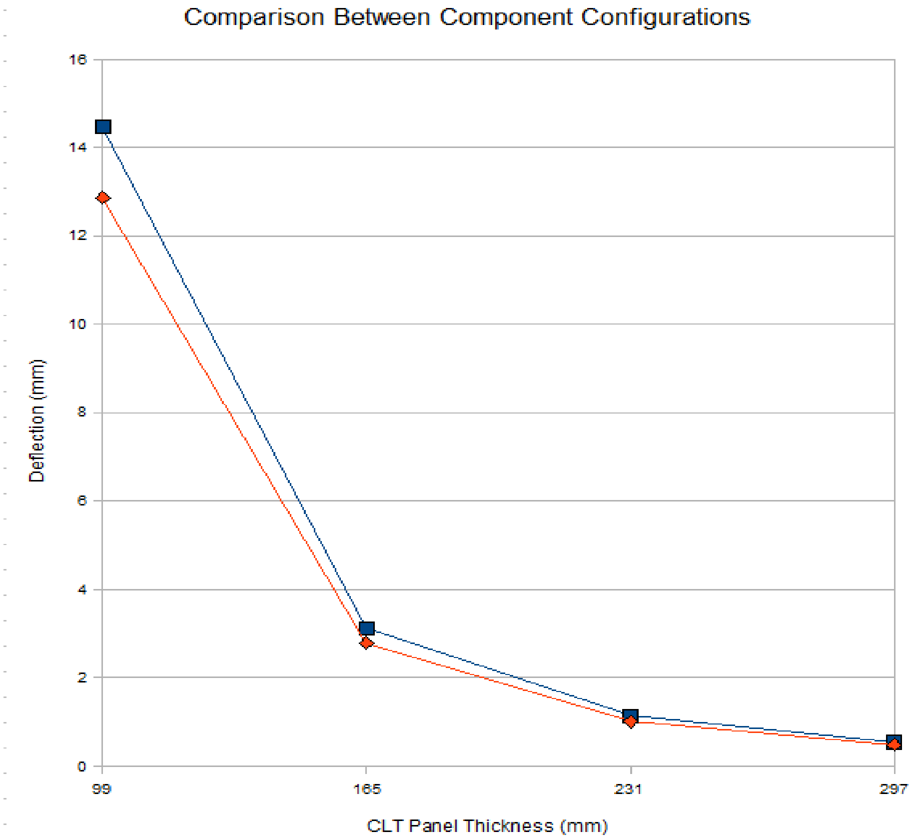
Table 18 - Theoretical Deflections for Components Comprised of Equal Volumes of Timber in both Primary and Secondary Directions.

	Thickness (mm)			
	99	165	231	297
Ply Layers	Deflection Values (mm)			
3 Ply	12.85	2.75	1.01	.48

Figure 23 - Comparison between Differing CLT Component Configurations

— = 3 ply CLT component with all layers equal in thickness

— = 3 ply CLT component with equal volumes of timber orientated in both primary and secondary directions



The above graph gives a graphical representation of the difference in deflection between the two CLT configurations for a 3 ply component. As can be seen, once the panels reach a sufficient depth, the difference in deflections for the components becomes negligible. This poses the question, is it worthwhile to outlay extra expense to change current milling specification for a percentage of extra strength?

Table 19 - Decrease in Deflection between Differing Configurations

	Thickness (mm)			
	99	165	231	297
Ply Layers	Deflection Values (mm)			
3 Ply (equal volume in each direction)	12.85	2.75	1.01	.48
3 Ply (layers of equal thickness)	14.46	3.12	1.14	0.54
Difference (As a %)	11.13	11.86	11.4	11.11

The average difference between the two different component models for differing thicknesses is approximately 11.38 %. This is a considerable increase in deflection resistance and can safely be assumed to hold true for any panel thickness. CLT components will be used as a majority for load bearing panels where the main limiting criteria is not the load bearing capacity at failure but the deflection limitation for serviceability limits. However at what cost does this come to Hyne Timber in order to change current milling procedures for an extra few percent decrease in deflection? This question has been the major factor in the design of all of the CLT panels and it was determined that the designs which provided the maximum strength properties and best deflection resistance with nil to extremely minimal changes to current practices should be adopted as the most feasible design.

6.6.0 - Stress Distributions & Failure Loads

Note: From here on in panel configurations which consist of an odd number of layers of equal thickness shall be referred to as Type 1 panels. Panels which possess equal volumes of timber orientated in both the longitudinal and tangential axis of the CLT component shall be referred to a Type 2 panels.

However as previously stated the increase in stiffness comes off the back of a trade off and decrease in the failure strength under the applied load. For panel design this is not a major concern as the limiting criteria is often governed by deflection limits. However in being able to create a versatile construction material from otherwise useless waste, the stress distribution for analysing the optimisation of CLT components should be considered.

Even though stated above that the failure strain for each component is equal and independent of the component's modulus and the number of layers it comprises, the ultimate stress differs between the components as it is dependent upon the combined modulus of the CLT component and not just that of the individual timber layers. As the number of layers in the CLT element increases the component becomes more 'tuned', the modulus of elasticity increases in the secondary direction at the cost of a decrease in the modulus in the primary longitudinal direction. With a constant failure stain at the extreme fibres of the component, a reduction in longitudinal modulus of elasticity which occurs with the addition of extra layers is effectively equal to a reduction in load bearing capacity. The question then asked was, where does the happy medium lie between deflection resistance and the reduction in strength?

Noted above in the table of the component properties are two different failure strains. One is the failure strain based on the maximum axial compressive force which the timber specimen can be made subject to before it will fail; the other is the timber's modulus of rupture. Depending on the type of test carried out to determine the wood's structural properties the modulus of rupture can effectively be taken as the applied failure stress at the extreme tensile fibres. For this preliminary analysis and due to the lack of information on utility grade specimens, it will be assumed that the modulus of rupture is equal to the ultimate tensile stress. It is also noted that the compressive face and tensile face have different failure strains. As a common rule of thumb, the extreme compressive fibres of the specimen under bending can only support two thirds of the failure stress of the tensile face. This means that initial failure will occur in the compressive region of the CLT panel, however although the compressive face has already failed the component will not completely fail until the stress of the tensile face (modulus of rupture) has been exceeded.

Table 20 - The Allowable Failure stress for Solid Timber Panels

E_x =	13700 MPa	Modulus of Rupture =	112 MPa
E_y =	616.5 MPa	Failure Strain =	.00817

Table 21 - The Allowable failure Stress for Type 1 Panels

Ply	E_x (MPa)	Allowable Stress – σ_{max} (MPa)
3 Ply	9336.55	76.33
5 Ply	8463.66	69.19
7 Ply	8089.85	66.14
9 Ply	7882.07	64.44
11 Ply	7749.84	63.36
13 Ply	7658.30	62.61
15 Ply	7591.17	62.06

Table 22 - The Allowable Failure Stress for Type 2 Panels

Ply	E	Allowable Stress – σ_{max} (MPa)
ALL	7154.83	58.49

The difference in rupture stress between a solid pine timber element and the type 1 panels range between 30% - 45% decrease as the number of layers in the panel increase. For type 2 panels, the decrease as a percentage loss of rupture strength is approximately 45%.

The maximum allowable load per unit width can then be theorised by multiplying the failure stress by the cross – sectional area;

$F_d = \sigma_{max} * A_{cs}$ Eqn 14

These theoretical results have been tabulated for the purpose of comparison; from them inferences were drawn on the possible modes of failure, whether the panels will fail ductile with sufficient warning or whether brittle failure will prevail resulting in catastrophic deconstruction of the assembly. The following tables are based on a panel design of an 1800 mm effective span and of unit width.

Table 23 - Allowable Loads based on Deflection Criteria

			Thickness (mm)			
PLY	Short-term deflection limit (mm)	Long-term deflection limit (mm)	99	165	231	297
			Allowable Load (MPa)			
3	7.2	3.6	0.0249	0.1153	0.3163	0.6722
5	7.2	3.6	0.0261	0.1210	0.3321	0.7058
7	7.2	3.6	0.0267	0.1235	0.3389	0.7202
9	7.2	3.6	0.0270	0.1249	0.3426	0.7282
11	7.2	3.6	0.0272	0.1257	0.3450	0.7333
13	7.2	3.6	0.0273	0.1263	0.3467	0.7368
15	7.2	3.6	0.0274	0.1268	0.3479	0.7394
Type 2 Panels						
ALL	7.2	3.6	0.0280	0.1297	0.3558	0.7562

The above table displays the short and long term deflection limits, as well as the maximum allowable load (in MPa) based on the long-term deflection criteria.

Table 24 - Allowable Loads based on Stress Limit State Criteria

PLY	Failure Stress (MPa)	Thickness (mm)			
		99	165	231	297
		Allowable Load (MPa)			
3	76.33	0.0076	0.0126	0.0176	0.0277
5	69.19	0.0069	0.0114	0.0160	0.0206
7	66.14	0.0065	0.0109	0.0153	0.0196
9	64.44	0.0064	0.0106	0.0149	0.0191
11	63.36	0.0063	0.0105	0.0146	0.0188
13	62.61	0.0062	0.0103	0.0145	0.0186
15	62.06	0.0061	0.0102	0.0143	0.0184
Type 2 Panels					
ALL	58.49	0.0058	0.0058	0.0058	0.0058

Equating the above allowable loads from a stress to a unit width, uniformly distributed force gives the range for allowable load combinations of live and static loads. For type 1 panels it is evident that the allowable loads for the panels should meet the minimum load requirements for most residential structures. Taking general load cases from AS 1170.0, Table 3.1, '*Reference values for imposed floor actions*' and considering the effects of static loads applied by the structure, it is proposed that the type 2 panels with a bearing capacity of 5.8 kPa at failure also meet the minimum requirements for load combinations of residential slab structures.

The representation of the above data also shows that the failure stress in all cases is exceeded by the time the limiting deflection stress is reached. This would indicate that the failures for both types of CLT panels are not ductile but brittle in nature, making the signs of failure hard to recognise. Due the deflection at failure being negligible to the naked eye, one of two precautionary actions is necessary. The first and most practical method to minimise the effects of brittle failure, it is recommended that the panels used should be over designed with a capacity factor of at least Φ= .7 to make sure the applied loading does not come close to the failure load. This added capacity factor is with respect to standard residential loading conditions only and panels used for other construction purposes must consider their own individual load cases. Using a capacity factor of Φ= .7 also allows for some accountability for variation in the individual timber elements used to create the CLT component. Note the Glued – Laminate code, AS 1328 applies a capacity factor of Φ= .8 for residential structures, this is due to the uni-directional nature of the laminates being produced as well as all members in the Glued - Laminate being of a pre-determined strength standard.

The problem with non-ductile failure within the CLT panels is that there is no discernable warning that panel failure is imminent. Theoretical models show that for the effective span of 1800 mm modelled, the deflection at failure is 80% - 92% less than the allowable deflection limits.

Table 25 - Deflection at Failure (based on theorised failure loads)

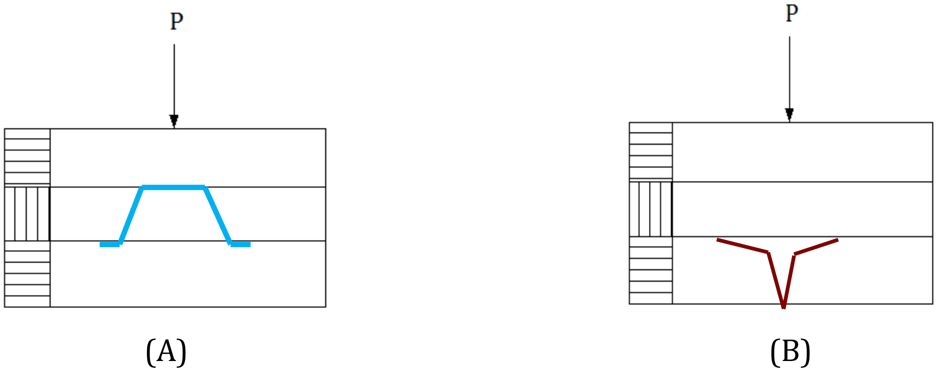
		Thickness (mm)			
PLY	Failure Stress (MPa)	99	165	231	297
		Deflection (mm)			
3	76.33	1.093	0.393	0.201	0.121
5	69.19	0.991	0.357	0.182	0.110
7	66.14	0.947	0.341	0.174	0.105
9	64.44	0.922	0.332	0.169	0.102
11	63.36	0.907	0.327	0.167	0.101
13	62.61	0.896	0.323	0.165	0.100
15	62.06	0.888	0.320	0.163	0.099
Type 2 Panels					
ALL	58.49	0.744	0.161	0.059	0.028

These theoretical deflection values at failure indicate beyond a doubt that the failure of the

CLT panels is brittle and catastrophic. The failure of the panel would be rapid with no apparent yield point in the material, that is at the instance of failure the mechanical properties of the CLT panel are effectively equal to zero and the panel loses all stiffness and strength.

The brittle failure of panels was investigated and it was found that the two most common failure scenarios which would impact the CLT panels are; tensile failures and shear failures. Tensile failure begins when tensile cracks appear after the in plane normal stress exceeds the transverse tensile strength of the plies. These cracks first appear on the first or outer most ply in the tensile region. Shear failures propagate from cracks caused by transverse shear stresses which more often than not originate at the mid surface of the plies. Investigation shows that while it is possible to theoretically predict when failure will occur, a detailed prediction of the final case at the end of the applied load cannot be reached. This is due to having to account for either tensile cracks which form on the bottom ply of the element, or from the shear cracks that are inclined to the mid plane created by contact stress at the applied load.

Figure 24 - (A) Tensile Failure cracks, (B) Shear Failure cracks

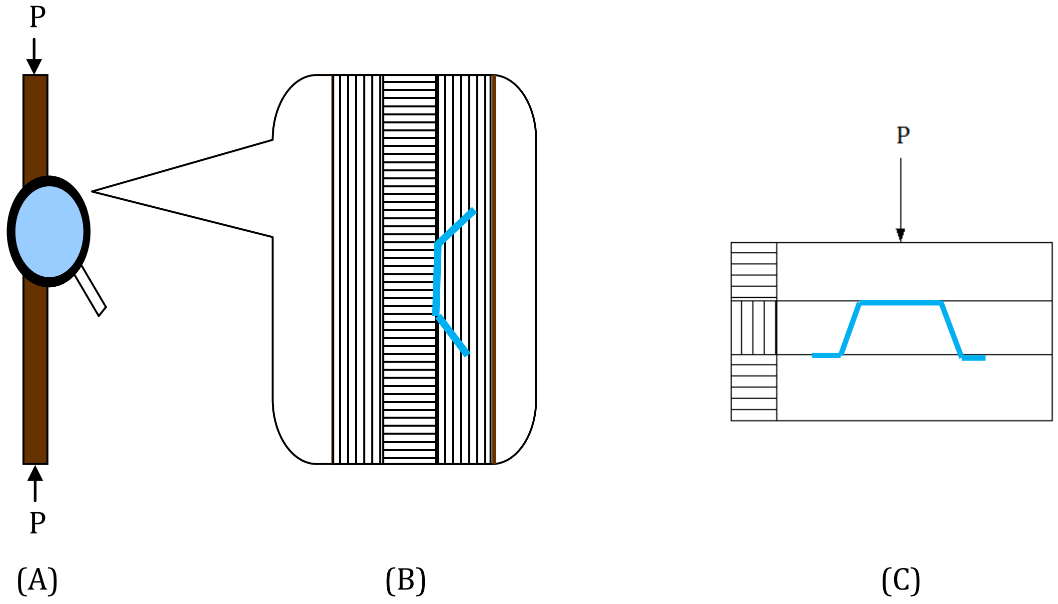


(A) (B)

For brittle materials, failure usually occurs where the tensile stress is at a maximum. This maximum becomes larger as the ratio of transverse elastic modular E_r/E_T becomes larger and the tangential stresses become greater on the applied loading surface. Also as the transverse ratio increases so too does the maximum shear force applied to the CLT component, increasing the element's susceptibility to shear fracture and ultimate failure. Under the theorised failure loads, Strand 7 is able to apply the laminate theory to the components in order to approximate the transverse shear distributions between adjacent layers as well as identify the region of maximum tensile stress.

