An investigation of selected mechanical and physical properties of young, unseasoned and finger-jointed *Eucalyptus grandis* timber

by

Philippus Lodewicus Crafford

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Supervisor: Mr. Brand Wessels
Faculty of AgriSciences
Department of Forest and Wood Science

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Summary

South Africa is a timber scarce country that will most probably experience a shortage of structural timber in the near future. In this study the concept of using young finger-jointed *Eucalyptus grandis* timber was evaluated for possible application in roof truss structures while the timber is still in the green, unseasoned state. 220 finger-jointed boards of cross-sectional dimension 48 x 73 mm and 36 x 111 mm timber, cut from 5-18 year old *Eucalyptus grandis* trees were obtained from Limpopo province, South Africa. The boards were manufactured using a polyurethane (PU) adhesive at moisture content levels above fibre saturation point and no drying was performed. The objectives of this study were to determine various mechanical and physical properties of this finger-jointed product. More specifically (1) to determine the strength and stiffness potential of the product in the wet and the dry condition, (2) to evaluate physical properties such as density, warp, checking and splitting, (3) to evaluate potential indicator properties to be used as structural grading parameters, and (4) to compare the flexural properties to the current SA pine resource and SANS structural grade requirements.

The boards were divided into two groups of the same size, which constituted the wet and the dry samples. Each sample was further separated into six different groups for testing the different strength and stiffness properties. The dry group was stacked in a green-house for nine weeks until equilibrium moisture content was reached. Afterwards selected physical properties such as warp, checking and splitting were assessed. Destructive testing was conducted on the boards and the results were used to determine various mechanical properties. Finally, each board was assessed for density and moisture content (MC) values.

The study showed that the young finger-jointed *Eucalyptus grandis* timber had very good flexural properties. Both mean modulus of elasticity (MOE) and modulus of rupture (MOR) 5th percentile strength values for wet and dry boards complied with the current SANS 10163-1 (2003) requirements for grade S7.The values of tensile perpendicular to grain and compression perpendicular to grain strength did not conform to SANS requirements for grade S5. The other strength properties for the wet and dry groups complied with one of the three SANS structural grades. The 5 year old (48 x 73 mm) boards' showed significantly higher levels of twist and checking compared to 11 year old boards of the same dimension. Only 46.3% of the finger-jointed products conformed to the density requirements in SANS 1783-2 (2004) for grade S7. There was a significant difference in density between the three age groups

(5, 11 and 18 years) presented in this study. The variation in both MOE and MOR values of the finger-jointed product proved to be significantly lower in comparison to currently used SA pine sources.

Based on the results from this study the concept of producing roof trusses from wet, unseasoned and finger-jointed young *Eucalyptus grandis* timber has potential. However, additional research on a number of issues not covered in this study is still required for this product including full scale truss evaluations, proof grading, PU adhesive evaluation at elevated temperatures, nail plate load capacity, and the possible need for chemical treatment of the product against *Lyctus* beetles.

Opsomming

Suid Afrika is ‘n land wat waarskynlik ‘n tekort aan strukturele hout sal ervaar in die nabye toekoms. In hierdie studie word die gebruik van jong gevingerlasde *Eucalyptus grandis* hout vir die moontlike gebruik in dakstrukture, terwyl nat en ongedroog, ondersoek. 220 gevingerlasde planke van deursnit 48 x 73 mm en 36 x 111 mm gesaag van 5-18 jaar-oue *Eucalyptus grandis* bome en afkomstig van die Limpopo provinsie in Suid Afrika, is gebruik. Die produk is vervaardig met poli-uretaan (PU) lym uit planke met vog inhouds vlakke bo veselversadigingspunt. Die doelwit van hierdie studie was om verskeie meganiese en fisiese eienskappe van die vingerlas produk vas te stel. Meer spesifiek (1) om die sterkte en modulus van elastisiteit (MOE) potensiaal van die vingerlas produk in die nat en droë toestand te analiseer, (2) om die fisiese eienskappe soos digtheid, vervorming, oppervlakbarse en spleting te ondersoek, (3) om potensiële graderingsparameters te evalueer, en (4) om die buigeienskappe van die produk te vergelyk met SA dennehout asook die SANS strukturele graad vereistes.

Die planke is verdeel in twee groepe, ‘n nat groep en ‘n droë groep. Elke groep is verder verdeel in ses kleiner groepe soos buig, trek en drukmonsters. Die droë groep was in ‘n kweekhuis geplaas vir nege weke totdat veselversadigingspunt bereik is. Daarna is geselekteerde fisiese eienskappe soos vervorming, oppervlak barse en spleting gemeet. Destruktiewe toetsing is uitgevoer op die planke en die resultate was gebruik om verskeie meganiese eienskappe vas te stel. Laastens is elke plank se digtheid en voggehalte gemeet.

Die studie het getoon dat die jong gevingerlasde *Eucalyptus grandis* hout goeie buigeienskappe het. Beide die gemiddelde MOE en buig sterkte 5de persentiel waardes van die nat en droë groep het voldoen aan die huidige SANS 10163-1 (2003) vereistes vir graad S7. Die sterkte-eienskappe van loodregte trekkrag en loodregte druk het nie die vereistes vir SANS graad S5 gemaak nie. Die ander sterkte-eienskappe van die nat en droë groep het voldoen aan een van die drie SANS strukturele graadvereistes. Die 5 jaar-oue (48 x 73 mm) planke het beduidend hoër vlakke van draai-trek en oppervlakbarste getoon as die 11 jaar-oue planke van dieselfe dimensie. Slegs 46.3% van die vingerlas produk het voldoen aan digtheidsvereistes vir SANS graad S7. Daar was ‘n beduidende verskil in dighteid tussen die drie ouderdomsgroepe (5, 11 en 18 jaar). Die MOE en buigsterkte-waardes van die Biligom produk het beduidend laer variasie as huidige SA denne houtbronne getoon.

Die resultate verkry in die studie toon dat die konsep om dakkappe te vervaardig van nat, gevingerlasde jong *Eucalyptus grandis* hout die potensiaal het om suksesvol toegepas te word. Bykomende navorsing oor ‘n aantal faktore wat nie in hierdie studie ingesluit is nie word steeds benodig. Dit sluit in ‘n volskaalse dakkap evaluasie, proefgradering, PU lym evaluasie by hoë temperature, spykerplaat ladingskapasiteit en die moontlike noodsaaklikheid van chemiese behandeling van die produk teen *Lyctus* kewers, insluit.

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$\text{Compression}_{//}$	Compression parallel to grain (MPa)
$\text{Compression}_{\perp}$	Compression perpendicular to grain (MPa)
EMC	Equilibrium moisture content (%). Moisture content at ambient conditions
FJ	Finger-jointed timber. Single layer solid timber laminates jointed by an adhesive in axial direction
FSP	Fibre saturation point. The point where wood has a moisture content of approximately 30% (free and bound water)
MC	Moisture content (%) of timber
MOE	Modulus of elasticity or stiffness of timber (MPa) determined by edgewise bending
MOE_{dyn}	Modulus of elasticity determined by frequency measurement technology
MOE_{flat}	Modulus of elasticity determined by bending timber piece on flat
MOR	Modulus of rupture or bending strength (MPa) determined by edgewise bending in this study
MPa	Mega Pascal (units for strength classification)
n	Number of pieces tested or sample size
PU	Polyurethane bonding adhesive
R	A correlation coefficient (%) between selected properties and their predictors. It indicates how well the variation of the selected property can be explained by the variation in the indicator property
R^2	The square of (R). Also known as the coefficient of determination
SANS	South African National Standards

S5	Structural grade five certification as in accordance with SANS 10163-1, 2003
$\text{Tension}_{//}$	Tension parallel to grain (MPa)
$\text{Tension}_{\perp}$	Tension perpendicular to grain (MPa)

1 Introduction

According to Crickmay and Associates (2012) US sawn timber, of a similar grade to SA pine grade S5, is sold at prices 65% lower than our sawn timber. In the same way sawn timber in European countries is also available at substantially lower prices. This is potentially a great concern for the SA sawn timber market, with the possible international competition in trading that might occur. A study done by Crickmay and Associates (2004) on demand and supply of softwood sawlogs and sawn timber in SA, indicates that sawn timber shortages were at that stage 27% and would go up to 53% by the year 2033. However, those figures were based on a sawlog rotation age of 28 years and without adjustments for increasing sawmill recoveries and the economic recession. The rotation age of 28 years was used in the predictions as it was proved to be the optimal economical age for the majority of softwood log producers during 2003 and 2004.

According to Chamberlain et al. (2005) timber imports are currently limited to particular wood types not available in South Africa. The current market conditions and transport cost make sawmilling expansion based on imported sawlogs unlikely and it will be more efficient to import sawn timber. The expected shortage and associated increase in domestic sawn timber prices may result in imports becoming feasible. At that stage only 4% of our structural timber supply was imported. Due to the scarcity of the raw material the logs are quite costly, as only 1% of South Africa’s land area is covered with forestry plantations (Godsmark, 2010). Shortages in structural timber cannot be easily solved by reducing the rotation ages of pine plantations or the use of short rotation crops earmarked for pulp or board production. In a recent study it was found that young *Pinus patula* timber proved to have very low stiffness and did not comply with the current SANS 10163-1 (2003) requirements for mean modulus of elasticity (MOE) in any of the visual or mechanical grades (Dowse, 2010).

Eucalyptus timber, especially *E. grandis*, might be a promising raw material for structural timber products. The mean annual increment of SA *E. grandis* in cubic meters per hectare, is 24.6, whereas SA pine shows a mean annual increment of 14.6 cubic meters per hectare (Crickmay and Associates, 2005). At present large volumes of *E. grandis* wood chips are being exported. According to Chamberlain et al. (2005) SA exported approximately 3 million bone dry tons of hardwood chips in 2003, which consisted of

70% eucalyptus - two million tons of *E. grandis* chips could potentially equal approximately 1 million tons of value added structural timber products.

Some of the possible reasons why *E. grandis* has not been used to a significant extent for structural timber production is the inherent tendency of mature trees to check or split upon felling, sawing and drying, as well as the occurrence of brittle heart. Logs are inclined to split after felling due to the presence of high levels of growth stresses in the tree (Wand, 1990). Brittle heart occurs when layers of new cells are added to the stem that are laid down in a state of tension, this cumulative effect may result in crushing or compressive failure occurring in the central part of the stem, due to the inherent counterbalancing compressive forces not being able to withstand the tension force (Malan, 1995). However, Walker (2010) reported that young trees are less likely to have brittle heart; perhaps because in young trees there has been less time for compressive creep, and so the wood is able to store more recoverable strain energy. Young *E. grandis* trees are also less likely to split when felled or during sawing due to the lower level of growth stresses present.

All these factors indicate that the SA structural timber market might be ready for the use of young *E. grandis* for structural timber given that the technical problems described above can be overcome. New and innovative products and processes might be the key for using this resource as structural component. Alternative grading systems have the potential to maximize yield and optimize grade conforming products for individual sawmills. New, engineered structural timber products, as opposed to solid timber, might also be a solution to the industry’s potential short comings in terms of grade conforming products. Engineered products such as finger-jointed timber can be manufactured from relatively young material (trees between 7-15years) and therefore increase the sustainability of the product. About 20 years ago research showed that wet gluing is possible with adhesives like phenol resorcinol-formaldehyde (Bin et al., 2005). Wet timber is defined here as timber which has a moisture content of above fibre saturation point (FSP). More recently single component polyurethane (PU) adhesives began to be used commercially for wet gluing. These PU adhesives enable manufacturers to finger-joint wet timber and utilize the product in construction in the wet state. Less expensive and shorter small diameter logs can be used to manufacture this product in any length. By using such technology the manufacturer saves a great deal of money as no kiln drying and less handling are necessary.

The Biligom concept

Diggersrest Farm has recently started production of young *E. grandis* timber that is finger-jointed while the wood is still at moisture content levels of above FSP (≈30%). This process and product has been patented and registered under a tradename, Biligom. The *E. grandis* trees used for this product are felled and then left to dry in the field for roughly six weeks. These partially dried stems are cut to short logs, which are sawn into dimension timber and finger-jointed into marketable lengths while the timber is above FSP using a polyurethane adhesive. The finger-joints are machined parallel to the width direction of the boards – unlike most other softwood sawmill finger-jointing processes in South Africa. After planing the product is sold ungraded in the green state into the informal market in Limpopo.

According to Mr. Spencer Drake (2011), proprietor of Diggersrest Farm and Biligom, they have been selling substantial volumes of this product in the past year and the market for the product seems to be growing rapidly (personal communication between Mr. Brand Wessels and Mr. Spencer Drake).

Diggersrest Farm would like to develop the Biligom product so that it can be used in the formal market as a structural product. The plan is that the green finger-jointed boards are proof-graded in tension parallel to grain. In doing this, each finger-joint will be evaluated and a high degree of confidence is obtained in the quality. These green boards will then air-dry within the fixed truss structure inside the roof of a building.

This study involves an investigation into the material properties of young, green finger-jointed *E. grandis* for the use in roof truss structures. The objectives of this study were as follow:

- to determine the characteristic strength and stiffness values of both unseasoned finger-jointed *Eucalyptus* boards as well as boards that have been dried to equilibrium moisture content;
- to investigate the variation in density, warp and checking in air dried finger-jointed *Eucalyptus* timber;
- to evaluate the potential of this finger-jointed product as a component in roof truss structures.

The young *E. grandis* product was developed to be used in the green state and drying will occur while the members are fixed in a truss structure. This study only dealt with individual product members. Thus the use of young finger-jointed *E. grandis* timber in roof truss structures, while still above FSP, should in future be investigated within a truss construction. It is important to note that this study did not include the following aspects of the concept that might also need investigation:

- the PU adhesive curing and bonding variability;
- application and strength of nail-plate connections onto the young *E. grandis* timber;
- the effect of shrinkage on a truss structure after drying;
- the effect of deformation and splitting on a truss structure after drying;
- the possible need for treatment of the sapwood against *Lyctus* beetles.

This thesis includes a literature review on relevant topics. The materials and methods used in the study are then presented followed by the results and discussion, conclusions and recommendations.

2 Literature Review

2.1 South African sawn timber situation

The trees required for sawn timber are grown on sawlog plantations, with the main genera grown in South Africa being Pine (96%) and Eucalyptus (3.7%), (Chamberlain et al., 2005). However, of the total plantation area, which includes pulp and paper logs, 40.4 % of the plantations consist of *Eucalyptus* trees (Godsmark, 2010). See Figure 1. This indicates that (currently) the majority of hardwood from plantations in SA is used in the pulp and paper industry. However hardwoods, especially *Eucalyptus*, are used in the South African timber market as mining supports (props) and in the pole industry; the combined intake of pole and mining timber companies was approximately 1 million cubic meters during 2001 (Crickmay and Associates, 2005).

According to Crickmay and Associates (2012) nearly 70% of South Africa's sawn pine timber is classified as structural timber. Structural timber is typically used in load bearing structures such as roof trusses, beams, floor supports and other commercial and residential building applications. In South Africa a substantial portion of structural timber is used in roof structures and the roof truss industry is arguably the single most important market for our sawmilling industry today.

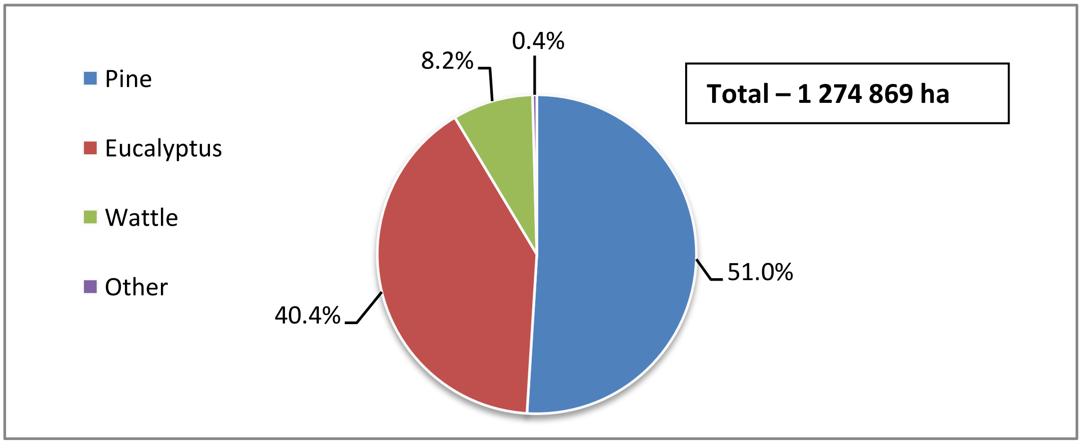

Figure 1: Plantation area (2009) by species in South Africa (Godsmark, 2010).

In the past Burdzik (2004) raised the question that the mechanical properties of SA pine are changing. The concern was that structural timber conforming to the SANS visual grade requirements might have inferior strength and stiffness properties compared to the actual requirements for the specific stress grades. Burdzik (2004) tested structural timber from four "low density" regions in South Africa and found that only one sawmill's timber made the grade for tensile and bending strength requirements. In a more recent study it was found that young *P. patula* timber proved to have very low stiffness and did not comply with the current SANS 10163-1 (2003) requirements for mean modulus of elasticity in any of the visual or mechanical grades (Dowse, 2010).

Also a fairly extensive study performed on the flexural properties and structural grading of a selected South African pine resource, showed that all six of the participating sawmills' timber conformed to SANS grade requirements for MOR, but three of the sawmills came short in terms of average MOE requirements using visual grading (Crafford and Wessels, 2011).

