Selected mechanical properties and the structural grading of young *Pinus patula* sawn timber

by
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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained herein is my own, original work, and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

December 2010

SUMMARY

In this study 1345 pieces of 38x114 mm timber sawn from 16-20 year-old *Pinus patula* trees were obtained from a wide variety of sites along the Mpumalanga escarpment in South Africa. The samples were tested for various mechanical and physical properties. The objectives of this study were (1) to determine the variation in the bending strength, tension strength, and stiffness of the sawn timber, (2) to assess the efficiency of the current visual and mechanical grading rules on this sample, and (3) to evaluate the potential of some indicator properties to be used as structural grading parameters on this resource.

A large number of non-destructive measurements were performed on all the samples, including scanning of the boards with a commercial X-ray density scanner, moisture content measurement, growth ring measurements, warp measurement, acoustic frequency measurement and measurement of the stiffness using a mechanical grader. The data from the X-ray density scanner was used to calculate a number of knot-related variables for each board. Visual grading according to the SANS 1783-2 (2005) specifications for structural timber was performed by a certified grader on all the boards. The timber was divided into two groups for destructive testing, one group each for bending and tension tests. Tests were conducted according to the SANS 6122 (1994) method for in-grade testing. Due to the sampling method followed, the destructive tests effectively used a random placement of defects with regard to the load application position. From the destructive tests the modulus of elasticity (MOE_{edge}), bending strength (MOR) and tensile strength were determined.

The study showed that the MOE_{edge} of the sawn timber was far below the requirements of the current national standard (SANS 10163-1) for all of the visual and mechanical grades. The mean MOE_{edge} of the visually graded S5 timber was about 30% lower than required. The 5th percentile values for bending strength of all the visual and mechanical grades were above the required values of SANS 10163-1. The 5th percentile values for tensile strength of all the visual and mechanical grades were similar to that required by the SANS 10163-1 standard.

Correlations between flatwise measured MOE (MOE_{flat}) and edgewise measured MOE (MOE_{edge}) were smaller than expected, as well as the correlations between both MOE_{edge} and MOE_{flat} with MOR. Dynamic MOE (MOE_{dyn}), calculated from acoustic frequency tests on the timber, was found to be the best single predictor of MOE_{edge}, MOR and tension strength. Multiple regression analysis showed that a combination of MOE_{dyn}, density and knot parameters can be used to improve the predictability of some of the strength and stiffness characteristics of the timber.

It is recommended that a comprehensive study on the structural grading of SA Pine be performed which includes (1) an analysis of market requirements in terms of strength and stiffness properties of timber, (2) in-grade testing of a representative sample of structural timber in South Africa, and (3) a review of the standards used in South Africa to regulate the structural grading of timber.

OPSOMMING

In hierdie studie is 1345 stukke 38x114 mm 16-20 jaar-oue *Pinus patula* planke, afkomstig van ‘n wye verskydenheid groeiplekke teen die Mpumalanga platorand in Suid Afrika, gebruik. Die planke is getoets vir verskeie meganiese sowel as fisiese eienskappe. Die doelwitte van hierdie studie was om (1) die variasie in buigsterkte, treksterkte en styfheid van die gesaagde planke te bepaal, (2) die effektiwiteit van die huidige visuele -en meganiese graderingsreëls op hierdie monster planke vas te stel, en (3) die potensiaal te evalueer van sommige eienskappe wat gebruik kan word as strukturele graderingsparameters.

‘n Groot hoeveelheid nie-destruktiewe toetse is op alle planke uitgevoer, wat ingesluit het skandering van planke met ‘n kommersiële X-straaldigt-heidskandeerder, metings van voginhoud, groeiringwydtes, deformasie, akoestiese frekwensie en die bepaling van styfheid met behulp van ‘n meganiese gradeerder. Die data van die X-straalskandeerder is gebruik om ‘n aantal kwasverwante veranderlikes vir elke plank te bereken. Visuele gradering is op alle planke uitgevoer ooreenkomstig met die SANS 1783-2 (2005) spesifikasies vir strukturele hout deur ‘n gesertifiseerde gradeerder. Die hout is in twee groepe opgedeel vir destruktiewe toetse, een vir buigtoetse en een vir trektoetse, ooreenkomstig met die SANS 6122 (1994) metode vir binnegraadse toetse. As gevolg van die monsternemingsmetodiek wat gevolg is, is daar effektief gebruik gemaak van ‘n lukrake plasing van defekte met betrekking tot die las-aanwendingsposisie. Die modulus van elastisiteit (MOE_{edge}), buigsterkte (MOR) en treksterkte is deur middel van destruktiewe toetsresultate bepaal.

Die studie het aangetoon dat die MOE_{edge} van gesaagde hout aansienlik minder as die vereiste van die huidige nasionale standaard (SANS 10163-1) is vir al die visuele en meganiese grade. Die gemiddelde MOE_{edge} van die visueel-gegradeerde S5 planke was omtrent 30% laer as vereis. Die 5^{de} persentiel waardes vir buigsterkte van alle visuele en meganiese grade was hoër as die vereiste waardes soos voorgeskryf deur SANS 10163-1. Die 5^{de} persentiel waardes vir treksterkte van alle visuele en meganiese grade was gelykstaande aan wat vereis word deur SANS 10163-1.

Korrelasies tussen MOE, gemeet op die wydte sy (MOE_{flat}), en MOE, gemeet op die diktesy (MOE_{edge}), asook die korrelasies van beide MOE_{edge} en MOE_{flat} met MOR van die planke was laer as verwag. Dinamiese MOE (MOE_{dyn}), wat bereken was vanaf die akoestiese frekwensie resultate, is vasgestel as die beste enkele indikator van MOE_{edge}, MOR en treksterkte.

Meervuldige regressie analise het aangetoon dat 'n kombinasie van MOE_{dyn}, digtheid en kwasparameters gebruik kan word om die voorspelbaarheid van sommige van die sterkte- en styfheids eienskappe van die hout te verbeter.

Daar word aanbeveel dat 'n omvattende studie gedoen word op die strukturele gradering van SA Dennehout, wat insluit (1) 'n analise van die markbehoeftes in terme van die sterkte- en styfheids eienskappe van hout, (2) binnegraadse toetsing van 'n verteenwoordigende monster strukturele hout in Suid Afrika, en (3) die hersiening van standaarde in gebruik in Suid Afrika om die strukturele gradering van hout te reguleer.

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TABLE OF CONTENTS PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

# Knots	The number of knots on a single piece of timber
Knot avg.	The mean area per knot on a piece of sawn timber (mm^2)
Knot area / board	Total area of the timber surface containing knot material (mm^2)
Knot max	Maximum knot size on a piece of timber (mm^2)
Knots 1-7F	Parameter calculated by the X-ray scanning device using data of a combination of 7 knots on each full piece of timber
$KPar_f$	Knot parameter from the most influential knot on the full board
$KPar_c$	Knot parameter from the most influential knot on the centre third of the board
KSC	The product of the knot size and the stress index of a specific knot where the stress index is a ratio of the bending stress at a specific knot to the maximum bending stress in a piece of timber
MC	Moisture content of timber (%)
MOE	Modulus of elasticity (stiffness) of timber (MPa)
MOE_{dyn}	Dynamic modulus of elasticity calculated from the acoustically determined natural frequency and the mean density of a piece of timber (MPa)
MOE_{edge}	Modulus of elasticity determined from an edgewise bending test where the neutral axis is parallel to the thickness edge of a piece of timber (MPa)
MOE_{flat}	Modulus of elasticity calculated from a flat-wise bending test where the neutral axis is parallel to the width of a piece of timber (MPa)

MOR	Modulus of rupture also known as bending strength (MPa) (determined in edgewise bending throughout this study)
N	The number of timber pieces tested (test sample size)
NDE	Non-destructively evaluated
Position	A position number allocated to each timber piece starting from the pith being 0
ρ_m	Mean density of a piece of timber calculated after kiln drying from manual measurements of dimensions and mass (kg/m³)
ρ_s	Mean density of timber measured after kiln drying by X-ray scanner (kg/m³)
r	A correlation coefficient between outcomes and their predictors or indicator properties. It indicates how good a property is at predicting another
R^2	The square root of r. Determination coefficient
Ring max	Maximum annual ring width in a single piece of timber (mm)
Ring min	Minimum annual ring width in a single piece of timber (mm)
Ring avg.	Mean annual ring width in a single piece of timber (mm)
St. Dev	Standard deviation
Tension	Tension strength measured parallel to grain (MPa)
Timber	Defect containing pieces of sawn wood
Warp	Collective term for timber that has deformed from its original position. Includes twist, spring and bow
X-Dev	Density deviations measured by X-ray scanning device within a single piece of timber.

1. INTRODUCTION

Nearly 70 percent of South Africa's sawn pine timber production is classified as structural or building timber (Crickmay and Associates, 2009). Structurally graded timber may be used in load bearing structures such as roof trusses, beams or floor supports. Concerns have been raised in the past that the mechanical properties of SA pine are changing (Burdzik, 2004). The main concern is that structural timber conforming to the SANS visual grade requirements might have inferior strength and stiffness properties relative to the requirements of a specific stress grade. Burdzik (2004) tested structural timber from four sawmills in "low density regions", and found that only one sawmill's timber made the grade requirements for bending and tensile strength. None of the sawmills' graded timber met the requirement for mean modulus of elasticity (MOE). However, the timber auditing company SATAS reported that timber from ten sawmills that has recently been tested in tension conformed to the grade requirements (personal communication between Brand Wessels and Abe Stears, 27/01/2009). Graded timber in South Africa is being used mainly in roof trusses of residential houses where the safety of the inhabitants, builders and maintenance workers is at stake. It is important for both the producers and users of structural timber that timber products comply with the strength and stiffness values used by designers of structures (as published in SANS 10163-1). The argument that we do not see many timber structures failing is insubstantial. Timber under stress looses strength over time - this is also referred to as the load duration effect. This means that the effect of non-compliance to grade strength requirements might only be seen in 10 or 15 year's time.

Timber grading can simply be explained as the sorting of timber into different strength classes without damaging it (Pellerin and Ross, 2002). A more detailed description of structural grading follows in the literature review section of this thesis. Although the actual strength of wood can only be determined by destructive tests, the non-destructive methods used during grading estimates the strength of the wood through the use of indicator or concomitant properties (Hanhijärvi and Ranta-Maunus, 2008). These are properties such as knots, density and stiffness. When timber falling into certain stress grades according to the current grading rules (i.e. visual or mechanical) does not comply with the required characteristic strengths or stiffness of that grade, it means that either the grading rules have to be altered or the characteristic strength and stiffness values have to be changed.

In this project a specific part of the South African sawn timber resource, young *Pinus patula* trees from the Mpumalanga area, was used as study material. Various properties of the timber were non-destructively evaluated after which the timber was destructively tested in bending and tension. The objectives of this study were as follow:

- to determine the variation in the bending and tension strength, and stiffness of sawn timber from young *Pinus patula* trees;
- to assess the efficiency of the current visual and mechanical grading rules on this resource (SANS 1783-2, 2005 and SANS 10149, 2002); and
- to evaluate the potential of some indicator properties that could be used as structural grading parameters on this resource.

Results from this study can either be used to reassure users of structural *P. patula* timber of the structural integrity of these products, or impress the need for new grade properties with regard to the current timber resource. It will also show the effectiveness of the different grading methods in separating timber according to its actual strength and stiffness properties. New, more refined grading methods can improve the efficient use of our current and future resources by better identification and assignment of timber into the appropriate strength classes. The proper grading of timber has the potential for increasing the profitability of sawmills as well as for the conservation of our natural wood resource.

2. LITERATURE REVIEW

2.1. Characteristic stress values of structural timber

The strength and stiffness of a piece of timber can be described by six different strength values and a stiffness or modulus of elasticity (MOE) value. Table 1 shows these values, also referred to as characteristic values, for the different structural grades of SA Pine (SANS 10163-1, 2003).

Table 1: Characteristic stresses for South African pine according to grade (SANS 10163-1, 2003). Values in MPa.

1	2	3	4	5	6	7	8
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
5	11.5	6.7	0.36	18	4.7	1.6	7800
7	15.8	10	0.51	22.8	6.7	2.0	9600
10	23.3	13.3	0.73	26.2	9.1	2.9	12000

These characteristic values are also referred to as “design values” or “5th percentile values”. The characteristic 5th percentile value is derived from destructively testing a large number of samples of a given grade. In simple terms: if 100 pieces of timber are destructively tested, the 5th lowest value will be the characteristic value for that grade. Testing in most countries is performed using a process called in-grade testing, where timber is tested destructively in order to evaluate and / or adjust the grading process. Madsen (1992) describes the in-grade testing process as follows:

- the testing should emulate the end use conditions of the material as closely as possible;
- representative samples of full-sized specimens are tested in sufficient quantities to reliably establish the characteristic strength (5th percentile);
- the concept of a proof load failing about 10-15% of the test specimens is used;
- relatively fast load application is employed in order to speed up the testing process;

- portable testing equipment is preferable so that the testing could be performed at the sawmill;
- bending tests are performed with a span to depth ratio of 17 to 1 and loads in the third point; and
- the worst defect is placed randomly with respect to tension zone and length.

The in-grade test procedures are different depending on the standards authority i.e. the ISO 13910 (2005) method requires the worst defect to be placed randomly whereas the SANS 6122 (1994) method requires the worst defect to be placed in the centre third of a bending test.

2.2. Structural grading of sawn timber

Grading is the process of sorting lumber into categories to which allowable design properties can be assigned using standardized methodology through non-destructive evaluation (Pellerin and Ross, 2002). The real strength of timber can only be determined by destructive tests (Hanhijärvi and Ranta-Maunus, 2008), therefore an in-grade testing procedure is needed to determine the characteristic values for each grade. In other words, timber must first be graded non-destructively before the characteristic values of a grade can be determined using in-grade testing. In-grade testing for grade verification is typically performed only when there are changes to the nature or character of a timber resource – which is normally not very often. The quality of a timber resource can change because of silvicultural factors, including forest management rule changes, harvesting cycle time changes and introduction of new timber species, as well as climate changes affecting seasonal growth and growth rate of trees (McKeever, 1997).