Actual experiments carried out by Turner '2010' show that the majority of CLT panels do fail in a manner similar to the tensile failure mode described previously. When analysis of this failure was conducted it was thought to have stated in the bonding resin however it was later concluded that the initial failure was located in the timber fibres immediately adjacent to the bonding layer.

Figure 25 - Experimental Setup conducted by Turner



(A), flexural loading configuration

(B), failure method from Turner's experiments

(C), known tensile failure pattern

This failure mode is ideal as it is in keeping with the previous assumption that the bonding resin will not fail before the surrounding timber structure.

The rest of Turner's results cannot be used to draw accurate comparisons between the theoretical models produces as the experimental results way analysed using simple ply theories and not laminate theory. Ply theory assumes that the outermost layers in compression and tension carry the entire compressive and tensile stresses and the inner layers are primarily used as a shear core and an effective way of increasing the panel depth. As the ply theory assumes that the entire stress applied during loading is carried by two layers of timber, one on the compression face and one on the tension face, the effective modulus of elasticity is greatly increased. If not accounted for, this apparent increase in longitudinal stiffness could affect the calculation of the theoretical failure load. This does not affect the experiments carried out by Turner as he was able to gather data on failure loads by testing his design CLT combinations to failure. The only problem which was encountered was trying to draw comparisons between the two data sets, namely; the theoretical data sets derived from using Strand 7 and laminate theory and Turner's data sets derived from experiments and ply theory.

6.7.0 - Accounting for Defects during Construction

The models produced and the theoretical data gained are all based on strength characteristics of average, clear, strait grained Slash Pine samples. However these strength characteristics do not accurately represent the utility grade elements which will be used in the actual construction of the CLT components. Due to the lack of information on the mechanics of utility grade timber and the uniqueness of each and every defect present, it is neither possible nor feasible to ever determine these characteristics. Technically the utility grade timber may be comprised of individual elements of up to MGP15 strength grade, with areas of defect making the entire length defective as the minimum trade span can no longer be met if the defect is cut out. Therefore it is quite possible that the elements used in the panels have considerable strength, but there is no sure way to tell. To accommodate for this discrepancy there is two courses of action to ensure that the capacity of the CLT panels are not taken beyond their limits. First; all sections of major defect must be removed from the individual timber elements used in the panel construction. Most importantly sap inclusions and wanes, these defects not only weaken the timber structure but there is also no structural material at all in the region of the defect. This leaves the resulting void to be filled by resin or air inclusions, both of which have detrimental effects on the panel. Resin filled voids alter the strength properties of the component by occupying area which should be filled by the timber fibres and air pocket inclusions will effect the way the material behaves due to shrinkage and swelling and would be incremental in contributing to resin failure. It is recommended that during construction that no more than 10% of the timber in any given cross – section of the CLT component be deemed as defective. This tactic ensures the chance of an unpredicted failure caused by the lack of strength at the point of the defect. Also by assuming that the is no more than 10% defects in any given cross – section, a factor of .9 (.9 + .1 = 1) can be applied to the theoretical results derived to provide a conservative estimate of the utility grade CLT components.

It is proposed that during the grading stages of the individual timber elements that the utility graded timber is sorted in relevant sub groups depending on the elements theoretical strength properties if defects were to be ignored. It is understood that this process adds one extra step in the process chain, however the benefits are numerous. It enables the highest quality utility grade members, which may be deemed non structural by defects which can be removed, to be utilised in the construction of CLT components while timber of sub F5 grade can be used to meet the current demand for the utility grade product. An advantage of this is that allows the CLT component to become more predictable, also allowing estimates of the materials mechanical and matrix strength properties more accurate.

Separation of utility grade timber elements into apparent strength groups of MGP 12, MGP 10 & MGP 8 and F5 and lower, as well as removing any considerable defects before construction will also help reduce the variability between panels. Knowing exactly what timber is being used in each panel gives a distinct advantage when trying to market the product. If buyers are able to determine that a vast majority of the individual elements within the CLT panel possess a high strength they would be more likely to invest into that product over panels that are built from elements comprised of random strengths.

With the release of the CLT product range, Hyne would normally have to supply with all purchases the minimum strength of the panels being sold. Without sorting in place, Hyne Timber would have to assume that it is a possibility that some panels would be comprised of entirely all F5 or less graded timber, significantly reducing the expected strength properties. This result would reduce the viability of the panels as a construction material as extreme variability in construction materials are considered as highly unfavourable and sales would suffer.

6.8.0 - Conclusion

The analysis of these results were carried out to gain an understanding of the possible changes to the material strength properties of differing CLT panel combinations as the panel dimensions were optimised. The models produced were subject to two different failure modes to ascertain if the optimisation process had any significant effects on the performance characteristics of the CLT combinations. These failure modes were based on deflection limits and ultimate failure limiting criterion. Results clearly show that the CLT combinations possess greater stiffness properties than their corresponding solid pine counterparts. Further analysis also proved that as the number of layers increase, independent of the panels thicknesses, the more 'tuned' the components become, giving the CLT components extra stiffness. However once the number of layers in the CLT component exceeds 9 layers, it was concluded that the outlay of cost and time required in the adding of more additional layers exceeded the benefits of the percentage increase in stiffness which would be gained.

A second type of panel was analysed based on the same criteria mentioned above. This panel consisted of equal volumes of timber orientated longitudinally and tangentially about the primary of the CLT component. These panels possess an equally 'tuned' modulus of elasticity in both longitudinal and tangential directions, which was equated to a further decrease in deflection under the given applied load. However as was discovered during this investigation, as the CLT components become more 'tuned' and the transverse modulus of elasticity for the component becomes greater, the ultimate failure strength of the CLT panel is decreased. This reduction of strength was found to be more acute as the transverse modulus was increased, making the plies which consisted of numerous layers the most desirable for resisting deflection but the weakest and least desirable when considering ultimate failure strength. These results were tabulated in the above analysis, including the limiting theoretical effective loads which satisfy deflection criteria as well as tables displaying the maximum theoretical failure loads for panels of a standard unit width.

Analysis of these tables led to the theory that when failure occurs it would be brittle and catastrophic in nature. This conclusion was reached after inspecting the difference between the allowable limiting deflection loads and the ultimate failure loads, which were much smaller. This analysis clearly shows that failure was more than likely to occur in the wood structure before any discernible deflection was evident as a result of the tensile strain limit being exceeded on the extreme tensile face.

Based on these finding, recommendations were made on the use of capacity reduction factors to help guarantee the structural soundness of the panels produced. These factors, although not exactly the same as, are based on reduction factors outlined in AS1170.0 of the Australian Standards. Recommendations were also made on the selection of appropriate, individual timber elements used in the construction of the CLT panels. It was suggested that the utility grade timber be sorted into their strength groups after all major defects have been removed and construction of the panels should only use timber members which possesses similar strength properties. This will ensure that although the elements which comprise the CLT panel are classified as utility grade, some degree of predictability and quality assurance can now be passed onto clients and buyers as some degree of the randomness in the material strengths have been removed.

It is hoped that these results will shed light on the optimisation and production of viable CLT panels for the use at the very least in the residential construction industry. However it is important to remember that these results are based on theoretical models and as a result carry no verification based on experimentally derived data. These models analysed are based on ideal construction conditions and any change to these will change the effectiveness of the data gathered.

Chapter 7

Conclusion

Summary

This conclusion will briefly discuss the results of the research carried out and list the recommendations which will be made to Hyne Timber Australia on the most optimised procedure for the selection, configuration and construction of viable CLT components. This conclusion will also reflect on the initial objectives of this research project to assess any changes to the initial project outline as well as assessing whether all objectives have been sufficiently met.

The primary objective of this research project was to find a viable method that allowed the use of utility grade timber in the current building construction industry. The stabilisation of the utility grade elements would be modelled via a process known as Cross lamination. This process involves orientation the alternating timber layers so that the grain direction between any two adjacent layers is perpendicular. CLT components create a panel type element of 'tuned' mechanical properties, with far more strength than the individual utility grade timber specimens.

In order to analyse the effectiveness of the cross – lamination process, theoretical models were simulated in the finite element modelling package, Strand 7. These models were comprised of differing amounts of timber layers, modelled around the current milling specifications of the Hyne Timber Australia's timber process plant in Maryborough.

Conclusions and Major Findings

- The CLT components vastly outperform their solid Slash Pine panel counterparts when considering the limiting deflection criteria. However this increase in deflection resistance comes at the cost of a loss in ultimate failure strength.

- The addition of extra layers independent of panel depth serves to homogenise the panel's mechanical properties in the primary and secondary directions. However the effect does have limitations and after a total of 9 layers have been added to the panel component, the benefits which would be gained by the addition of extra layers would be outweighed by the cost and extra time associated with the construction of the end CLT product.

- Theoretical failure modes indicate that failure of the CLT panels is brittle in nature, resulting in catastrophic de-lamination once the failure load has been exceeded.

- During construction no more than 10% of any given cross section of any given CLT panel should be considered as being defective material, otherwise failure regions may become unpredictable.

- Panels should be constructed out of utility grade timber elements which possess similar strength characteristics. If individual elements are too dissimilar early failure will occur at the weakest point, substantially reducing the ultimate failure strength of the panel.

Future areas of Research

"Developing a method of sorting and analysing utility grade timber specimens of similar strength characteristics"

- This research is needed and is essential in developing an accurate data set of mechanical properties which can be given as a minimum assurance for all the individual members which make up the CLT panels.

"Analyse data gained from performed experiments in order to validate the conclusions reached by this research paper"

- This research paper analyses theoretical, computer generated models. Experimental data is needed to either validate or disprove the conclusions reached in this paper, as well as show possible differences and alterations in the predictability and methods used to analyse the CLT structures.

"The analysis of viable connections for joining CLT members"

- This research is of primary importance to the viability of a commercially available CLT product. It is obvious that the panels will not be tailor made and will be manufactured to a standard size; smaller lengths will be cut to the required size and lager lengths will need to be joined. However it is currently unknown what effects joining the panels will have on the stress distributions between the two components or what effect will joining have on the cross lamination in the region surrounding the join.

"The Study and Selection of an Appropriate Bonding Resin"

- This research paper assumed that the timber elements would fail before the surrounding layers of bonding resin. However this assumption is untested and further research is needed on the appropriate selection of the most suitable bonding resin, including; the resins chemical composition, mechanical properties and the resulting strength which the bonding layer will contribute to the CLT structure.

Other areas of possible interest include;

- Natural frequency analysis
- Acoustic and sound property analysis
- Fire ratings and thermal properties
- Housing of essential services
- Effects of using multiple wood species

Further analysis of all these topics would help build a comprehensive data base on the use, limitations and mechanical properties of this new construction material.

Assessment of objectives

The aim of this research project was to investigate the structural performance of cross laminated timber panels for the use of load bearing plates and to develop an optimised CLT component suitable for manufacture. Before this research was conducted a series of objectives were formulated to serve as guidelines to ensure that viable results would be produced.

Objective 1

- *Conduct a review of the current literature on CLT panels and beams to gain an understanding and appreciation of the current technologies associated with CLT design.*

An in depth literature review was conducted on the topic and many areas of importance were outlined. One area of difficulty however was finding valid data for the purpose of comparison. Many companies regard the data which they have already gathered as their company's secrets and were unwilling to share optimisation data, material properties or results of experiments when asked.

Objective 2

- *Create computer based, finite element models of different CLT combinations and orientations using Strand 7 to explore what component specifications will give the most structurally performing CLT panel.*

This objective was the prime focus of this research project and therefore had by far the most time dedicated to making sure it was fulfilled in all regards. Models based on multiple layers, orientations and different layer combinations were produced and analysed to ascertain exactly how these variables affect the outcome of the engineered panel design. The results and recommendations made in this research paper based on the theoretical models directly fulfil the requirements of this objective.

Objectives 3 & 4

- *Acquire test specimens provided by Hyne Timber. These specimens will be based on the specifications of the finite element modelling.*

- *Test the specimens to validate the data gathered by the theoretical modelling.*

Early on in the initial stages of this project it was determined that these objectives were no longer valid to this dissertation. This was due to the sheer number of computer models which were being produced as well as not having any concrete conclusions on the optimisation of which variables would produce the most structural superior components. It was therefore suggested that the primary focus should stay with the analysis of the finite element models and the base conclusions and recommendations on these findings.

Objective 5

- *Using both theoretical and experimental results suggest to Hyne Timber a viable CLT panel design.*

The recommendations made to Hyne Timber Australia are, as stated above only based upon conclusions reached through the analysis of the theoretical models. It is envisioned that recommendations based on experimental results, as to the viability of constructing CLT panels from utility grade timber will be carried out by like minded students in the upcoming years.

References

Abrate, S. (1991). "Impact on laminated composite materials." "*Applied Mechanics reviews*" 44(4), p155-190.

Altus, E., and Ishai, O. (1992). "Delamination buckling criterion for composite laminates; A macro approach." *Engineering Fracture Mechanics* 41(5), p737-748

AYERS S R and VAN ERP G M (2004), *"Australian Approaches to Standardizing Design Properties for Fibre Reinforced Laminates in Civil Engineering Structures,"* Proceedings of the Polymer Composite III Conference, Morgantown, West Virginia, USA.

Elliot, G. (1978), "*Partial loading on Orthotropic Plates*," Cement and Concrete Association Technical Report 42.591, LONDON

Falk, R. H. & Colling, F. (1995), "Laminating Effects in Glued-Laminated Timber Beams, *Journal of Structural Engineering* **121**(12), 1858 – 1863.

Gsell, D., Feltrin, G., Schubert, S., Steiger, R., Motavalli, M. (2007), Cross Laminated Timber plates: Evaluation and verification of homogenised elastic properties. *Journal of Structural Engineering,* 133(1), p132-138

Gsell, D., Gulzow, A., Steiger, R., (2008), Non Destructive Testing of Elastic Material Properties of Cross Laminated Timber. *Conference COST E52, 29th-30th Oct*

Gsell, D., Feltrin, G., Schubert, S., Steiger, R. & Motavalli, M. (2007), Cross-Laminated Timber Plates: Evaluation and Verification of Homogenized Elastic Properties‟, *Journal of Structural Engineering* **133**(1), 133 – 138.

Gulzow, A., Richter, K., Steiger, R., (2009-2010), Influence of wood moisture content on bending and shear stiffness of cross laminated timber panels. *Paper No: DOI10.1007/s00107-010-0416-z*

Lee, J. & Kim, G. (2000), Study on the estimation of the strength properties of structural glued laminated timber I: Determination of optimum MOE as input variable‟, *Journal of Wood Science* 46(2), 115 – 121.

Green**,** D. Kretschmann, D. & Winandy, J **'***Wood Handbook' 'Chapter 4. Mechanical Properties of Wood', 'Orthotropic Nature of Wood 4–1'*

Liu, S., & Chang, F.K. (1993). "Matrix cracking and delamination propagation in laminated composites subject to transversely concentrated load." "*Composite Materials*" 27(5) p436-460

Moody, R.C. & Hernandez, R. (1997), *Engineered wood products – A guide for specifiers, designers and users,* PFS Research Foundation, Madison, WI.

Müller, C. (2000) Laminated Timber Construction,

Paper No. ISBN 3-7643-6267-7, Birkhauser, Basel.

Soltis, L. & Rammer, D. (1993), Shear strength of unchecked glued-laminated beams‟, *Forrest Products Journal* **53705**(1), p51 – 57.