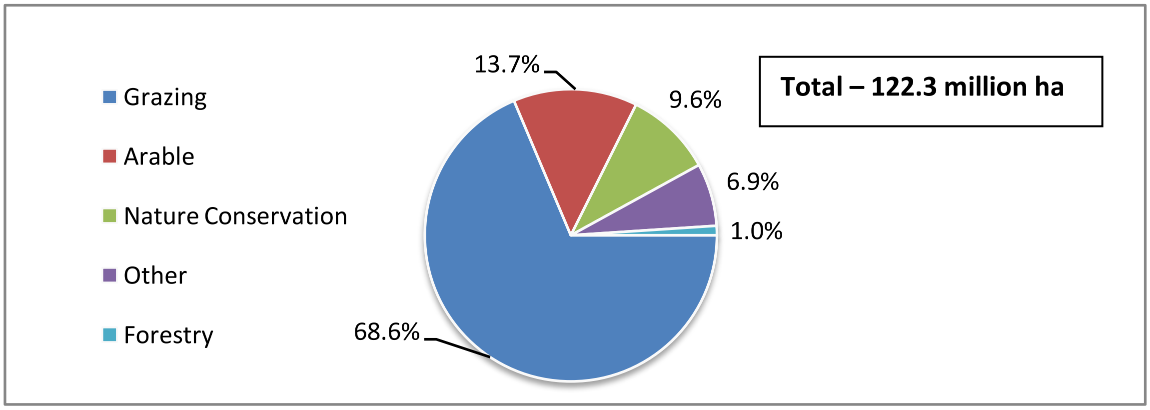

Figure 2: Land use in South Africa (Godsmark, 2010).

Other very big challenges facing the sawmilling industry at the moment are, first, the scarcity of pine sawlog resources, only 1% of South Africa's land area is covered with forestry plantations (Godsmark, 2010). Secondly, the rising cost of producing sawn timber - which is also in part a result of the sawlog scarcity and subsequent log price increase, but also perhaps the outdated sawmill manufacturing equipment and methods. The price of structural Southern Yellow Pine from the USA is currently about 65% lower than Grade S5 SA pine and even in Europe sawn pine prices are substantially lower than in South Africa (Crickmay, 2012).

According to Chamberlain et al. (2005) timber imports at present are limited to particular wood types not available in South Africa. The current market conditions and transport cost (and the inefficiencies of transporting sawlogs) make sawmilling expansion based on imported sawlogs unlikely, and it will be more efficient to import sawn timber. The expected shortage and associated increase in domestic sawn timber prices may result in imports becoming feasible.

Also, during the 'building boom' in 2006 the demand for structural timber started to outstrip supply in South Africa and since then noticeable volumes (at present 4 %) of structural timber have been imported from countries such as New Zealand and Argentina at competitive prices (Crickmay, 2012). The danger therefore exists for our local producers that ever more international timber producers might exploit South Africa as a potential market.

2.2 In-grade testing philosophy

In-grade testing is usually done in one of two cases, either for grade verification or for grade determination. Hence, when there are changes to the nature of a timber resource or when a new resource or product is evaluated, in-grade testing is performed. Before the design values of a grade can be determined by using in-grade testing, timber must first be tested non-destructively by the selected grading procedure. Silvicultural factors, including forest management changes, harvesting cycle time changes and introduction of new timber species, as well as climate changes affecting seasonal growth and growth rate of trees, can change the quality of a timber resource (McKeever, 1997). The reduction in rotation age of sawlog trees will result in logs with a relatively high proportion of juvenile wood. It is a well-established fact that the properties of juvenile wood can differ quite dramatically from that of mature wood (Zobel and Sprague, 1998).

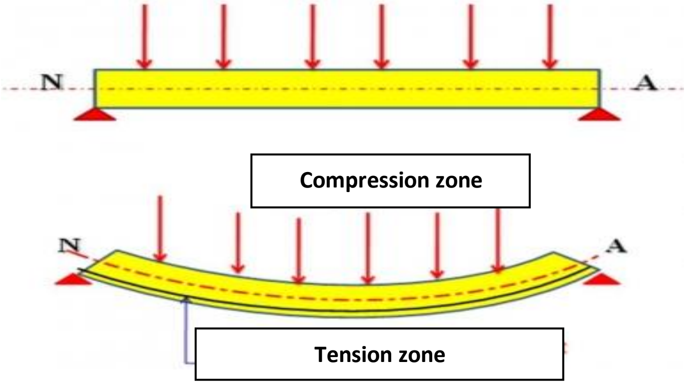

Figure 3: Tension and compression zone in a bending member.

In-grade test results should, as closely as possible, reflect the structural end use conditions to which the timber products would be subjected, (Madsen, 1992). For example if it is general practice in construction to place the worst defect in the tension zone, then the testing should specify the same rule; if not, random orientation would be appropriate (Figure 3). To form accurate conclusions, in grade testing must emulate end use conditions of the timber as closely as possible. Bailleres et al. (2009) found that random placement in bending tests can produce better R^2 values for the correlations between density, MOR and MOE than in the case of biased testing. See Table 1.

Table 1: Degrees of determination (R^2) between density, MOE and MOR for different pine species with different bending test setups (Bailleres et al., 2009). Values (MPa), properties listed are relations.

Test position	Resource		Dry density	MOE
Biased	Radiata E	MOE (MPa)	0.46	0.64
		MOR (MPa)	0.37	
	Radiata R	MOE (MPa)	0.27	0.55
		MOR (MPa)	0.12	
	Caribbean	MOE (MPa)	0.10	0.49
		MOR (MPa)	0.04	
Random	Radiata E	MOE (MPa)	0.50	0.66
		MOR (MPa)	0.35	
	Radiata R	MOE (MPa)	0.42	0.56
		MOR (MPa)	0.17	
	Caribbean	MOE (MPa)	0.10	0.61
		MOR (MPa)	0.06	

Table 2: **Test results for biased and random samples, values in MPa (Crafford, 2011)**

Test Position	Standards	MOR 5th per	MOR mean	MOE mean	Sample
Biased	SANS	16.3	37.4	8633	569
	BS	15.1			
Random	SANS	15.2	40.2	8761	566
	BS	16.4			

The ISO 13910 (2005) method requires the worst defect to be placed randomly, whereas the SANS 6122 (2008) method requires the worst defect to be placed (biased) in the centre third of a bending test (Dowse, 2010). In Table 2 the slight difference in mean MOR and MOE values is observable (Crafford, 2011). Two different methods for calculating the 5th percentile value were investigated; the conventional SANS 6122 (1994) method and the British Standard (BS EN 14358, 2006) method. However, no statistical significant difference regarding the 5th percentile characteristic bending strength and mean MOE values were obtained at the 0.05 level.

When investigating solid timber properties large sample sizes are required, due to the large coefficient of variation in terms of strength and stiffness. For example, to determine the 5th percentile strength value for a specific timber resource and dimension, 200 samples would be sufficient to give a statistically sound answer (Madsen, 1992). However, when evaluating a more uniform product, like glulam and other composite structural materials a smaller sample size is sufficient. The 5th percentile values are also referred to as the characteristic values. The stiffness and strength of timber can be described by seven different properties. Table 3 displays these properties and requirements for the different structural grades of South African pine. No separate SANS code of structural grades for hardwood (Eucalyptus) timber does exist. Also the general grade conforming requirements of glulam, for both hardwood and softwood, are specified in the SANS 1460 (2006) standards as one and the same.

Table 3: Characteristic stresses for SA pine according to grade (SANS 10163-1, 2003), Values in MPa. *Values from draft version of SANS 10163-1

1	2	3	4	5	6	7	8	9
Grade	Bending	Tension parallel to grain	Tension perpendicular to grain	Compression parallel to grain	Compression perpendicular to grain	Shear parallel to grain	Modulus of elasticity	Modulus of elasticity (Mean)
S5	11.5	6.7	0.36	18	4.7	1.6	4630*	7800
S7	15.8	10	0.51	22.8	6.7	2	5700*	9600
S10	23.3	13.3	0.73	26.2	9.1	2.9	7130*	12000

2.3 Finger-jointed timber

Finger-jointed timber is a well known product and is used across the globe. Much research has been done throughout the years on finger-jointed timber in terms of adhesives, finger-jointed profiles and glulam or laminated beams. In many cases the research was performed on commercially used species at equilibrium moisture content (EMC) and not green timber. More than 20 years ago research showed wet or green gluing is possible with adhesives like phenol resorcinol-formaldehyde, a separate application, fast-set adhesive (Bin et al., 2005). Wet or green timber is defined here as timber which has a moisture content equal to or in excess of FSP.

Research performed by Pizzi (1989) over 20 years ago, showed that separate application fast-set adhesives for exterior use, such as structural glulam and finger-jointed timber for green timber application, were possible. Even more recently single component polyurethane (PU) adhesives began to be used commercially for green gluing. According to Bin et al. (2005) the quality of the PU adhesives is of such high standards that the now unified Western European standards for structural timber have recently been revised and changed to allow any percentage wood failure in bonded timber. Although PU has excellent joint strength properties, it often shows wood failure of a lower percentage compared to other, older requirements (Bin et al., 2005). The SANS 10096 (2004) standard for structural finger-jointed timber also states similar bond failure (Table 4) requirements where at least a specified percentage of the joint-area should consist of wood fracture at a certain minimum tensile strength level.

Table 4: The allowable wood failure (%) in accordance with minimum tensile bonding strength limits of finger-jointed specimens of 250 x 25 x 10 mm (SANS 10096, 2004).

Wood failure %	Failing load, min (MPa)
10 to 29	22.4
30 to 49	20.0
50 to 69	16.8
70 to 89	13.6
90 to 100	11.2

According to SANS 10096 (2004), if the structural finger-jointed timber on average, shows certain minimum tensile strength properties, then wood failure, according to the percentages given in Table 4 is acceptable. The minimum wood failure (%) requirements clause in the SANS 10096 is not relevant to newly developed PU adhesive systems, or for that matter any adhesive system, which tend to show low wood failure levels. Instead the focus of the test must be the bonding breaking strength and not the wood failure area (%). However, recently, the SANS 10183 (2009) adhesives for wood standards were introduced. The SANS 10183 – 2 (2009) includes the EN 15425 (2008) standards for one component PU for load bearing timber structures, which allows any percentage of wood failure in bonded timber.

The main problem of PU adhesives may be their low rigidity. These adhesives might show ambient creep and temperature dependent creep, depending on the specific formulation. According to Radovic et al. (2003), of the few commercial PU adhesives approved and used in Europe for green timber application, some present no creep, some present medium level creep and some present a potentially disastrous level of creep. A recent study done by Bin et al. (2005) on three commercial PU adhesives proved that all three adhesives showed evidence of temperature-creep, see Figure 4.

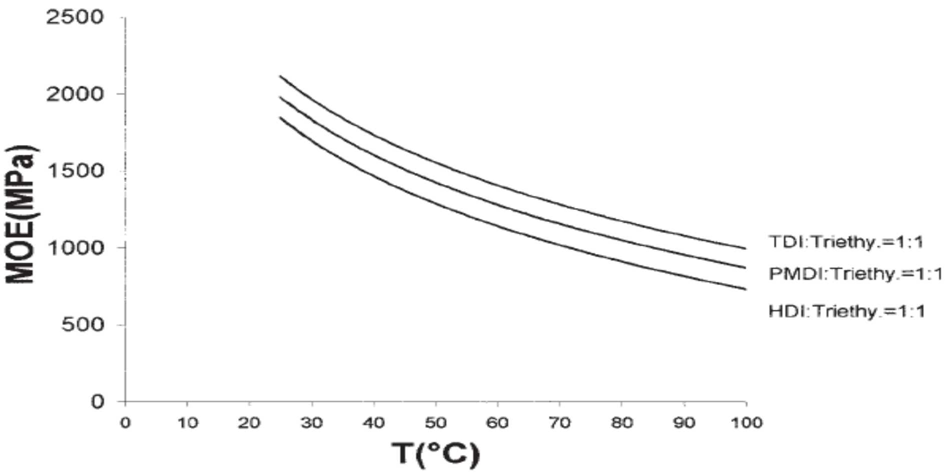

Figure 4: **Variation of MOE as a function of temperature in isothermal thermomechanical analysis in bending of cured beechwood joints bonded with polyurethanes obtained from triethylenetetramine (TET) reacted with TDI, pMDI, and HDI isocyanates (Bin et al., 2005).**

The occurrence of temperature dependent creep in certain adhesives used for structural applications (depending on the application and product) might be a potentially hazardous property. In South Africa the majority of structural timber is used in roof structures, where temperatures might reach as high as 70˚C (Bin et al., 2005).

However in the case of finger-jointed timber joint strength properties at higher temperatures might be more important compared to the intrinsic creep properties of certain adhesives. Even if lower MOE is to be expected at higher temperature and ambient conditions, the adhesive’s joint strength is essential for the structural integrity of finger-jointed timber. Glulam and other structural timber-composite products, however, might require adhesives with better creep characteristics. Figure 5 explains why glulam and finger-jointed timber requires (according to the author's theory) structural adhesives comprising different key intrinsic properties.

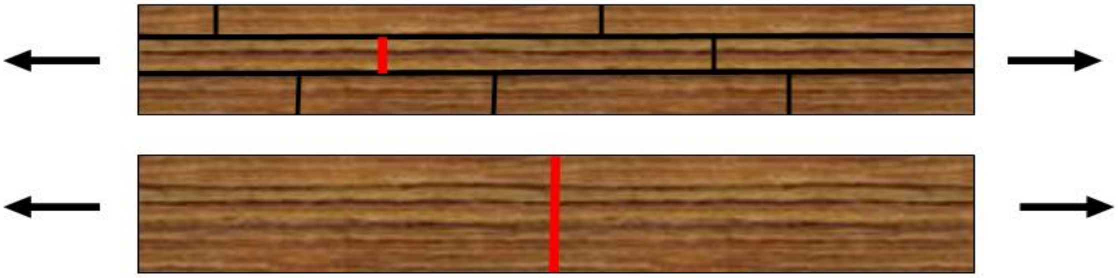

***Figure 5**: **Weak joint strength (thick line) occurrence in glulam (top) and finger-jointed boards (bottom) under load. Finger-jointed boards require adhesives with very good joint strength, whereas glulam consisting of multiple smaller wood pieces require adhesives with a lower creep tendency for optimal performance in service.**

*Note; this illustration was based on the authors theory alone.

Quality control and quality management procedures are very important in the manufacturing of this product. According to the SANS 9001 (2008) code the general quality management process; a) *needs to demonstrate its ability to consistently provide product that meets customer and applicable statutory and regulatory requirements, and b) aims to enhance customer satisfaction through the effective application of the system, including processes for continual improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements.*

Quality control and, more important, continual quality guarantee, might be quite challenging and complex in the finger-jointing manufacturing process. However, by including proof-grading in the grading process as opposed to alternative grading methods, quality guarantee might be fairly simple and effective, as described in the next section.

2.4 Structural grading of sawn timber

Structural grading of sawn timber can be classified into two main categories; based on either the mechanical properties or structural grading based on timber evaluated (indicator) properties related to the mechanical properties. The first method is also known as proof-grading and the second can be further classified as machine, or visual, grading.

2.4.1 Indicator properties of *Eucalyptus grandis*

Research done by Zitto et al. (2009) on the relationship between timber quality and the influence of moisture content above FSP and the presence of pith material on mechanical properties, in beams of fast-growing Argentinean *E. grandis* gave quite interesting results. Table 5 shows the results of 96 pairs of visually graded *E.* grandis boards which were graded into two classes, boards containing pith material and boards without pith material. The paired sample was also further divided into seasoned and unseasoned boards.

Table 5: **Results of MOR and MOE corresponding to two visual grades and of seasoned and unseasoned *E. grandis* boards of dimension 1900 x 100 x 50 mm, age 14 years (Zitto et al. 2009).**

Visual grade	**Moisture condition**	**N**		**Mean (MPa)**	**Sdev (MPa)**
Without pith	Seasoned	52	MOR	55.9	14
			MOE	12900	2400
	Unseasoned	52	MOR	41.9	8.4
			MOE	9800	1500
With pith	Seasoned	44	MOR	46.6	13.1
			MOE	11400	1300
	Unseasoned	44	MOR	40.5	7.5
			MOE	9100	1400

According to Piter et al. (2004), the presence of pith is often associated with other defects, such as fissures, which significantly reduce the strength and the stiffness of this sawn timber. In the Argentinean standard IRAM 9662-2 (2006) the pith feature is also considered the most important visual property for strength grading the *E. grandis* material. Knot occurrence and ratio is considered the second parameter for visual grading, although a relatively poor correlation between this visual feature and mechanical properties was found (Piter et al., 2004). Research done by Perez del Castillo (2001) also reported better strength and stiffness values for boards of Uruguayan *E. grandis* distant from the pith, than for others next to it. This compares well to the findings of Wand (1990) which documented that density of *E. grandis* increases rapidly from pith to bark.

Also, in Table 5 the differences between seasoned and unseasoned timber specimens are quite noticeable. Thus there was a significant difference in MOR and MOE values between the seasoned and unseasoned paired samples. Using wet timber as a structural product is not included in the SANS code. However, in other countries such as New Zealand and many European countries building with wet timber is a fairly common practice. In New Zealand the current grading standards include a green grade G8 (Amendment 4 NZS3603:1993) which may have moisture content above 25%. This green grade G8 has the same structural properties after drying as the New Zealand mechanical grade MSG 8 and visual grade VSG 8. The green properties of this grade are also included so that the engineer can use either or both green and dry characteristic stresses as required.

It is also interesting to note that in South Africa the moisture content of softwood timber is not allowed to be above 17% (SANS 1783-1, 2004). However, it is common practice to treat SA pine timber with waterborne preservatives such as CCA which cause an increase in the moisture content of the timber to well above FSP. This timber is usually not dried again and is installed in the wet state in roof truss structures. In terms of the effect on mechanical properties of timber, this practice will be similar to the young, finger-jointed *E. grandis* concept of building with a green product.

2.4.2 The effect of moisture on selected strength properties

Work done by Madsen (1992) on the relationship between moisture content and strength made it possible to obtain relevant information to produce a set of MC adjustment factors for commercial softwood timber. It is important to note that the following adjustment factors were obtained from softwood species only.

Table 6: Suggested moisture content Adjustment Factors to be used for Wet commercial Softwood timber against timber at EMC (Madsen, 1992). Both timber and clear wood adjustment factors are based on mean or average values.

Property	Timber	Clear wood	Note
Bending Strength	1	0.84	
Bending Stiffness	1	0.94	E-value
Shear	0.8	0.96	
Tension Parallel to Grain	1	0.84	
Compression Parallel to Grain	0.8	0.69	
Tension Perpendicular to Grain	0.5	0.85	Glulam
Compression Perpendicular to Grain	0.4	0.67	

In Table 6 it is interesting to note the difference between the adjustment factors of timber and the clear wood specimens. This simply indicates the presence of strength reducing defects such as knots present in timber. Madsen found that compression and tension strength perpendicular to grain are highly sensitive to MC, as well as compression strength parallel to grain.