The problem with structural grading is that concomitant or indicator properties must be used to predict the actual strength and stiffness of sawn timber and the efficiency of grading depend on the strength of the relationship between this indicator property and strength or stiffness. The following section describes some of these indicator properties and the relationship with timber strength and stiffness. It is important to realise that timber containing defects has a different failure mode to clear wood (Madsen, 1992). For this reason timber (wood containing all the natural growth characteristics) and clear wood have to be viewed as two different materials when strength properties are determined. A considerable part of research in the past focused on clear wood strength properties which are not applicable to structural grading of timber.

2.2.1. Properties which influence timber strength and stiffness

For structural grading systems it is important that the indicator properties used to grade the timber have a strong relationship with timber strength and stiffness. The following growth characteristics or properties of timber influence the strength and stiffness thereof.

2.2.1.1. Knots

The average knot volume in a stem is generally between 0.5 to 2%. The affected surface area of the timber, however, is up to 3 times greater than that of the knot itself, as the alignment of the axial tracheids around the knot is disturbed (Walker, 1993). Walker also notes that knot volume is proportionally greater in young stands, especially with wide initial spacing and thinning, where the trees have larger branches. Large knots drastically reduce strength and are a major cause of downgrade in timber. Edge knots are knots that borders on the side or edge of the board, and are normally under tension or compression. They behave as if they are internal knots of approximately twice their actual size (Walker, 1993).

Knots alone are poor predictors of strength, but when locations of knots are taken into account, prediction values improve somewhat (Johansson in Thelandersson and Larsen, 2003). Both Johansson and Giudiccandrea and Verfurth (2006) compared different studies and found degrees of determination (R^2) of 0.20 to 0.42 between various knot parameters and timber MOR and tension (see Tables 2 and 3). When knot parameters were measured using a modern X-ray scanner an R^2 of 0.5 with MOR of some of the European pines were found (Bacher, 2010). In a study done by Johansson et al. (1998) it was found that in destructive bending or tension tests the failure is caused almost exclusively by knots, while Johansson et al. (in Thelandersson and Larsen, 2003) found that knots account for up to 66% of downgrades during visual grading. Knuffel (1984) found from laboratory data that visual grading could be improved by placing more emphasis on knot data than on density.

Table 2: Degrees of determination (R^2) from various investigations of the relationship between strength and other properties of Norway spruce timber (Picea abies) – the sources of the investigation are numbered from 1 to 6 (Hoffmeyer in Thelanderson and Larsen, 2003)

Characteristics that can be measured non-destructively	**Degree of determination** R^2						
	MOR				**Tension**		
Source	[1]	[2]	[3]	[4]	[1]	[5]	[6]
Knots	0.27	0.2	0.16	0.25	0.36	0.42	0.30
Annual ring width	0.21	0.27	0.2	0.44	0.36	0.33	0.28
Density	0.16	0.3	0.16	0.4	0.38	0.29	0.38
MOE, bending or tension	0.72	0.53	0.55	0.56	0.70	0.69	0.58
MOE, flatwise, short span							0.74
Knots + annual ring width	0.37	0.42	0.39		0.49		
Knots + density	0.38		0.38		0.55	0.61	0.64
Knots + MOE	0.73	0.58	0.64		0.70	0.76	0.78

[1]. Johansson et al. (1992), [2].Hoffmeyer (1984), [3].Hoffmeyer (1990),
[4]. Lackner et al. (1988), [5]. Glos et al. (1982), [6] Johanssen (1976)

Table 3: Degrees of determination (R^2) for MOR predictions by different indicator properties (from Glos, 2004 as recreated by Giudiccandrea and Verfurth, 2006).

Indicator properties to predict timber strength (Grading modulus)	**Degree of determination** R^2
Knots	0.15 – 0.35
Density (using X-ray etc)	0.20 – 0.40
Frequency (acoustics)	0.30 – 0.55
MOE	0.40 – 0.65
Knots & density (data combined)	0.40 – 0.60
Knots & density & frequency	0.55 – 0.80

2.2.1.2. Density

Density is a direct measure of the amount of cell wall material in the timber (Walker, 1993). Although density has traditionally been considered as the most important "quality property" in wood (Zobel and Van Buijtenen, 1989), its correlations with the strength of timber are generally regarded as poor, with Table 2 showing R^2 values of 0.16 to 0.40 between density and bending or tensile strength. Guidiccandrea and Verfurth (2006) reported R^2 values of 0.2 to 0.4 between density and strength (MOR). Hanhijärvi and Ranta-Maunus (2008) however found an R^2 of 0.55 between density and MOR of 38x100 mm *P. sylvestris* from Europe.

Density in wood increases considerably from earlywood to latewood. A study done on ten 80-100 year-old Scots pine trees from Australia showed the latewood percentage to be an important criterion in assessing wood properties (Wimmer, 1991). Density is also affected by the silvicultural interventions typical of plantation forestry. Moschler et al. (1988) showed a decrease in earlywood density after thinning (425 kg/m^3 to 408 kg/m^3) and an increase in density for latewood (576 kg/m^3 to 643 kg/m^3) for 16 year-old *Pinus taeda* trees.

2.2.1.3. MOE

MOE, or stiffness, is normally seen as the best individual predictor of strength, with results found by Johansson et al. (in Thelandersson and Larsen, 2003) and those in Table 2 reporting R^2 values of between 0.51 and 0.73 between edgewise MOE and tension or MOR. Glos (2004) found R^2 values of between 0.4 and 0.6 (Table 3). Knuffel (1984) found an R^2 value of 0.47 between MOR and MOE_{flat} of SA Pine using a 600 mm span.

These values are confirmed by the results in Table 4, which depicts correlation results from the tests done by Bailleres et al. (2009). This study also compared the difference in results when locating the worst defect in the central third of the test span (biased) vs. random placement of defects (random). The r values of 0.7 to 0.81 for the correlations between MOE_{edge} and MOR are equivalent to R^2 values of 0.49 to 0.66.

Tests done by Gaunt (1999) show MOE and MOR comparisons done on both old crop as well as 19 year old radiata pine from New Zealand. Flatwise stiffness values (MOE_p at the point of lowest stiffness) were related to MOR as well as MOE_{edge} values for the two samples. The R^2 values found are shown in Table 5. The differences can however not be said to be only because of the crop age differences, as the 19 year old crop was tested at the position of lowest MOE, while the old crop was tested with random defect placement.

Table 4: Degrees of determination (R^2) between density, MOE and MOR for different pine species with different bending test setups (Bailleres et al., 2009)

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

Table 5: Comparison of old and new crop R^2 values for New Zealand radiata pine (Gaunt, 1999)

	Old crop	**19 year old crop**
$MOE_{p\ min}$ vs. MOR	52.4	15.03
$MOE_{p\ min}$ vs. MOE_{edge}	68.37	47.87

2.2.1.4. Microfibril angle

Cellulose occurs in the predominant cell wall layer (S2) as very long crystalline microfibrils, wrapped in a steep helix, which provides longitudinal stiffness in the direction of the microfibril axis (Cave and Walker, 1994).

The term microfibril angle refers to the angle between the direction of the helical windings of cellulose microfibrils in the secondary cell wall of fibres and tracheids and the long axis of the cell (Barnett and Bonham, 2004).

Microfibril angle affects both the strength and dimensional stability properties of wood. The overall strength of juvenile wood of *P. radiata* has been found to be affected more by differences in microfibril angle than wood density (Cave and Walker, 1994). Cave and Walker concluded that fibril angle was the only factor that alone could account for the pronounced decrease in MOE of this species from pith to bark. Microfibril angle, however, cannot be measured rapidly and economically as is required for industrial grading systems.

2.2.1.5. Spiral grain

Spiral grain is grain that does not run parallel to the longitudinal axis of a tree. In sawn timber it manifests in the grain of the piece of timber not being parallel to the length axis of the board. Therefore, the actual strength values will be a combination of parallel-to-grain and perpendicular-to-grain characteristics.

Hankinson (1921) developed an equation to calculate the strength of timber at any grain angle when the parallel-to-grain and perpendicular-to-grain strength values are known. The longitudinal tension strength has been found to be more severely affected by grain deviation than longitudinal bending strength and compression strength (Dinwoodie, 2000). Glos (2004) stated that severe spiral grain occurs very seldom, but when it occurs it has a negative effect on the strength of timber. The influence of spiral grain is, however, more pronounced in some species and growth regions than others. For these reasons, restrictions are included in many structural timber grading standards i.e. EN 518 (1995), SANS 1783 (2005) and AS 2858 (2003).

Other defects in wood that will affect strength but are not discussed here include, amongst others, fissures, cracks, resin pockets, soft rot and compression breaks.

2.2.1.6. Juvenile wood

Juvenile wood has a very strong bearing on various wood properties. These include density, microfibril angle, fiber lengths and other properties.

The inner part of the tree is called juvenile wood and generally has lower strength and stiffness properties than the outer or adult wood (Walker, 1993). The less desired properties of juvenile wood include low basic density, a tendency to contain above average amounts of compression wood and a greater longitudinal shrinkage, giving a higher percentage of warped timber (Walker, 1993). The change in timber quality has to do with the gradient in density and other properties from pith to the bark that generally occurs in pines. The lower density wood in the 5 to 10 growth rings surrounding the pith is called juvenile or corewood (Walford and Gaunt, 2006).

Figure 1 shows the increase in density up to 20 years, after which it flattens out.

In the relatively few studies that compared MOR and MOE of juvenile and mature wood, consistently lower values were found for juvenile wood (Larson et al., 2001).

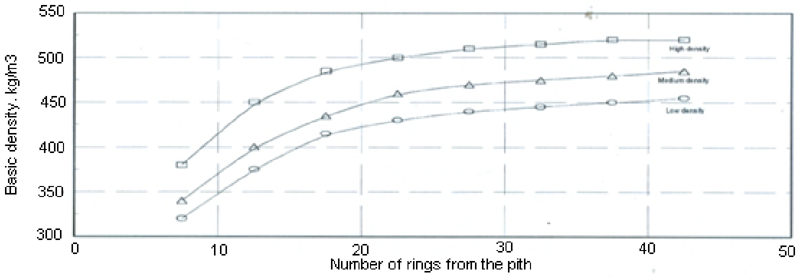

Figure 1: Density variation in radiata pine trees from the pith to the outer part of the tree
(Walford and Gaunt, 2006)

2.2.1.7. Natural vibration frequency

Jayne (1959) proposed the hypothesis that the energy storage and dissipation properties of wood are controlled by the same mechanisms that determine static behaviour of the wood. As a consequence useful relationships between the acoustic and vibrational properties, and static elasticity and strength are attainable. For instance, a strong relationship exists between the microfibril angle, an important determinant of wood stiffness, and the acoustic velocity in wood.

Wang et al. (2007) reported a degree of determination (R^2) value of 0.86 between acoustic velocity and microfibril angle of radiata pine. Evans and Ilic (2001) reported similar values. There are a number of techniques that can be used to measure these energy storage and dissipation properties of timber but the method of choice, for the majority of researchers as well as industry role players, is that of measuring the natural vibration frequency using acoustic measurement devices.

Natural vibration frequency testing is fairly simple because of the fact that the force one needs to induce a vibration is not very big (Hanhijarvi et al., 2005). The sample is hit at one end, generating a compression wave that moves down the sample 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 sample and the tensile wave is reflected and travels back down the sample (Pellerin and Ross, 2002).

The modulus of elasticity is calculated with the equation (Bacher, 2008):

$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)^2$ where:

MOE_{dyn} is the modulus of elasticity calculated from frequency tests, in MPa;

ρ is the density of the test specimen at the time of testing, in kg/m^3;

l is the length of the test specimen in meters; and

f is the frequency of the wave, in Hertz.

Bucur (2005) explains that care must be taken to ensure that frequency losses through the suspension system used to support the test samples are not significant compared to losses through the specimen itself.

Fast Fourier Transformation (FFT) is a widely used signal processing and analysis method for frequency measuring. Frequency measuring as a method for strength determination, as well as the variables that affect it, is discussed in an honours report on the subject (Dowse, 2009). The study showed high correlation values of about 88% between MOE_{dyn} and MOE_{edge}, although this was on a very small sample size (25 samples). Different frequency analysing programs were also tested in this study and finally the AG-Portable software (Falcon Engineering) was suggested for use in follow-up tests. Görlacher (1984) found the natural frequency method to correlate very well with the statically determined MOE. Blass and Gard (1994) obtained an R^2 of 0.45 between natural frequency and strength of Douglas fir, while the relationship between MOE_{edge} and bending strength gave an R^2 of 0.50. Table 2 shows R^2 values of between 0.3 and 0.55 obtained between MOE_{dyn} and MOR.

Larsson (1997) tested Norway spruce and obtained R^2 values of 0.68 to 0.91 between MOE_{dyn} and MOE_{edge}.

2.2.1.8. Combinations of properties

Several commercial grading systems on the market today can measure a combination of dimensions, density, natural vibration frequency, moisture content, knots and other defects in timber. They make use of cameras, optical lasers, radiation and ultrasound or frequency measurement units (Bacher, 2008; Rais et al., 2010; Schajer, 2001). Destructive tests were in many cases performed to identify the correct machine settings for a specified species (Rais et al., 2010). Schajer (2001) compared the X-ray method, where density was used together with knots and knot positions, with destructively measured MOR and found an R^2 of 0.7, whereas traditional bending based lumber strength grading machines had R^2 values of around 0.55 or less. The X-ray method was equally successful in predicting tension, compression strength and MOR.

In practice, grading machines consider the knots in the full length of the board and not only the centre part, where laboratory testing machines are not always able to test the full length of the timber because of the test setup. Rais et al. (2010) found a five percent increase in the correlation between the indicator property and MOR by combining knots with MOE. The study also showed that the additional knot information is of more importance in higher strength classes. This can be expected as the stronger wood is normally found on the outside part of the tree where the branch diameters are bigger than closer to the pith. Bacher (2008) compared some combination machines and found the GoldenEye-706 to have the highest grading performance for an industry strength grader. It was found to measure timber density with an R^2 of 0.89. A knot parameter comparison to timber strength with the use of a GoldenEye X-ray scanner also showed R^2 values as high as 0.5, depicted in Figure 2, (Bacher, 2010).