MacKenzie, C 2009, *'Program Proposal To Develop Ecopanel'* , Feasibility analysis, Timber Queensland Ltd, viewed 20 March 2009 2000, http://mail.timberqueensland.com.au/ftp/EcoSLAB%20Information/

Szilard, R. (1974), *"Theory and Analysis of Plates – Classical and Numerical Methods,"* Prentice – Hall Inc., Englewood Cliffs, New Jersey

University of southern Queensland, (2008),. "*Composite Material Behaviour*." Chapter 4 - ENG8803 Mechanics and Technology of Fibre Composites, University of Southern Queensland, Toowoomba

U.S. Department of Agriculture, Forest Products Laboratory, The Wood Handbook: Wood as an engineering material. *General Technical Report 113*, Madison, WI.

Appendix A – Project Specifications

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Geoff Stringer & Karu Karunasena

TOPIC: The Investigation into the Optimisation of CLT Panels for use in the Australia Building Industry

SUPERVISOR: A/ Karu Karunasena as well as industry input from Geoff Stinger

SPONSERSHIP: Hyne Timber Australia

PROJECT AIM: The use of CLT is new in Australia. The aim of this research is to investigate the initial optimisation to produce a product that is suitable to Australian conditions and construction needs.

PROGRAMME: (Issue B, 23 July 2010)

1. Research initial background information. Looking specifically to the European nations where the use of CLT panels is quite common place. This will involve validation of what these countries have agreed upon to use as standards and what engineering validation has been made to prove their integrity.

2. Design and analyse different CLT combinations on Strand 7. Supplying any information that is important to Alan Turner. This step will comprise most of the optimisation research and will look at;
    a. The use of an effective timber grade
    b. Laminating/bonding properties
    c. Timber layer thickness
    d. Layer orientation

3. List recommendations on the optimum construction process of a CLT panel, based on findings from the finite element analysis conducted in Stand 7.

AGREED ________________ (student) ________________ (supervisor)
Date: / / 2010 Date: / / 2010
Examiner/Co-examiner:________________________

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Geoff Stringer & Karu Karunasena

TOPIC: The Investigation into the Optimisation of CLT Panels for use in the Australia Building Industry

SUPERVISOR: A/ Karu Karunasena as well as industry input from Geoff Stinger

SPONSERSHIP: Hyne Timber Australia

PROJECT AIM: The use of CLT is new in Australia. The aim of this research is to investigate the initial optimisation to produce a product that is suitable to Australian conditions and construction needs.

PROGRAMME: (Issue A, 21 March 2010)

1. Research initial background information. Looking specifically to the European nations where the use of CLT panels is quite common place. This will involve validation of what these countries have agreed upon to use as standards and what engineering validation has been made to prove their integrity.

2. Design and analyse different CLT combinations on Strand 7. Supplying any information that is important to Alan Turner. This step will comprise most of the optimisation research and will look at;
   a. The use of an effective timber grade
   b. Laminating/bonding properties
   c. Timber layer thickness
   d. Layer orientation

3. Contact Hyne Timber and Geoff Stringer and have some test samples made.

4. Validate my theoretical results with the test data.

IF TIME PERMITS

If time permits, which is unlikely, I will attempt to shed some light on the area of joining CLT panels together. However I suspect that this would be an individual research area in its own right.

AGREED ________________ (student) ________________ (supervisor)
Date: / / 2010 Date: / / 2010
Examiner/Co-examiner:________________________

Appendix B - Relevant Tables associated with Australia Standards

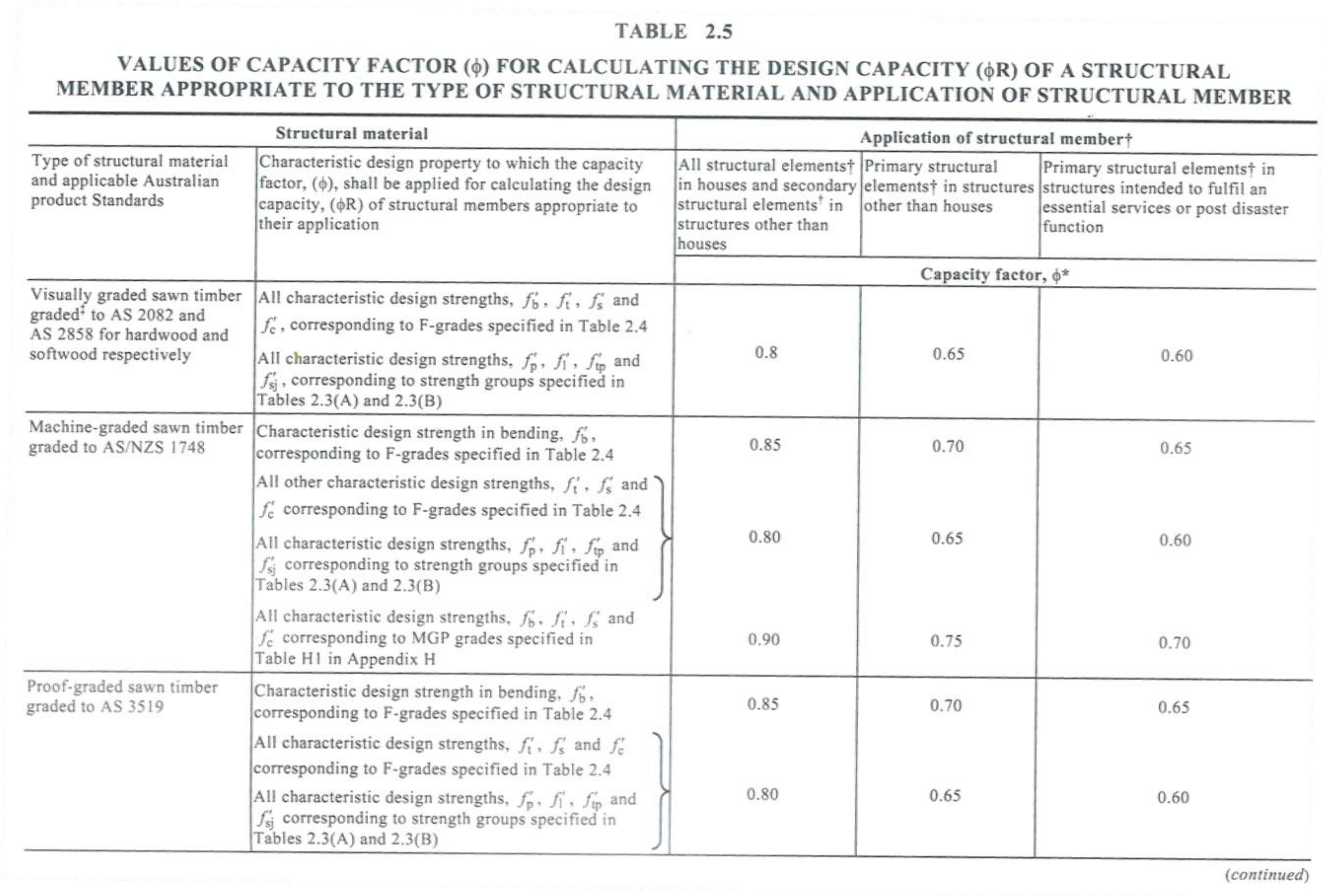


TABLE 2.5

VALUES OF CAPACITY FACTOR (ϕ) FOR CALCULATING THE DESIGN CAPACITY (ϕR) OF A STRUCTURAL MEMBER APPROPRIATE TO THE TYPE OF STRUCTURAL MATERIAL AND APPLICATION OF STRUCTURAL MEMBER

Structural material		**Application of structural member**[†]		
Type of structural material and applicable Australian product Standards	Characteristic design property to which the capacity factor, (ϕ), shall be applied for calculating the design capacity, (ϕR) of structural members appropriate to their application	All structural elements[†] in houses and secondary structural elements[†] in structures other than houses	Primary structural elements[†] in structures other than houses	Primary structural elements[†] in structures intended to fulfil an essential services or post disaster function
		Capacity factor, ϕ*		
Visually graded sawn timber graded[‡] to AS 2082 and AS 2858 for hardwood and softwood respectively	All characteristic design strengths, f'_b, f'_t, f'_s and f'_c, corresponding to F-grades specified in Table 2.4	0.8	0.65	0.60
	All characteristic design strengths, f'_p, f'_l, f'_{tp} and f'_{sj}, corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)			
Machine-graded sawn timber graded to AS/NZS 1748	Characteristic design strength in bending, f'_b, corresponding to F-grades specified in Table 2.4	0.85	0.70	0.65
	All other characteristic design strengths, f'_t, f'_s and f'_c corresponding to F-grades specified in Table 2.4	0.80	0.65	0.60
	All characteristic design strengths, f'_p, f'_l, f'_{tp} and f'_{sj} corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)			
	All characteristic design strengths, f'_b, f'_t, f'_s and f'_c corresponding to MGP grades specified in Table H1 in Appendix H	0.90	0.75	0.70
Proof-graded sawn timber graded to AS 3519	Characteristic design strength in bending, f'_b, corresponding to F-grades specified in Table 2.4	0.85	0.70	0.65
	All characteristic design strengths, f'_t, f'_s and f'_c corresponding to F-grades specified in Table 2.4	0.80	0.65	0.60
	All characteristic design strengths, f'_p, f'_l, f'_{tp} and f'_{sj} corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)			

(continued)

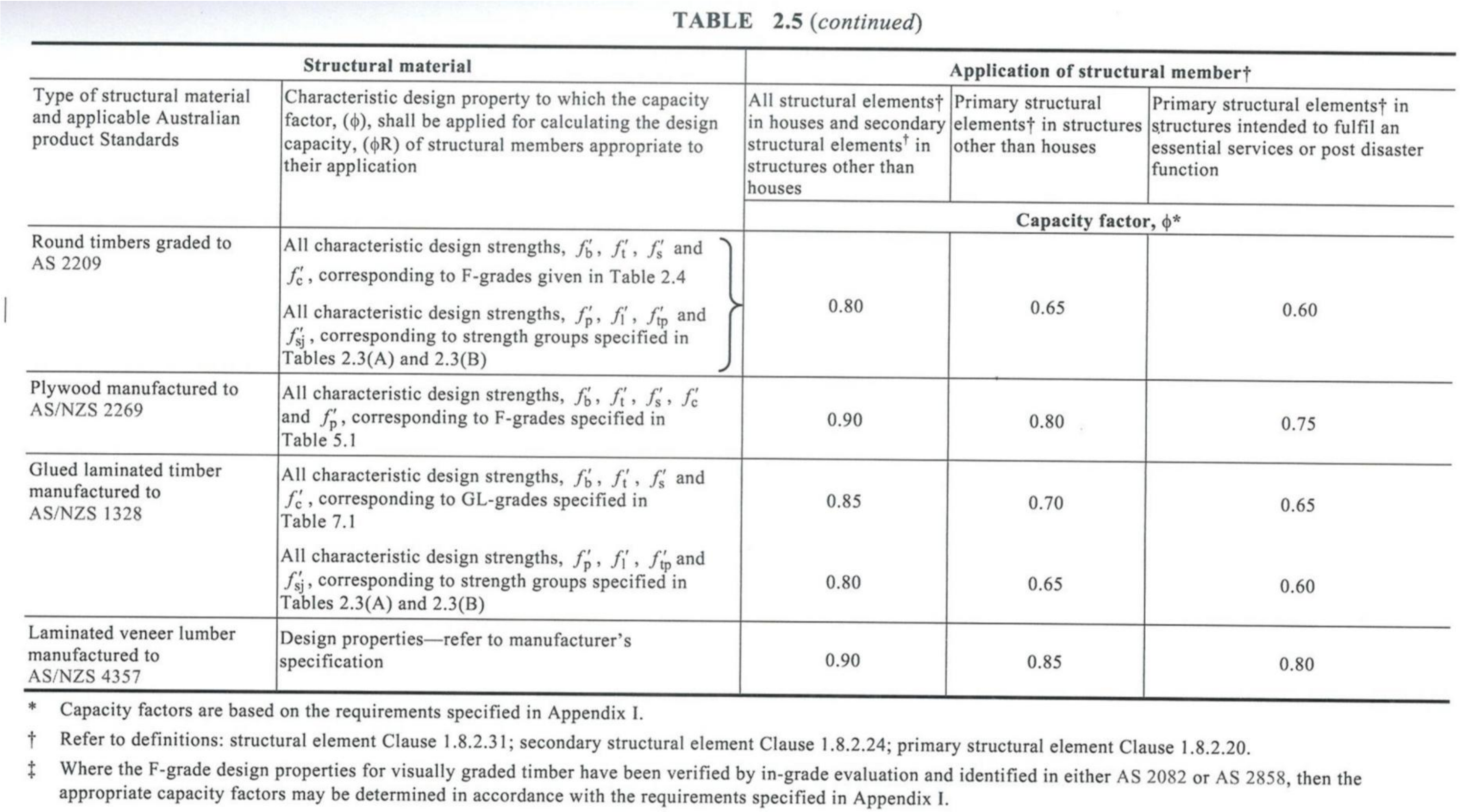


TABLE 2.5 (*continued*)

Structural material		Application of structural member†		
Type of structural material and applicable Australian product Standards	Characteristic design property to which the capacity factor, (ϕ), shall be applied for calculating the design capacity, (ϕR) of structural members appropriate to their application	All structural elements† in houses and secondary structural elements† in structures other than houses	Primary structural elements† in structures other than houses	Primary structural elements† in structures intended to fulfil an essential services or post disaster function
		Capacity factor, ϕ*		
Round timbers graded to AS 2209	All characteristic design strengths, f'_b, f'_t, f'_s and f'_c, corresponding to F-grades given in Table 2.4 All characteristic design strengths, f'_p, f'_l, f'_{tp} and f'_{sj}, corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)	0.80	0.65	0.60
Plywood manufactured to AS/NZS 2269	All characteristic design strengths, f'_b, f'_t, f'_s, f'_c and f'_p, corresponding to F-grades specified in Table 5.1	0.90	0.80	0.75
Glued laminated timber manufactured to AS/NZS 1328	All characteristic design strengths, f'_b, f'_t, f'_s and f'_c, corresponding to GL-grades specified in Table 7.1	0.85	0.70	0.65
	All characteristic design strengths, f'_p, f'_l, f'_{tp} and f'_{sj}, corresponding to strength groups specified in Tables 2.3(A) and 2.3(B)	0.80	0.65	0.60
Laminated veneer lumber manufactured to AS/NZS 4357	Design properties—refer to manufacturer's specification	0.90	0.85	0.80

* Capacity factors are based on the requirements specified in Appendix I.

† Refer to definitions: structural element Clause 1.8.2.31; secondary structural element Clause 1.8.2.24; primary structural element Clause 1.8.2.20.

‡ Where the F-grade design properties for visually graded timber have been verified by in-grade evaluation and identified in either AS 2082 or AS 2858, then the appropriate capacity factors may be determined in accordance with the requirements specified in Appendix I.