Work done by Thelandersson et al. (2003) showed similar results and compression perpendicular to grain together with compression parallel to grain was found to be the most sensitive to MC (Table 7). It seems that in the case of softwood species, MC has no significant effect on bending, tension parallel to grain and MOE. However, Madsen (1992) reported that bending strength is sensitive to MC in the strong (mature wood) portion of the strength distribution.

Table 7: Suggested moisture content Adjustment Factors to be used for Wet commercial Softwood timber against timber at EMC (Thelandersson et al., 2003). The timber adjustment factors are for characteristic values and the clear wood values are based on average effects.

Property	Timber	Clear wood
Bending Strength	1	0.67
MOE	0.83	0.87
Shear	-	0.75
Tension Parallel to Grain	1	0.79
Compression Parallel to Grain	0.75	0.58
Tension Perpendicular to Grain	-	0.83
Compression Perpendicular to Grain	0.75	0.58

2.4.3 Visual and machine grading

Non-destructive testing is based on timber strength (indicator) properties which are used to predict the actual strength and stiffness of sawn timber. The efficiency of grading is equal to the relationship between these indicator properties and the strength and stiffness of the timber.

Properties such as knots, density, deformation and other defects are used in visual grading to separate timber into different grades or strength classes. The focus is mainly on knot properties to grade timber, and the visual grading rules were concluded based on many destructive tests. Grading rules are valid for a defined species from a specified growth area. This means changing factors such as new (hybrid) planted species or climatic changes require new grading rules to be written. Fortunately, better grading methods do exist. Timber graders study the rules and grade their resource according to their specific rules and instructions. In South Africa the SANS 1783-1 and 1783-2 (2004, 2005) describe the visual grading rules for softwood structural timber.

The grading procedure where timber properties are measured by machines or electronic devices is called machine grading. Internationally measurement of modulus of elasticity, (flat-wise bending) is the most recognized machine grading principle. Müller (1972) did valuable research and development on machine stress grading practices in South Africa. MOE can be measured by bending the timber on flat

(MOE$_{flat}$), on edge or by longitudinal acoustic measures. MOE$_{flat}$ can either be measured by deformation of timber subjected to constant loads, or by measuring the loads required to keep the timber at a constant deformation, (Leicester, 2004).

2.4.4 Acoustic grading

Acoustic grading (natural vibration frequency testing) is fairly simple to perform. The board is hit on the one end, generating a compression wave that moves down the board as the particles at the leading edge of the wave become excited, while the particles that are at the trailing edge come to rest. The wave hits the other end of the board and the tensile wave gets reflected and travels back (Pellerin and Ross, 2002). The resonance frequency is then used together with the board density to determine the dynamic MOE (MOE$_{dyn}$). According to Dowse (2010), acoustic frequency tests were found to be the best single predictor of MOE bending on edge, modulus of rupture and tension strength on young South African *Pinus patula* timber.

2.4.5 X-ray density and ViSCAN grading

Special grading systems on the market today can measure a combination of dimensions, density, natural vibration frequency, moisture content, knots, grain deviation and other defects in timber. They make use of optical sensors, lasers, radiation and ultrasound or frequency measurement units (Bacher, 2008; Rais et al., 2010; Schajer, 2001). X-ray density scanning machines use a combination of knots, knot position, density and other indicator properties to predict the MOR, tension or compression strength values of timber.

Rais et al., (2010) found a five percent increase in the correlation between the indicator property and MOR by combining knot parameters with MOEdyn. Table 8 shows degrees of determination (R^2) for MOR by different indicator properties (from Glos, 2004 as recreated by Giudiccandrea and Verfurth, 2006). Stiffness or MOE is normally seen as the best single predictor of strength in timber, (Madsen, 1992).

Table 8: **Degrees of determination (R^2) for MOR predictions by different indicator properties (Glos, 2004).**

Characteristics that can be measured non-destructively	**Degree of determination R^2**
Knots	0.15 – 0.35
Density	0.20 – 0.40
Frequency, ultrasonic speed	0.30 – 0.55
MOE	0.40 – 0.65
Knots & density	0.40 – 0.60
Knots & MOE	0.55 – 0.75
Knots & density & frequency	0.55 – 0.80

In Table 8 it is clear that the degree of determination (R^2) percentage increases as the number of indicator predictors increases. For example, by using only knots as predictor property of MOR the degree of determination various between 15% and 35%. However, when using knots, density and frequency as predictors for MOR the correlation or prediction percentage varies between 55% and 80%. The problem with this phenomenon is that the measuring of each additional predictor property requires extra time and cost. Therefore the more accurate multiple predictor non-destructive grading systems are more expensive.

2.4.6 Proof grading

An alternative to traditional strength grading is grading based on proof-loading. Since the grading parameter is the strength, there is no loss in yield due to weak correlation between grading parameter and strength, Rune Ziethen (2008). Proof loading is basically testing a material with respect to grade required strength, also known as the characteristic stresses or 5th percentile values. If the component withstands the load, it makes the grade. It has been argued that some boards might be weakened during the test without breaking; however, in actual fact it has been found that the 5th percentile strength of samples tested to destruction was higher than during the initial proof loading (Madsen, 1992). However, Leicester (1985) found that proof grading in bending does not accurately remove weak tension boards for a variety of Australian species. Also, Knuffel (1983) found that tension proof grading on South African pine does not predict bending strength effectively.

According to Leicester (2004), at one time about 20 mills in Australia made use of proof grading, but the commercially available proof testing machines were not suitable for mill grading operations and have fallen into disuse. Except for higher yields and better resource utilization, proof loading can be particularly useful for mills with small throughputs, with many different species or grading for specific end-use products. The equipment needed for proof grading is very simple and rugged and no highly-skilled workers are required to assure quality control. In most cases proof grading is done by loading the timber on edge or in bending, as it would be in service. Tension stress can be equally suitable or preferable (truss/laminate/finger-jointed industry) for proof grading.

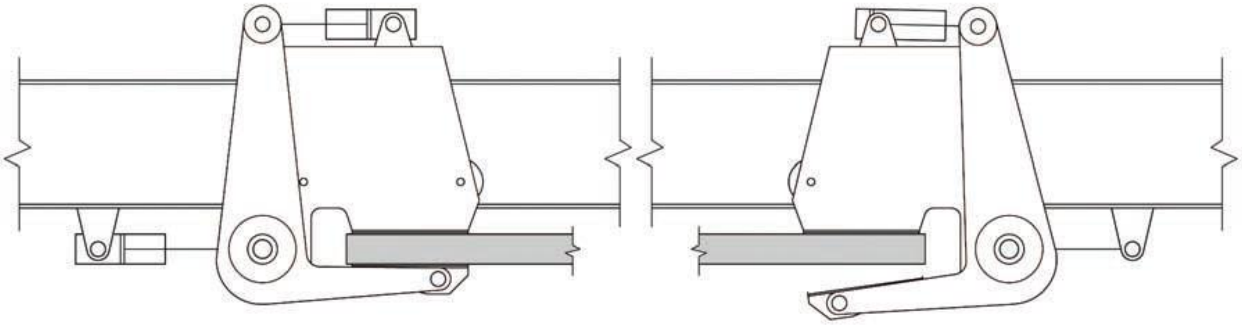

Figure 6: **In-line proof grading in tension parallel to grain setup (MetriGuard, 2012).**

Effective grading has the potential for increasing the profitability of producers or mills. Alternative grading methods might improve the efficient use, as well as conservation, of our wood resource. In a recent grading study performed on South African pine (only 195 specimens) four grading methods were analysed and visual grading was found to be the least effective method (Crafford and Wessels, 2011). Unfortunately, in South Africa and many other countries visual grading is still the most implemented grading method.

Natural vibration frequency grading and proof-grading are two of the most promising grading methods. Proof-grading is a fairly old method compared to frequency grading. Companies such as Microtech have also developed grading machines that can measure dynamic MOE values which correlate very well ($R^2=0.87$) with static MOE values, (Bacher, 2008).

However, proof grading in tension is arguably the most effective and efficient way of grading finger-jointed timber, because the entire volume of every board is exposed to the prescribed minimum load. Research done by Katzengruber et al. (2006) on more than 5000 boards proved that no significant material damage was detected on finger-jointed timber that was tested in tension proof loading at two and three incremental loads. Also Woeste et al. (1987) conducted experiments on 1200 boards with single and reverse bending loads and detected no damage due to proof loading.

2.5 Important properties for roof truss design

A recent study done by Petersen and Wessels (2011) showed that the mean strength capacity of SA pine structural timber utilised in truss designs was less than 50% for all of the properties and all of the dimensional sizes. This indicates that on average less than 50% of the characteristic strength and stiffness capacity of the SA Pine timber resource was utilized in the selected roof truss designs. They also concluded that of all the individual strength properties, bending strength was the most influential in truss design. In Figure 7 it is clear that only a small fraction of bending strength capacity is utilized in truss designs. Local deflection, which is related to the stiffness (MOE) of timber, was also important in truss design. However, a 30% reduction in the mean MOE of Grade S5 SA Pine timber had a minor effect in terms of the timber usage and cost when the roof trusses in their project were re-designed. Other properties such as compression parallel to grain, tension parallel to grain and shear were clearly less influential in truss design.

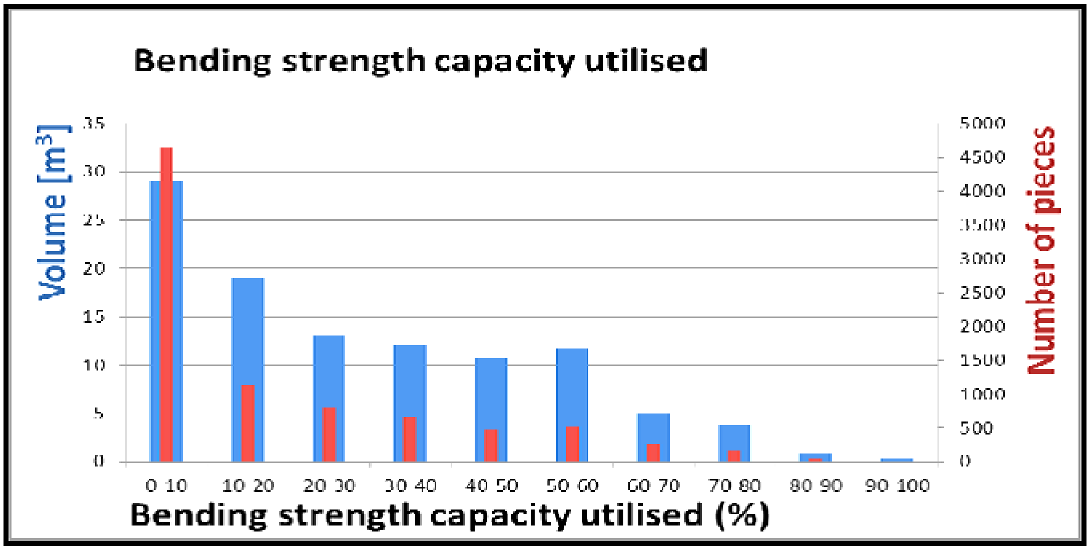

Figure 7: **The bending strength capacity (%) utilized in roof truss designs. The thick bars show volume and the thin bars the number of pieces (Petersen and Wessels, 2011).**

All these factors stated above indicate three things; our structural timber resource is extremely limited, it is variable, and so therefore the grading systems must be adaptable and, thirdly, there is a need for higher strength grades and higher yields. The final point also touches on the worldwide sustainable resource awareness and practices which are becoming more and more relevant. This is an indication that our structural timber market is ready for new sustainable products and more efficient grading systems.

3 Materials and Methods

Figure 8 below shows the process that was followed in this project.

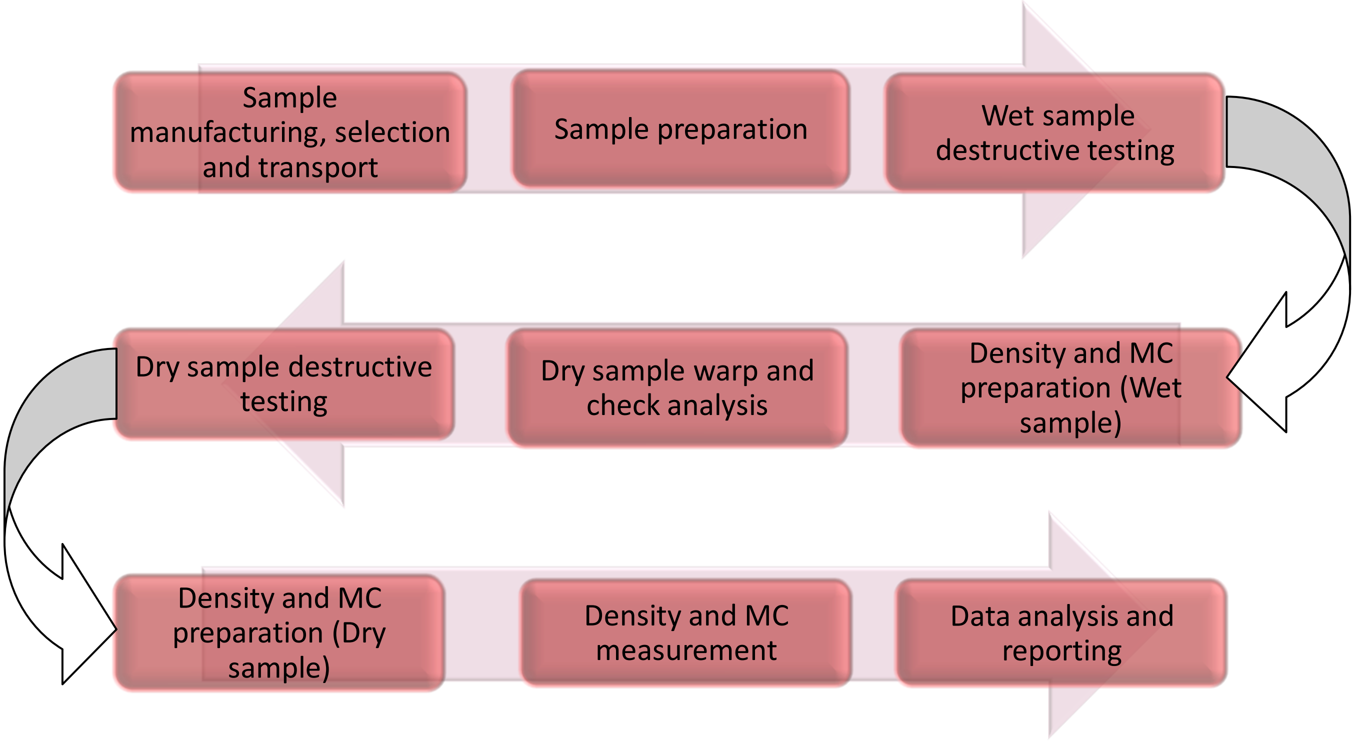

Figure 8: **Summary of procedure from initial sampling to final data analyses and reporting**

3.1 Sampling and transport

The samples used in this study were obtained from Diggersrest mill in Limpopo, South Africa. The mill produces wet finger-jointed, *E. grandis* timber. The manufacturing process started with the felling of the young trees. Then the trees were left in the forest for approximately six weeks, which is believed to help with stabilizing growth stresses. Next the green logs were cut to shorter lengths and processed into dimensional timber. Finally the wet boards were finger-jointed, cross-cut and planed to regularized dimension. After production of the timber, the boards were wrapped in plastic to prevent drying during transport and storage.

The samples were sent from Tzaneen to Stellenbosch at the beginning of February 2012. A total of 220 boards were received. Different batches of product were selected so that trees of a range of different ages were included in the sample – from 5 to 18 year-old trees. Samples included the dimensions 48 x

73 mm and 36 x 111 mm, 110 of each dimension. In total 720 specimens were cut from the long-length boards at random and prepared for testing. It is important to note that the sample selection was performed by the mill. Therefore, due to elevating costs, our sample and specimen sizes were limited. Also the specimens' age and dimensional sizes were not selected by the author, but included in the shipment. Ideally, the sample size should have been larger but this was out of the control of the author.

3.2 Sample preparation

The group of 220 boards was randomly divided into two groups of 110 samples each. One group was destined for testing in the green condition and the other for drying and then testing in the dry condition. Three different ages were represented in the sample, which was also accounted for in the sample separation, see Table 9.

Table 9: **The sampling and specimen plan.**

	48 x 73 mm								**36 x 111 mm**							
Tree age (yrs)	**Board length (m)**	**Full board n**	**Specimen quantity cut from full boards**						**Length (m)**	**Full board n**	**Specimen quantity cut from full boards**					
			Bend n	**Tens// n**	**Tens⊥ n**	**Comp// n**	**Comp⊥ n**	**Shear n**			**Bend n**	**Tens// n**	**Tens⊥ n**	**Comp// n**	**Comp⊥ n**	**Shear n**
5	5.4	20	20	20	6	6	8	13								
	6	20		40	12	14	12	5								
11	4.2	20	40		9	9	7	12	4.2	20	40					
	5.4	20	20	20	8	6	9	10	5.4	20	20	20	19	20	16	
	6	20	20	20	5	5	4		6	20		40	2	2	4	4
18									4.2	20	40					
									5.4	20			16	15	17	34
									6	20		40	3	3	3	2
Total		**100**	**100**	**100**	**40**	**40**	**40**	**40**			**100**	**100**	**40**	**40**	**40**	**40**

The boards was cut to specific destructive testing lengths, according to SANS 6122 (2008) and AS/NZS 4063 (2010) standards, see detail in the following section. Defect placement during testing was random. This is different from the current prescription of SANS 6122, but the latest draft of this document does specify random placement and it was thus decided to follow the draft version's method. In any event, a recent study on the differences between random and biased defect placement showed that there was no significant difference in 5th percentile results for bending strength for SA Pine timber (Crafford and Wessels, 2011). The defect placement of timber used in buildings is also randomly assigned, therefore it was decided to continue with this method.