Numerous tests done on spruce and pine by Hanhijärvi *et al.* (Hanhijärvi and Ranta-Maunus, 2008), showed that combining two good NDE measurements raises the R^2 values in most cases by about 0.1. By combining density and knot measurements, R^2 values of 0.5 to 0.7 were obtained.

The results from Table 2 show the ability of NDE methods to predict MOR and tension. Table 3 also shows R^2 values for MOR predictions by different combinations of indicator properties. Both Tables 2 and 3 show a moderate correlation when combining knots and density as a predictor of timber strength. That value is increased when frequency is added as a predictor.

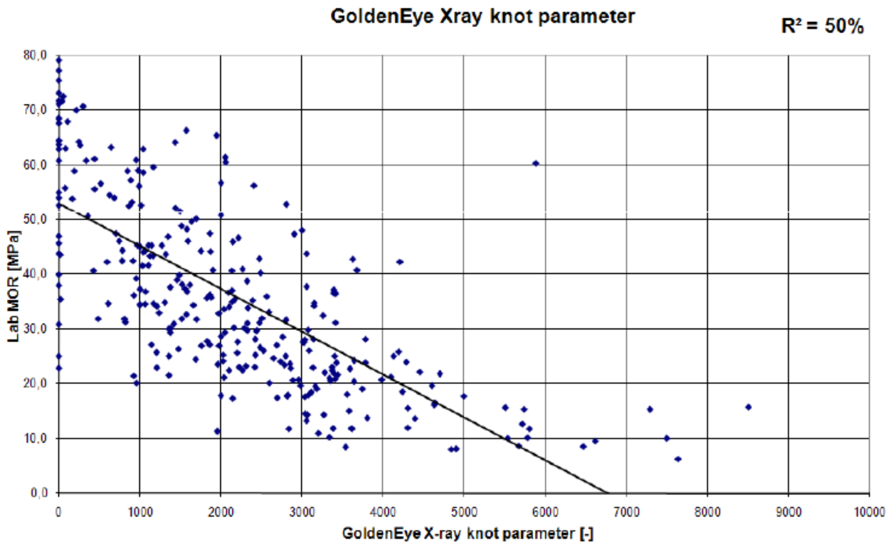

Figure 2: Knot parameters against MOR (Bacher, 2010)

Rais et al. (2010) compared two indicator properties. The one was based on dynamic MOE (MOE_{dyn}) (eigenfrequency and density) alone and the other on MOE_{dyn} and knot information. The inclusion of knots led to an increase in the degree of determination (R^2) for MOR by about five percent over MOE_{dyn} alone.

It is very important that the machine settings are calibrated regularly. Tests were done by Dowse (2009), on a combination X-ray machine of which the settings were not correctly calibrated. The study showed very poor results with the dimension measurement accuracy in particular.

2.2.2. Visual and machine grading

Some of the measurable properties discussed in the previous section are used in both visual and machine grading systems to separate timber into strength classes.

Visual grading focuses mostly on knot properties to grade timber and the visual grading rules were established in various countries based on many destructive tests.

These rules are valid for a defined species from a specified growth area. The grading rules are observed by the visual grader, but it is assumed that he will not change the rules according to the timber source (Rais et al., 2010). Rules regarding visual grading for structural timber are described in the SANS 1783-1 and 1783-2 (2004; 2005). According to SANS 1783-2 (2005), the main purpose of grading structural timber is “to establish and maintain an acceptable uniformity in the products of different mills, so that a given grade will represent the same quality and be usable for the same purpose, regardless of the nature of the raw materials from which it was derived or the mill by which it was produced”. In a study done on radiata pine timber from New Zealand, Walford and Gaunt (2006) found that visual grading will be able to take care of strength but not stiffness of timber. For this reason, they conclude, visual grading needs to be accompanied by machine stress grading where MOE is of importance.

Machine grading refers to any grading process where properties are measured by mechanical or electronic devices. In the past, machine grading was limited to the measurement of MOE by a flatwise bending apparatus. Currently there are many types of machine grading systems which measure single properties or combinations of properties (Glos, 2004) as discussed in the previous section.

2.2.3. Proof grading

The only way to know how strong a material sample is would be to test it to destruction. Madsen (1992), however, explains that if you are only concerned with how weak the sample is, proof loading can be applied. Since the characteristic stresses of a grade are 5th percentile values, it means that if you set the test load at the 5th percentile value only stronger pieces will survive the test. It has been argued that some timber 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). In a study done by Gaunt (1999), on radiata pine, it was found that different proof loading regimes before grading generally effect no change in bending stiffness or compression strengths, but effect a consistent improvement in the bending and tension strengths. Since this study does not involve proof grading it will not be discussed in depth here.

2.3. Structural grading and grade verification in South Africa

Vinopal et al. (1978) published findings on the basic strength properties of SA pine, which was then used by the South African Bureau of Standards to draw up visual stress grading rules. Knuffel (1984) published a report containing results from an in-grade test verifying that the design stresses of the visual and mechanical grading methods under industrial conditions did in fact match up to the predicted values derived from laboratory tests. This report suggested the revision of both grading systems in use at the time. Subsequently Knuffel (1984) performed in-grade testing of the then existing SABS visual grades at four Eastern Transvaal sawmills. A new set of grading rules was designed, and they were able to increase allowable bending, tension and compression grade stresses by 30 to 38% with exactly the same yields as before.

Burdzik (2004) tested timber in bending, tension and compression from selected mills in areas in South Africa known to produce low density timber. Between the four mills tested the results showed a 5^{th} percentile MOR value of 10.64 MPa, mean MOE_{edge} of 6513 MPa, and 5^{th} percentile tension of 5.44 MPa. None of these values conform to the current requirements for the lowest structural grade as published in SANS 10163-1 (2003). According to Mr. Abe Stears of the independent timber auditing company SATAS, they recently destructively tested timber samples in tension from ten saw mills and all of the results conformed to the current SANS grade requirements (personal communication between Brand Wessels and Abe Stears, 27/01/2009).

Walford (2002) compared the characteristic MOE and MOR values of structural grades in the USA, Europe, Australia, New Zealand and South Africa with each other. The characteristic MOE of SA’s SANS grades S5, S7 and S10 is comparable to the values of structural grades in other countries while the MOR values are in most cases lower, as shown in Figure 3. However, the author does not mention the relative volume distribution of timber between the structural grades in the different countries.

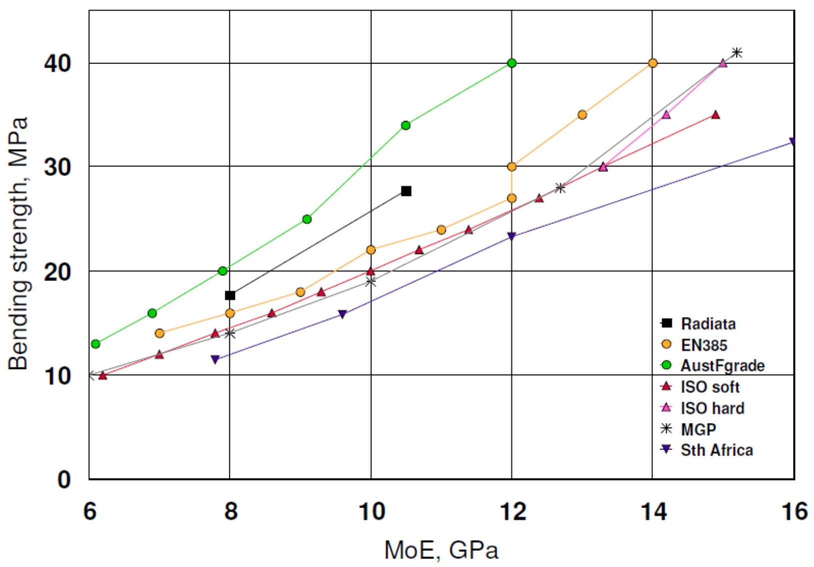

Figure 3: Comparison of New Zealand radiata pine with various strength class systems. SANS 10163-1 values depicted by bottom line

In South Africa the recent fires as well as economic pressure forced many forestry companies to harvest relatively young plantations. Harvesting age has been found to affect some structural properties of timber. Larson et al. (2001), refer to data from a study by Pearson and Ross (1984) comparing wood from a 15 year-old loblolly pine progeny test and a 25 year-old commercial plantation. They also refer to data from Bendtsen and Sendft (1986) based on a 30 year-old loblolly pine plantation. Results from the aforementioned comparisons are shown in Tables 6 and 7. A clear increase in both MOE_{edge} and MOR can be seen from the 15 year-old to the 25 year-old trees in Table 6. Table 7 shows a 5 fold increase in MOE_{edge} from year one to year 15. These results suggest that there can be a big difference between young and old trees.

Table 6: Average value of specific gravity, MOE_{edge}, and MOR at average number of rings from the pith for two different age trees (Pearson and Ross in Larson et al., 2001)

Number of rings from pith	Specific gravity		MOE ($x10^6$ lb/in^2)[a]		MOR (lb/in^2)	
	25 yr-old tree	15 yr-old tree	25 yr-old tree	15 yr-old tree	25 yr-old tree	15 yr-old tree
0+	0.4	0.38	0.88	0.64	9,080	7,260
2+	0.43	0.39	1.31	1.04	10,600	8,980
5+	0.47	0.44	1.53	1.36	13,100	11,400
10+	0.5	0.52	2.08	1.64	16,700	13,900

[a]1 lb/in^2 = 6.9 kPa

Table 7: Average properties by age for loblolly pine (Bendtsen and Sendft in Larson et al., 2001)

Age (years)	Specific gravity	MOR (lb/in^2)[a]	MOE ($\times 10^6$ lb/in^2)[a]	Maximum crush (lb/in^2)[a]	Tracheid length (mm)	Fibril angle (deg)	Ring width (in.)[b]
1	0.412	4,200	0.289	2,020	1.57	36.5	0.394
2	0.384	4,240	0.294	1,880	1.73	39.0	0.508
3	0.400	3,800	0.293	1,620	1.95	39.3	0.360
4	0.400	4,400	0.349	1,730	2.14	37.0	0.367
5	0.436	5,470	0.498	2,160	2.37	31.0	0.348
6	0.423	5,490	0.514	2,100	2.53	33.7	0.312
7	0.467	6,470	0.642	2,550	2.68	33.2	0.260
8	0.502	6,848	0.710	2,960	2.82	29.5	0.223
9	0.514	8,160	0.904	3,190	3.03	24.5	0.181
10	0.531	9,820	1.120	3,430	3.16	27.3	0.164
15	0.582	11,570	1.541	4,140	3.51	22.0	0.138

[a]1 lb/in^2 = 6.9 kPa.
[b]1 in. = 25.4 mm.

2.4. In-grade testing variables

The results from both bending and tension tests may differ simply because of a difference in the test setup, or the placement of the test piece within the setup. Some of these differences are discussed in the next section.

2.4.1. Defect placement

The timber test piece can be placed in the test setup in two ways. Biased testing has the biggest strength reducing defect in the test piece situated in the centre of the test setup, where the maximum stress will be applied. During random testing the defect placement is not considered. In biased testing the weakest edge of the timber can also be placed in tension.

Leicester et al. (1998) compared three different in-grade testing rules for bending and tension tests. It was found that a difference of up to 20% in both the MOE_{edge} and MOR values can be obtained between different load configurations and setups. In bending, the European methods, in which the biggest defect is situated in the centre of the test setup, showed lower MOE_{edge} and MOR values than the Australasian and ISO methods where random defect location is used. For the tension tests the longer length test samples showed lower tension values, most probably because of the fact that even though the worst defects were selected, there's a higher chance of a big defect contained in the longer test specimen (Leicester et al., 1998).

Bailleres et al. (2009) tested different species of pine using both random and biased testing methods. From the results of that study, shown in Table 8, it is noticed that there can be a big variation of strength properties with the two testing methods. The mean MOR and MOE values for the three pine species tested are roughly 44% and 13% lower respectively with biased testing than when random testing was used. The mean MOR values are clearly more affected by the test setup than mean MOE. Unfortunately the difference in 5th percentile values is not reported and cannot be accurately estimated from the data provided.

Table 8: Results from both biased and random bending tests on three different species of pine (Bailleres et al., 2009)

Test position	Resource		Mean	Std. Deviation	N
Biased	Radiata E	Dry density (kg/m^3)	**484**	*51*	517
		MOE (MPa)	**7912**	*2349*	516
		MOR (MPa)	**28**	*13*	517
	Radiata R	Dry density (kg/m^3)	**508**	*40*	434
		MOE (MPa)	**8041**	*2706*	432
		MOR (MPa)	**25**	*15*	435
	Caribbean	Dry density (kg/m^3)	**564**	*71*	558
		MOE (MPa)	**9847**	*2842*	541
		MOR (MPa)	**38**	*17*	558
Random	Radiata E	Dry density (kg/m^3)	**489**	*51*	207
		MOE (MPa)	**9328**	*2411*	207
		MOR (MPa)	**46**	*17*	207
	Radiata R	Dry density (kg/m^3)	**508**	*41*	255
		MOE (MPa)	**9915**	*2873*	254
		MOR (MPa)	**44**	*22*	255
	Caribbean	Dry density (kg/m^3)	**561**	*72*	338
		MOE (MPa)	**10374**	*3007*	335
		MOR (MPa)	**52**	*21*	338

2.4.2. Density measurement

Densities can vary within a timber specimen, and therefore local density measurements are usually taken at the point of failure. Studies, however, show that there is a very good correlation between local density measured at the point of failure and average density (Vinopal et al., 1978; Hanhijarvi et al., 2005; Hanhijärvi and Ranta-Maunus, 2008).

2.4.3. Rate of loading

Dr. R.A. Spencer, of the department of Civil Engineering at the University of British Columbia, conducted bending tests on 1052 pieces of structural size timber, applying different rates of loading ranging from 0.06 seconds to 3 days (Madsen, 1992). The results are depicted in Figure 4.

From the results it can be seen that the rate of loading only starts to play a more significant role for timber with a MOR stronger than 35 MPa, which is higher than the 5th percentile values of most structural timber grades. Tests performed by Madsen also suggest that tension is not much affected by the rate of loading over the range tested.