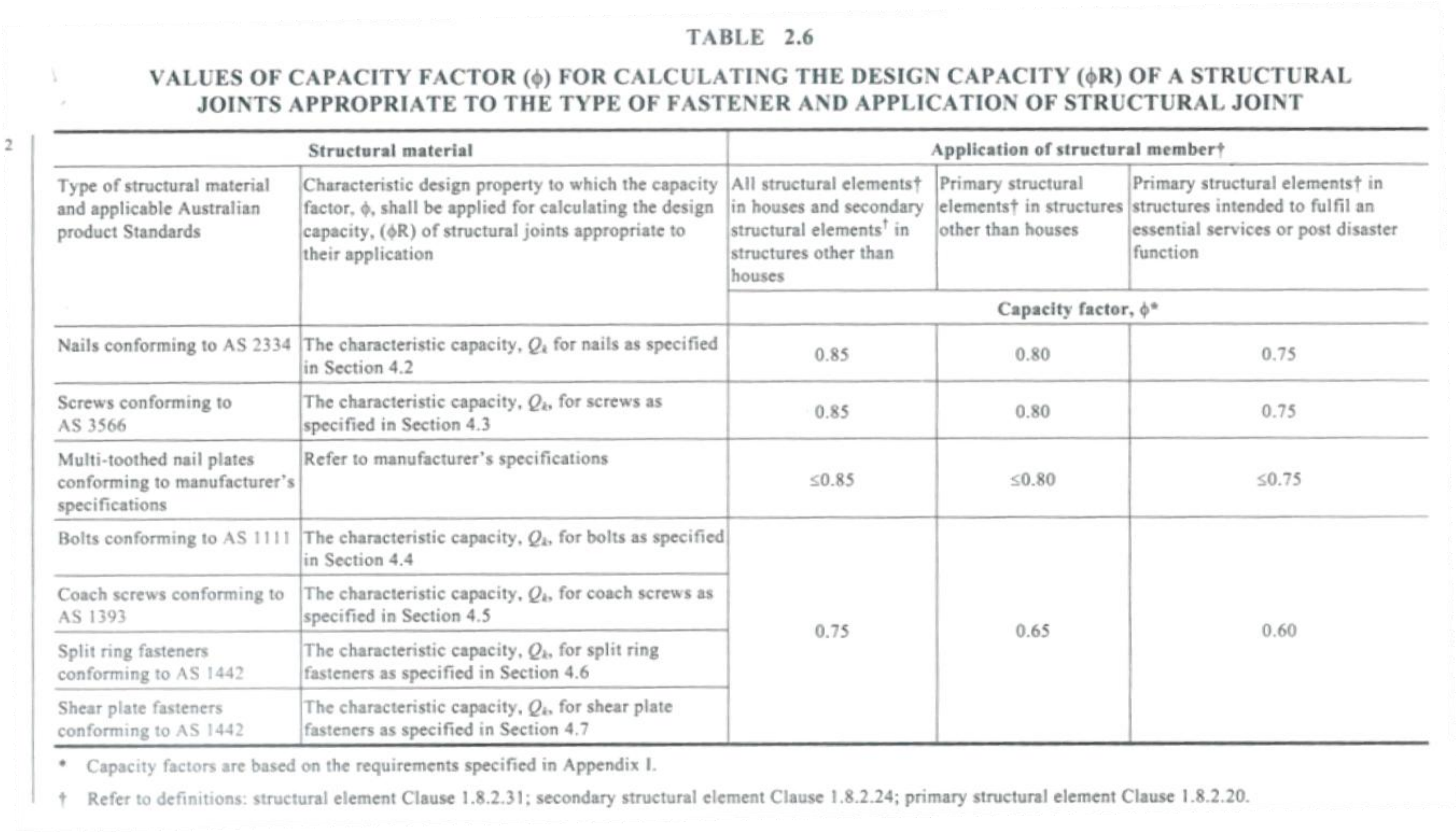


TABLE 2.6

VALUES OF CAPACITY FACTOR (ϕ) FOR CALCULATING THE DESIGN CAPACITY (ϕR) OF A STRUCTURAL JOINTS APPROPRIATE TO THE TYPE OF FASTENER AND APPLICATION OF STRUCTURAL JOINT

Structural material		Application of structural member†		
Type of structural material and applicable Australian product Standards	Characteristic design property to which the capacity factor, ϕ, shall be applied for calculating the design capacity, (ϕR) of structural joints appropriate to their application	All structural elements† in houses and secondary structural elements† in structures other than houses	Primary structural elements† in structures other than houses	Primary structural elements† in structures intended to fulfil an essential services or post disaster function
		Capacity factor, ϕ*		
Nails conforming to AS 2334	The characteristic capacity, Q_k for nails as specified in Section 4.2	0.85	0.80	0.75
Screws conforming to AS 3566	The characteristic capacity, Q_k, for screws as specified in Section 4.3	0.85	0.80	0.75
Multi-toothed nail plates conforming to manufacturer's specifications	Refer to manufacturer's specifications	≤0.85	≤0.80	≤0.75
Bolts conforming to AS 1111	The characteristic capacity, Q_k, for bolts as specified in Section 4.4	0.75	0.65	0.60
Coach screws conforming to AS 1393	The characteristic capacity, Q_k, for coach screws as specified in Section 4.5			
Split ring fasteners conforming to AS 1442	The characteristic capacity, Q_k, for split ring fasteners as specified in Section 4.6			
Shear plate fasteners conforming to AS 1442	The characteristic capacity, Q_k, for shear plate fasteners as specified in Section 4.7			

* Capacity factors are based on the requirements specified in Appendix I.

† Refer to definitions: structural element Clause 1.8.2.31; secondary structural element Clause 1.8.2.24; primary structural element Clause 1.8.2.20.

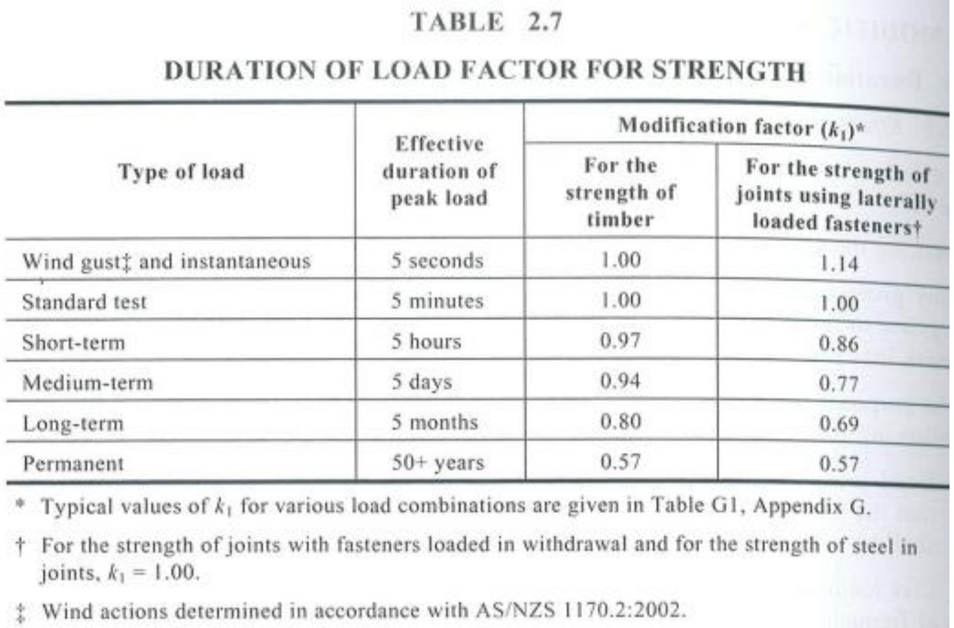


TABLE 2.7

DURATION OF LOAD FACTOR FOR STRENGTH

Type of load	Effective duration of peak load	Modification factor (k_1)*	
		For the strength of timber	For the strength of joints using laterally loaded fasteners†
Wind gust‡ and instantaneous	5 seconds	1.00	1.14
Standard test	5 minutes	1.00	1.00
Short-term	5 hours	0.97	0.86
Medium-term	5 days	0.94	0.77
Long-term	5 months	0.80	0.69
Permanent	50+ years	0.57	0.57

* Typical values of k_1 for various load combinations are given in Table G1, Appendix G.

† For the strength of joints with fasteners loaded in withdrawal and for the strength of steel in joints, $k_1 = 1.00$.

‡ Wind actions determined in accordance with AS/NZS 1170.2:2002.

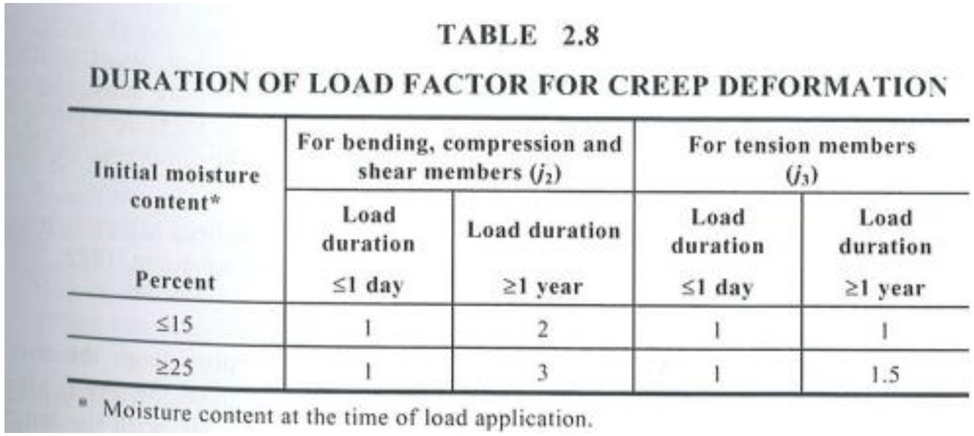


TABLE 2.8

DURATION OF LOAD FACTOR FOR CREEP DEFORMATION

Initial moisture content*	For bending, compression and shear members (j_2)		For tension members (j_3)	
Percent	Load duration ≤1 day	Load duration ≥1 year	Load duration ≤1 day	Load duration ≥1 year
≤15	1	2	1	1
≥25	1	3	1	1.5

* Moisture content at the time of load application.

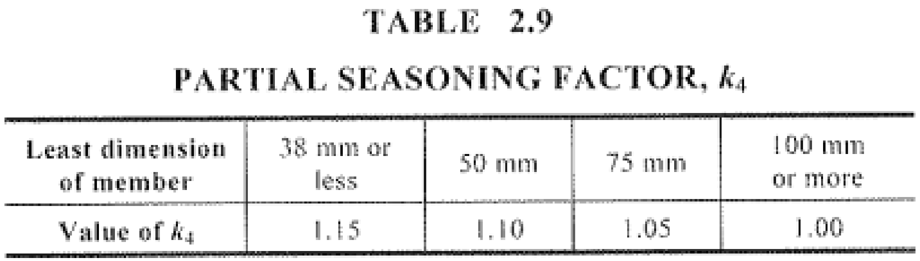


TABLE 2.9

PARTIAL SEASONING FACTOR, k_4

Least dimension of member	38 mm or less	50 mm	75 mm	100 mm or more
Value of k_4	1.15	1.10	1.05	1.00

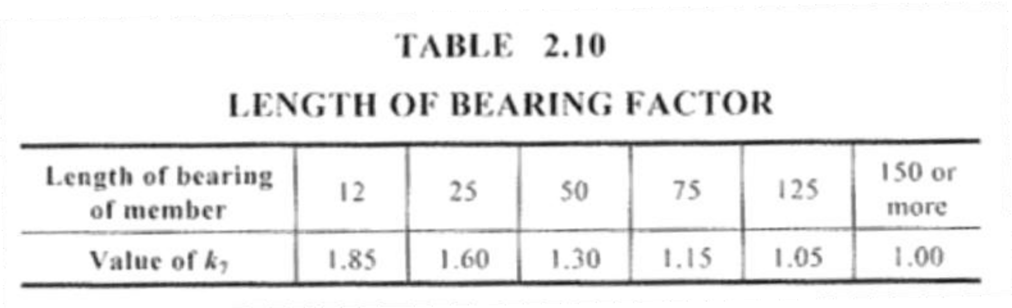


TABLE 2.10

LENGTH OF BEARING FACTOR

Length of bearing of member	12	25	50	75	125	150 or more
Value of k_7	1.85	1.60	1.30	1.15	1.05	1.00

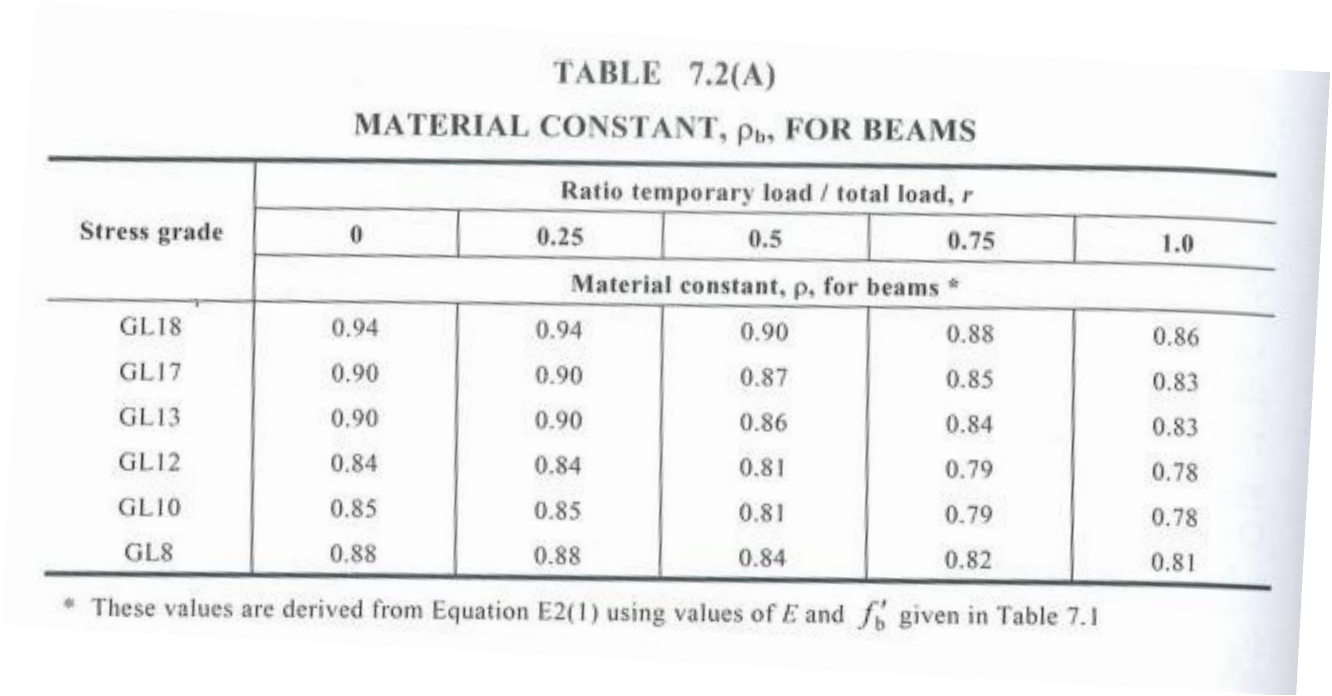


TABLE 7.2(A)

MATERIAL CONSTANT, ρ_b, FOR BEAMS

Stress grade	Ratio temporary load / total load, *r*				
	0	**0.25**	**0.5**	**0.75**	**1.0**
	Material constant, ρ, for beams *				
GL18	0.94	0.94	0.90	0.88	0.86
GL17	0.90	0.90	0.87	0.85	0.83
GL13	0.90	0.90	0.86	0.84	0.83
GL12	0.84	0.84	0.81	0.79	0.78
GL10	0.85	0.85	0.81	0.79	0.78
GL8	0.88	0.88	0.84	0.82	0.81

* These values are derived from Equation E2(1) using values of E and f'_b given in Table 7.1