In total there were 720 test specimens required from 220 long length boards. More than one testing specimen was cut from each full length board – see the sampling plan in Table 9. For solid timber this would not be acceptable, as it would reduce the variability of the raw material. Also, where biased defect placement is specified, such as in SANS 6122 (2008), full length boards are required. However, since random defect placement was used in this study and because each board already consisted of a number of different laminates finger-jointed together, which increase the raw material variability, it was decided that multiple samples from a single board would be acceptable. Once again, the limited number of boards available also influenced the decision.

All the boards were weighed on arrival to compute wet density. The wet specimens were kept in a climate controlled room at a humidity of 65% and temperature of 18˚C to retard drying as much as possible while testing commenced. The exact width and thickness of the dry specimens were noted by marking every laminate exceeding 100mm to compute shrinkage. Figure 9 shows the greenhouse or drying-tunnel where the dry specimens were kept for 9 weeks until equilibrium moisture content (EMC) was reached. The drying conditions in the greenhouse were severe and temperatures of above 50˚C and humidity equaling 30% were measured during March. In comparison, the same measurements were performed inside the ceiling of a nearby tiled roof building, and surprisingly, temperatures were below 40˚C and humidity above 40%.

Figure 9: **Specimens stacked in the green-house for drying**

The specimens were stacked with wide spacings between the layers. Three layers of timber at the most were stacked on each other to reduce the variation in conditions between layers and not to restrain warp. Analysis and testing of dry specimens only proceeded after equilibrium moisture content was established and this was determined by weighing 10 sample boards several times until their mass stabilized.

3.3 Destructive testing

Both the wet and dry sample groups were tested destructively. Exactly the same methods were used for wet and dry sample testing. The AS/NZS 4063 (2010) standard was used where a specific test method (such as the shear test) was not described in SANS 6122 (2008). Note that both SANS 6122 (2008) and AS/NZS 4063 (2010) national characteristic strength standards are prescribed for solid wood timber and not necessarily finger-jointed timber. However, no in-grade testing standards exist primarily for finger-joint timber, as far as the author is aware. Calculations, formulas and the statistical analysis that were used in this project are displayed in section 3.6.

3.3.1 Bending tests

All the specimens were tested at Stellenbosch University's strength testing laboratory at the Department of Forest and Wood Science. The Instron testing machine was used to perform all destructive testing except for analyzing tension parallel to grain (Figure 10). The tension or compression edge was randomly selected when the boards were placed in the test setup.

Figure 10: The bending test setup (left) and tension$_{//}$ test machine setup (right).

Both wet and dry sample groups consisted of 100 samples. The specimens varied in length from 1.46m, and 2.1m to 2.2m, depending on the original group it was cut from and its dimension. Half of the group was 48 x 73 mm and the other half was 36 x 111 mm dimension boards. The prescribed test span, according to SANS 6122 (2008) is 18 times the width of the bending specimen, which equals 1314mm and 1998mm for the two different test dimensions.

3.3.2 Tension Parallel to grain testing

For both wet and dry sample groups 100 tension samples were tested destructively. The sample consisted equally of 48 x 73 mm and 36 x 111 mm boards. The tensile testing machine parameters were such that the 48 x 73 mm batch had to be machined to 40x73 mm to fit in the grips. According to SANS the test span needs to be at least 7 times the width of the test specimen, which resulted in a minimum test span of 777 mm. Considered the overall length distribution in the original sample, the maximum tensile specimen length of 2.6 m was obtained. As a result, the test span was 1.860 m, which can be seen as satisfactory. Tensile testing was done on a test machine at a commercial sawmill in the region (Figure 10). The maximum load that the machine could apply was 88.7 kN which translated to a stress close to 22.2 MPa when testing 36 x 111 mm samples and 30.3 MPa when testing 40 x 73 mm samples. The exact rate of deformation or load application is unknown. However, the machine had recently been calibrated by the SABS.

3.3.3 Tension Perpendicular to grain testing

Once again both wet and dry samples were investigated. Only 40 specimens per group were tested destructively for each of the remaining four (less important) test configurations. These sample sizes were selected because a limited number of specimens were available and because these properties were deemed less important in truss structures (Petersen and Wessels, 2011). The specimens were randomly selected and cut from either the wet group or dry group. The specimen preparation and test procedure were performed according to the AS/NZS 4063 (2010) standards. Both specimen preparation and testing required great precision and accuracy. Special steel components for each test configuration were carefully machined and made according to specifications. Figure 11 shows the test configuration of the tension perpendicular and compression parallel to grain tests.

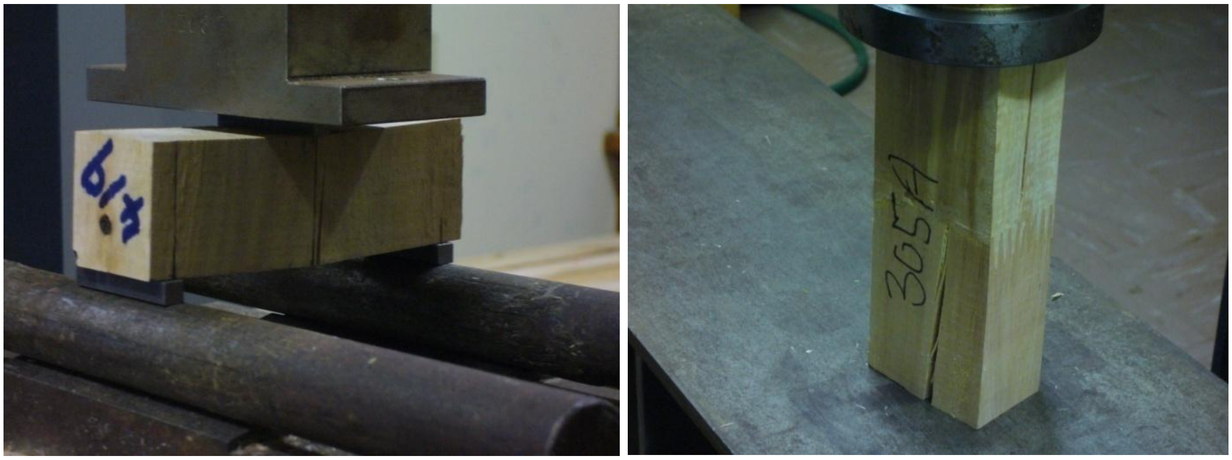

Figure 11: **The tension$_{\perp}$ test setup (left) and compression$_{//}$ test setup (right).**

3.3.4 Compression Parallel to grain testing

The SANS 6122 and AS/NZS 4063 (2010) prescribes different test methods for calculating compression parallel to grain. The AS/NZS 4063 (2010) standards contain both compression parallel to grain and bearing strength test methods. The SANS 6122 include only the compression parallel to grain testing method, which compares nearly exactly with the AS/NZS 4063 bearing strength method. Considering the extent of the AS/NZS 4063 standard and that it had been more recently revised than the SANS standards, the AS/NZS 4063 bearing strength method was followed to perform the compression parallel to grain tests.

3.3.5 Compression Perpendicular to grain testing

The AS/NZS 4063 (2010) standard's bearing strength perpendicular to grain method was used to perform compression perpendicular to grain tests. To avoid confusion in this project we chose to refer to bearing strength as compression strength. Once again random boards were selected to obtain the two groups of 40 specimens each. Every specimen was cut and prepared exactly according to the prescribed method. The test configuration of the compression perpendicular to grain and shear tests can be seen in Figure 12.

Figure 12: **The compression⊥ test setup (left) and shear test setup (right).**

3.3.6 Shear tests

For preparing the shear specimens the AS/NZS 4063 (2010) standards were also used. The specimen test length had to be exactly 6 times the width of the board. Once again nominal dimensions were specified, which were 48 x 73 mm and 36 x 111 mm boards. Figure 12 shows shear test setup of a 36 x 111 mm specimen.

3.4 Density and Moisture Content measurement

Density and MC are both elements that were considered potentially important properties in this specific project. The maximum moisture content method (Diana Smith) for determining specific gravity (basic density) for small wood samples was followed for all density calculations (Smith, 1954). This procedure also allowed for determining an accurate MC at the time of testing, by using the specimen weight (green-weight) at the time of testing and oven dry weight of that same specimen. These two different masses were used to calculate the MC for each sample.

The density specimens were carefully cut from the complete cross sectional area of the destructively tested boards. One specimen was obtained from each laminate in a board, at a length of approximately 20mm and without any visible defects. The small wood specimens were then numbered according to the original board and laminate numbering notation. The rationale was to investigate the correlation between the density and MC data and failure mode, stiffness and other physical properties of the boards. To minimize possible change in MC the specimens were cut from the destructively tested boards and weighed as soon as possible after testing.

After the specimens were cut and weighed, they were put into a pressure and vacuum cylinder for the saturation treatment procedure. It comprises a 48hr pressure and vacuum cycle period where a pressure of 600 kPa was applied for 24 hrs and vacuum of -100 kPa for the remaining time. The samples were left in water for a while to stabilize and were weighed after stabilizing to obtain the saturated weight for each specimen. Finally, to obtain the specimen oven-dry mass the specimens were dried for 24hrs at 100˚C.

3.5 Warp, Checking and Shrinkage measurement

These analyses were performed only on the dry sample. Note that the sample was exposed to quite severe conditions (discussed previously) and therefore more moderate drying conditions might have resulted in slightly different results. However, the drying conditions within a roof structure might in many cases be fairly severe depending on the roof covering material and location.

3.5.1 Warp

The term warp or deformation in timber includes bow, spring, cup and twist, see Figure 13. Bow, spring, cup and twist were all measured on the same measuring apparatus (jig), see Figure 13 for examples. Three index pins were used to support the board. The board was secured by a weight at one end containing the two pins. The other end was supported by only one pin, which allowed its natural bend to occur. Every board was centered by aligning pre drawn lines on the jig and board. Three measurements of each board were noted, two in the middle and one at the end (in line with the pin). Each board was visually inspected for spring and if any was detected, spring was also measured. The same jig was used for measuring spring by simply turning the board on its side and placing it on the two aligning pins. Then the maximum deflection measurement was noted.

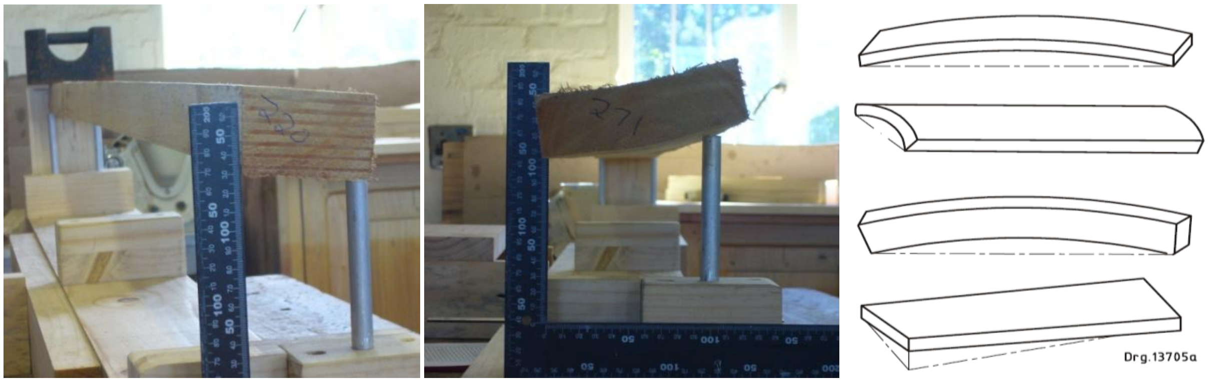

Figure 13: **The jig used to measure warp (left and centre) and drawings of bow, cup, spring and twist (right).**

3.5.2 Check, Split and Wane

Surface defects were measured for each laminate in each board. Exact measurements for every check, split and wane were noted and photographed. Also the exact length of each laminate was measured. Surface cracks wider than 1mm, defined as checks, were noted by giving the maximum width, length and laminate position. Splits in timber occur at the end of boards due to the faster drying open-grain area. Once again the maximum width, length and position of each split were measured. In the same way wane was measured. Figure 14 illustrate an example of a severe surface check and end-split.

Figure 14: Severe surface check (left) and end-split (right).

3.5.3 Shrinkage and Swelling

The dimensions of the 200 boards that made up the dry sample were carefully measured in the green state at the time of arrival. The width and thickness of each laminate were measured with a handheld caliper and the measurement place was marked. The same caliper was used to re-measure all the laminates at the exact same position at EMC. These two separate measurements of each dimension were used to compute the mean shrinkage due to drying.

3.6 Calculations and analysis

In this project (due to the nature of this wet finger-jointed product) both South African and other international standards were considered for the various test methodologies. In each case the most relevant method was selected.

3.6.1 Calculation of strength and stiffness values

The following formulas were used to compute strength and stiffness. The boards we received were planed to regularized dimensions and therefore standard roof truss dimensions could be used to calculate strength and stiffness values. Also roof truss designing software programs use regularized dimensions in their designs. The SANS 1783-2 (2005) stipulates the precise dimensions and permissible tolerances for structural timber.

MOE_{edge} according to SANS 6122 (2008)

$MOE_{edge} = (F \cdot L^3) / (5.4 \cdot b \cdot h^3 D)$, where:

MOE_{edge}	is the static modulus of elasticity measured on edge at a third of the span, in MPa;
F	is an increment in load below the proportional limit, in Newtons;
L	is the test span, in millimetres;
b	is the test specimen thickness, in millimetres;
h	is the test specimen depth, in millimetres; and
D	is the increment in deflection of the test specimen under the increment in load F, in millimetres.

MOR according to SANS 6122 (2008)

$MOR = (F \cdot L) / (b \cdot h^2)$, where:

MOR	is the bending strength (modulus of rapture), in MPa;
F	is the failure value, in Newtons;
L	is the test span, in millimetres;
b	is the test specimen thickness, in millimetres; and
h	is the test specimen depth, in millimetres.

Tensile strength according to SANS 6122 (2008)

$Tension = F/A$, where:

Tension	is the tensile strength, in MPa;
F	is the failure load, in Newtons; and

A	is the actual cross-sectional area of the test specimen, in millimetres squared.

Tension perpendicular to grain according to AS/NZS 4063 (2010)

$\text{Tension}_{\perp} = \left(\frac{3.75 \cdot F}{b \cdot l}\right) \cdot \left(\frac{0.025 \cdot \mathrm{b} \cdot \mathrm{l}^2}{10^7}\right)^{0.2}$, where:

$\text{Tension}_{\perp}$	is the tensile strength perpendicular to grain, in MPa;
F	is the failure load, in Newtons;
b	is the test specimen thickness, in millimetres;
d	is the test specimen depth, in millimetres; and
l	is the length cut from the graded timber (should be d/3), in millimetres.

NOTE: (b x d) comprise the full cross-section of the graded piece of timber.

Compression parallel to grain according to SANS 6122 (2008)

$\text{Compression}_{//} = F/A$, where:

$\text{Compression}_{//}$	is the compression strength parallel to grain, in MPa;
F	is the failure load, in Newtons; and
A	is the actual cross-sectional area of the test specimen, in millimetres squared.

Compression perpendicular to grain according to AS/NZS 4063 (2010)

$\text{Compression}_{\perp} = F/(50 \cdot b)$, where:

$\text{Compression}_{\perp}$	is the compression strength perpendicular to grain, in MPa;
F	is the value of the load applied corresponding to a 2.0 millimetre deformation, in Newton; and
b	is the breadth of the test specimen (≥ 35 mm), in millimetres.

Shear strength according to AS/NZS 4063 (2010)

Shear = $(0.75 \cdot F) / (b \cdot d)$, where:

Shear	is the beam shear strength, in MPa;
F	is the failure load, in Newtons;
b	is the test specimen thickness, in millimetres; and
d	is the test specimen depth, in millimetres.

5th Percentile values

The 5th percentile values for the various tests were obtained according to the SANS 6122 (2008) method. First the values were ranked from low to high, then a 5th percentile rank was determined by the formula *0.05(n-1)*, where *n* is the number of specimens. The value at that position was defined as the characteristic or 5th percentile value.

3.6.2 Calculation of physical properties

The following properties were once again measured and analysed according to the best suited method.

Density according to Diana Smith (1954)

Density = $\frac{1}{\left(\frac{m_s - m_o}{m_o}\right) + \left(\frac{1}{1.53}\right)}$, where:

Density	is the specific gravity (basic-density), in kg/m^3;
m_s	is the saturated test specimen mass, in kilograms; and
m_o	is the oven dry test specimen mass, in kilograms.

Moisture content according to the oven dry method

Moisture content = $\left(\frac{m_w - m_o}{m_o}\right) \cdot 100$, where:

Moisture content	is the MC of the test specimen at time of measuring, in %;

m_w is the mass of the wet specimen, in grams; and

m_o is the mass of the oven dry specimen, in grams.

Warp and Surface analysis according to SANS 1783-2 (2004) and SANS 1707-1 (2010)

These two standards presented exactly the same requirements for both warp (twist, bow, spring and cup) and surface analysis (check, splitting and wane). The SANS 1783-2 (2004) is specifically written for soft-wood sawn timber, whereas the SANS 1707-1 (2010) is in fact written for sawn Eucalyptus timber.

3.6.3 Statistical analysis

All of the data collected from the various tests was transferred to an Excel spreadsheet according to board numbers. Faulty or erroneous data was checked and removed or corrected if required. The data was imported into Statistica, a statistical analysis program. F-tests were performed to explain and compare the difference in mean value for various strength properties (eg. MOE and MOR). For the single correlation analysis, simple Pearson correlations were performed on all the variables which were deemed to be significant in order to achieve a correlation matrix which includes possible indicator properties. Simple scatterplots were drawn up for selected variables using a Least Squares approach with a linear model fitted ($Y = a + b \cdot X$).

When performing the equality of variation analysis, an F-test was used to explain the variability within the various samples and Bonferonni post hoc tests were performed additionally, to analyze the specific variation between each sample.

4 Results and Discussion

4.1 Selected physical properties of green-glued *E. grandis* finger-jointed timber

Selected physical properties

Properties that were deemed to be practically and commercially important were: density, moisture content, warp (bow, cup, spring and twist), checking, end-splits and shrinkage.

4.1.1 Density

The mean basic density of the complete sample, which consisted of 720 specimens and 1556 laminates, was 425.3 kg/m^3. The standard deviation for basic density was (61.9 kg/m^3) which indicated that a portion of boards had quite low basic density values as well. Density usually has a positive relationship to the strength and stiffness properties of wood. In the SANS 1783-2 specification for structural softwood, as well as the SANS 1707-1 (2010) specification for sawn Eucalyptus timber and other structural timber specifications, there are minimum density boundaries for individual grades (Table 11).