The effect of the rate of loading on the MOE of timber was, however, not discussed in this study. For normal in-grade testing the rate of loading, therefore, does not seem to be such a critical factor. Testing speed for this study will however still be kept reasonably conservative.

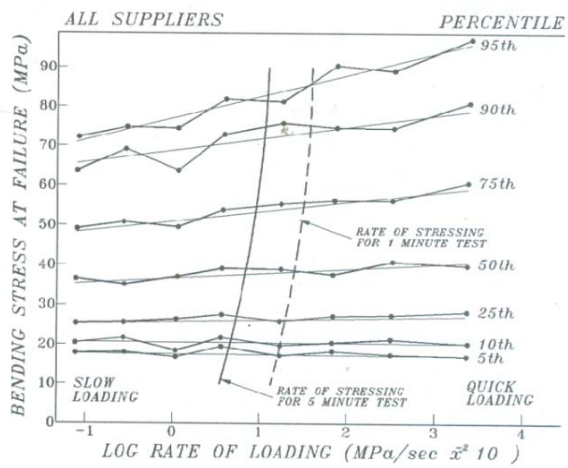

Figure 4: Failure stress versus logarithm of rate of loading (Madsen, 1992).

2.4.4. Size effect

The size effect refers to the effect that different size timber pieces has on the strength and stiffness of timber.

Tension members

Tension members are loaded by a constant force along the entire length of the member, which means that failure will occur at the weakest point between the grips. The longer the tension span the higher the probability of a weak spot where failure will occur. When a knot is situated in the centre of the cross section, the load stress is distributed along the timber on the sides of the knot. This means that the smaller the cross section, the less material is available to support the knot-affected material. This leads to a weaker timber specimen.

Bending members

Bending moment varies across the length of the test piece, and the strength depends on whether a large defect is located where the maximum bending moment occurs.

Madsen (1992) describes a test comparing 5th percentile strength values to beam depth for different species. It was found that, for all species, the strength declines with an increase in beam depth. Size effect factors for 3 different grades were determined in order to bring the data to a common value. The size effect factors needed to bring the data to a common value are shown in Table 9.

Table 9: Size effect factors for 3 different grades (Madsen, 1992)

Size effect factors				
	38x89	**38x140**	**38x184**	**38x235**
Select Structural	1/1.27	1/1.13	1	1/0.86
#2 Grade	1/1.28	1/1.13	1	1/0.85
#3 Grade	1/1.31	1/1.15	1	1/0.83

The results from the size-effect tests showed that, under normal circumstances, the material with smaller depths are under-utilized, while material with larger depths are overstressed.

2.5 Requirements for a grading system

Since this study evaluates specific grading systems and techniques it might be of interest to discuss the requirements of a structural grading system – which often has practical limitations not covered in academic literature.

Madsen (1992) lists the following requirements for a grading system:

- the grading system must result in premium prices for a sawmill and a new grading system must generate more value than before for the average sawmill;
- the grade strength properties must be reliable and consistent;
- only products used for single members require high reliability and needs high quality control requirements. For less important members descriptive standards can be used;
- the number of grades should be kept small, because extra warehousing space for more grades is costly, and in order to justify big enough price differences, the strength differences between the grades also need to be relatively large;
- the overlapping of the strength of the grades should be kept to a minimum and the coefficient of variation should be as small as possible;
- restrictions with regard to appearance and straightness have to be imposed in order for the products to be suitable for the intended end-use. Yet it is important that these requirements are not overly restrictive but reflect the real needs of the market; and
- there should be a demand for the quantities developed in the different grades, as there is no use in having timber in a grade for which there is no demand.

3. METHODS AND MATERIALS

Figure 5 shows a schematic of the process steps that were followed in this study.

3.1. Tree and log sampling

The logs used for this study were obtained from 17 different compartments in the Mpumalanga escarpment (Fig. 6). The compartments varied between 810 and 1930 m above sea level, had a mean annual rainfall of between 840 and 1640 mm and a mean annual temperature of between 13.7 and 19.4 ºC. The variability in growth sites should ensure that most of the variability in strength and stiffness for this species from the Mpumalanga escarpment is present in the samples.

The compartments were selected to represent the different growth conditions within the sample area, with the tree ages varying between 16 and 20 years. The strength of timber increases with tree age, therefore the strength distributions of the timber will increase slightly with more mature trees, and the correlations between different indicator properties and strength may also change. The results from this young sample should however provide meaningful insight into the current strength properties and relationships between properties within a tree, especially when shorter rotation periods are considered in future.

All the trees were pruned up to a height of five meters, while some compartments were pruned up to seven and nine meters in height respectively. The trees were felled and two saw-logs were removed from each tree trunk. Figure 7 schematically shows the sampling procedure where one log was removed from the pruned section and one from the unpruned section. The logs were kept under water sprinklers for roughly two months before further processing took place. The sample consisted of 170 trees which were processed firstly into 340 logs (two logs per tree) and finally into 1402 boards.

The material used in this study was obtained from another research project which examined the effect of site on some wood properties. It was thus not possible to specify any changes to the tree sampling strategy for this specific study. However, the resource used here is typical of the intake of some sawmills and will be representative for some processors in South Africa. The effect of site is intentionally not examined in this study as it will be covered in a different research project.

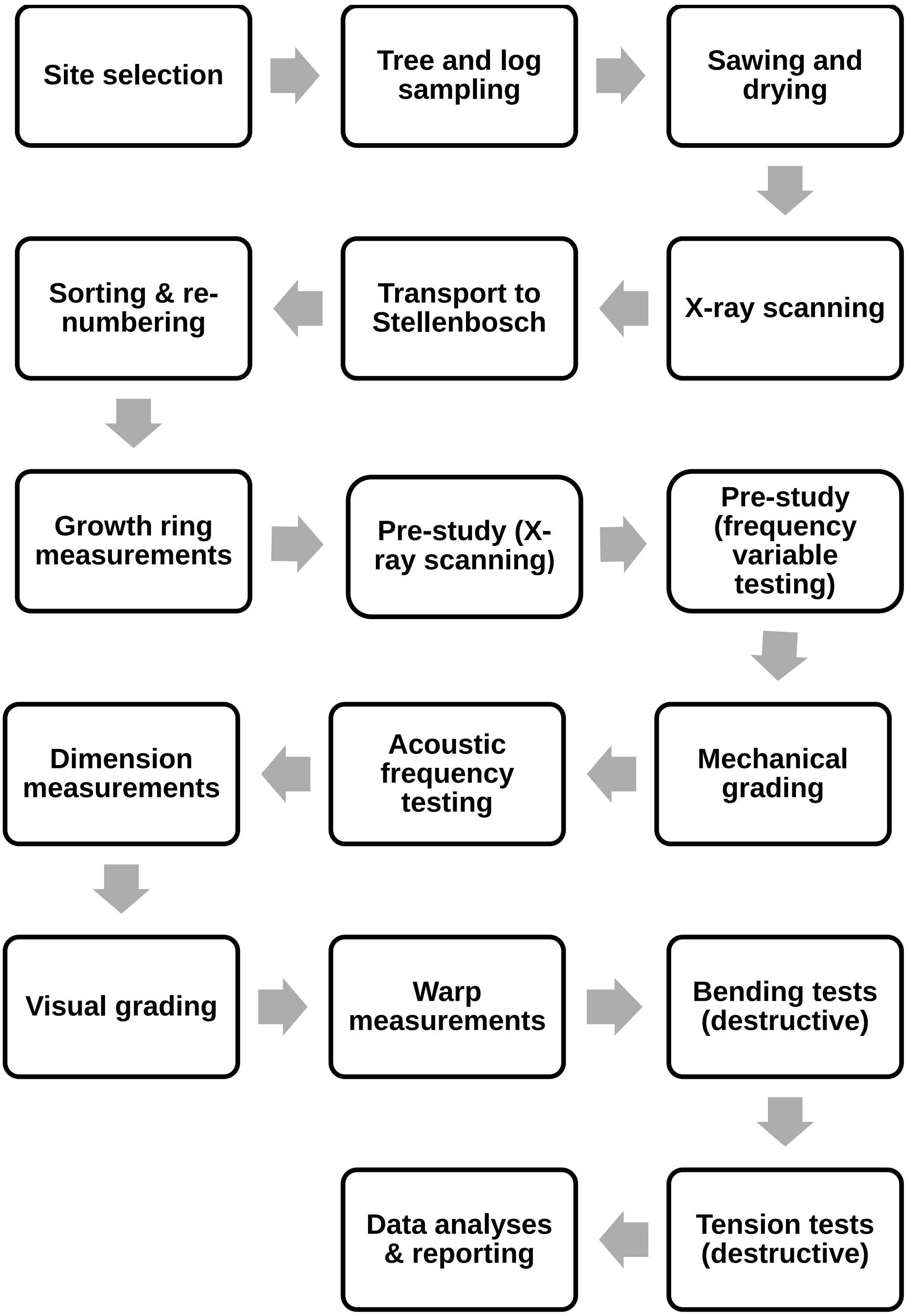

Figure 5: Summary of process steps from log sampling to the final data analyses and reporting

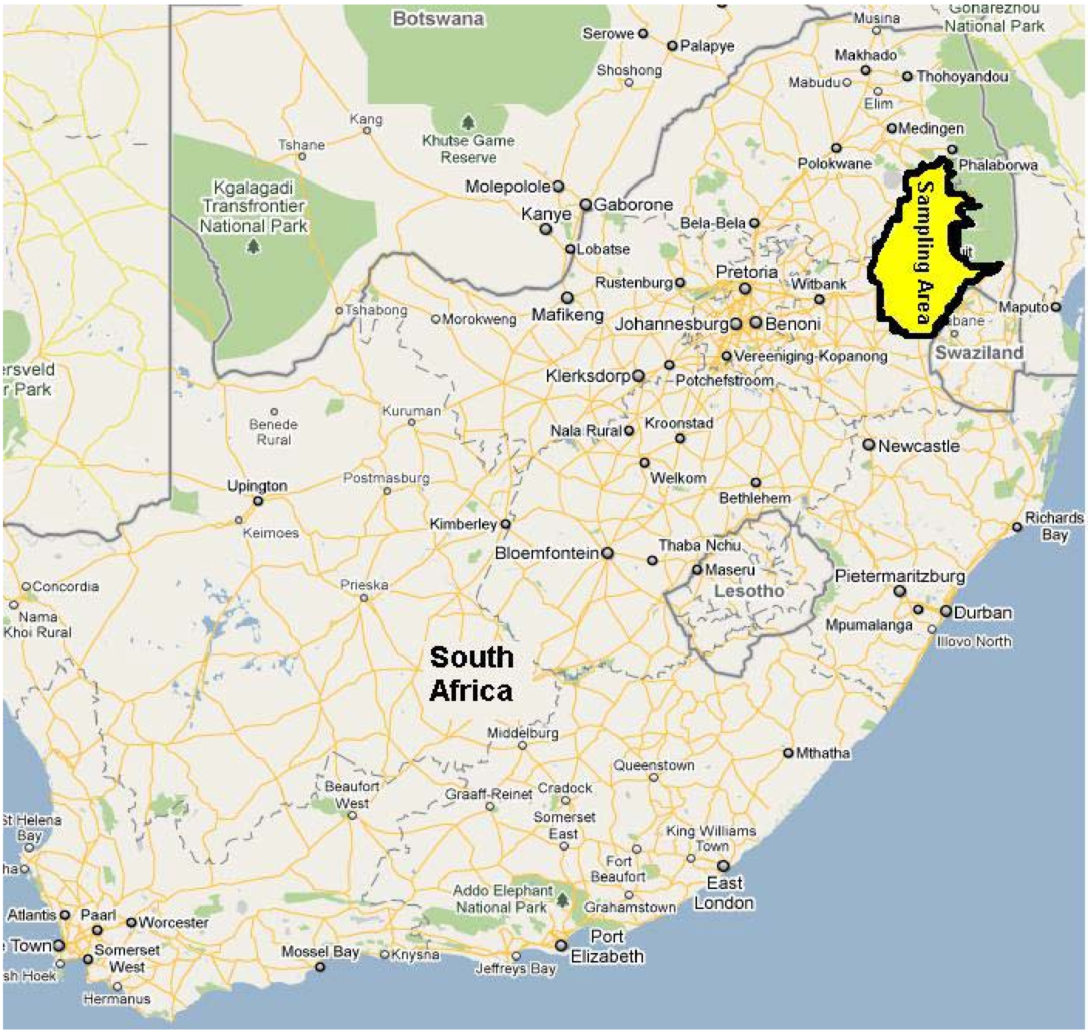

Figure 6: Map of SA highlighting the material sampling area

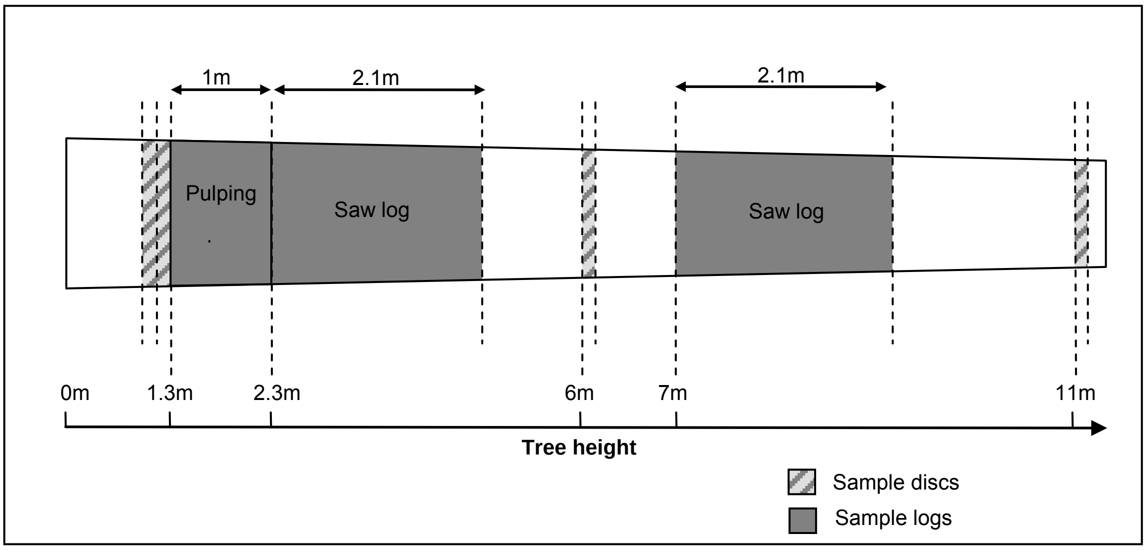

Figure 7: Log initial breakdown showing samples removed from each tree

The logs were processed at York's Nicholson and Mullin sawmill in White River using frame-saws and a cant sawing pattern (Fig. 8). Each log was turned so that the plane of curvature was vertical (sometimes referred to as "horns-up" sawing) before it entered the primary breakdown saw. The log was centred and some boards removed from the sides by the primary breakdown saw so that a cant of thickness 120 mm (wet size) remained. The cant was centred and sawn with the secondary breakdown saw into 40 mm (wet size) boards. The secondary breakdown saw used a curve-sawing device so that the grain of the boards was parallel to the longitudinal direction. Each board was numbered with a unique number to identify the site and the tree from which the board originated. A device which measured the time-of-flight of an acoustic stress wave, the Fakopp Treesonic, was used on each wet board to obtain the dynamic MOE of each wet board.