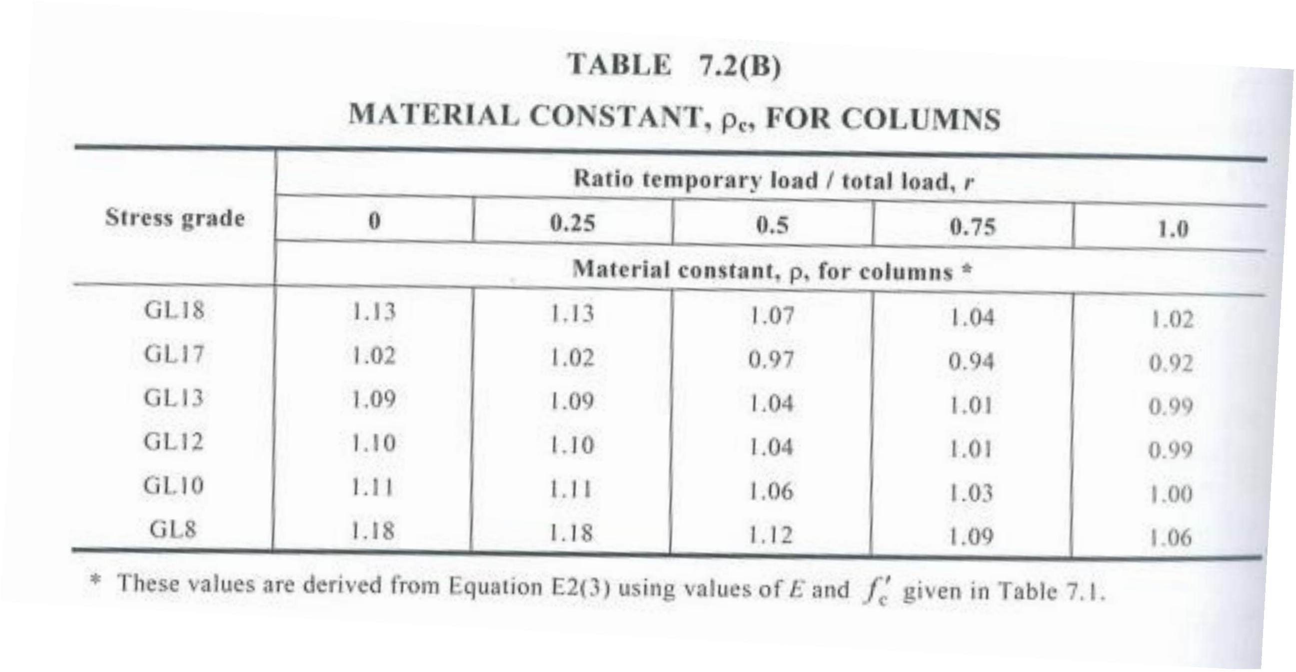


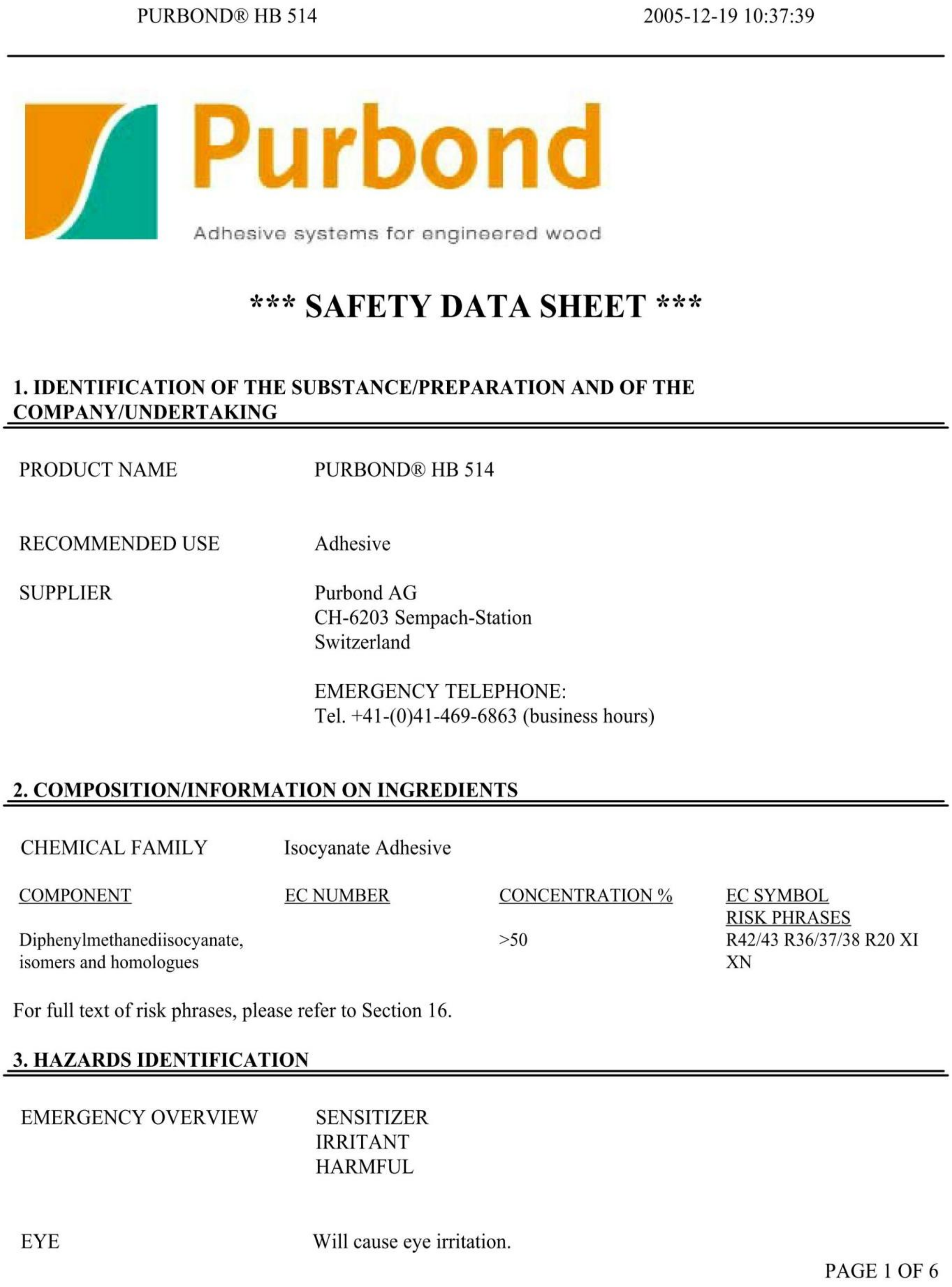
TABLE 7.2(B)

MATERIAL CONSTANT, ρ_c, FOR COLUMNS

Stress grade	Ratio temporary load / total load, *r*				
	0	**0.25**	**0.5**	**0.75**	**1.0**
	Material constant, ρ, for columns *				
GL18	1.13	1.13	1.07	1.04	1.02
GL17	1.02	1.02	0.97	0.94	0.92
GL13	1.09	1.09	1.04	1.01	0.99
GL12	1.10	1.10	1.04	1.01	0.99
GL10	1.11	1.11	1.06	1.03	1.00
GL8	1.18	1.18	1.12	1.09	1.06

* These values are derived from Equation E2(3) using values of E and f'_c given in Table 7.1.

Appendix C – Technical Data Sheets for mentioned Resins



Purbond

Adhesive systems for engineered wood

*** SAFETY DATA SHEET ***

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

PRODUCT NAME	PURBOND® HB 514
RECOMMENDED USE	Adhesive
SUPPLIER	Purbond AG CH-6203 Sempach-Station Switzerland EMERGENCY TELEPHONE: Tel. +41-(0)41-469-6863 (business hours)

2. COMPOSITION/INFORMATION ON INGREDIENTS

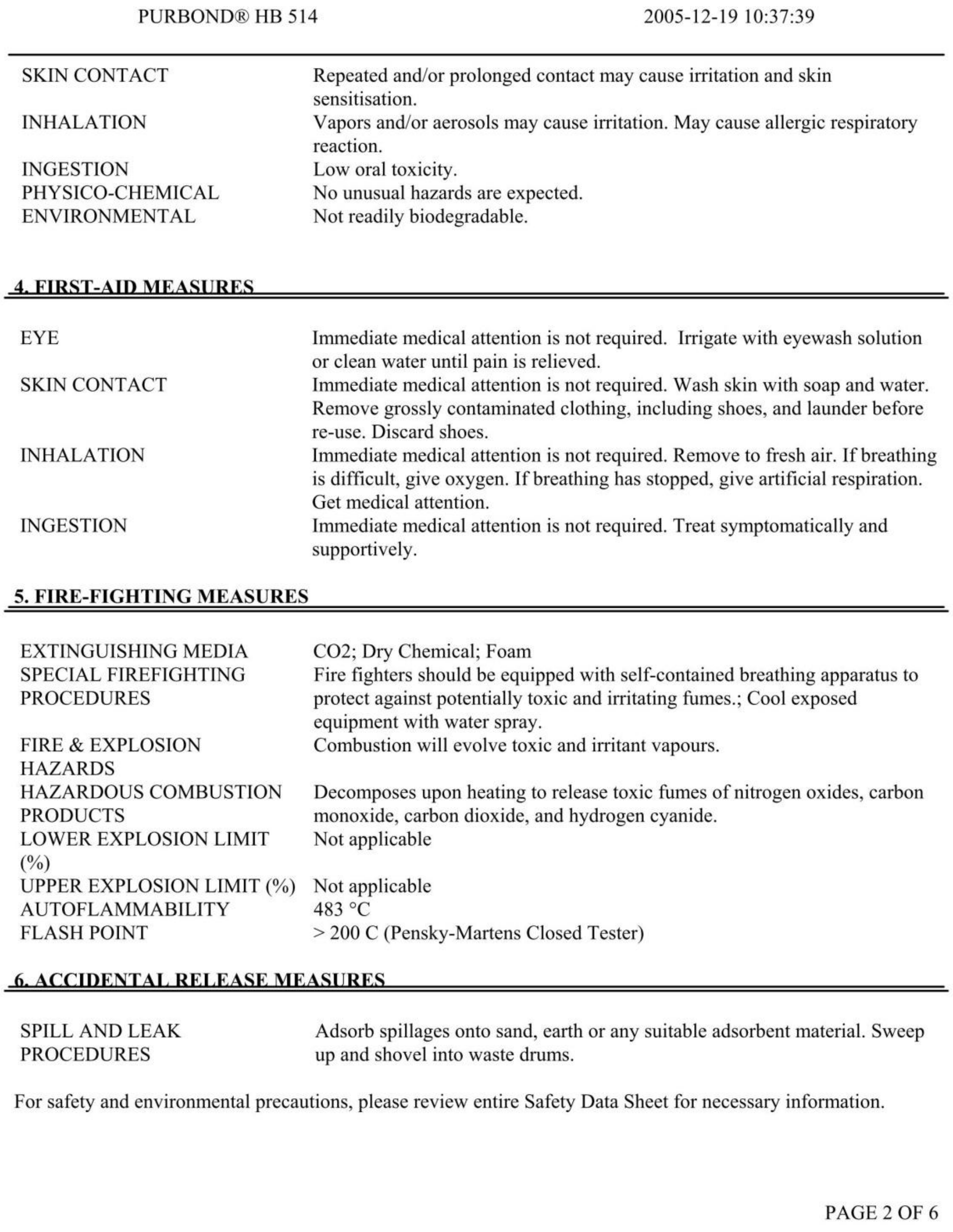
CHEMICAL FAMILY Isocyanate Adhesive

COMPONENT	EC NUMBER	CONCENTRATION %	EC SYMBOL RISK PHRASES
Diphenylmethanediisocyanate, isomers and homologues		>50	R42/43 R36/37/38 R20 XI XN

For full text of risk phrases, please refer to Section 16.

3. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW	SENSITIZER IRRITANT HARMFUL
EYE	Will cause eye irritation.



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SKIN CONTACT	Repeated and/or prolonged contact may cause irritation and skin sensitisation.
INHALATION	Vapors and/or aerosols may cause irritation. May cause allergic respiratory reaction.
INGESTION	Low oral toxicity.
PHYSICO-CHEMICAL	No unusual hazards are expected.
ENVIRONMENTAL	Not readily biodegradable.

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. FIRE-FIGHTING MEASURES

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 vapours.
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
AUTOFLAMMABILITY	483 °C
FLASH POINT	> 200 C (Pensky-Martens Closed Tester)

6. ACCIDENTAL RELEASE MEASURES

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

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

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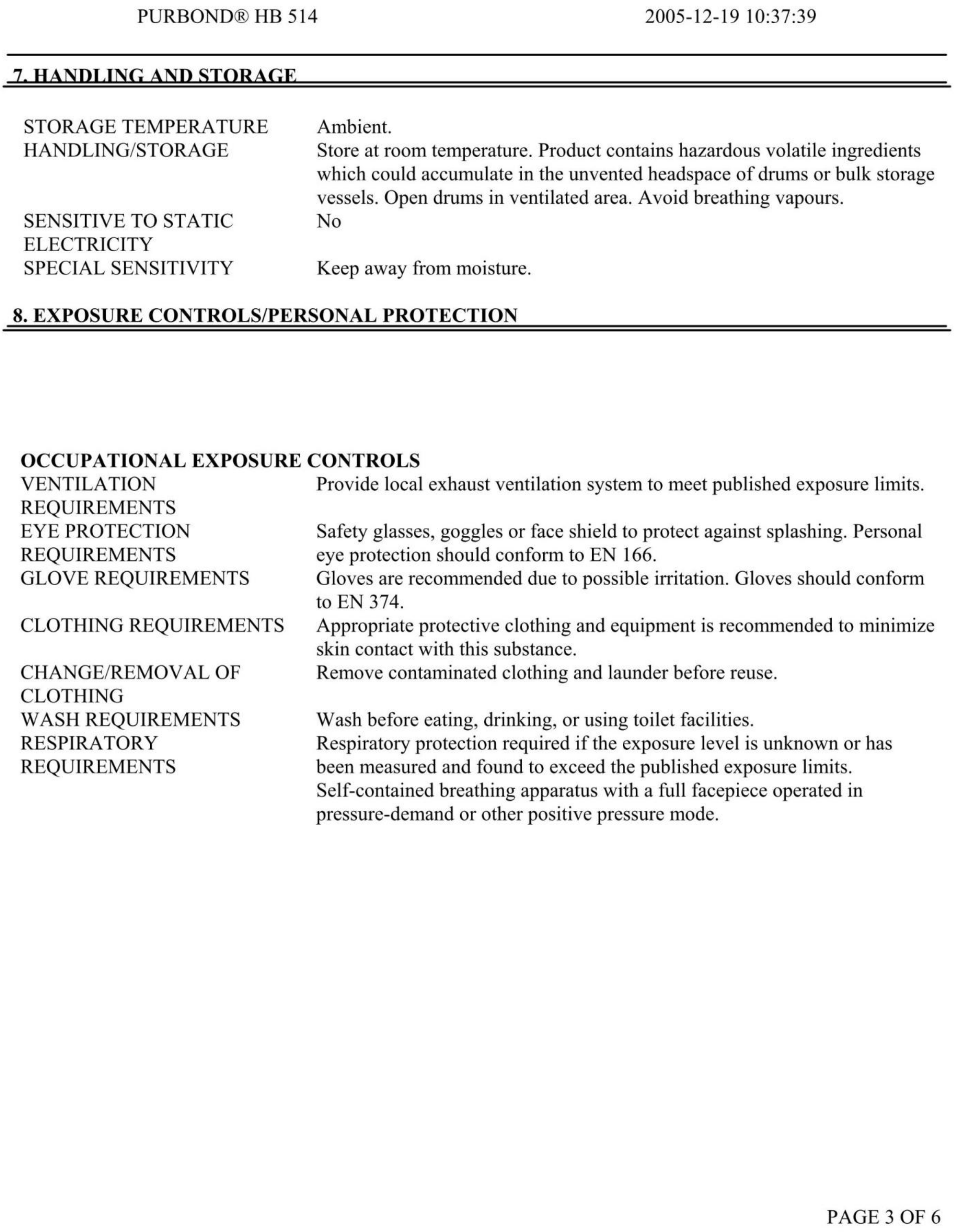