Density also has a direct influence on the load capacity of nail plated joints, which are the joining method of choice for the roof truss industry. However, the necessity of the relatively high density requirements for the S7 and S10 timber is questioned. If there are strength and stiffness requirements for each grade, the density requirement is purely necessary for nail plated joint load capacity. A single minimum density requirement might be sufficient to obtain the proper nail plate joint strength. Also, the nail plate joint area and/or nail configuration can be increased to increase the joint load capacity. Therefore the minimum density boundaries for individual grades should be investigated. A single minimum density requirement would increase yield and grade potential for structural timber. Density values will always vary between saw log resources and species, due to the inherent differences between juvenile and mature wood and hardwood and softwoods.

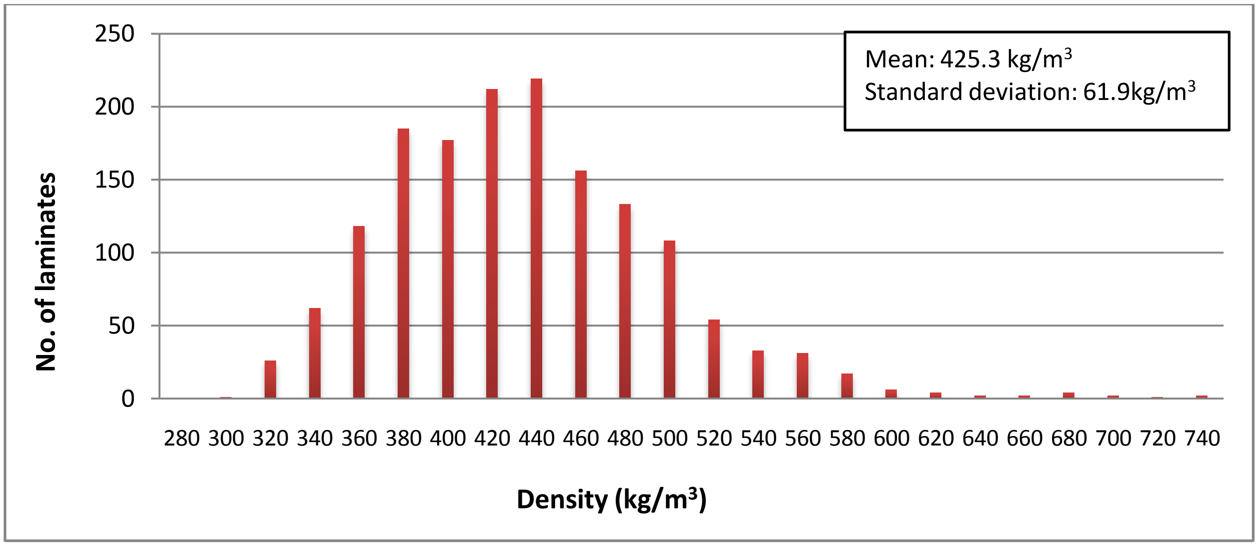

Figure 15: **The density distribution of individual laminates of young *E. grandis* finger-jointed boards.**

Table 10: **The mean basic density of specimens of young *E. grandis* finger-jointed boards for different dimensions and ages. Sample size (n) also included. Values in same row containing different superscripts ($^{a,b\ etc.}$) are significantly different ($p<0.05$)**

	Dimension (mm)		**Age (years)**		
	48 x 73	**36 x 111**	**5**	**11**	**18**
Mean Density (kg/m³)	399.5^{a}	435.9^{b}	374.5^{1}	429.2^{2}	462.8^{3}
n	360	360	156	391	173

The mean basic densities of the three different age groups (5, 11 and 18 years) differ significantly at the 0.05 level (Table 10). This occurrence is evidence of the difference in density in juvenile wood in the various stages of a tree's life cycle – juvenile wood is known for large variation in properties. It was also interesting to note the significant ($p<0.05$) difference in basic density of the two different dimension groups. The density of the 36 x 111 dimension boards was, on average significantly higher than that of the 48 x 73 dimension boards. This result is to be expected since the smaller 48 x 73 mm group comprised a sizeable proportion (43%) of timber cut from five year old trees. In the same way the 36 x 111 mm group consisted of a similar proportion (48%) of timber cut from 18 year old trees. In practice, at sawmills, smaller dimensioned boards are usually cut from smaller logs.

Table 11: **The yield (%) of different grades based only on the basic density of specimens and individual laminates of young *E. grandis* finger-jointed boards. Density requirements according to SANS 1783-2 (2004) are also included.**

Grade yield	**Grade**			
	xxx	**S5**	**S7**	**S10**
SANS 1783-2 (2004) density requirements (kg/m³)	**-**	**360**	**425**	**475**
Whole boards yield (720) %	9.3	90.7	46.3	15.6
Single laminates yield (1556) %	13.3	86.7	46.7	18.8

The mean density of the specimens was relatively good, compared to softwood structural timber requirements. Comparing this to the SANS 1783-2 minimum density requirements for stress graded timber, 90.7% of the specimens would comply with S5 density requirements if only S5 was graded for. For grades S7 and S10 46.3% and 15.6% respectively of the overall sample will reach SANS requirements based on density alone. This means that only 46.3% of this sample will meet S7 and S10 grades, which makes density a very important grade determining factor. Once again the question needs to be asked, is there any true significance in having one categorical set of density boundary requirements for all the various resources, species and different grades? The necessity of density boundaries for nail plate joint strength should be further investigated. The required density boundary or boundaries for the young *E. grandis* product in terms of the required nail plate load capacity should also be determined.

4.1.2 Moisture content

The wet sample, which consisted of 110 full length boards and 582 laminates, had a mean moisture content of 40.1%. The variation in moisture content of the wet and dry samples can be seen in Figure 16a and Figure 16b. Only two laminates of the wet sample had a moisture content of less than 20% and 169 laminates had a moisture content between 20% and 30%. By far the largest part of laminates' moisture content was above fibre saturation point (FSP) which is usually close to 30%. Below fibre saturation point many properties of wood start to change. For instance, the strength and stiffness of clear wood samples usually increase from FSP up to 0% moisture content – in some cases quite significantly. Above fibre saturation point these properties stay constant. For structural timber which contains defects like knots, the effect of moisture content on strength and stiffness is often less dramatic when compared with clear wood samples (Madsen, 1992).

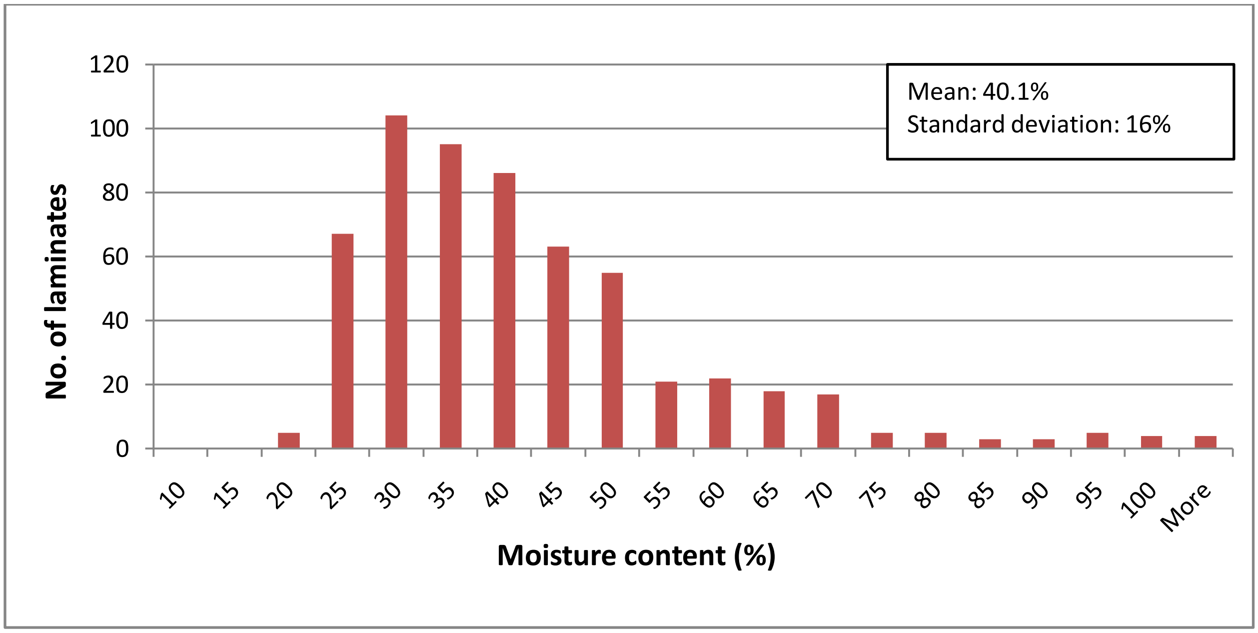

Figure 16a: **The moisture content distribution of individual laminates of wet finger-jointed boards.**

In Table 12 the MC of the wet sample between different dimensions and age groups is displayed. The mean MC percentages (≈ 40%) of both dimension groups, and age groups 11 and 18, were very similar. The 5 year old boards had a lower mean MC of 33.4%. However, no statistical significant difference in MC was found between the three age groups and two dimensional sizes.

Table 12: Then mean moisture content percentage of the wet sample's specimens for different dimension and age groups. Values in same row containing different superscripts ($^{a,b\ etc.}$) are significantly different (p<0.05)

Wet sample	Dimensions (mm)		Age (years)		
	48 x 73	36 x 111	5	11	18
MC (%)	41.9^a	40.1^a	33.4^1	43.6^1	40.7^1
n	100	100	40	120	40

The dry sample, which also consisted of 110 full length boards and 572 laminates, was found to have a mean moisture content of 14% after drying which was close to the EMC of the Stellenbosch region of 12%. Only 10 laminates had a moisture content of above 20%. However, the MC standard deviation of 2.6% and MC maximum value of more than 25 % was higher than expected for the dry timber.

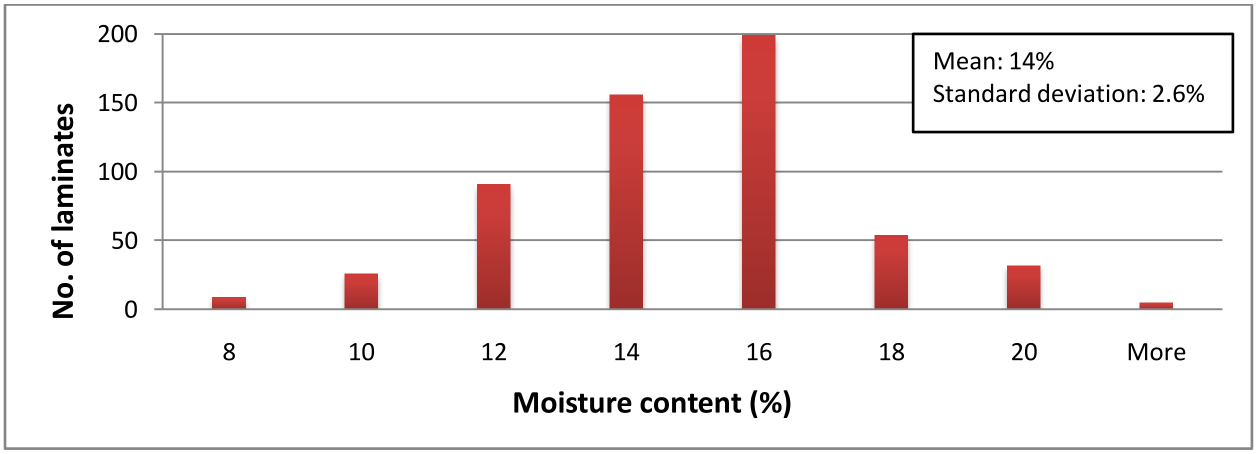

Figure 16b: **The moisture content distribution of individual laminates of dry finger-jointed boards.**

Once again the variance in MC of the dry sample could be partially explained by analyzing the 5 year old boards. The 5 year old group had a mean MC of 14.5%, where the other two age groups were both below 14% (Table 13). Also, it must be kept in mind that MC measurement was done only after destructive testing had been performed. In the case of the tensile parallel to grain testing, 100 boards had to be transported to a different location for 5 days. In that period the boards became completely soaked due to rain. That sample included 30 (of the 40) five year old boards and those 30 boards had a mean MC of 15%, whereas the combined 100 boards had a mean MC of 14.6%. The mean MC percentages (≈ 14%) of both dimension groups, and age groups 11 and 18, were very similar.

Table 13: Then mean moisture content percentage of the dry sample's specimens for different dimension and age groups.

Dry sample	Dimensions (mm)		Age (years)		
	48 x 73	**36 x 111**	**5**	**11**	**18**
MC (%)	14	13.9	14.5	13.8	13.8
n	100	100	40	120	40

4.1.3 Warp (bow, cup, spring and twist), Checking and End-splits

Checking and splitting limitations are included in the SANS 1783-2 structural timber specification, as they may influence strength and also cause problems during construction. When individual boards are dried and warping occurs, truss and other timber constructions become difficult or impossible, hence the specifications on warp for structural timber. It must be noted that the concept of building roof trusses with wet members, as intended with this young *E. grandis* product, will make the effect of warp during construction irrelevant. In this case warp within the completed truss structure and possible problems afterwards should be investigated.

For the following results, specimen length was used, and not original board length. However, the stress graded structural specifications of SANS 1783-2 were designed to accommodate various lengths and dimensions of timber. Hence the 200 test lengths, consisting of 100 bending and 100 tensile, can be seen as satisfactory for analyzing warp, checking and end-splits. In the wet state virtually no checking, end-splitting or warping was observed in the young finger-jointed Eucalyptus timber. In the dry sample after exposure to quite severe drying conditions in the greenhouse, the warp, end-splitting and checking results can be seen in Tables 14 and 15 and Figure 17.

Figure 17: The distribution of the 200 dry boards of twist expressed as a percentage of that allowed. Including both 48 x 73 and 36 x 111 dimension boards.

The distribution in Figure 17 consisted of both 48 x 73 and 36 x 111 mm boards and age groups 5, 11 and 18 years. The boards that did not make the permissible twist limits were all grouped under rejected. The maximum allowable twist values in SANS 1783-2 (2004) were used as limits. The relatively flat distribution indicates that certain boards showed the tendency to twist, whereas others showed little or no such tendency. The results in Tables 14, 15 and 16 will emphasize this occurrence.

Table 14: **The percentage of (200) boards from the dry sample that did not conform to warp requirements for structural grade softwood timber according to SANS 1783-2 (2004). Including both 48 x 73 and 36 x 111 sizes.**

Warp	**Bow**	**Spring**	**Twist**			**Cup**		
Width (mm)	73&111	73&111	73&111	73	111	73&111	73	111
Reject (%)	0	0	30	45	14	0.5	1	0

Although the unrestrained boards dried under rather severe conditions, cup, bow and spring did not appear to be a problem. Thirty percent (30%) of the dry sample did not make the twist requirements for structural softwood timber, according to the SANS 1783-2 (2004) standard. This was surprisingly good compared to young, kiln dried, *Pinus Patula*, where a study done by Dowse (2010) showed that 57% of the boards did not make the structural timber requirements for twist. One of the possible reasons for the relatively low percentage of twist of this young resource was the finger-joints. The finger-joint configuration might have reduced the effect of severe twist in some laminates within full boards as the different laminates will twist in different directions and some laminates will have less twist than others – resulting in a full board having lower twist value. In some finger-joint lines, grain deviation and other defects which can elevate deformation are removed before jointing takes place. However, the product will be used in the wet state before twist will occur. Measurement of this property should also be done within a truss construction where additional mechanical bracing such as nail-plates could help restrain warp.

Forty five percent (45%) of the 100 smaller dimension (48 x 73) boards had twist levels above the SANS requirements, whereas only 14% of the 100 larger dimension (36 x 111) boards did not conform to SANS twist limitations. In this project the majority of 48 x 73 dimension boards were obtained from the pith or centre of the log. This might indicate that boards (from this resource) containing mainly pith material is more prone to twist. Also, due to the specific sample that was obtained, 40 of the 100, 48 x 73 dimension boards were only 5 years old. Whereas the 100, 36 x 111 dimension group consisted of boards of 11 years and older. The undesirable properties of juvenile wood are low basic density, a tendency to contain a large amount of compression wood as well as a greater longitudinal shrinkage, higher level of spiral grain, leading to a higher percentage of warped timber (Walker, 1993). See Table 16.

Table 6: **The percentage of (200) boards from the dry sample that did not make checking and end-splitting requirements for structural grade softwood timber according to SANS 1783-2 (2004).**

Defect	**Checks**			**End-splits**		
Width (mm)	73&111	73	111	73&111	73	111
Reject (%)	35.5	54	17	1.5	1	2

Severe checking occurred in many laminates and 35.5% of the boards did not make the checking requirements of SANS 1783-2 (2004). Once again, the practical effect of the checking of this product should rather be investigated in a truss arrangement, and not on single boards as was done here. The majority (54%) of the checking occurred in the 100, 48 x 73 dimension timber boards and only 17% of the 100, 36 x 111 dimension timber boards would be rejected due to checking. The higher level of checking in the smaller dimension timber is once again evident of boards consisting of a large proportion of pith material. Surprisingly, only 1.5% of the dry boards had end-splitting of above SANS restrictions. End-splitting, which might manifest in dry young *E. grandis* boards, might be a potential problem in construction. However, it might be possible to restrain end-splitting by either nail-plates or side-boards (facia-boards) which could solve the problem before it arises depending on the fixing method.