After all the wet measurements were completed the boards were kiln dried, together with other timber from the Nicholson and Mullin sawmill, using a medium temperature schedule (temperatures below 100 ^{o}C).

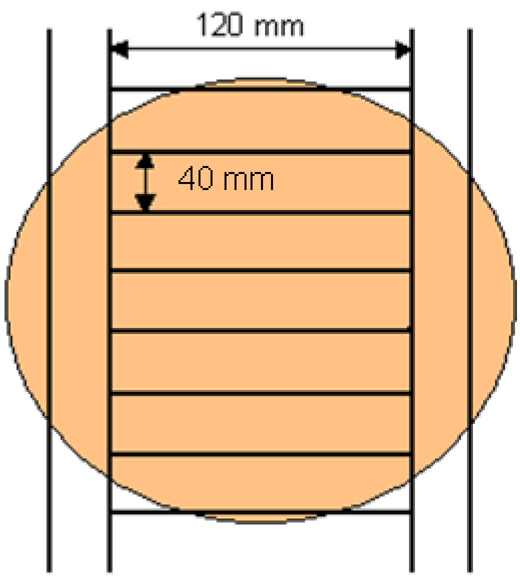

Figure 8: The cant sawing pattern used

3.2. X-ray scanning

The boards were scanned at York Timbers in Sabie with a Goldeneye-702 commercial X-ray scanner from Microtec. Figure 9 shows an example of a scanned board. At the time of testing the scanner was being used for the optimization of cuts for the finger jointing of timber. The Goldeneye scanner has a number of sensors including optical cameras, a laser scanning device and an X-ray density scanning device to measure a number of knot parameters including knot location and quality, board dimensions, board warp, presence of pith, density, cracks, resin pockets and bark.

Through a pre-study by the author of this thesis (Dowse, 2009), it came to light that some results, especially dimensions and warp, as measured by the scanner were not very accurate. During discussions with the manufacturers in 2010 it was found that the machine had not been calibrated for some length of time prior to the time of scanning the sample, and, therefore, some sensors could have been inaccurate. Knot location and size measurements, however, were deemed to be reasonably accurate and results from the data obtained should be reliable.

All questionable data from the scanner (warp, density, and dimensions) were manually measured and only this manually measured data were used in the study.

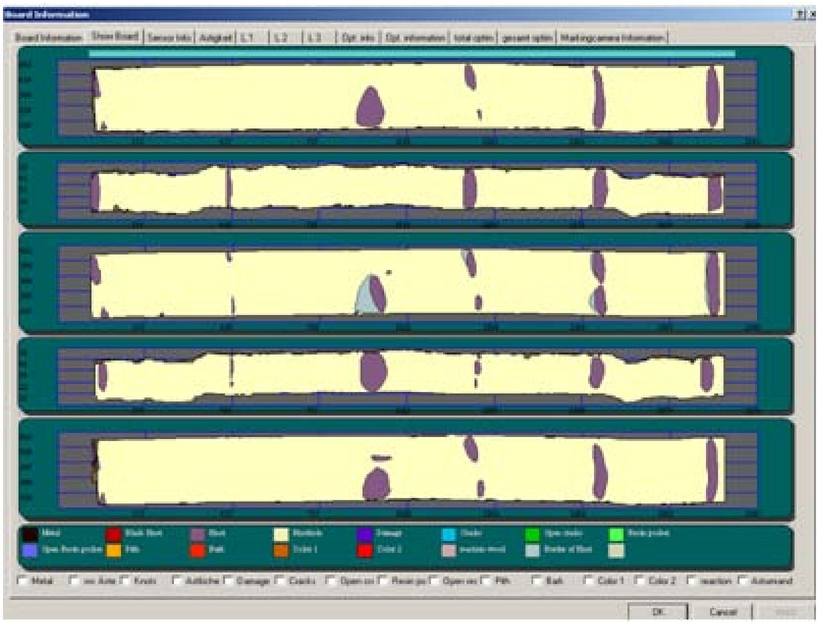

Figure 9: Example of scanned board showing optical and X-ray views

3.3. Growth ring measurements

The boards were transported to the Department of Forest and Wood Science at Stellenbosch University for further analysis. On arrival the boards were sorted into the original positions within a log and re-numbered so that the location of a board within a log could be identified (Fig. 10). The ends of the boards were sanded to provide clearly visible annual rings. Roughly 55 boards were lost somewhere after the drying process and before transport of the boards to Stellenbosch.

The number of annual rings on each board was counted and numbered from the pith outwards. The cambial age (mean, maximum and minimum) of the wood within each board was therefore known. The cambial age is the age by ring count from the pith. A line drawn from the pith to the bark and perpendicular to the growth rings (Fig. 11) was used to do ring width measurements using a dial calliper. The line was drawn to include the maximum number of rings in each board. Measurements were rounded to the nearest 0.1 mm. For each board the minimum, maximum, and mean ring width was calculated.

Figure 10: Material storage and sorting before sanding of board ends

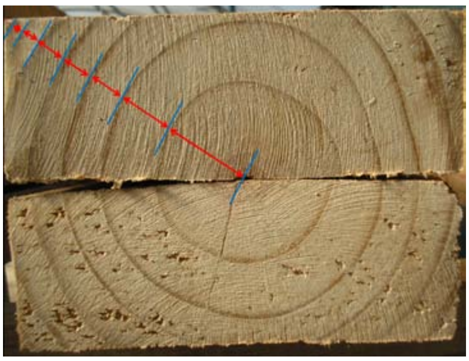

Figure 11: Annual ring-width measurements taken perpendicular to annual rings

3.4. X-ray scanning and acoustic frequency pre-study

The pre-study is fully explained in the honours project report by Dowse (2009). The study was performed with 25 samples selected to represent the compartments from which the trees originated from as well as the range of MOE_{dyn} values obtained with the Treesonic device on wet boards at the sawmill.

3.4.1. X-ray scanner comparisons

Each of the 25 selected samples was evaluated by comparing the Microtec X-ray scanning data to actual measurements. From the saved data for the knots and defects, measured by all of the different sensors in the scanner, the virtual knot and defect locations were marked on the boards with different coloured permanent markers. The distance between the actual knot and defect locations and the virtual ones were measured and recorded. An average offset value of 12 mm per knot was found. The most probable reason for this offset was explained by a technician from Microtec as being the fact that the sensor calibration was slightly off because of the poor service records. It can be assumed that the offset value of 12 mm should not have too big an influence on the predictions of the strength characteristics.

The other measurable properties such as warp and density values were also compared. The scanner spring, bow and twist values were very inaccurate, and it was decided to only use manual measurements for this project. Dimension measurements were also found to be less accurate than can be expected from commercial grading machines. According to Microtec, all of the above mentioned inaccuracies of the scanner data were probably due to the fact that the scanner had not been serviced recently.

By using the knot information gathered from the X-ray scanner, the following knot parameters were determined:

# Knots	is the number of knots on a single piece of timber;
Knot average (knot avg.)	is the mean size (area in mm^2) of individual knots on a particular piece of sawn timber. X-ray scanning evaluated each board in its thickness direction and the area measurement is similar to the knot-covered area one will see if you look from above at a knot in a transparent board. Take note that this is different to

	the knot area ratio (KAR) often used in research studies;
Knot area / board	is the total area of the piece of timber that contains knot material (mm^2);
Knot maximum (knot max)	is the size of the biggest knot on a piece of timber (mm^2);
Knots 1-7F	is a knot parameter calculated by the X-ray scanning device (programmed by Microtec) using data from a combination of 7 knots on each full piece of timber. The exact method of calculation was not available;
$KPar_f$	is a knot parameter from the most influential knot on the full board (programmed by Microtec). The exact method of calculation was not available;
$KPar_c$	is a knot parameter from the most influential knot on the centre third of the board (programmed by Microtec). The exact method of calculation was not available; and
KSC	is the product of knot size and the stress index of a specific knot. The stress index is a ratio of the bending stress at a specific knot to the maximum bending stress in a piece of timber (the stress index in the centre third of the board will be higher than at the ends). This parameter was determined during the data analysis process.

3.4.2. Acoustic frequency variables

The test setup was located in a laboratory at Stellenbosch University. Different variables were tested including hammer and support material, testing surface and the frequency analyzing software.

The results showed that the ends where the hammer impact occurs can be a rough surface, as long as there are no tags or other materials attached to the impact area.

Hammer material

The best hammer material to be used in future studies was determined to be either wood or steel, with repeatability results of between 98 and 100%. The rubber hammer showed excellent repeatability, however, correlations with MOE_{edge} results showed a group of outlying values when using the rubber hammer. For the best consistency with regards to MOE prediction the use of either a steel or wooden hammer was suggested for this study.

Analysis program

The two analysis programs compared were those of the FFT analyzer, provided by FAKOPP Enterprise, and the A-Grader portable provided by Falcon Engineering. The comparisons showed that either one can be used with good accuracy and repeatability. The differences are that the Fakopp software is faster, as there is no need for the input of dimensions, as is the case with the A-Grader portable software. The A-grader software on the other hand automatically selects the correct frequency waves, which describes the different modes of the waves going through the timber. With the Fakopp software attention needs to be given to ensure the correct frequency waves are selected.

The preferred program to use is up to the user and the circumstances under which the tests will be performed. The A-Grader was selected for use in this project as it automatically selects the correct frequencies and therefore accurate results are ensured.

Board supports

Results suggested that the location of the supporting material underneath the boards needs to be constant. Correlating, for example, results obtained with the support material on the extreme ends of the boards to results with the supports near the decided optimum placement, gave an R^2 value of 54.8%, which is quite poor. The provider of the frequency software suggested support distances of 0.22 times the length of the board from the ends.

3.5. Mechanical grading

The first test that was performed after the pre-study was completed was flatwise mechanical grading of all the samples (Fig. 12). A mechanical grading machine, known as a TRU-grader, from Cape Sawmills in Stellenbosch was brought to the department to perform the tests. The grader performs a flatwise static bending test with the load applied on the centre of the span. It has a span of 914 mm between the two bottom supports. The board is placed on the supports with the weakest part, estimated by visual observation, in the centre. A load of 1200 N was applied and the deflection of the board at the centre point was measured.

During the mechanical grading there were about 14 boards that failed under the test load. These boards were thrown out as they could not be used for further testing.

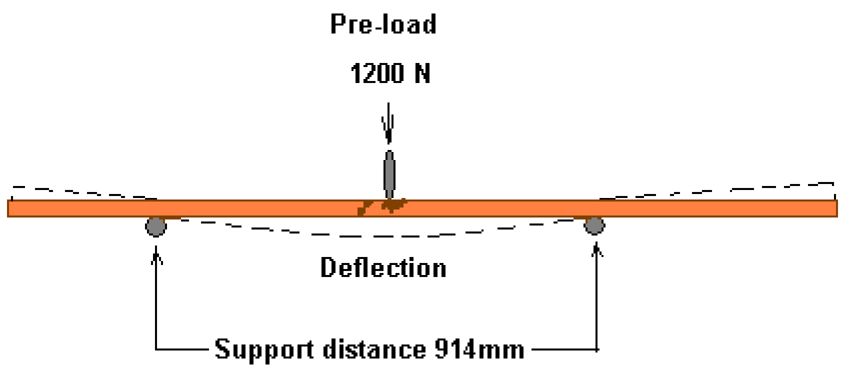

Figure 12: Flatwise mechanical grading of test material

3.6. Acoustic frequency testing

The test setup and software used was based on the findings in the pre-study (Dowse, 2009). The frequency test was set up on a flat, clean surface at a comfortable working height. The boards were placed on two polystyrene supports, 450 mm from each end, to provide clearance between the boards and the table (Fig. 13), as well as to prevent frequency channelling through the table. A quick hit was then made with the use of a wooden hammer which sends a vibration through the board. The sound caused by the resonance of the wave was recorded with a microphone on the opposite end of the board. The vibration was analysed by the frequency analysis software installed on a computer (A-Grader Portable from Falcon Engineering) which gives the resonance frequency for each board tested. Each board was tested twice to ensure the correct reading. During testing a 5% trigger level was used with a 5512 Hz frequency range.

The dynamic MOE was then determined from the frequency and the density, measured by use of mass and volume, with the following formula:

$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)^2$ where:

MOE_{dyn} is the dynamic modulus of elasticity, in MPa;

ρ is the density of the test specimen at the moisture content at the time of testing, in kg/m^3;

l is the length of the test specimen in meters to the closest mm; and

f is the frequency of the test specimen, in Hertz.