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7. HANDLING AND STORAGE

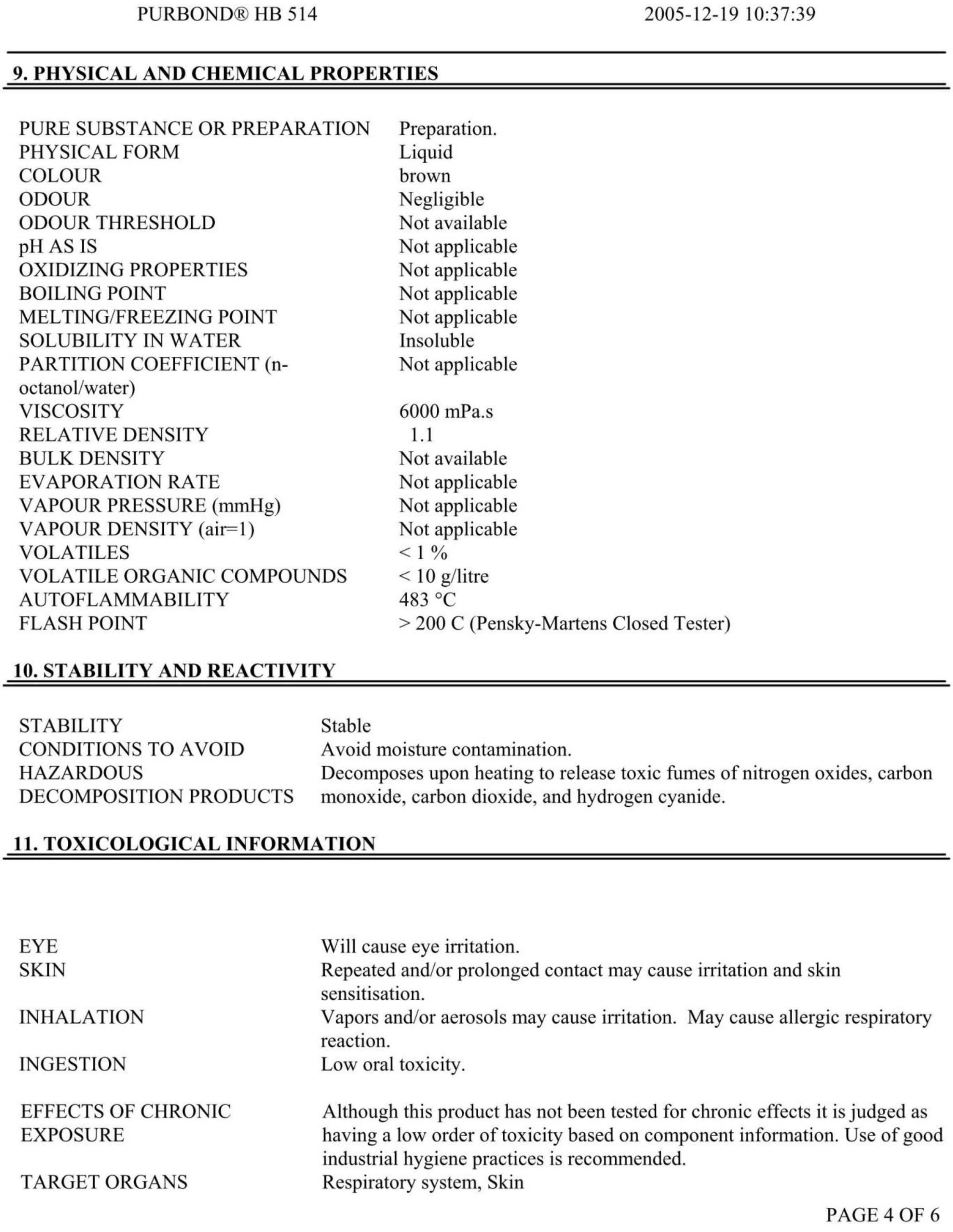
STORAGE TEMPERATURE	Ambient.
HANDLING/STORAGE	Store at room temperature. Product contains hazardous volatile ingredients which could accumulate in the unvented headspace of drums or bulk storage vessels. Open drums in ventilated area. Avoid breathing vapours.
SENSITIVE TO STATIC ELECTRICITY	No
SPECIAL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

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

OCCUPATIONAL EXPOSURE CONTROLS

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.
RESPIRATORY 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.

PAGE 3 OF 6



9. PHYSICAL AND CHEMICAL PROPERTIES

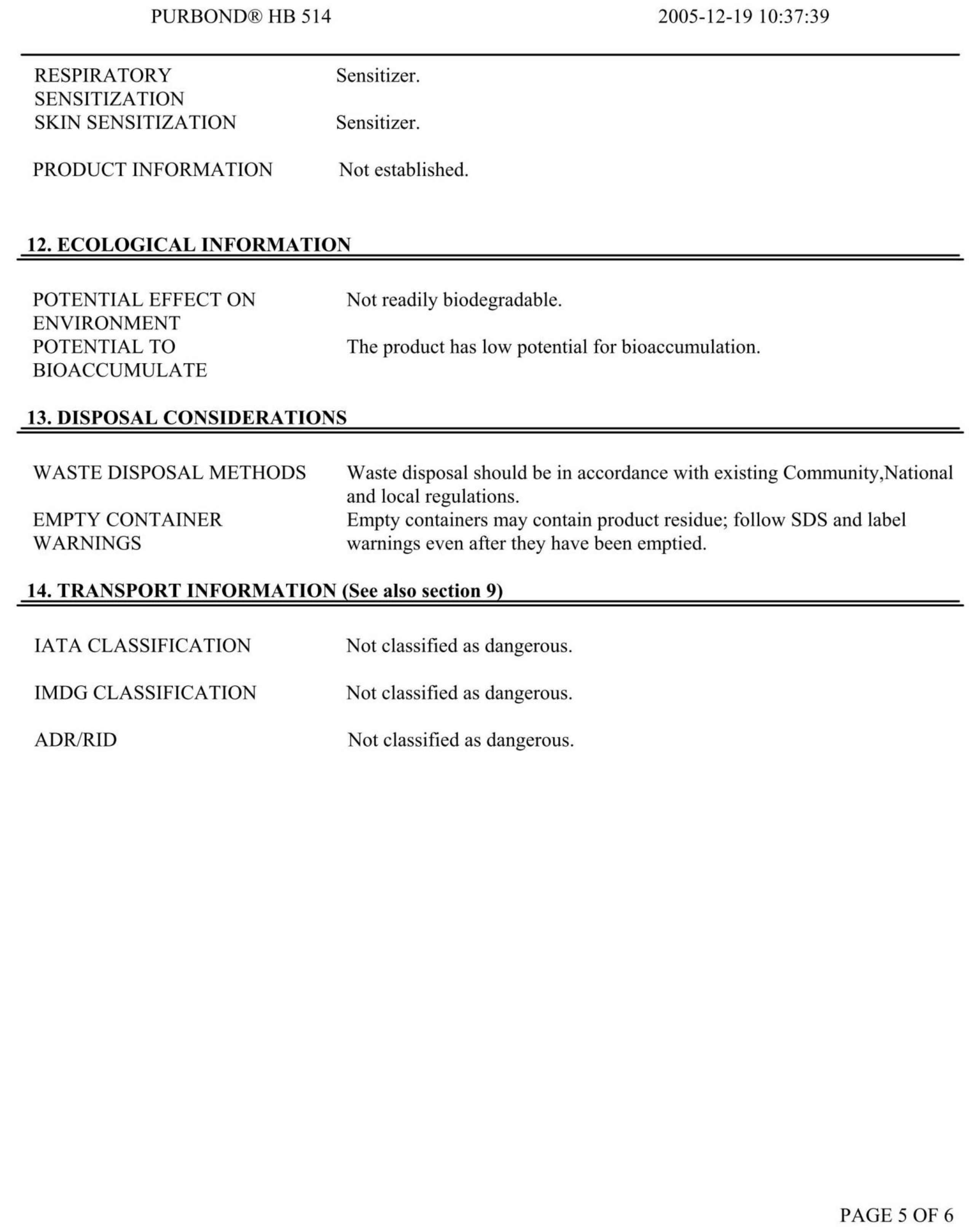
PURE SUBSTANCE OR PREPARATION	Preparation.
PHYSICAL FORM	Liquid
COLOUR	brown
ODOUR	Negligible
ODOUR THRESHOLD	Not available
pH AS IS	Not applicable
OXIDIZING PROPERTIES	Not applicable
BOILING POINT	Not applicable
MELTING/FREEZING POINT	Not applicable
SOLUBILITY IN WATER	Insoluble
PARTITION COEFFICIENT (n-octanol/water)	Not applicable
VISCOSITY	6000 mPa.s
RELATIVE DENSITY	1.1
BULK DENSITY	Not available
EVAPORATION RATE	Not applicable
VAPOUR PRESSURE (mmHg)	Not applicable
VAPOUR DENSITY (air=1)	Not applicable
VOLATILES	< 1 %
VOLATILE ORGANIC COMPOUNDS	< 10 g/litre
AUTOFLAMMABILITY	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

EYE	Will cause eye irritation.
SKIN	Repeated and/or prolonged contact may cause irritation and skin sensitisation.
INHALATION	Vapors and/or aerosols may cause irritation. May cause allergic respiratory reaction.
INGESTION	Low oral toxicity.
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.
SKIN SENSITIZATION	Sensitizer.
PRODUCT INFORMATION	Not established.

12. ECOLOGICAL INFORMATION

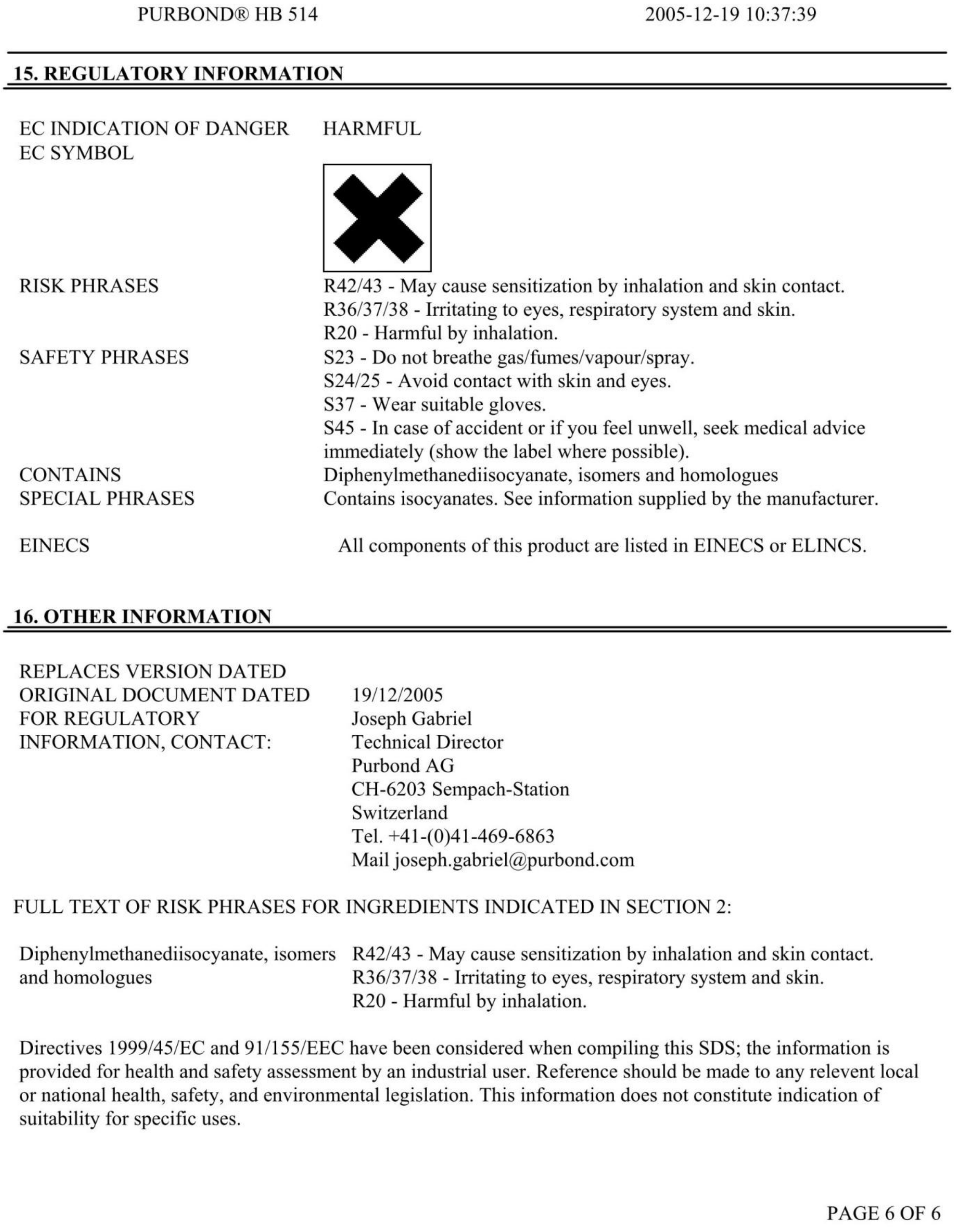
POTENTIAL EFFECT ON ENVIRONMENT	Not readily biodegradable.
POTENTIAL TO BIOACCUMULATE	The product has low potential for bioaccumulation.

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 SDS and label warnings even after they have been emptied.

14. TRANSPORT INFORMATION (See also section 9)

IATA CLASSIFICATION	Not classified as dangerous.
IMDG CLASSIFICATION	Not classified as dangerous.
ADR/RID	Not classified as dangerous.



15. REGULATORY INFORMATION

EC INDICATION OF DANGER	HARMFUL
EC SYMBOL	✖
RISK PHRASES	R42/43 - May cause sensitization by inhalation and skin contact. R36/37/38 - Irritating to eyes, respiratory system and skin. R20 - Harmful by inhalation.
SAFETY PHRASES	S23 - Do not breathe gas/fumes/vapour/spray. S24/25 - Avoid contact with skin and eyes. S37 - Wear suitable gloves. S45 - In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible).
CONTAINS	Diphenylmethanediisocyanate, isomers and homologues
SPECIAL PHRASES	Contains isocyanates. See information supplied by the manufacturer.
EINECS	All components of this product are listed in EINECS or ELINCS.

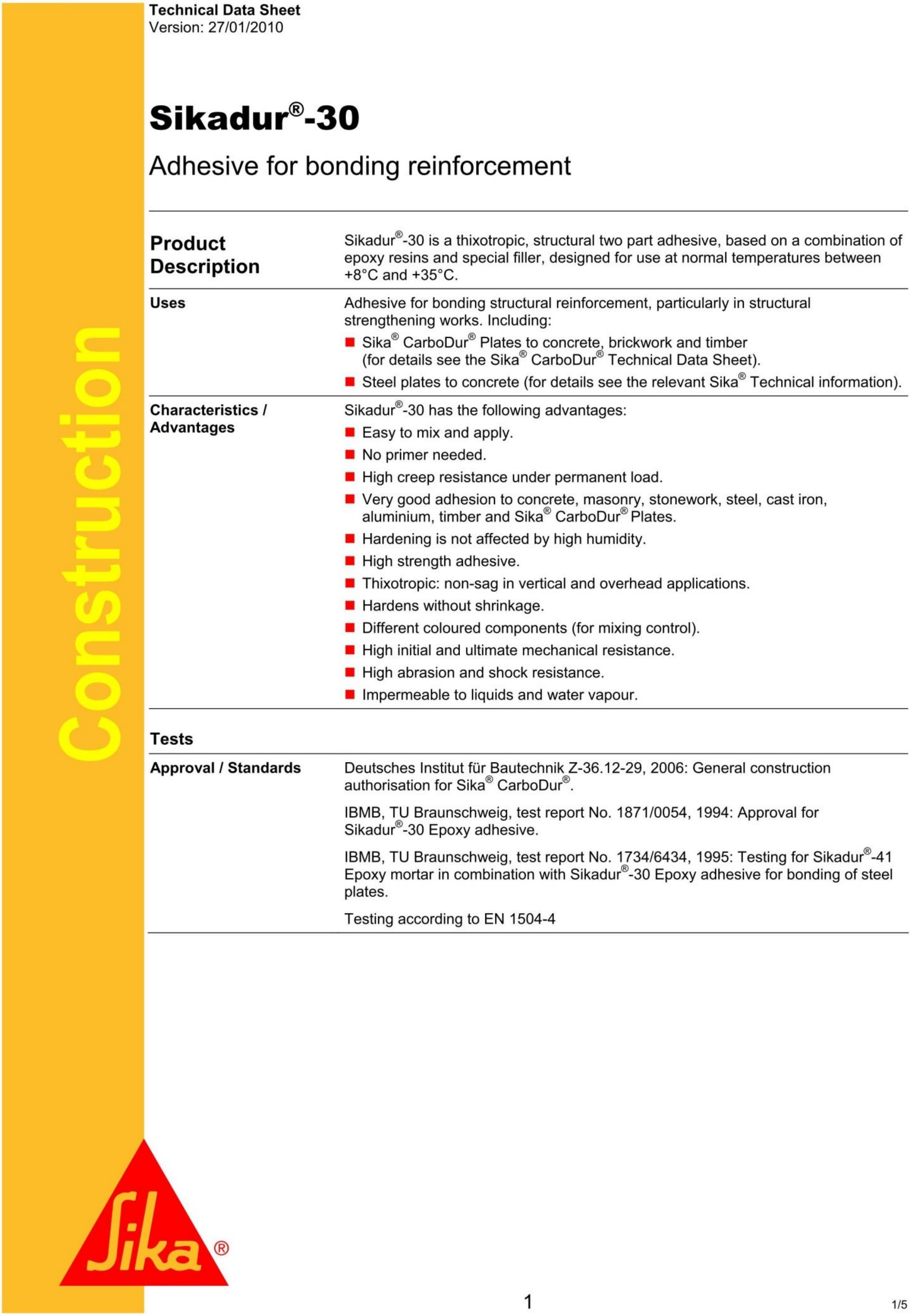
16. OTHER INFORMATION

REPLACES VERSION DATED	
ORIGINAL DOCUMENT DATED	19/12/2005
FOR REGULATORY INFORMATION, CONTACT:	Joseph Gabriel Technical Director Purbond AG CH-6203 Sempach-Station Switzerland Tel. +41-(0)41-469-6863 Mail joseph.gabriel@purbond.com

FULL TEXT OF RISK PHRASES FOR INGREDIENTS INDICATED IN SECTION 2:

Diphenylmethanediisocyanate, isomers and homologues	R42/43 - May cause sensitization by inhalation and skin contact. R36/37/38 - Irritating to eyes, respiratory system and skin. R20 - Harmful by inhalation.