Table 7: **The percentage of (100) 48 x 73 dimension boards from the dry sample that did not make twist and checking requirements for structural grade softwood timber according to SANS 1783-2 of ages 5 and 11.**

		Twist		**Checks**	
48 x 73 (mm)	**Age**	**5**	**11**	**5**	**11**
	Reject (%)	72.5	26.7	70.0	43.3
	n	40	60	40	60

Twist and checking of the young 5 year old boards of dimension 48x74 occurred at high levels of 72.5% and 70%. The mean twist and checking for 5 year old boards was significantly different to the 11 year old boards of the same dimension (48 x 73). For the 11 year old boards only 26.7% and 43.3% of twist and checking respectively did not conform to SANS 1783-2 standards. These results clearly indicate that the very young 5 year old boards were quite inferior compared to the 11 year old boards, when it comes to twist and checking. In this study the pith containing portion within every board was not measured, because finger-jointed boards consisted of multiple laminates which blocked the cross-sectional plane for observation. However, a noticeable amount of pith material was present within the younger (5 and 11 year) boards, especially the 5 year old batch. This could be due to the mill's sawing pattern, where for example, a 5 year old log would produce two boards containing a large proportion of pith material. In the same way an 11 year old log would be able to produce four boards containing less pith material. No statistical significant difference was found in checking and twist results between the 11 and 18 year old timber of dimension 36 x 111 mm.

4.1.4 Shrinkage

Table 17: Mean shrinkage (%) of different age groups.

Age (years)	5	11	18
Shrinkage (%)	2.1	2.9	3.3
N	40	120	40

The mean shrinkage of the (200) boards initially measured wet and then dry was 3.0%. The measurements were done on the width and thickness and will therefore be a combination of radial and tangential shrinkage. This average of 3% in shrinkage was quite good compared to shrinkage values in literature of radial and tangential shrinkage of timber, which varied between 2 – 12% when measured at both green and oven dry conditions (Simpson et al., 1999). In Figure 18 a trend line which was drawn between shrinkage and MC below FSP can be seen. The average shrinkage in this project that was evident at moisture levels of 28% and 14% was plotted, whereas the shrinkage at 0% MC was extrapolated. If the relationship between MC and shrinkage stayed linear, which is usually the case according to literature (Simpson et al., 1999), then the shrinkage at 0% MC for this timber will be 6%.

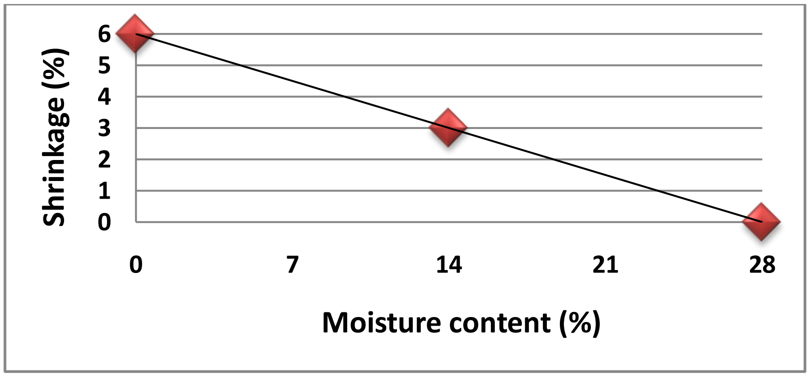

Figure 18: The average shrinkage (combination of radial and tangential) against MC (%). The shrinkage at 0% MC was extrapolated.

The five year old boards had a mean shrinkage percentage of 2.1 %, whereas the older (18 year) boards had a mean shrinkage of 3.3 % (Table 17). The majority of boards in the sample were 11 years of age and showed a mean shrinkage of 2.9%. The slightly higher shrinkage percentage of the older boards was expected, since older wood material contains a bigger proportion of thicker-walled wood cells, which can cause more shrinkage below FSP. Longitudinal shrinkage, which is usually much smaller compared to radial and tangential shrinkage, was not measured in this project.

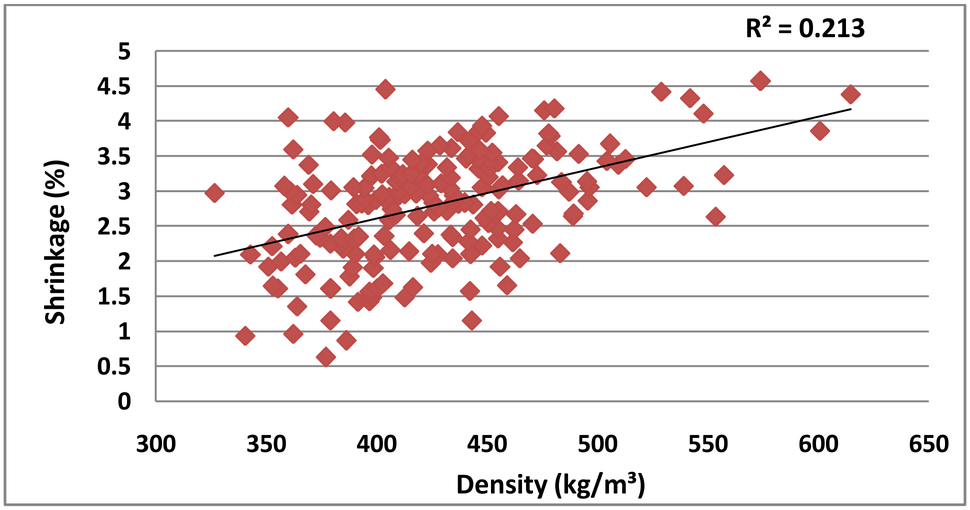

Figure 19: The average shrinkage (combination of radial and tangential) against average basic density (kg/m^3) within the 200 dry boards.

Figure 19 shows that the higher density boards had a slightly higher shrinkage tendency. This compares well with the findings in Table 17, where the denser 18 year old timber had a slightly higher shrinkage percentage in comparison with the boards from the 5 and 11 year groups. It is well known fact that greater shrinkage (in general) is associated with greater density (Simpson et al., 1999).

4.2 Destructive test results

4.2.1 Bending and Tension failure mode

The following photos display the general failure mode of the wet and dry young *E. grandis* product in bending and tension parallel to grain. Although the analysis of the adhesive properties and adhesive system was not included in the scope of this project, the failure mode was still very interesting, and of potential importance to observe.

Figure 20: The failure modes of wet (top left) and dry young *E. grandis* 48 x 73 mm bending specimens.

The majority of failures of the bending and tensile test specimens occurred at or close to the finger-joint part. This was true for both wet and dry specimens as well as 48 x 73 and 36 x 111 dimension boards. What was also interesting was the significant portion of boards that showed “clean” breaks at the pith region. It seemed that the pith material might be a weak link. Observe, for instance the wood failure in the centre of the finger-joint area around the pith section of the laminate on the right in the bottom photo, Figure 20. Sterley (2012) reported in her study on the characterization of green-glued wood adhesive bonds, that low density wood usually contains a higher amount of free water due to its higher porosity, which in turn influences the penetration of the adhesive, with the risk of a “starved” bond. However, the excellent strength results of the *E. grandis* product in the following section will show that there is no cause for concern when it comes to its ability to attain mechanical strength.

Results from the destructive tests, performed according to the SANS 6122 (2008) and AS/NZS 4063 (2010) are shown in Table 18. The table also contains the required characteristic stress values of the different structural grades for SA pine (SANS 10163-1, 2003).

Table 8: The characteristic stress values for wet and dry young green-glued finger-jointed *E. grandis* timber with the SANS 10163-1 (2003) characteristic grade stresses. Values in same row containing different superscripts ($^{a,b\ etc.}$) are significantly different ($p<0.05$)

	Wet specimens				Dry specimens				SANS characteristic grade stresses		
	n	Min	5th perc	Mean	n	Min	5th perc	Mean	5th perc		Mean
Bending strength (MPa)	100	14.9	20.8	37.1^{a}	100	19.5	25.9	43.7^{b}	S5	11.5	
									S7	15.8	
									S10	23.3	
Modulus of elasticity (MPa)	100	5355	7041	9900^{a}	100	5945	7334	9826^{a}	S5	4630*	7800
									S7	5700*	9600
									S10	7130*	12000
Tensile$_{//}$ strength (MPa)	100	3.3	14.9	21.1	100	11.3	14.1	20.7	S5	6.7	
									S7	10	
									S10	13.3	
Tensile$_{\perp}$ strength (MPa)	40	0.2	0.48	0.9	40	0.28	0.3	1.04	S5	0.36	
									S7	0.51	
									S10	0.73	
Compression$_{//}$ strength (MPa)	40	15.4	19.3	24	40	24.8	24.8	26.3	S5	18	
									S7	22.8	
									S10	26.2	
Compression$_{\perp}$ strength (MPa)	40	3.85	4.16	5.8	40	2.92	3.91	7.75	S5	4.7	
									S7	6.7	
									S10	9.1	
Shear strength (MPa)	40	1.55	2.21	3.6	40	2.15	2.7	4.23	S5	1.6	
									S7	2	
									S10	2.9	

***Values from draft version of SANS 10163-1**

4.2.2 Bending strength (MOR) results

The characteristic bending strength values for both the wet and dry samples were surprisingly good. The wet sample (20.8 MPa) conformed to grade S7 and the dry sample (25.9 MPa) to grade S10 requirements (Table 18). The minimum values for both the wet and dry group were also very good, which indicates that no very low strength finger-joints were evident. However, there was a statistical significant difference at the 0.05 level between the wet and dry samples' mean MOR values, which were 37.1 MPa and 43.7 MPa respectively.

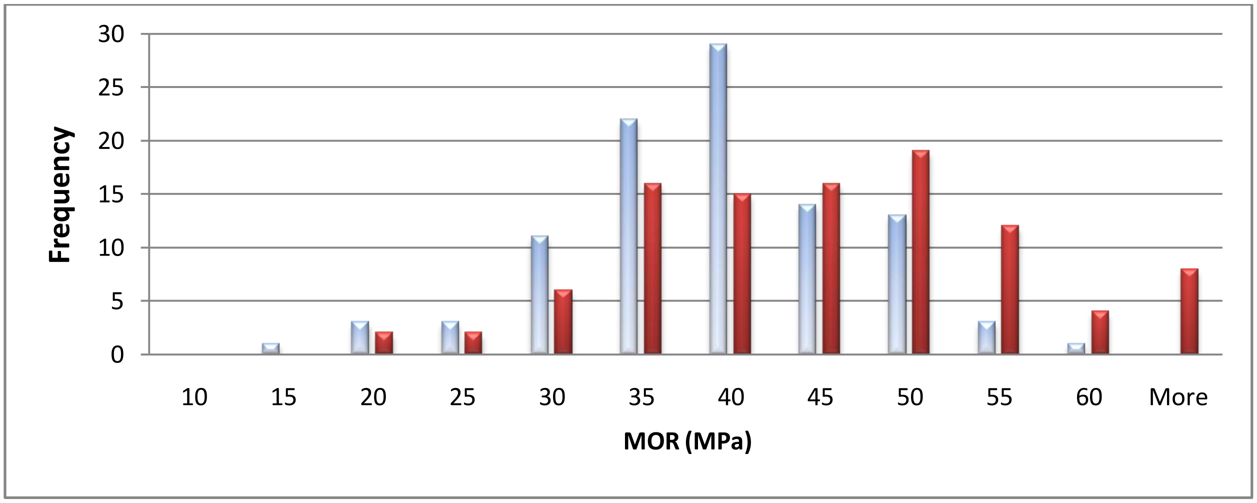

Figure 17: **The MOR distribution of the wet (light) and dry (dark) bending specimens.**

In Figure 21 it is clear that the dry bending sample had more specimens with MOR above 40 MPa. This tendency of higher MOR values at lower MC levels is usually true for solid wood timber, especially in clear wood samples and on average strength comparisons. This compares well to the MC adjustment factors for average bending strength values between wet and dry conditions (Madsen, 1992), displayed in Tables 6 and 7. The MOR results are further discussed and compared to SA pine in the grading section.

4.2.3 Modulus of Elasticity (MOE) results

The stiffness of this product was high, compared to SA pine (Crafford and Wessels, 2011). In both the wet and dry state the 5th percentile MOE and mean MOE requirements of grade S7, according to the SANS, was achieved. It was interesting to note the slightly higher mean MOE value of the wet group (9900 MPa), compared to the dry group (9826 MPa). The slightly lower mean MOE value of the dry group could be partially due to the deformation that occurred during drying. The MOE value for each specimen was computed at a load (approximating characteristic bending strength load of grade S5) where the deflection of the specimen could have happened partly due to deformation such as twist and checks. However, the minimum and 5th percentile value of the dry group was slightly higher than that of the wet group. There was no statistically significant difference between the wet and dry MOE mean values (Figure 22) at the 0.05 level.

The MOE values of the dry sample were also determined (55% of characteristic bending strength load of grade S5) in the wet condition and gave a mean value of 10106 MPa. The same 100 boards were evaluated at EMC and obtained a mean value of 9259 MPa. However, in the case of this dry sample there was a statistically significant difference between wet and dry condition at the 0.05 level. Forty one percent (40.7%) of the dry boards which had a higher MOE value in the wet condition had developed twist and checking values above SANS limits in the dry condition. Therefore deformation such as twist and checking could have negatively influenced MOE values of dry boards. In the testing setup the boards first need to deform so that all the surfaces are parallel to the supports of the testing jig – an action which could possibly result in lower MOE values. Another possible explanation of the slightly lower MOE values in the dry condition could have been the result of heat on the PU adhesive system.

These were very good MOE results compared to SA pine standards and they are further discussed and compared to SA pine in the grading section.

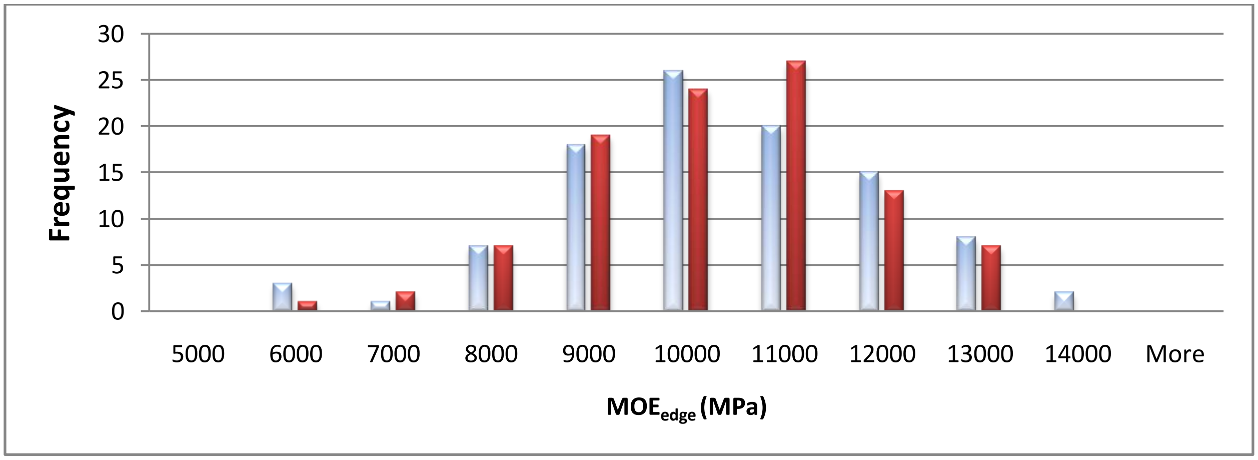

Figure22: **The MOE distribution of the wet (light) and dry (dark) bending specimens**

4.2.4 Tension Parallel to grain results

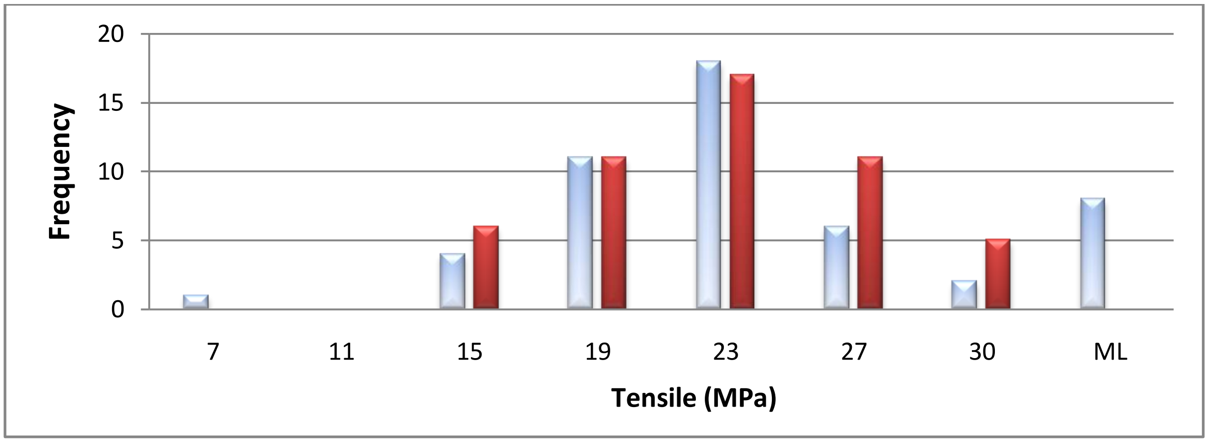

Figure 23a: **The maximum load distribution of the wet (light) and dry (dark) 48 x 73 mm tensile$_{//}$ specimens. ML was the machine limit and equaled 30.4 MPa.**

The 5th percentile tensile parallel to grain maximum load values of the wet (14.9 MPa) and dry (14.1 MPa) group was high compared to SA pine. Both the wet and dry group conformed to grade S10 requirements for tensile strength. Tensile stress in the axial direction is a very important property for roof truss timber material, especially for the bottom-chord of a truss.

The wet sample of the smaller dimension tensile group had one outlier or very weak board (3.3 MPa). Such low strength rogue boards would definitely have been removed if proof grading had been performed. Figure 23a shows a slightly lower level of maximum loads of the dry group compared to the wet group. None of the 48 x 73 mm dry group specimens had reached the 30.4 MPa machine limit (ML), compared to the 8 of the wet group. The lower level of tensile stress of certain dry boards is directly linked to the high percentage (48%) of boards failing at the clamp area as a result of drying deformation. The smaller dimension boards consisted of 60% five year old timber and 40% eleven year old timber. See the following section and Tables 19 and 20. Note; the number of boards that fell within the machine limit category might have had even higher strength values, and therefore tensile$_{//}$ average values need be treated with caution.