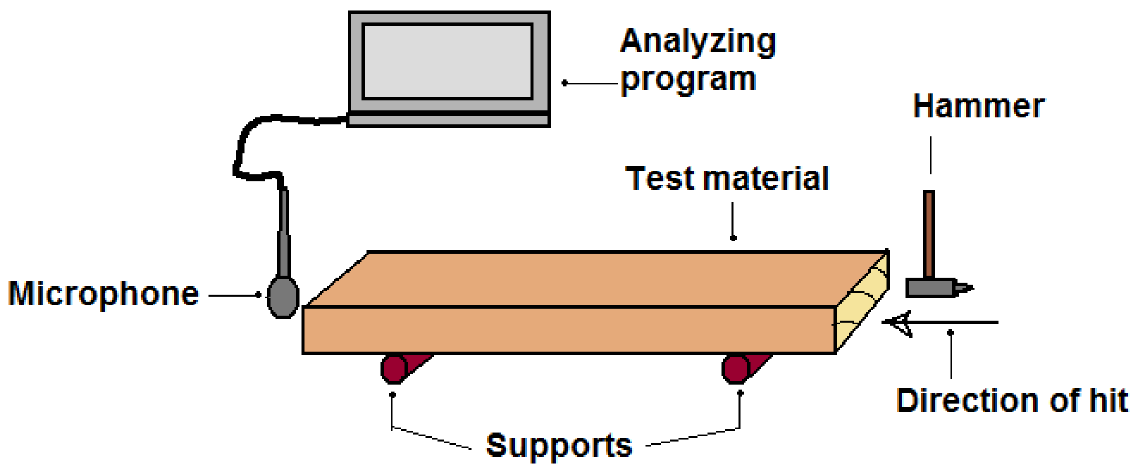

Figure 13: Frequency testing setup

3.7. Dimension measurements

During frequency testing the dimensions of each board were also measured for volume determination. Separate width and depth measurements were taken randomly on three places along the board length. The length of each board was also measured. From these measurements the volume of each board was calculated.

3.8. Visual grading

Visual grading of all of the boards was done by a SANAS (South African National Accreditation System) accredited professional visual grader from the independent company SATAS (South African Timber Auditing Services).

The boards were graded according to SANS 1783-2 (2005) visual grading rules. Moisture content measurements were taken using a resistance moisture meter. Each board was weighed and the density was determined with the volume measurements previously done. Density was determined at the kiln dried moisture content of roughly 9%. For grading according to density, density was determined at 12% moisture content according to SANS 1783-1 (2004) and graded accordingly. For analytical purposes the boards were allocated a grade considering all the defects (as would be the case in a mill setup). The reason for downgrade of each board was also noted i.e. density, warp (twist, spring and bow) and defects (knots, damage etc.). During visual grading for this study, a separate grade allocation was documented for each board in 3 categories. These categories included the grades allocated according to density, knots (sizes and distribution) and other defects including wane, warp, resin and mechanical damage. The grading was fairly meticulous in the sense that unlike visual grading in a sawmill, the grader measured actual knot sizes when there was any doubt about the grade. The visual grading took four days for all the boards (roughly 340 boards per day and 34 boards per hour).

3.9. Warp measurements

Warp measurements, which include twist, spring and bow, were performed on a flat surface with the aid of a measurement wedge. The boards were secured on one end while measurements were taken. For twist the deflection of the opposite corner was measured with the board laying flat and one end secured (Fig. 14). Spring was measured with the board on its side at the point of highest deflection from the flat surface (Fig. 15). Bow was measured similar to spring, but with the board lying on a flat face (Fig. 16). Note that the warp measurement was not part of the visual grading process and was performed by a different operator.

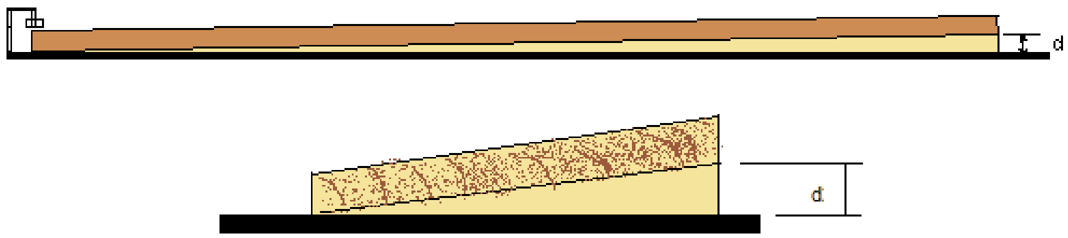

Figure 14: Method for twist measurement

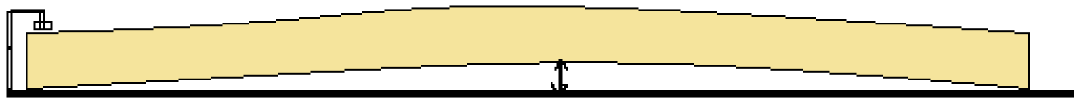

Figure 15: Method for spring measurement

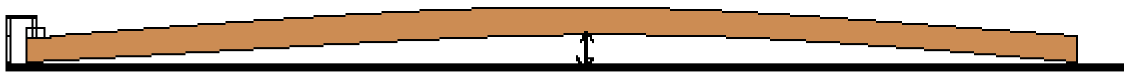

Figure 16: Method for bow measurement

3.10. Destructive tests

The sample material was divided into two groups based on the board position and a random allocation function. Pith boards were marked 0, the two boards on each side of the pith boards 1, the two boards further removed from the pith boards 2 etc. A random function was used to allocate the boards from the same position in a log (i.e. the two 1 boards) into the two different groups. All of the destructive tests were performed in a testing laboratory at Stellenbosch University. Table 10 shows the testing parameters for both the bending and tension tests.

Table 10: Testing parameters for four-point bending and tension tests

Nominal board width (mm)	114
Nominal board thickness (mm)	38
Total span in bending (mm)	1950
Distance between load applicators presses in bending (mm)	650
Total span in tension between grips (mm)	880
Testing speed in bending (mm/min)	14
Testing speed in tension (mm/min)	15

3.10.1. Bending tests

The timber used in this study was of 2.1 m length. Seeing that the bending test span was about 2 m, this meant that worst defect selection for the centre part of loading was impossible and effectively random placement of the samples was used. Leicester et al. (1998) found that random placement in bending tests can produce up to 20% higher 5th percentile MOE_{edge} and MOR values than is the case with selective defect placement. In practice the defect placement of timber used in structures are also random, and for this reason the implemented testing method used in this study can be seen as satisfactory.

The tests were performed in the laboratory at Stellenbosch University with an Instron testing machine.

A four-point bending test with a span of 1950 mm between the bottom supports was performed on all of the boards in the bending group. Because of limitations in the testing setup, this span is slightly less than the specified span to depth ratio of 18:1 specified in SANS 6122 (1994). A load was applied from above on two points at one third of the span (650 mm). The test setup is described in SANS 6122 (1994). The four-point bending setup creates a region of zero shear in the centre of the board at maximum moment, as depicted in Figure 18. The specimen rested freely on rounded edges to allow for movement. In the case of extremely deformed specimens, lateral support was provided on the sides to prevent from completely twisting out of the setup.

A small number of the specimens had shorter lengths due to erroneous cross-cutting during the X-ray scanning process and, therefore, the support distances were adjusted accordingly. The formulas for the MOE_{edge} and MOR results were also adjusted for these boards.

The tests were performed at a rate of deformation of 14 mm/min. Research from Madsen (1992) suggests that the testing speed for timber only starts to play a role with material stronger than 35 MPa, which is stronger than normal commercial timber (Madsen, 1992). The rate of deformation used for these tests were, therefore, relatively conservative.

Load and deflection values were recorded every 0.02 seconds during testing on the Instron's data recording software. A very detailed load-deflection curve was, therefore, obtained for each test. In addendum A, two deflection measurement possibilities were compared. Tests, however, showed these to be similar.

Of the total bending sample of 699 only 683 tests were completed due to samples that twisted out of the test setup. Eight of the boards tested were of slightly shorter lengths, and the calculations of the strength properties were adjusted accordingly.

Figure 17: The four-point bending test setup on the Instron

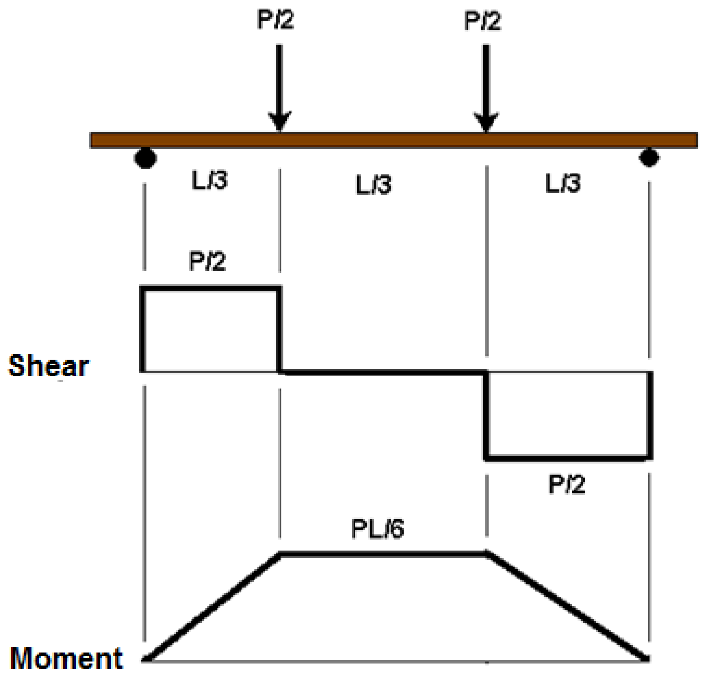

Figure 18: Shear and moment diagrams for four-point bending tests

3.10.2. Tension tests

All of the tension tests were performed with the same Instron testing machine that was used for the bending tests. The machine parameters are such that all the test specimens for the tensile tests had to be cut to a length of 1060 mm to fit into the testing setup. The test load was also limited to 100 kN.

The selected boards were tested in tension parallel to grain in order to determine the tensile strength. A rate of deformation of 15 mm/min was used for testing, which is a very moderate testing speed compared to other literature (Madsen, 1992; Rayda, 2003).

The machine grips were the same width as the test specimen, and the depth of contact area between specimen and grip was on average about 90 mm, with the span between the grips about 880 mm. That is the maximum length possible in the Instron machine but less than prescribed in the SANS 6122 (1994) standard. Because of the construction of the grips a bigger contact area could not be achieved. The openings of the grips were also a limiting factor, as approximately 3 mm in thickness had to be planed off the ends of some test specimens in order for the timber to fit into the grips.

The tension tests on the stronger portion of the timber proved problematic as the surface area of the machine grips in contact with the timber was simply too small. This caused the strong test pieces to break prematurely at the grips. The maximum load capacity of the load cell, which was 100 kN, was also not high enough to test the strongest pieces to failure. Results from the tension tests, therefore, will be inaccurate for the higher grades, S7 and S10.

The worst defect, (visually estimated to be the largest knot or knot group) in each 2.1 m board was selected to fall within the test span of 880 mm. For the tension tests there were, therefore, a biased placement of the worst defect in each board. Considering the fact that structural timber in South Africa is usually much longer than 2.1 m, however, the effect of biased placement will be less than is typical in the South African structural timber resource.

Of the total tension sample of 623 only 607 tests were completed due to samples of which the slippage was too bad for the strength results to be considered.

Figure 19: Tension test setup on the Instron

3.11. Calculations and analysis

3.11.1. Calculation of strength and stiffness values

The formulas used for calculating strength and stiffness are shown below. Take note that rough sawn timber was used for this testing but that the actual dimensions of each piece were used to calculate stress and stiffness values. The reason is that I did not want dimensional variability to influence the results. Roof trusses, which constitute the main end-use of structural timber in South Africa, use planed timber where dimensions are relatively constant.

MOE_{flat} according to SANS 10149 (2002)

$MOE_{flat} = F \cdot a \cdot (3 \cdot L^2 - 4 \cdot a^2)/4 \cdot b \cdot h^3 \cdot D$, where:

MOE_{flat} is the static modulus of elasticity measured on the flat at centre span, in MPa;

F is the test load, in Newton;

a is the distance from the support to the mid-span, in millimetres;

L is the test span, in millimetres;

b is the width off the specimen, in millimetres;

h is the height of the specimen, in millimetres; and

D is the deflection under the applied load, in millimetres.

MOE_{edge} according to SANS 6122 (1994)

$MOE_{edge} = FL^3 / 5.4 \cdot bh^3D$, 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 (1994)

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

MOR	is the bending strength (modulus of rupture), 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 (1994)

Tension = F/A, where:

Tension	is the tensile strength, in MPa;
F	is the failure load value, in Newtons; and
A	is the actual cross-sectional area of the test specimen, in millimetres squared.

5th Percentile values

5th percentile values were determined according to the method given in SANS 6122 (1994). The values achieved for MOE_{edge}, MOR and tensile strength respectively were arranged in order from low to high. The formula 0.05(n-1) was then used to determine the position of the 5th percentile value, where n is the number of specimens in the arranged sample.

3.11.2. Statistical evaluation

All of the data gathered from the various tests performed during this study was transferred to an Excel spreadsheet according to the board numbers. The data was then imported into Statistica, a statistical analysis program. Before analysis faulty or duplicate data were removed.

For single correlation analysis, simple Pearson correlations were performed on all the variables in order to achieve a correlation matrix which includes all the possible indicator properties. Cook's distance was also used to determine some outliers from the testing process. 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 multiple regressions, a summary of best subsets, Mallows' Cp and forward stepwise regression was done in order to quantify co-linearity between the different variables and to decide which variables were significant enough to add to the multiple regression statistics.

Only the variables which were deemed to be significant were used in the multiple regression results depicted in the following chapters.

It is possible for certain combinations of variables to achieve a slightly higher correlation with a certain dependant variable, however, the variables are not necessarily significant and can lead to a false perception of the best possible combinations of predictor variables.

Excell was used to determine simple statistics including yield percentages and some averages.

I am well aware that there might be better statistical models and procedures which can be applied on the data in order to possibly achieve better fits to the data. However, I believe that the simple statistics applied should give an adequate picture of the results obtained for timber quality.