Directives 1999/45/EC and 91/155/EEC have been considered when compiling this SDS; the information is provided for health and safety assessment by an industrial user. Reference should be made to any relevent local or national health, safety, and environmental legislation. This information does not constitute indication of suitability for specific uses.



Technical Data Sheet
Version: 27/01/2010

Construction

Sikadur®-30

Adhesive for bonding reinforcement

Product Description

Sikadur®-30 is a thixotropic, structural two part adhesive, based on a combination of epoxy resins and special filler, designed for use at normal temperatures between +8°C and +35°C.

Uses

Adhesive for bonding structural reinforcement, particularly in structural strengthening works. Including:

- Sika® CarboDur® Plates to concrete, brickwork and timber (for details see the Sika® CarboDur® Technical Data Sheet).
- Steel plates to concrete (for details see the relevant Sika® Technical information).

Characteristics / Advantages

Sikadur®-30 has the following advantages:

- Easy to mix and apply.
- No primer needed.
- High creep resistance under permanent load.
- Very good adhesion to concrete, masonry, stonework, steel, cast iron, aluminium, timber and Sika® CarboDur® Plates.
- Hardening is not affected by high humidity.
- High strength adhesive.
- Thixotropic: non-sag in vertical and overhead applications.
- Hardens without shrinkage.
- Different coloured components (for mixing control).
- High initial and ultimate mechanical resistance.
- High abrasion and shock resistance.
- Impermeable to liquids and water vapour.

Tests

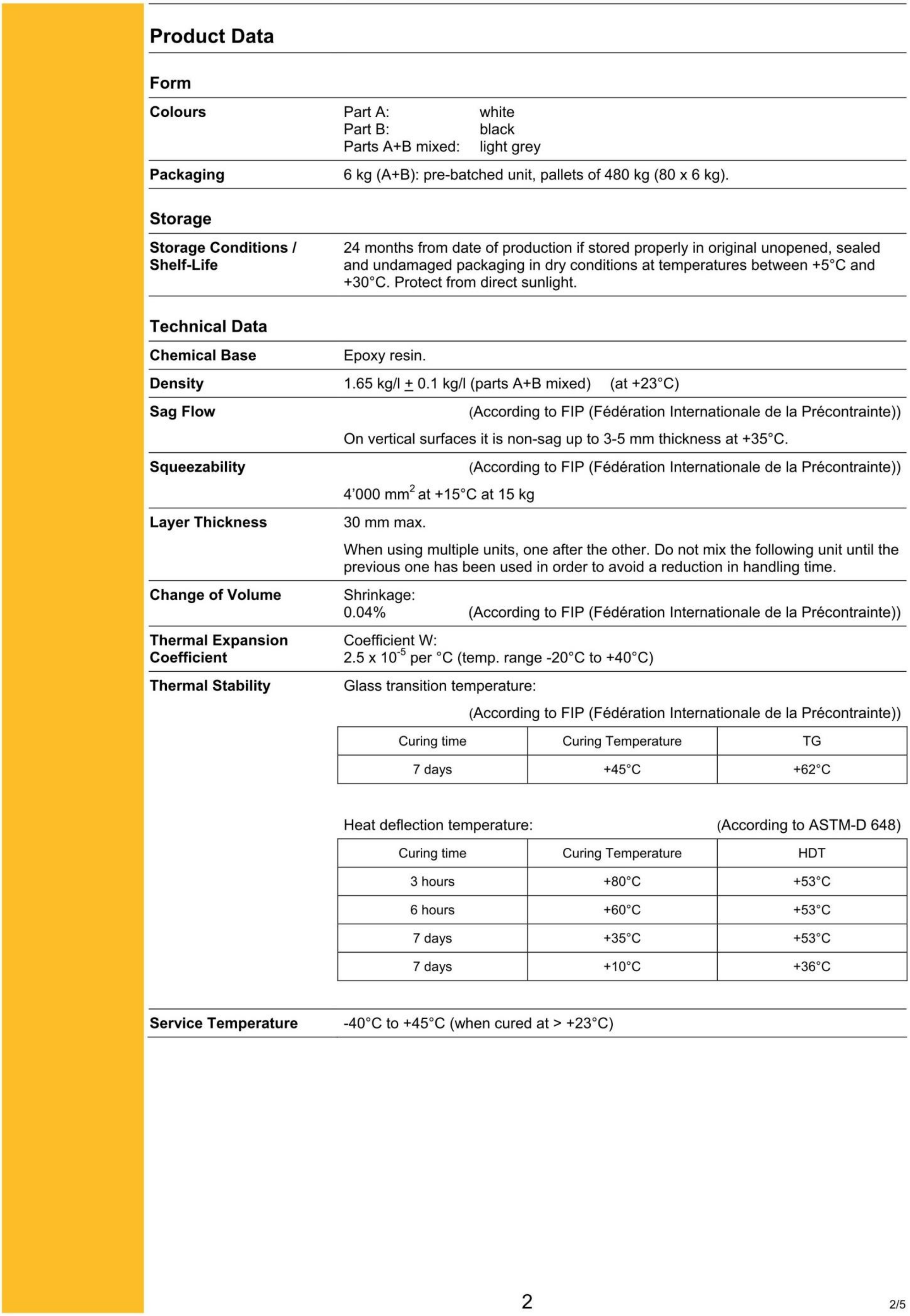
Approval / Standards

Deutsches Institut für Bautechnik Z-36.12-29, 2006: General construction authorisation for Sika® CarboDur®.

IBMB, TU Braunschweig, test report No. 1871/0054, 1994: Approval for Sikadur®-30 Epoxy adhesive.

IBMB, TU Braunschweig, test report No. 1734/6434, 1995: Testing for Sikadur®-41 Epoxy mortar in combination with Sikadur®-30 Epoxy adhesive for bonding of steel plates.

Testing according to EN 1504-4



Product Data

Form

Colours	Part A: white Part B: black Parts A+B mixed: light grey
Packaging	6 kg (A+B): pre-batched unit, pallets of 480 kg (80 x 6 kg).

Storage

Storage Conditions / Shelf-Life	24 months from date of production if stored properly in original unopened, sealed and undamaged packaging in dry conditions at temperatures between +5°C and +30°C. Protect from direct sunlight.

Technical Data

Chemical Base	Epoxy resin.
Density	1.65 kg/l ± 0.1 kg/l (parts A+B mixed) (at +23°C)
Sag Flow	(According to FIP (Fédération Internationale de la Précontrainte)) On vertical surfaces it is non-sag up to 3-5 mm thickness at +35°C.
Squeezability	(According to FIP (Fédération Internationale de la Précontrainte)) 4'000 mm^2 at +15°C at 15 kg
Layer Thickness	30 mm max. When using multiple units, one after the other. Do not mix the following unit until the previous one has been used in order to avoid a reduction in handling time.
Change of Volume	Shrinkage: 0.04% (According to FIP (Fédération Internationale de la Précontrainte))
Thermal Expansion Coefficient	Coefficient W: 2.5 x 10^{-5} per °C (temp. range -20°C to +40°C)
Thermal Stability	Glass transition temperature:

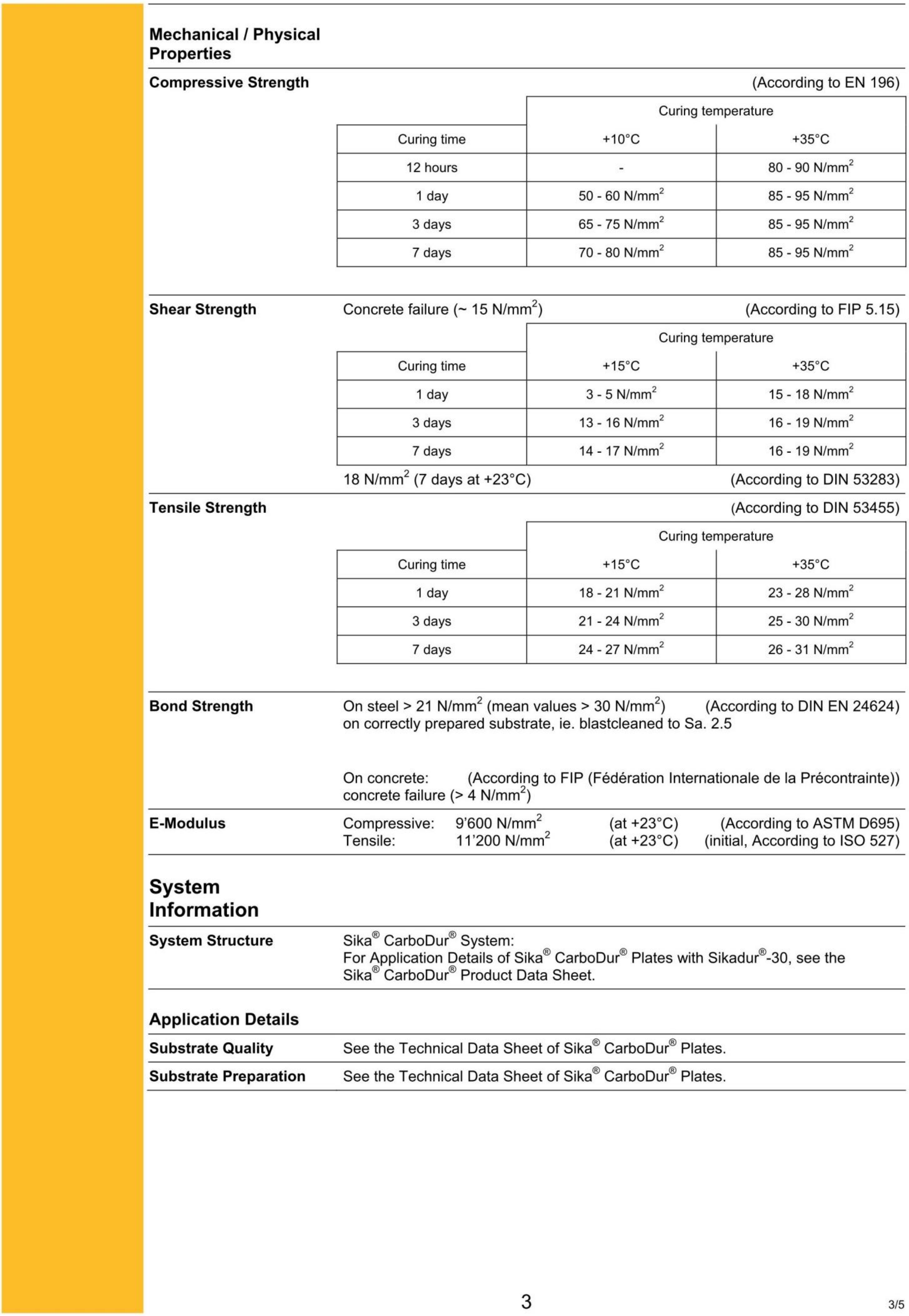
(According to FIP (Fédération Internationale de la Précontrainte))

Curing time	Curing Temperature	TG
7 days	+45°C	+62°C

Heat deflection temperature: (According to ASTM-D 648)

Curing time	Curing Temperature	HDT
3 hours	+80°C	+53°C
6 hours	+60°C	+53°C
7 days	+35°C	+53°C
7 days	+10°C	+36°C

Service Temperature	-40°C to +45°C (when cured at > +23°C)



Mechanical / Physical Properties

Compressive Strength (According to EN 196)

	Curing temperature	
Curing time	+10°C	+35°C
12 hours	-	80 - 90 N/mm^2
1 day	50 - 60 N/mm^2	85 - 95 N/mm^2
3 days	65 - 75 N/mm^2	85 - 95 N/mm^2
7 days	70 - 80 N/mm^2	85 - 95 N/mm^2

Shear Strength Concrete failure (~ 15 N/mm^2) (According to FIP 5.15)

	Curing temperature	
Curing time	+15°C	+35°C
1 day	3 - 5 N/mm^2	15 - 18 N/mm^2
3 days	13 - 16 N/mm^2	16 - 19 N/mm^2
7 days	14 - 17 N/mm^2	16 - 19 N/mm^2

18 N/mm^2 (7 days at +23°C) (According to DIN 53283)

Tensile Strength (According to DIN 53455)

	Curing temperature	
Curing time	+15°C	+35°C
1 day	18 - 21 N/mm^2	23 - 28 N/mm^2
3 days	21 - 24 N/mm^2	25 - 30 N/mm^2
7 days	24 - 27 N/mm^2	26 - 31 N/mm^2

Bond Strength On steel > 21 N/mm^2 (mean values > 30 N/mm^2) (According to DIN EN 24624) on correctly prepared substrate, ie. blastcleaned to Sa. 2.5

On concrete: (According to FIP (Fédération Internationale de la Précontrainte)) concrete failure (> 4 N/mm^2)

E-Modulus				
	Compressive:	9'600 N/mm^2	(at +23°C)	(According to ASTM D695)
	Tensile:	11'200 N/mm^2	(at +23°C)	(initial, According to ISO 527)

System Information

System Structure Sika® CarboDur® System:
For Application Details of Sika® CarboDur® Plates with Sikadur®-30, see the Sika® CarboDur® Product Data Sheet.

Application Details

Substrate Quality See the Technical Data Sheet of Sika® CarboDur® Plates.

Substrate Preparation See the Technical Data Sheet of Sika® CarboDur® Plates.

Application Conditions / Limitations

Substrate Temperature	+8°C min. / +35°C max.
Ambient Temperature	+8°C min. / +35°C max.
Material Temperature	Sikadur®-30 must be applied at temperatures between +8°C and +35°C.
Substrate Moisture Content	Max. 4% pbw When applied to mat damp concrete, brush the adhesive well into the substrate.
Dew Point	Beware of condensation. Substrate temperature during application must be at least 3°C above dew point.