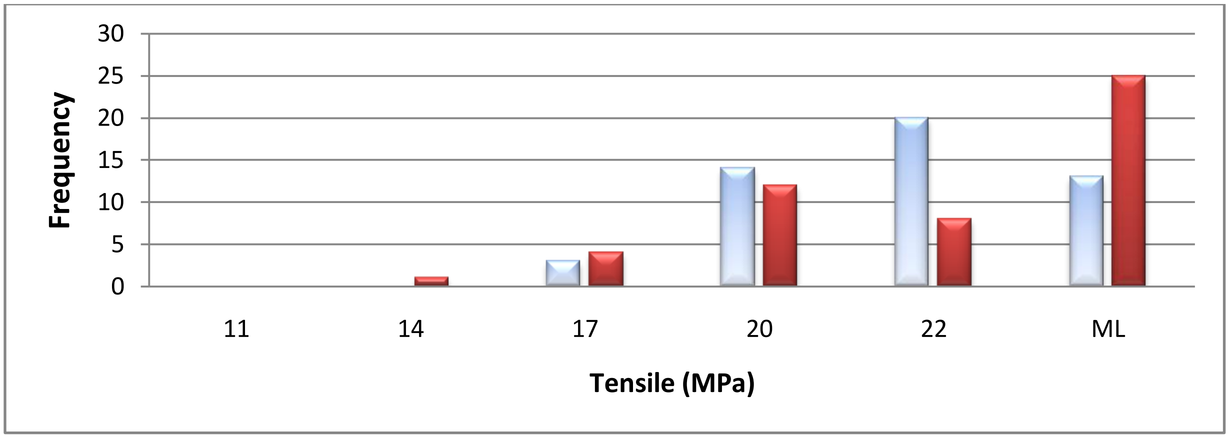

Figure 23b: **The maximum load distribution of the wet (light) and dry (dark) 36 x 111 mm tensile$_{//}$ specimens. ML was the machine limit and equaled 22.2 MPa.**

The opposite was true for the 36 x 111 mm tensile parallel to grain specimens. The dry tensile group had twice the number of specimens that made the machine limit, when compared to the wet 36 x 111 mm specimens, see Figure 23b. The 36 x 111 mm tensile boards had 40% eighteen year old timber and 60% eleven year old timber. These specimens contained less pith material and were therefore more stable during drying. Only 17% of the 36 x 111 mm dry samples' tensile failures that occurred were due to failures at the clamping area. The tensile results might have been even higher, since eight values of the sample's lowest 30 values occurred as a result of specimens failing at the clamp area (Table 19 and 20). Those failure modes were called clamp failures.

Table 19: The percentage of boards of the wet and dry tensile$_{//}$ sample that failed due to clamp pressure.

Max Tensile$_{//}$	n	Width (mm)	Clamp Failure (%)	Clamp Failure (%)	No. of specimens reaching ML
Wet sample	100	73	26.2	26.6	21
		111	27		
Dry sample	100	73	48	38.4	27
		111	17.4		
Comb. sample	200	73 & 111	–	32.5	48

Table 20: **The percentage boards in the lowest 15% test values of the wet and dry tensile$_{//}$ sample according to dimension, twist, checking and clamp failures.**

	n	48 x 73	36 x 111	Twist	Check	Clamp Failure
Wet Tensile$_{//}$ lowest 15%	15	53%	47%	–	–	13%
Dry Tensile$_{//}$ lowest 15%	15	67%	33%	40%	53%	40%

The high percentage of smaller dimension (48 x 73) boards present in the lowest (15%) tensile value region was not surprising. Since the 48 x 73 mm boards contained a large portion of pith material, which tends to have inferior warp and check characteristics compared to the 36 x 111 mm boards. Also the large percentage of twist (40%) and especially checking (53%) in the bottom 15% of the tensile stress values was rather significant. The relationship between twist and checking and weak boards as well as clamp failure in the dry sample, tended to be fairly obvious. Still, the smaller dimension (containing very young wood material) wet finger-jointed timber product performed better than expected, considering the relatively high 5th percentile strength values.

4.2.5 Tension Perpendicular to grain results

The following properties; tension perpendicular to grain, compression perpendicular to grain, compression parallel to grain and shear strength are often considered as less important structural timber properties. This was also the finding in a study on the required properties for roof truss material (Petersen and Wessels, 2011). The limited test material available in the project was considered, and therefore it was decided to allocate less sample material to these tests than the bending and tensile parallel to grain properties. The SANS 6122 (2008) in-grade testing standard does not even contain test methods for the analysis of three of these four properties. Therefore the test methods contained in the AS/NZS 4063 (2010) standards were applied.

Table 18 also displays the characteristic stress values of these four strength properties. The wet perpendicular tensile samples' 5th percentile value (0.48 MPa) conformed to SANS requirements for grade S5. The dry sample (0.3 MPa) did not conform to the required 5th percentile value for grade S5.

The lower characteristic strength value of the dry sample was as a result of pith checking that was present in some of the perpendicular tensile specimens. See Figure 24. The mean value of the dry perpendicular tensile stress sample was still slightly higher (1.04 MPa) than that of the wet (0.9 MPa) sample. This can be explained by the lower MC of the dry group, which has a positive effect on the mean perpendicular tensile strength (Madsen, 1992). Also, checking had a bigger effect on the 5th percentile values than the mean values. Note, only 40 specimens were present in each group, wet and dry, and results should be interpreted with caution.

Figure 24: **Severe checking around the pith in a juvenile tensile⊥ specimen (left) and compression⊥ specimen (right).**

4.2.6 Compression Parallel to grain results

The 5th percentile value of the wet sample conformed to SANS grade S5 requirements and the dry group to S7 grade requirements. Also, the mean compression parallel to grain stress of the dry group (26.3 MPa) compared to the 24 MPa of the wet group, indicates that the dry compression sample tends to show higher strength values. The lower compression 5th percentile value of the wet sample in relation to the higher dry sample value (0.78) compares very well to the prescribed MC adjustment for softwood species of 0.75 (Thelandersson et al., 2003).

4.2.7 Compression Perpendicular to grain results

In this test neither the wet (4.16 MPa) nor the dry (3.91 MPa) samples conformed to the 5th percentile requirement (4.7 MPa) of compression perpendicular to grain of grade S5. The mean of the dry sample (7.75 MPa) was higher than the mean of the wet sample (5.8 MPa), which shows that the dry wood tends to give higher perpendicular compression values on average. The ratio of the mean compression value of the wet sample to the dry sample of 0.75 was exactly the same as found by (Thelandersson et al., 2003) for softwood species. The weak minimum value (2.92 MPa) and the low 5th percentile value of the dry sample were, once again, caused by severe drying defects such as large checks in some of the young material, see Figure 24.

4.2.8 Shear tests results

Both the wet (2.21 MPa) and dry (2.7 MPa) groups conformed to the 5th percentile requirements of grade S7 for shear strength according to the SANS standards. The mean shear strength of the dry group was 4.23 MPa, whereas the wet group had a mean strength of 3.6 MPa.

The specimens used for the compression parallel to grain, bending, tensile parallel to grain and shear tests were all tested under load application in a general axial direction of the fibres within the timber. In theory this means that the complete cross-sectional area is still able to help support axial load (even if checking is present). Therefore the dry sample of those tests usually showed superior characteristic stresses and mean MOE values to that required for S5 timber (SANS 10163-1, (2003), whereas perpendicular tension and perpendicular compression test results showed that the wet samples' 5th percentile values were better than those of the dry sample. This was true because fibres inside the wood are oriented in an axial direction and drying defects such as checking break the weak inter-fibre bonding in the transverse direction, which creates an even weaker surface perpendicular to grain. These drying defects are typical for Eucalyptus timber but rather uncommon for SA pine.

Research by Petersen and Wessels (2011) on timber properties and South African roof truss designs did not include the investigation of perpendicular compression and perpendicular tension. Unfortunately the tension perpendicular to grain and compression perpendicular to grain values were not available in the answer file of the truss analyzing software. However, according to Schalk Brits from Mitek (2011), limitations in the allowable bearing surface area and the joint design ensure that these stresses are not too high. This means that certain minimum nail-plate and wall-plate standards that are set in place would prevent truss structures from failing due to these properties not being stressed to their characteristic stress limits.

4.3 Results related to structural grading

Structural grading of sawn timber can be classified into two main categories; the first is known as proof-grading and the second can be classified as machine or visual grading. Proof grading is arguably the most effective and reliable structural timber grading method, if grading for a specific property. Also, in the case of a resource or product with low strength and stiffness variability, and when one grade is required, this method might also be the most economical method, since proof-loading would be able to guarantee required grades with the best possible yields.

Non-destructive grading is based on timber strength indicator properties which are used to predict the actual strength and stiffness of sawn timber. The efficiency of grading is related to the relationship between these indicator properties and the strength and stiffness of the timber. The following section will show various properties that can be used to predict timber strength and stiffness (although the current planning is based on proof grading of the young *E. grandis* products). The remaining section compares the variability and mean strength and stiffness of the young South African *E. grandis* finger-jointed timber to South African pine solid structural timber.

4.3.1 Correlations between selected measured properties

In the following section selected wood properties (density, MC, and dimension) of the E. *grandis* finger-jointed timber that were deemed to be important were correlated to strength and stiffness properties. All the correlation coefficients (R) measured between various strength properties are shown in Tables 21a, 21b and 21c. The negative values indicate a correlation in the negative direction, for instance MOE goes down as MC increases. Modulus of elasticity of the wet sample (MOE_wet) and modulus of elasticity of the dry sample (MOE_dry) and, finally, modulus of elasticity of the combined wet and dry sample (MOE_wet&dry) were compared to each other as well as to the MOR values of the wet, dry and combined condition. Apart from the fact that some of the relationships reported here might be used for strength grading, it also gives insight to the material behaviour of this timber.

Table 9a: **The Pearson correlation (R) percentage between the flexural properties for E. *grandis* finger-jointed timber. All of the values had a significant correlation ($p<0.05$)**

Property	MOE_wet& dry	MOE_wet	MOE_dry
MOE_wet&dry	100	–	–
MOE_wet	–	100	85.91
MOE_dry	–	85.91	100
MOR_wet&dry	40.37	–	–
MOR_wet	–	37.82	–
MOR_dry	–	–	50.39
n	**200**	**100**	**100**

MOE against MOR

The correlation between stiffness (MOE) and bending strength (MOR) is arguable the most used relationship in timber grading. The correlations between MOE and MOR for all three of the different scenarios (wet, dry and wet&dry) were of statistical significance at the 0.05 level, although this was quite low, compared to other literature (Bailleres et al., 2009). This, however, is expected considering that this finger-jointed timber (consisting of strong and high quality wood) tended to break at the finger-jointed bonding area and not in the solid wood section (Figure 20). Still it is interesting to note that MOE_dry vs. MOR_dry with R = 50.39% and R^2 = 25.4% shows a considerably better correlation compared to MOE_wet vs. MOR_wet with R = 37.82% and R^2 = 14.3%. This clearly indicates that moisture content will have to be considered if a non destructive grading system is introduced. Hence, two different linear equations might be required for predicting wet and dry finger-jointed timber strength.

MOE_wet against MOE_dry

The dry batch consisting of 100 boards was tested in both the initial wet stage (MC was above FSP) and after drying to the EMC. The R-value of 85.91% and R^2 = 73.8% is not that good compared to literature by Emms et al. (2003), where a R^2 = 90.98% between wet and dry solid Douglas fir timber was obtained. However, the lower correlation could be expected since the severe checking and twist that occurred during the drying period could have had a negative effect on MOE in the dry state. Also, I only discovered that there was still a relatively high variability in MC after destructive testing had taken place. This could also have influenced the results.

Table 21b: **The Pearson correlation (R) percentage between various properties of wet E. *grandis* finger-jointed timber and selected strength properties. Shaded areas did not have a significant correlation (p>0.05)**

Wet sample	MOE	MOE_48x 73	MOE_36x 111	MOR	MOR_48x 73	MOR_36x 111
DENS_Min	58.06	52.31	52.31	36.41	28.93	47.99
DENS_Max	58.75	47.81	48.76	16.67	7.95	25.53
DENS_Avg	58.74	50.01	41.48	21.48	14.98	35.13
DENS_Diff	12.85			-22.61		
MC_Min	-32.14	4.76	-29.97	-8.23	3.74	-16.68
MC_Max	-15.14	-3.85	-31.7	-19.88	-17.13	-28.58
MC_Avg	-25.82	-2.63	-30.23	-12.98		
MC_Diff	6.58			-18.41		
n	**100**	**50**	**50**	**100**	**50**	**50**

Both minimum density (DENS_Min) and maximum density (DENS_Max) were obtained from small cross sectional density specimens. The specimens were cut from the laminate section close to where failure occurred within the board. In the case of a finger-jointed breakage, density samples were taken from both adjacent laminates and the lowest and highest density were, respectively, the Min. and Max. values. In the same manner the difference in density (DENS_Diff) was calculated by subtracting the Min. from the Max. value. The average density (DENS_Avg) was simply calculated by adding al the laminates' density values and dividing the total by the number of laminates. MC data was obtained in exactly the same manner.

MOE_wet against Density

In the wet sample, density showed a significant correlation with MOE (Table 21b). The various Dens vs. MOE_wet correlations were very similar. The correlation between MOE and Dens_Min, Dens_Max and Dens_Avg were R=58% and R^2 =34% respectively which compares very well to work done by Bailleres et al. (2009) and Gloss (2004). There was little difference between the two dimensional wet sample groups, 48 x 73 and 36 x 111 mm. This indicates that density can be considered a potential predictor of finger-jointed timber stiffness in the wet state. Dens_Diff has no significant level of correlation with MOE. Figures 25 depict the relationships of Dens_Min with MOE. The scatterplot in Figure 25 shows a linear trend which underlines the significant correlation.

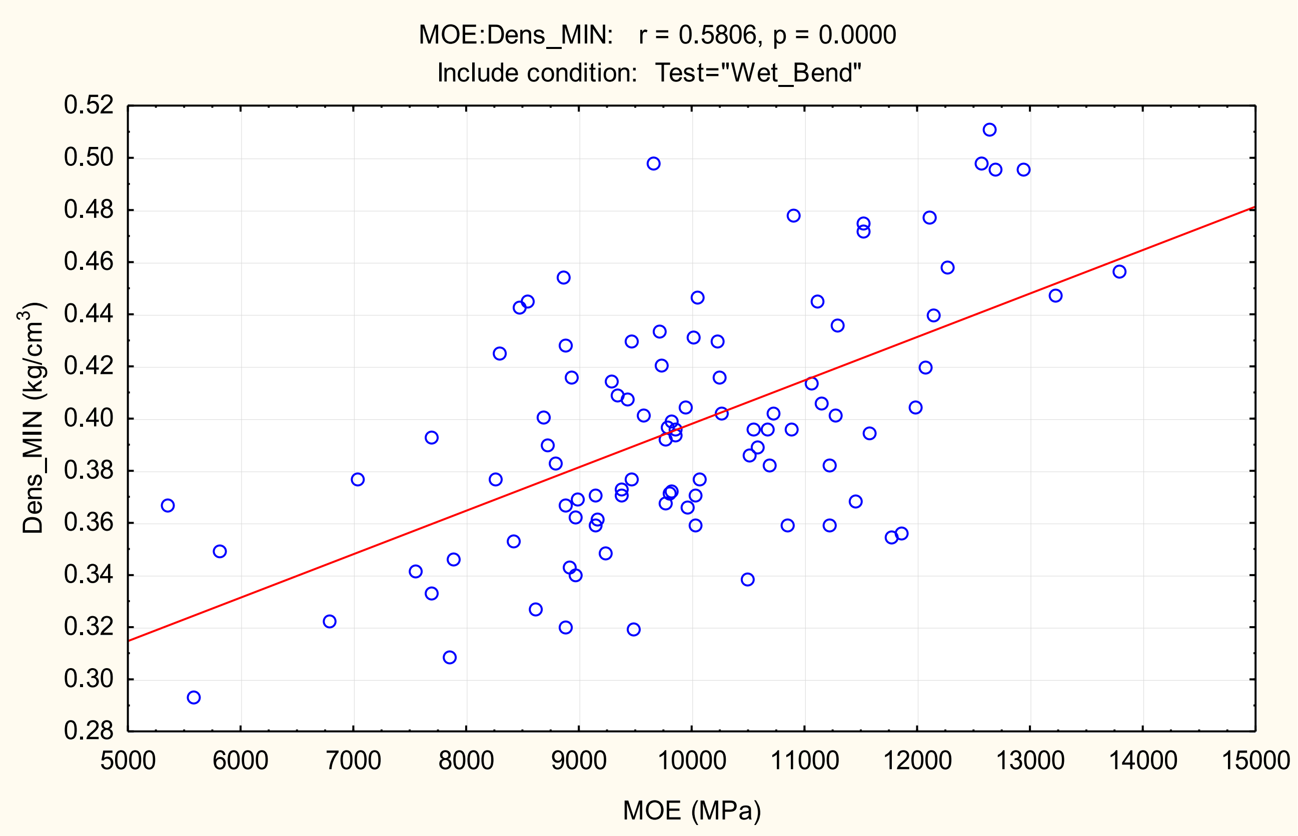

Figure 25: **Scatterplot of MOE against Dens_Min**

MOR_wet against Density

Dens_Min against MOR showed the best correlation (R = 36.41% and R^2 =13.26%) compared to Dens_Max, Dens_Avg and Dens_Diff with MOR. MOR against Dens_Min of the 36 x 111 mm group showed an even better correlation (R = 47.99% and R^2 =23.03%) than the combined MOR_wet dimension and smaller 48 x 73 mm boards. Sterley (2012) also reported that low density specimens might influence joint-ability due to higher MC in the wet condition, which could be a reason for the low correlation value (R = 28.93%) between Dens_Min and MOR of the 48 x 73 mm boards. Therefore these correlation levels were rather low and potentially of little use as a grading parameter on their own. It is interesting to note the correlation R = -22.61% and R^2 = - 5.11% of Dens_Diff vs. MOR, although low, was statistically significant. Density difference was deemed potentially important in this project because finger-jointed timber consists of random boards with varying densities.