3.12 General observations

Measurements during this project were spread over several months. There was an especially long period between X-ray scanning of the boards at the York sawmill and other laboratory tests in Stellenbosch (6 months). Moisture changes might have occurred during this period that might result in poorer correlations between the X-ray scanning derived properties and some other properties.

4. RESULTS AND DISCUSSION

The results obtained in this study are analysed and discussed in this chapter.

4.1. Selected physical and mechanical properties of *P. patula* sawn timber

4.1.1. Non-destructively evaluated (NDE) properties

The results for the NDE properties from the timber in this study are depicted in Table 11. The table also shows the yield percentage of structural grades if grading was based on only the specific property evaluated.

Table 11: NDE properties of the 1345 sawn 38x114x2100 mm Pinus patula boards

Property	Mean	Standard deviation	Maximum	Minimum	Yield according to specific property (%)			
					XXX	S5	S7	S10
Density* (ρ_m) (kg/m^3)	428	41.2	640	332	2.23	49.4	36.8	11.6
MOE$_{flat}$ (MPa)	5320	1934	14490	1961	49.6	35.8	12.6	2.4
MOE$_{dyn}$ (MPa)	8732	2295	16937	4251	-			
Annual ring width (mm)	10.3	4.73	41.8	0.60				
Bow (mm)	2.24	2.6	45.0	0	0.24	99.8		
Spring (mm)	2.62	2.11	23.0	0	0.16	99.8		
Twist (mm)	13.3	8.13	45.0	0	56.9	43.1		
Moisture content (%)	8.72	0.96	12.0	4.00	-			

*Density was determined at the kiln dried moisture content of each board

Density has always been considered an important timber property in the prediction of some timber quality and strength properties. Based on density alone 2.23% of the boards will be rejected, 49.4% will fall into the S5 class, 36.8% into the S7 class and 11.6% into the S10 class. This means that density is quite an important grade determining property for this resource, allowing less than half of the timber to be in the S7 and S10 grades. The question is whether this is still a sensible requirement. It is strength and stiffness that matters in structural design and it can be argued that density should only be used as a predictor of these in combination with other predictor variables, and not as a grade determining factor. Where density does play a role is in the joint strength of nail plates, but it should be relatively easy to increase nail plate joint areas if it is found that density becomes a problem – depending on whether increasing nail plate area is a financially better option than grade losses due to density.

Almost 50% of the timber tested would be classified as rejects (XXX) if grading was done only by means of MOE_{flat}, as described in the SANS 10149 (2002) standard – which might be one of the reasons why so few sawmills in the country use mechanical grading. This property will be discussed in depth in the next section together with the MOE_{edge} values determined with the destructive tests.

The absolute values for MOE_{dyn}, which is the dynamic modulus of elasticity calculated from the natural frequency and density, is not really important on its own but is used as predictor of the other strength and stiffness properties (see section 4.2). It is, however, noted that the values are higher than MOE_{flat}, and indeed MOE_{edge} discussed in the next table. MOE_{dyn} is an elasticity property influenced by the full volume of material in a board, unlike MOE_{flat} and MOE_{edge} which is mainly determined by the localised wood properties around the highly stressed areas of a specific bending test setup.

The relatively high mean annual ring width of 10.3 mm is probably a result of the low age of the trees used for this study. In some European countries, ring width is used as a grading parameter.

The values for bow, spring and twist are used in structural grading due to the practical requirements for relatively straight timber when manufacturing products from it. It does not directly influence the timber strength and stiffness properties. It can be noticed that the values for bow and spring are very low, and far below the allowable values prescribed in the SANS 1783 (2005) standard. Less than 1% of the timber sample does not comply with the grade requirements for bow and spring. The mean value for twist, however, is 13.36 mm which is above the allowable twist of 10 mm for a 2.1 m length timber piece with a nominal width of 114 mm (SANS 1783, 2005). Based on twist alone, 56.9% of the boards will be rejected. This is probably due to the proximity of most of the boards to the pith, where spiral grain can play a big role in the twisting of timber (Nyström and Grunberg, 2007). In modern processes, cross-cutting, finger jointing and appropriate drying under restraint can be used to lessen the problem of twist. According to Madsen (1992) "restrictions with regard to appearance and straightness have to be imposed in order for the products to be suitable for the intended end-use. Yet it is important that these requirements are not overly restrictive but reflect the real needs of the market". Market requirements, analysis and corrective actions for the high levels of twist, however, falls outside the scope of this study.

4.1.2. Destructive test results

Results from the destructive tests according to the SANS 1783 (2005) visual and SANS 10149 (2002) mechanical grade allocation of timber (including warp and other non-structural requirements of the grading rules) are shown in Table 12. The table also contains the characteristic stress values for SA pine (SANS 10163-1, 2003).

Table 12: Timber strength and stiffness properties determined by means of destructive tests. Visual grading in accordance to SANS 1783 (2005) and mechanical grading in accordance to SANS 10149 (2002).

Property	SANS visual grade	Visual grading					Mechanical grading					Grade potential (%)	SANS 10163-1 requirement*	
		N	Mean (MPa)	5th percentile (MPa)	Yield (%)	Yield excl. warped timber (%)	N	Mean (MPa)	5th percentile (MPa)	Yield (%)	Yield excl. warped timber (%)			
MOE_{edge}	**All**	683	5622	3493			683	5622	3493					
	XXX	351	5335	3485	51.4	19.6	346	4858	3339	50.6	49.6	26.1		
	S5	244	5493	3382	35.7	60.6	272	6162	3459	39.9	35.8	32.5	4630 (5th)	7800 (mean)
	S7	68	7001	4216	10	15.1	64	7375	4235	9.40	12.6	25.2	5700 (5th)	9600 (mean)
	S10	20	7790	4529	2.93	4.66	1	9278	-	0.15	2.4	16.3	7130 (5th)	12000 (mean)
MOR	**All**	683	30.0	15.1	-	-	683	30	15.1	-	-	-	-	
	XXX	351	28.1	14.7	51.4	19.6	346	24.4	12.9	50.6	49.6	1.5	-	
	S5	244	28.8	14.5	35.7	60.6	272	33.7	17.9	39.9	35.8	5.4	11.5 (5th)	
	S7	68	39.8	17.8	10	15.1	64	44.2	17.7	9.40	12.6	20.8	15.8 (5th)	
	S10	20	49.5	27.2	2.93	4.66	1	52.1	-	0.15	2.4	72.3	23.3 (5th)	
Tension	**All**	605	12.0	7.8	-	-	607	12	7.8	-	-	-	-	
	XXX	286	10.9	6.6	47.3	16.8	307	9.59	6.64	50.6	48.4	2.9	-	
	S5	228	11.3	7.2	37.7	59.5	232	13.3	7.89	38.2	33.3	43.7	6.7 (5th)	
	S7	67	16.5	9.7	11.1	16.6	68	18.1	10.1	11.2	15.2	52.9	10 (5th)	
	S10	24	18.4	11.6	3.97	7.13	-	-	-	-	3.13	0.5	13.3 (5th)	

**The 5th percentile MOE values were obtained from the draft SANS 10163-1 document*

Visual and mechanical grade yields

The grade yield of this resource according to visual grading standards is quite poor with roughly only half the timber suitable for structural grades in both the bending and tension sample. Most of the downgrading to rejects with visual grading was due to the high twist values in the timber (Note: the measurements for the warp values and grade recoveries in the previous Table 11 were performed separately from the visual grading by a different operator – therefore the fact that according to Table 11 there will be 56.9% of the timber rejected if only twist is taken into account whereas Table 12 shows that the total reject yield in both the bending and tension sample is less than that value). When warp is not taken into account in visual grading (in the "Yield excluding warped timber" column), only 19.6% of the bending sample and 16.8% of the tension sample is rejected. Better drying practices can lower warp in timber, and, with modern finger jointing operations the problem of twist can be reduced by simply cross-cutting twisted pieces and joining them again – although there are some recovery losses and significant extra costs involved in such an operation.

With mechanical grading the yields are very similar to visual grading. The only difference is that when warp is not taken into account the yields remain poor. This means, off course, that most of the pieces with a significant amount of twist will still be downgraded due to stiffness.

MOE_{edge} results

Table 12 clearly depicts that the mean MOE_{edge} values for all the grades are far below that required by SANS 10163-1 for both visual and mechanical grades. The same applies to the 5^{th} percentile MOE values compared to the values that are listed in the current draft version of SANS 10163-1. In fact, the mean MOE_{edge} value obtained for visually graded grade S10 is below the required mean MOE_{edge} for that of grade S5. Figure 20 shows the MOE_{edge} distribution of values of the full sample and also the sample mean and SANS S5 5^{th} mean value. Mechanical grading is, for obvious reasons, much better at separating timber according to stiffness. The mean stiffness for mechanically graded rejects is 4858 MPa whereas it is 5335 MPa for visually graded rejects. For all the other classes the mean MOE of mechanically graded timber is higher than that of visually graded timber – clearly showing the greater effectiveness of mechanical grading.

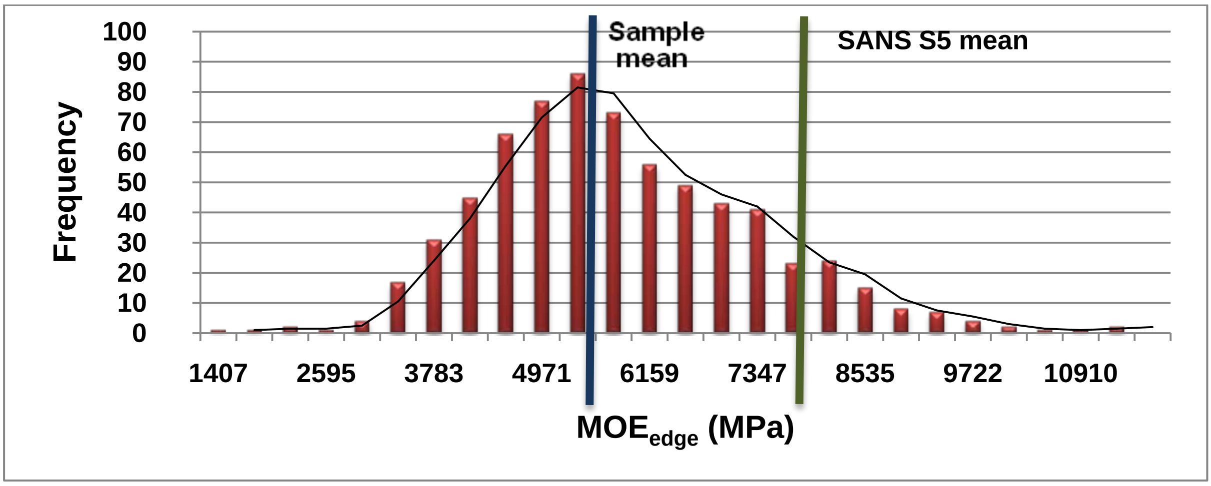

Figure 20: Distribution for MOE_{edge} of all timber tested

The MOE_{edge} results are a cause for concern. With the mean MOE_{edge} value for the visually graded S10 not even conforming to the SANS standards for S5 graded timber, it is clear that sawmills using a juvenile *P. patula* resource are unlikely to even get close to conforming to the SANS requirements for stiffness. The grade potential column shows the actual percentage of pieces that conformed to a specific grade based on the 5th percentile MOE values listed in the current draft version of SANS 10163-1. According to these values roughly 26.1% of the timber will be rejected, 32.5% will fall in grade S5, 25.2% in grade S7 and 16.3% in grade S10. This effectively means that if you have a “perfect” grading system that these will be the absolute maximum grade recoveries that can be obtained. Off course it does not take into account the mean MOE values required for each grade.

One also needs to consider the fact that our testing was performed on short boards, and also effectively a setup of “random location” of the worst defect. Longer boards will increase the probability of a weaker section. According to literature (Leicester et al. 1998, Bailleres et al. 2009) one might expect a MOE_{edge} value of between 13-20% lower when “biased location” of the worst defect is used. The values in SANS 10163-1 against which we are comparing our results were obtained using biased testing. In other words, the MOE_{edge} values will most probably look even worse if the biased test method was used.

One might view stiffness as a non-critical property which only affects deflection values in structures. This is actually not true since stiffness can be the cause for buckling failures in compression members. The fact that no 5th percentile values for stiffness have been published in the current and past SANS 10163-1 timber design code is, therefore, quite surprising. The next version of the design code will, according to the current draft version, include these values.

Bending strength (MOR) results

In contrast to the low MOE_{edge} values, the 5th percentile MOR values for all of the visual and mechanical grades are above the required values for each of the grades. Figure 21 shows the MOR distribution of the sample tested.