Application Instructions

Mixing Part A : part B = 3 : 1 by weight or volume

Mixing Time

Pre-batched units:
Mix parts A+B together for at least 3 minutes with a mixing spindle attached to a slow speed electric drill (max. 600 rpm) until the material becomes smooth in consistency and a uniform grey colour. Avoid aeration while mixing. Then, pour the whole mix into a clean container and stir again for approx. 1 more minute at low speed to keep air entrapment at a minimum. Mix only that quantity which can be used within its potlife.

It is important to entrain as little air as possible when mixing Sikadur®-30. Air entrainment will result in lower compressive strength development.Do not dilute the product with solvent as this will affect the cure and service performance.

Consumption

Laminate type	Sikadur®-30
S512 / H514	~ 0.31 kg/m
S612 / S614 / M614	~0.38 kg/m
S812	~ 0.50 kg/m
S914 / M914	~ 0.56 kg/m
S1012	~ 0.62 kg/m
S1212 / S1214 / M1214	~ 0.74 kg/m

Application Method / Tools See the Technical Data Sheet of Sika® CarboDur® Plates.

Cleaning of Tools Clean all tools and application equipment with Sika® Colma Cleaner immediately after use. Hardened / cured material can only be mechanically removed.

Potlife (According to FIP (Fédération Internationale de la Précontrainte))

Temperature	+8°C	+20°C	+35°C
Potlife	~ 120 minutes	~ 90 minutes	~ 20 minutes
Open time	~ 150 minutes	~ 110 minutes	~ 50 minutes

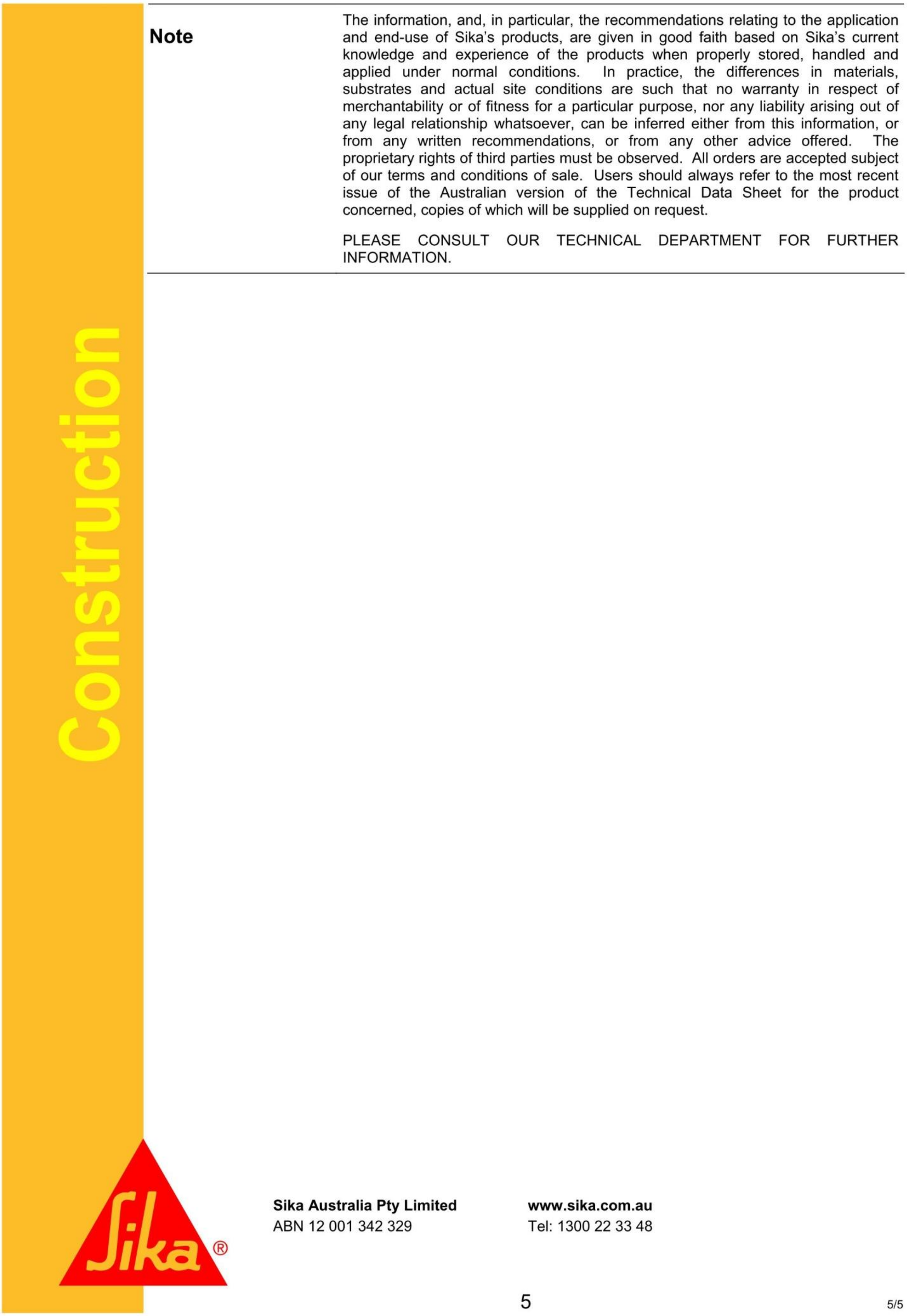
The potlife begins when the resin and hardener are mixed. It is shorter at high temperatures and longer at low temperatures. The greater the quantity mixed, the shorter the potlife. To obtain longer workability at high temperatures chill parts A+B before mixing them (not below +5°C).

Value Base

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.



Note

PLEASE CONSULT OUR TECHNICAL DEPARTMENT FOR FURTHER INFORMATION.

Construction

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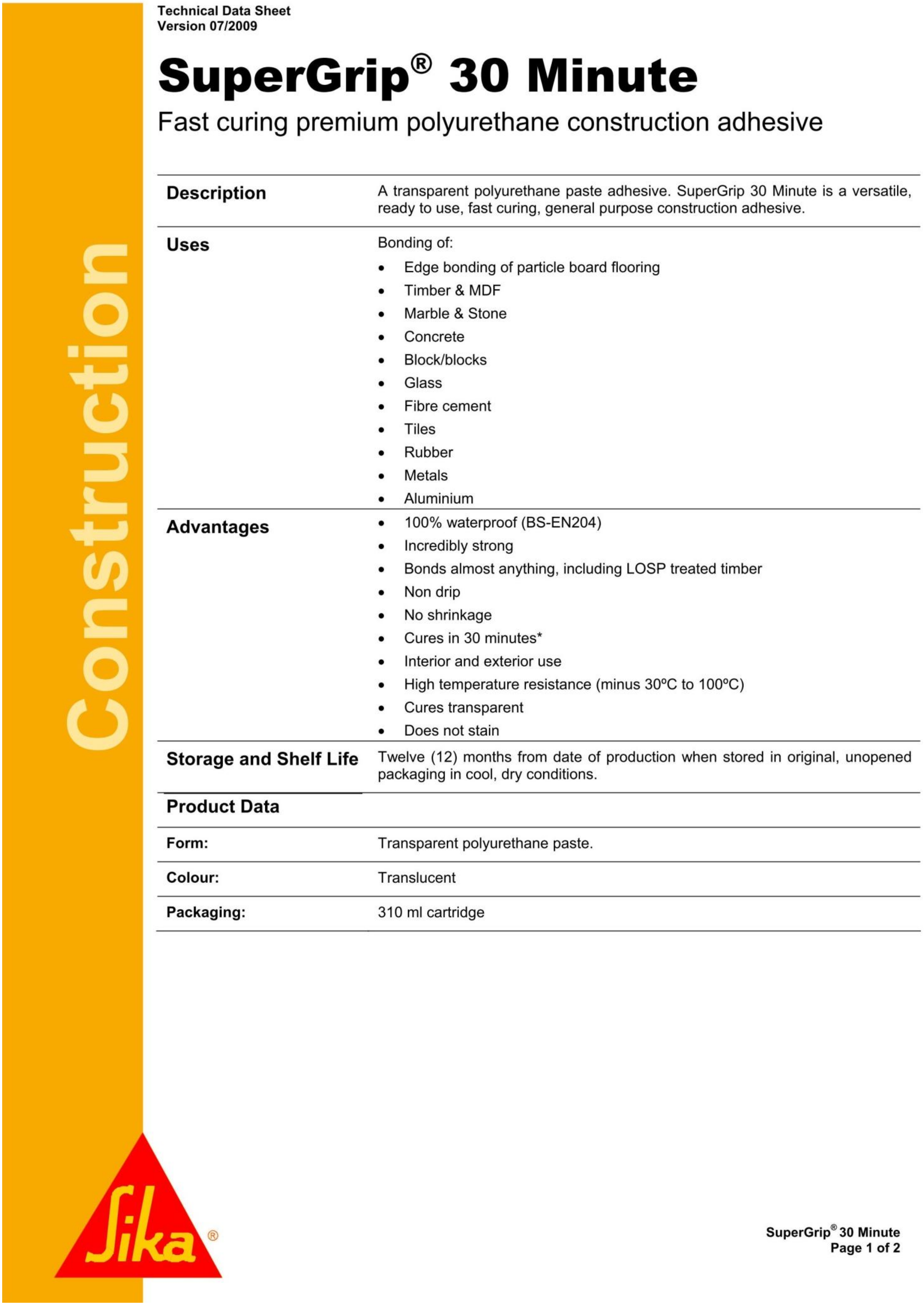


Technical Data Sheet
Version 07/2009

SuperGrip® 30 Minute

Fast curing premium polyurethane construction adhesive

Description

A transparent polyurethane paste adhesive. SuperGrip 30 Minute is a versatile, ready to use, fast curing, general purpose construction adhesive.

Uses

Bonding of:

- Edge bonding of particle board flooring
- Timber & MDF
- Marble & Stone
- Concrete
- Block/blocks
- Glass
- Fibre cement
- Tiles
- Rubber
- Metals
- Aluminium

Advantages

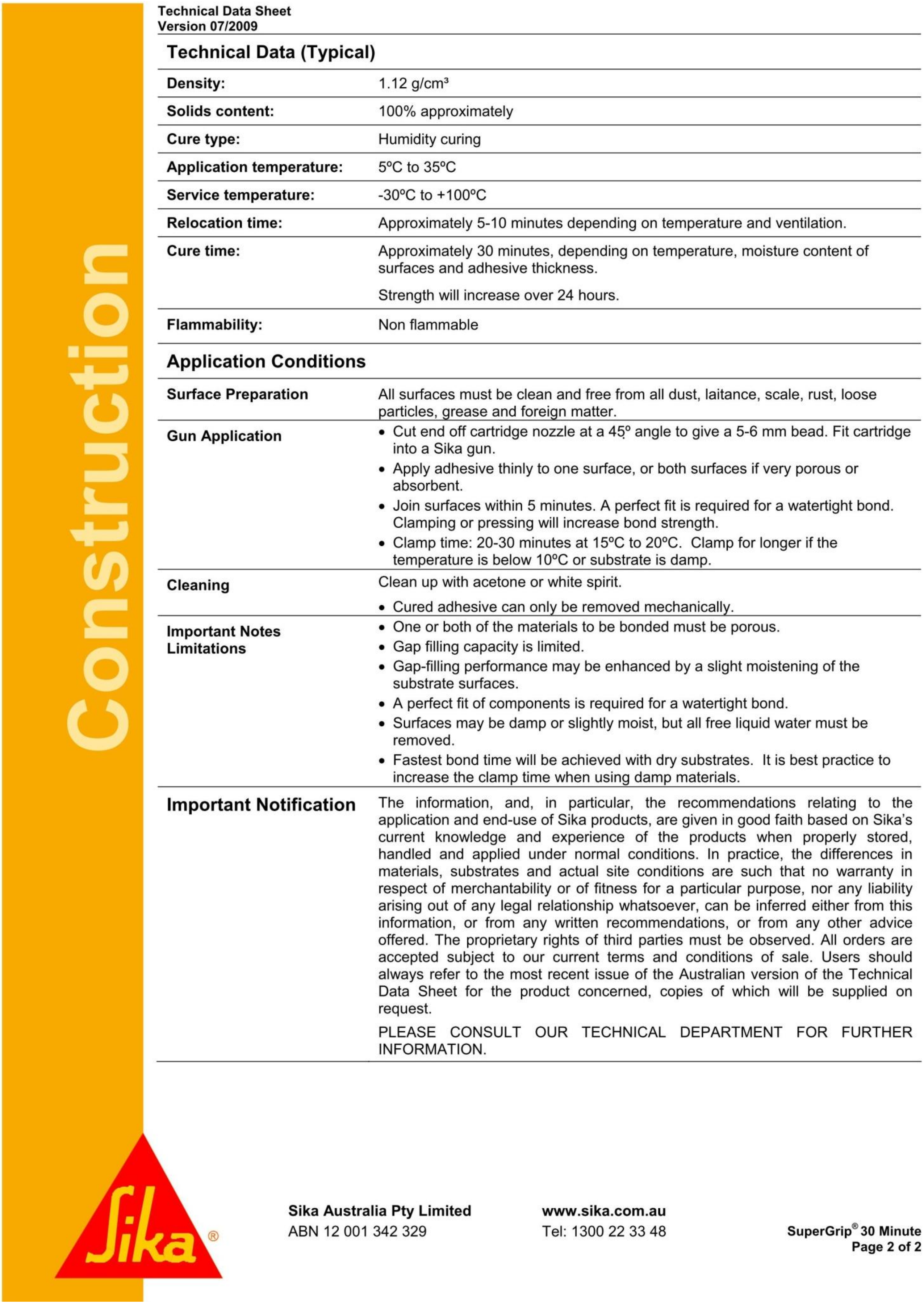
- 100% waterproof (BS-EN204)
- Incredibly strong
- Bonds almost anything, including LOSP treated timber
- Non drip
- No shrinkage
- Cures in 30 minutes*
- Interior and exterior use
- High temperature resistance (minus 30ºC to 100ºC)
- Cures transparent
- Does not stain

Storage and Shelf Life

Twelve (12) months from date of production when stored in original, unopened packaging in cool, dry conditions.

Product Data

Form:	Transparent polyurethane paste.
Colour:	Translucent
Packaging:	310 ml cartridge



Technical Data Sheet
Version 07/2009

Technical Data (Typical)

Density:	1.12 g/cm³
Solids content:	100% approximately
Cure type:	Humidity curing
Application temperature:	5ºC to 35ºC
Service temperature:	-30ºC to +100ºC
Relocation time:	Approximately 5-10 minutes depending on temperature and ventilation.
Cure time:	Approximately 30 minutes, depending on temperature, moisture content of surfaces and adhesive thickness. Strength will increase over 24 hours.
Flammability:	Non flammable

Application Conditions

Surface Preparation	All surfaces must be clean and free from all dust, laitance, scale, rust, loose particles, grease and foreign matter.
Gun Application	• Cut end off cartridge nozzle at a 45º angle to give a 5-6 mm bead. Fit cartridge into a Sika gun. • Apply adhesive thinly to one surface, or both surfaces if very porous or absorbent. • Join surfaces within 5 minutes. A perfect fit is required for a watertight bond. Clamping or pressing will increase bond strength. • Clamp time: 20-30 minutes at 15ºC to 20ºC. Clamp for longer if the temperature is below 10ºC or substrate is damp.
Cleaning	Clean up with acetone or white spirit. • Cured adhesive can only be removed mechanically.
Important Notes Limitations	• One or both of the materials to be bonded must be porous. • Gap filling capacity is limited. • Gap-filling performance may be enhanced by a slight moistening of the substrate surfaces. • A perfect fit of components is required for a watertight bond. • Surfaces may be damp or slightly moist, but all free liquid water must be removed. • Fastest bond time will be achieved with dry substrates. It is best practice to increase the clamp time when using damp materials.

Important Notification

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms and conditions of sale. Users should always refer to the most recent issue of the Australian version of the Technical Data Sheet for the product concerned, copies of which will be supplied on request.

PLEASE CONSULT OUR TECHNICAL DEPARTMENT FOR FURTHER INFORMATION.

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SuperGrip® 30 Minute
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