MOE_wet against MC

The correlation between MOE_wet and MC_Min (combined 48 x 73 and 36 x 111 mm) showed the best values of R = -32.14% and R^2 = - 10.33% compared to MC_Max, MC_Avg and MC_Diff. It was very interesting to note the significant difference between the correlation values for MC vs. MOE of the two groups, 48 x 73 and 36 x 111 mm boards. The 48 x 73 mm boards showed no significant correlation between MC and MOE. The MOE of the larger 36 x 111 mm boards all had a significant correlation with MC. A possible explanation could be that the higher density 36 x 111 mm boards contained a smaller moisture variation in the wet state, due to their thicker cell wall structure, and would therefore have a better correlation with MOE in comparison to the 48 x 73 mm boards with high moisture content.

MOR_wet against MC

Modulus of rupture and MC correlations prove to be very weak for this finger-jointed timber product. This was positive, in the sense that MC had no significant role in bending strength. Not one of the various MC variables; MC_Min, MC_Max, MC_Avg or MC_Diff showed significant correlation with MOR_wet of the combined 48 x 73 and 36 x 111 mm dimension boards. However, the correlation between MOR_wet and MC_Max of the 36 x 111 mm group were -28.58% (R) and -8.17% (R^2), and the best correlation of this group. Although it was a quite weak correlation, it was statistically significant. Again, this might be due to a smaller variation in the moisture content of this larger dimension group.

Table 21c: **The Pearson correlation (R) percentage between various single indicator wood strength properties of dry E. *grandis* finger-jointed timber and selected strength properties. Shaded areas did not have a significant correlation (p>0.05)**

Dry sample	MOE	MOE_48x 73	MOE_36x 111	MOR	MOR_48x 73	MOR_36x 111
DENS_Min	53.53	61.4	46.7	44.22	60.53	-3.04
DENS_Max	51.16	57.71	42.22	20.76	27.78	-6.44
DENS_Avg	48.16	54.38	37.09	24.95	31.58	-9.09
DENS_Diff	3.44			-18.8		
MC_Min	0.80			4.05		
MC_Max	8.03			-9.92		
MC_Avg	4.89			-6.47		
MC_Diff	4.12			-13.79		
n	**100**	**50**	**50**	**100**	**50**	**50**

MOE_dry against Density

Density showed a significant correlation with MOE in the dry sample (Table 21c). The various density variables vs. MOE_dry correlations were very similar for the combined 48 x 73 and 36 x 111 mm dimension boards. The correlation between MOE and Dens_Min, Dens_Max and Dens_Avg were approximately 51% R and 26% R^2 which was similar to the wet sample. The highest R-values of the correlation between MOE_dry and density were 61.4% and 46.7%, for the 48 x 73 and 36 x 111 mm groups respectively. Dens_Diff had no significant correlation with MOE.

MOR_dry against Density

Density minimum compared to MOR_dry was the only MOR correlation (R = 44.22% and R^2 = 19.55%) with statistical significance. Dens_Max, Dens_Avg and Dens_Diff had no real statistically significant correlation with MOR_dry for any of the dimensional groups. However, it was interesting to note the significantly higher R-value, 60.53%, of the 48 x 73 mm boards compared to the non-significant R-value of -3.04% of the 36 x 111 mm boards for MOR_dry vs. Dens_Min. There were noticeably better correlations between both density vs. MOE and density vs. MOR for the 48 x 73 mm group, when compared to the 36 x 111 mm group. According to Sterley (2012) low density wood usually contains a higher amount of free water in the green condition, due to its higher porosity, which in turn influences the penetration of the adhesive, with the risk of a “starved” bond. This could possibly have led to a weaker correlation of the 48 x 73 mm boards and MOR in the wet state and vice versa. This occurrence simply indicated that density was a good predictor of MOE and MOR for the lower density juvenile 48 x 73 mm boards of this *E. grandis* finger-jointed product in dry state. A higher level of MC counteracted or negatively affected the correlation between density and MOE or MOR for these 48 x 73 dimension boards, whereas a low MC level negatively affected the correlation between density and MOR for the 36 x 111 mm boards.

MOE_dry and MOR_dry against MC

No significant correlation ($p>0.05$) between MOE in the dry state and MC was evident. The same was true for the correlation between MOR_dry and MC. This was expected, since the boards in this sample were dried to roughly EMC and therefore MC levels showed low variability, hence the low level of correlation.

The correlation values that were obtained in this study between indicator properties (density and MC) and flexural properties were, in general quite poor. This was partly expected for finger-jointed timber, which consists of a number of individual solid wood boards. However, it should be noted that proof grading is viewed as a potentially better alternative as a grading method for this product – see the following section.

4.3.2 Comparison between the *E. grandis* finger-joint timber and SA pine structural timber

In the following section the variability in mean strength and stiffness of young *E. grandis* finger-jointed timber and South African pine structural timber are compared and analysed. This comparison will be quite important as the young *E. grandis* finger-jointed timber will, if acceptable, compete against SA Pine in the structural timber market.

Table 22: **The mean, standard deviation, coefficient of variation and characteristic stress values for MOE and MOR of wet and dry young finger-jointed *E. grandis* timber and different SA pine sources and dimensions. Values in same row containing different superscripts (^{a,b}) are significantly different ($p<0.05$)**

	Dimension	**48 x 73 and 36 x 111 mm**		**36 x 111 mm boards**						**36 x 73 mm**
	Source	**Wet_FJ *E. grandis***	**Dry_FJ *E. grandis***	**Wet&Dry_FJ E. *grandis***	**George SA pine**	**Singisi SA pine**	**Langeni SA pine**	**Boskor SA pine**	**Tzaneen SA pine**	**Tzaneen SA pine**
MOE (MPa)	**Mean**	9900.3	9825.8	10627.1	9961.4	8273.6	7898.8	8060.0	6875.6	7557.2
	Std Dev	1601.4^{a}	1493.7^{a}	1248.8^{a}	1853.7^{b}	2065.6^{b}	2160.3^{b}	2490.9^{b}	2181.7^{b}	2632.3^{b}
	Coeff Var (%)	16.2	15.2	11.8	18.6	25.0	27.3	30.9	31.7	34.8
	5th per	7040.8	7334.2	8419.4	6732.3	5488.1	4533.8	4511.8	3437.7	3184.7
MOR (MPa)	**Mean**	37.07	43.72	41.26	39.56	35.61	35.56	37.48	26.34	28.48
	Std Dev	8.27^{a}	12.54^{b}	7.12^{a}	14.13^{b}	15.67^{b}	15.90^{b}	16.06^{b}	11.54^{b}	14.24^{b}
	Coeff Var (%)	22.3	28.7	17.3	35.7	44.0	44.7	42.8	43.8	50.0
	5th per	20.82	25.91	29.79	21.02	17.16	14.99	19.23	11.06	7.87
	n	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note; random selection occurred and no grading was performed prior to testing specimens.

MOE variation

In Table 22 one can clearly see the difference in variation of MOE between the various structural timber sources by looking at the standard deviation results. The *E. grandis* finger-jointed timber, in all three different scenarios, showed significantly lower variation in MOE compared to the SA pine structural timber sources. Also, by looking at the coefficient of variation percentages of MOE, the finger-jointed timber varied between 11.8 and 16.2%, whereas the SA pine solid timber varies between 18.6 and 34.8%. This indicates that the separation of this finger-jointed product into a single grade would be possible with a higher degree of confidence than is the case with these selected solid timber sources which have large variation within a single resource. Also see the following section for the SANS grade potential of this product.

MOR variation

The variation of MOR for the finger-jointed product in the three different states, wet, dry and combined, were also very low compared to the variation in MOR of the SA pine sources. The wet finger-jointed and combined (wet&dry) finger-jointed timber showed statistically significant lower variation in MOR compared to dry finger-jointed and various SA pine timber sources at the 0.05 level. The difference in MOR standard deviation between the wet and dry groups can probably be explained by the severe drying defects that occurred in the (48 x 73 mm) dry boards. However, considering the coefficient of variation for the three finger-jointed timber groups (22.3%, 28.7% and 17.3%) against the coefficient of variation for the SA pine sources (which varied between 35.7% and 50.0%) a large difference in variability in MOR strength between this finger-jointed and solid timber was evident.

The high level of flexural strength and stiffness and low level of variation in both MOE and MOR of the *E. grandis* finger-jointed product was very positive, indicating potential for this product as a structural building component.

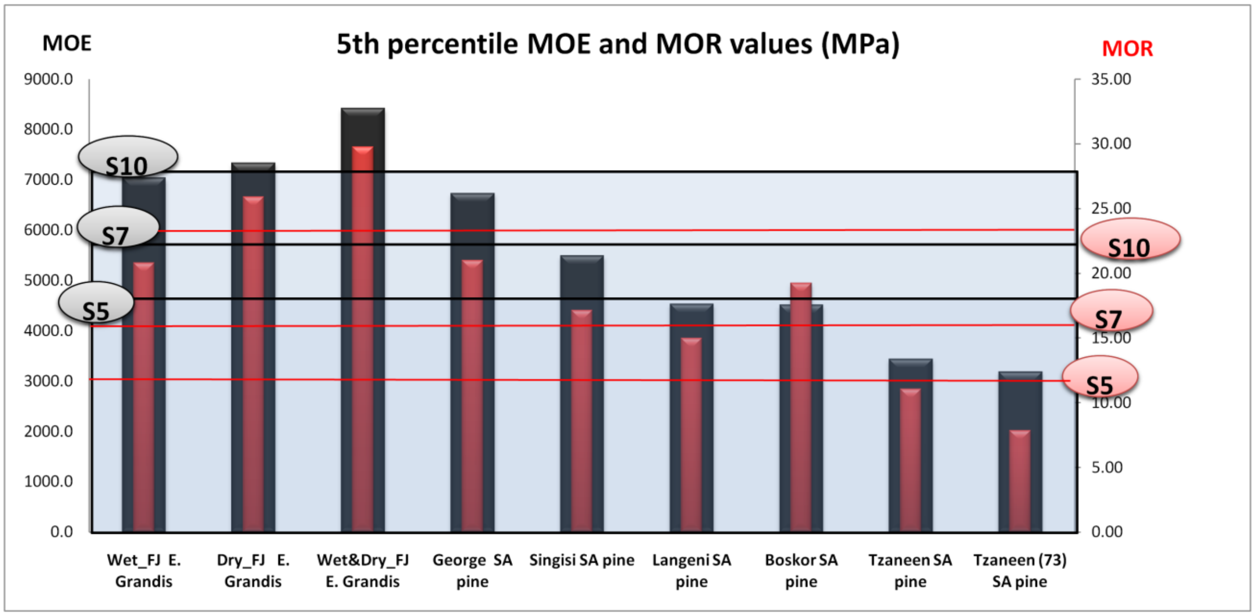

Figure 26: **Histogram for MOE and MOR of (36 x 111 mm) wet and dry young finger-jointed *E. grandis* timber and SA pine from different sources and of different dimensions. Also different 5th percentile grade requirement levels, indicated by dark lines (MOE) and light lines (MOR) from the SANS 10163-1 draft document.**

The results in Figure 26 were obtained from Table 22 and clearly illustrate the superior bending and stiffness of young finger-jointed *E. grandis* timber compared to the SA pine solid timber from various sources. According to research by Petersen and Wessels (2012) MOE and MOR are two of the most important strength properties for truss design. By first looking at the MOE 5th percentile values of the various sources, one can see the noticeable drop in 5th percentile MOE value between the finger-jointed *E. grandis* and solid SA pine timber. The MOE 5th percentile of 7040.8 MPa of the combined dimension sample of wet finger-jointed timber is well above the required value for S7 of 5700 MPa. Even more surprising were the results of the dry finger-jointed timber and combined wet and dry (36 x 111 mm) finger-jointed timber. The MOE 5th percentile values were 7334.2 MPa and 8419.4 MPa respectively and were above the required value of 7130 MPa for S10. In comparison the level of the MOE 5th percentile values of the SA pine solid timber sources were lower. Only one source (George sawmill) was above S7 (5700 MPa) requirements, one above S5 (4630 MPa) requirements and the remaining four sources did not conform to S5 requirements for the MOE characteristic value. Note that random selection occurred in all sampling and that no grading of any sort was performed for any of these sources. Therefore the results were a representation of the sources' intrinsic strength potential and not of any particular grade or grading system. However, the finger-jointed timber clearly out performed the solid SA pine timber in this comparison.

The same was true for the MOR characteristic values, where the finger-jointed timber once again showed very good levels compared to the selected SA pine sources. The MOR 5th percentile of 20.82 MPa of the combined dimension wet finger-jointed timber was well above the required value for S7 of 15.8 MPa. Also the results of the dry finger-jointed timber and combined wet and dry (36 x 111 mm) finger-jointed timber were very good. The MOR 5th percentile values were 25.91 MPa and 29.79 MPa respectively and well above the required value of 23.3 MPa for S10. Once again, the MOR 5th percentile values of the SA pine timber were rather low. Three of the six SA pine sources conformed to SANS grade S7 requirements and the highest source had an MOR 5th percentile value of 21.02 MPa. One source conformed to S5 (11.5 MPa) requirements and the remaining two SA pine sources did not even conform to MOR grade S5 standards. These results in Table 22 and Figure 26 clearly show the superior strength and grade potential of this ungraded green, or wet manufactured, finger-jointed *E. grandis* timber product compared to some ungraded SA pine resources in terms of MOE and MOR.

The values of tensile perpendicular to grain and compression perpendicular to grain strength of the young *E. grandis* finger-jointed product did not conform to SANS requirements for grade S5. Shear strength and compression parallel to grain properties for the wet and dry groups complied with one of the three SANS structural grades. Unfortunately no values of these four 'less important' properties of the current SA pine sources were obtainable for comparisons.

4.3.3 Proof grading

The relatively weak correlations obtained in the previous section indicate the potential difficulty and complexity of utilizing visual or machine grading for this product. However, inline proof grading in either tension or bending (depending on the demand or best practice) will ensure minimum grade strength requirements for one of these properties. Since finger-joints were most often the source of failure it is likely that bending proof grading (in 2 directions) will ensure compliance of tension strength and vice versa. Sample proof grading – where only a sub-sample of boards are tested instead of each board - might also be sufficient if accurate process and quality control are sustained in the manufacturing of the finger-jointed product. In this project the variability in terms of MOE and MOR were quite low, which indicates that sample proof grading might be an option.

4.4 The Biligom concept

The physical and mechanical properties of the green-glued *E. grandis* system have been investigated. Density, warp, checking and shrinkage were deemed important physical properties for this product. All these properties were found to be quite good, considering the samples' age (5-18 years) and compared to SA pine. However, the 48 x 73 mm five year old boards showed considerable amount of twist and checking in the dry state. The mechanical properties and, especially, the flexural properties of the Biligom product in both the wet and dry condition performed surprisingly well compared to SA pine. Tension parallel to grain was also very good and conformed to S10 requirements in both conditions. Shear strength and compression parallel to grain properties for the wet and dry groups complied with one of the three SANS structural grades.

Unfortunately the mechanical properties, which are often considered less important, such as tension and compression perpendicular to grain strength compared less positively to the SANS grade requirements. These properties were not analysed in as much depth as bending and parallel tensile properties due to the limited availability of sampling material. Therefore those results should also be interpreted with caution.

The ratios between different strength properties for this product were very different to SA pine. For instance, the characteristic bending strength : characteristic tension perpendicular to grain strength for SA pine is 1:32 compared to 1:86 for the dry finger-jointed Eucalyptus. It will therefore be very inefficient and wasteful to use the SA Pine softwood grade requirements in terms of characteristic values for this timber resource. For structural design purposes a different table of characteristic values and grades with the values typical for this resource should be included in the SANS 10163-1.

The potential risks regarding this product which were not investigated include the effect of heat on the PU adhesive system, the effect of warp, splitting and checking on nail-plate or mechanical joints, the load capacity of nail plates on this timber, the effect of shrinkage within the truss system, and the possible need for treatment of the sapwood against *Lyctus* beetles.

The issues mentioned above as well as proof grading, as a possible method for structural grading in either bending or tension, should receive attention in future work.

5 Conclusions and Recommendations

The following conclusions are made:

1. The young *E. grandis* finger-jointed timber product tested in this study had very good flexural properties in both the wet and the dry condition. Both mean MOE and MOR 5th percentile strength values complied with the current SANS 10163-1 (2003) requirements for grade S7 without grading.

2. The 5th percentile tensile parallel to grain of both the wet (14.9 MPa) and dry (14.1 MPa) groups conformed to SANS grade S10 requirements.

3. The 5th percentile values of shear conformed to SANS requirements for grade S7 for both the wet and dry groups.

4. The 5th percentile values of compression parallel to grain conformed to SANS requirements for grade S5 for the wet group and grade S7 for the dry group.

5. The 5th percentile values of tensile perpendicular to grain and compression perpendicular to grain strength did not conform to SANS requirements for grade S5.

6. A large number of the 200 dried boards were rejected according to SANS 1783-2 (2004) due to twist (30%) and checking (35.5%). The 5 year old (48 x 73 mm) boards showed significantly higher levels of twist and checking compared to 11 year old boards of the same dimensions.

7. The mean density of this finger-jointed product was low compared to the structural grade density requirements in SANS 1783-2 (2004), and only 46.3% of the finger-jointed product conformed to the requirements for grade S7. There was a significant difference in density between the three age groups (5, 11 and 18 years) presented in this study.

8. The variation in both MOE and MOR values of the finger-jointed products proved to be significantly lower in comparison with SA pine solid timber resources.

9. Based on the results from this study the concept of producing roof trusses from wet, unseasoned and finger-jointed young *Eucalyptus grandis* timber has potential. However, additional research on a number of issues not covered in this study is still required.

The following recommendations are made:

1. A full scale study should be performed on the mechanical and physical behaviour of this *E. grandis* finger-jointed timber product as a structural component within truss structures. The truss structures should consist of wet finger-jointed timber and be fixed as if in a roof construction. Natural seasoning should be allowed before evaluating the truss structures for mechanical integrity and deformation.

2. Proof grading by means of either a tensile or bending-on-flat (in both directions) setup should be further investigated for grading this product. The possibility of sample proof grading should also be considered.

3. Different characteristic strength and stiffness values than those that are appropriate for SA pine is preferable for the *E. grandis* finger-jointed product. In-grade testing on larger sample sizes is required to produce the required characteristic values.

4. Further research is required on the PU adhesive bonding strength and stiffness in a high temperature environment, the application and strength of nail-plate connections onto the young finger-jointed product, and the possible need for treatment of the sapwood against *Lyctus* beetles.

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