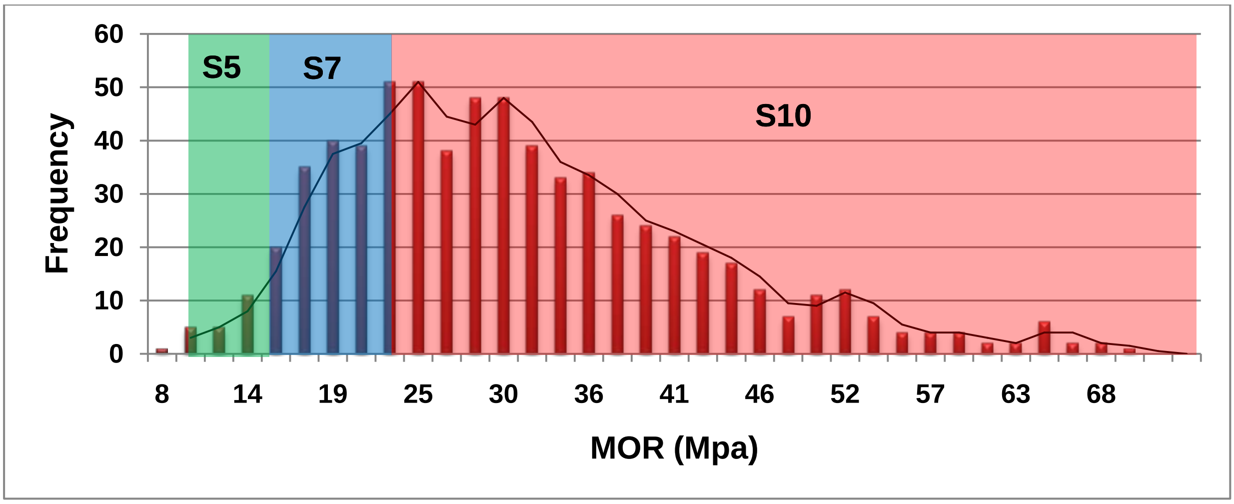

Figure 21: Distribution for MOR of all timber tested

The 5th percentile MOR for the entire sample before grading is 15.1 MPa, which is just below the current S7 grade standard of 15.8 MPa. This suggests that even with no grading systems in place, the entire timber sample will pass for S5 when only the MOR values are taken into account. The grade potential values shows that 72.3% of the pieces had a bending strength above the required 5th percentile value of grade S10 and 93.1% of the pieces a bending strength above the required S7 5th percentile value. Even when lowering the mean MOR by 20%, which literature suggests the difference might be between random and biased defect placement on long test material (Leicester et al. 1998), the full samples' 5th percentile value will still be 12.05 MPa which is above the required 5th percentile value for grade S5. Mechanical grading is also better than visual grading at separating timber according to MOR. The 5th percentile MOR for mechanically graded rejects is lower than that of visually graded timber whereas the values of grades S5 and S7 are higher than visually graded timber. The 5th percentile MOR value of 17.9 for the mechanically graded S5 timber is well above the required value for S7 of 15.8 MPa. This means that mechanically graded S5 timber from this resource can be sold as S7 if only MOR is taken into consideration (though it is clearly not possible with this resources' stiffness properties). The bending strength of the sample is clearly not a problem when comparing it to the current requirements in the SANS 10163-1 document. In fact when looking at bending strength in isolation and depending on the effect that defect placement has in this specific resource, there might be the potential to either increase grade recoveries of the higher structural grades or alternatively increase the characteristic values of the current grades.

Tension strength results

In the first place it must be mentioned again that most of the boards that were tension tested failed at the grips, which would negatively affect the strength values. Normally these values would have been discarded, but since grip-failures include most of our sample it was decided that it should be included in the results. The tension grips make use of a wedge effect to increase the clamping force at the grips as the tension load increases. The wood at the grips get compressed and failure is usually due to a combination of the tension stress and the grip compression. Even though the absolute failure values of most of the samples will be lower than those which could have been achieved with no grip failures, the test results still provide useful information. Most importantly, with no grip-failures, values would have been higher (cannot be lower) so the results provide a very conservative picture of tension strength. The other limitation of the testing equipment used is that the maximum load that could be applied successfully during tension testing was not high enough to provide an accurate representation of the upper portion of the tension values. Grip-failures also occurred mostly at higher loads (i.e. above the 5th percentile load for S5 grade). The tension values should, therefore, in reality be better for the higher grades, since this was where grip-failures and upper load limitations mostly occurred. The visually graded S5 tension tested timber has a strength about 8% higher than the current standard, S7 3% lower and S10 13% lower. This shows a gradual decrease in the strength results towards the higher strength timber, which is consistent with the theory of the negative affect that the testing grips had on the test pieces. Mechanical grading again proved to be more effective in separating timber according to tension strength – both the 5th percentile values for grades S5 and S7 are higher than required. Even though it is not possible to quantify the effect of grip-failures on the 5th percentile values for the different grades of tension samples, it seems as if tension strength is not a problem in this resource. Despite the limitations of the testing method, the grade potential column shows that 96.6% of all the samples fall within either grade S5 or S7.

The tension test samples were selected so that the worst defect in each 2.1 m board sample falls within the 880 mm test span – which makes it a biased placement of the worst defect. However, structural timber in South Africa is usually much longer than 2.1 m and the biased positioning will not have the same effect as in a sample which can be considered as representative of the South African resource in terms of length. The tension testing results can, therefore, be described as a setup between biased and random defect placement.

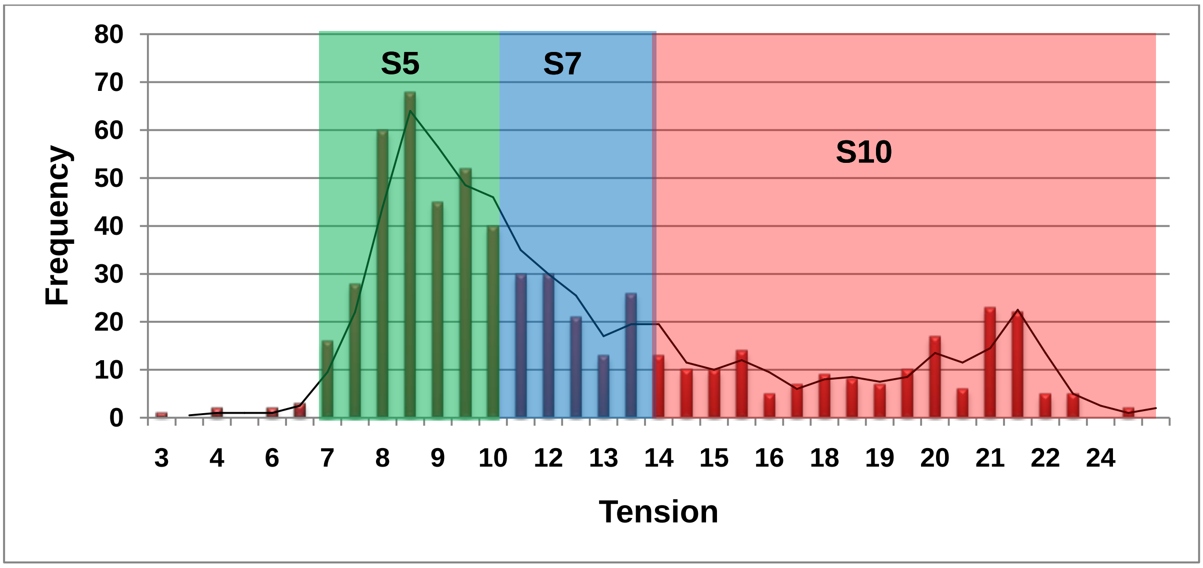

Figure 22: Distribution for tension of all timber tested

Board position within a tree

The effect of the board position within the log on the MOE_{edge} and MOR was evaluated and is depicted in Table 13. Position 0 represent pith containing boards, position 1 are boards next to the pith, and 2/3/4 are the outer boards close to the bark. For MOE_{edge} it can be said that there is a relatively large difference between the mean values of the pith boards, position 1 boards and the outer boards (2, 3 and 4). The MOE_{edge} mean of 6668 MPa for the outer boards is, however, still far below the required mean of 7800 MPa for grade S5 boards. The 5th percentile values for position 0 and 1 is nearly the same, and only increasing with positions 2/3/4. It seems unlikely that the timber produced with a few extra years of growth will increase the mean stiffness of the timber to a level required by the current SANS standards (although this is only speculation). Additionally, according to anecdotal evidence from forest growers, sawlog tree rotation periods of more than 25 years are not likely in the future.

The mean MOR values increase from the pith outwards. The 5th percentile MOR for the outer boards is roughly the same as for the inner boards – in fact pith boards have a slightly higher 5th percentile value than outer boards. It is speculated that MOR in the weakest portion of the sample is influenced mainly by knot sizes. Boards close to the pith will have smaller knots than boards close to the bark and might, therefore, have higher MOR values in the weak section of the strength distribution curve.

Table 13: Bending strength and stiffness properties according to board position within a tree

Property	**MOE_{edge} (MPa)**				**MOR (MPa)**			
Position	**All**	**0**	**1**	**2, 3, 4**	**All**	**0**	**1**	**2, 3, 4**
N	683	245	273	123	683	245	273	123
Mean	5622	5017	5689	6668	30	26.7	29.6	38
5th Percentile	3493	3488	3484	4008	15.1	16	14.5	15.2

Defect placement with in-grade testing

In the discussion of results there were many references to defect placement during testing and this topic may require even more attention. The current South African in-grade testing standard (SANS 6122, 1994) prescribe biased placement of the worst defect in destructive testing of a sample. The sampling and material that was obtained for this study was initially only meant to be used for a different project and the 2.1 m log lengths effectively meant that random placement of the worst defect in a sample occur for bending tests. For tensile test samples with a testing span of 880 mm the test results can be viewed as “limited” biased testing since the 2.1 m board length is much shorter than is normal for South African structural products. The current Australian and New Zealand in-grade testing standards (AS/NZS 4063, 1992) and the ISO 13910 (2005) standard prescribe random testing of samples. Madsen (1992) is of the view that random placement of the sample is the more correct method for in-grade testing since that is what occurs during construction of timber structures – the worst defect is not always, and never deliberately, placed in the highest stressed area. I am, together with many experts in the field, of the view that this is the more sensible method of testing and a change to the current SANS 6122 standard should be considered. In hindsight, it might have been better to also use completely random testing for the tensile samples.

4.2. Results related to structural grading

When grading timber for structural purposes the relationships between properties that can be evaluated non-destructively in a fast and cost-effective way and the strength and stiffness properties of timber are of interest. In the following section the correlations between different measured properties are analysed. The remaining sections analyse combinations of properties that can be used to predict timber strength and stiffness and using some of these NDE properties in grading systems.

4.2.1. Correlations between measured properties

All correlation coefficients (r) between the measured properties are shown in Tables 14a and b. Negative values simply explains a correlation in the negative direction, for instance MOR goes down as knot sizes go up and, therefore, the pair has a negative correlation. Due to the fact that different specimens were used for the bending and tension tests, the correlation between tension and both MOE_{edge} and MOR could not be calculated.

MOE vs. MOR

One of the most widely used relationships in timber grading is that between stiffness and bending strength. The correlation between both MOR vs. MOE_{edge} (r = 58.41%, R^2 = 34.12%) and MOR vs. MOE_{flat} (r = 64.20%, R^2 = 41.21%) are low compared to most other literature sources (Bacher, 2010; Glos, 2004; Hanhijärvi and Ranta-Maunus, 2008; Thelandersson and Larsen, 2003), where values of between 40% and 73% R^2 were obtained. Gaunt (1999), however, found that younger *P. radiata* material has a much lower MOE vs. MOR correlation than older material. Figure 23 better illustrates this relationship by means of a scatterplot. The low correlation makes the determination of new grading rules more difficult, as it shows that timber with a high stiffness does not necessarily ensure a high MOR. It is interesting to note from Table 14a that MOE_{flat}'s correlation with MOR, although low, is higher than that between MOE_{edge} and MOR. It is speculated that the reason for this is because the MOE_{flat} value is determined at the weakest point of the timber with a smaller span and that it relates better to the failure load which is related to this local weak point. The MOE_{edge} value is a function of a longer maximum moment section which might include the weakest point but also other stronger and stiffer material in the sample.

Table 14a: Pearson's correlation coefficient (r) between destructive and non-destructively tested values. Shaded areas has no significant correlation (p>0.05)

Coefficient of variation	MOE_{edge}	MOR	Tension	MOE_{dyn}	MOE_{flat}	ρ_m	ρ_s	Ring max	Ring min	Ring avg
MOE_{edge}	100.00	-	-	-	-	-	-	-	-	-
MOR	58.41	100.00	-	-	-	-	-	-	-	-
Tension	-	-	100.00	-	-	-	-	-	-	-
MOE_{dyn}	70.63	70.13	79.96	100.00	-	-	-	-	-	-
MOE_{flat}	64.20	65.85	69.60	86.56	100.00	-	-	-	-	-
ρ_m(Density manual)	49.53	40.36	58.00	66.75	59.92	100.00	-	-	-	-
ρ_s (Density scanner)	43.67	37.08	51.93	57.25	53.64	87.97	100.00	-	-	-
Ring max	-44.02	-40.24	-48.03	-60.07	-49.03	-39.83	-31.48	100.00	-	-
Ring min	-39.59	-33.67	-51.18	-51.32	-41.33	-44.05	-38.47	61.73	100.00	-
Ring avg	-50.21	-42.90	-56.21	-65.29	-53.74	-48.60	-41.41	85.40	90.57	100.00
Position	35.13	33.32	47.35	52.41	50.19	24.69	19.87	-51.27	-32.82	-47.93
X-dev	-25.63	-18.14	-37.34	-33.99	-37.44	-18.86	-27.50	34.00	16.77	29.66
Knot avg (avg. knot area)	-26.58	-36.75	-37.77	-34.54	-33.81	-21.04	-19.46	19.02	13.62	19.96
Knot max (Max. knot area)	-35.80	-42.82	-48.63	-45.97	-43.73	-18.70	-20.68	33.76	21.08	32.40
Knot Area /Board	-40.15	-45.44	-51.61	-57.02	-50.80	-23.78	-22.65	41.82	25.83	39.26
# Knots	-17.36	-14.73	-25.80	-29.41	-24.97	-3.97	-5.27	29.60	14.99	24.43
KSC (Knot stress calculation)	-21.54	-42.01	-27.20	-25.57	-24.79	-6.91	-8.10	7.34	1.59	5.00
$KPar_f$ (Knot parameter full board)	-27.25	-39.06	-37.13	-39.12	-39.03	-6.20	-3.21	26.75	19.37	27.48
$KPar_c$ (Knot parameter centre third)	-23.65	-36.74	-29.58	-31.59	-35.43	-6.87	-3.81	24.31	14.33	23.17

Correlation matrix including all possible indicator properties. Casewise deletion applied for missing data. N = 562 for all properties except those with tension for which N = 517. (Samples sizes apply for tables 14a and b)

Table 14b: Pearson's correlation coefficient (r) between destructive and non-destructively tested values. Shaded areas has no significant correlation (p>0.05)

Coefficient of variation	Position	X-dev	Knot avg	Knot max	Knot Area / Board	# Knots	KSC	$KPar_f$	$KPar_c$
X-dev	-59.15	100.00	-	-	-	-	-	-	-
Knot avg (avg. knot area)	-19.10	-1.85	100.00	-	-	-	-	-	-
Knot max (Max. knot area)	-46.12	42.13	58.72	100.00	-	-	-	-	-
Knot Area / Board	-56.15	40.10	51.92	70.01	100.00	-	-	-	-
# Knots	-48.49	57.73	-37.99	16.87	47.72	100.00	-	-	-
KSC (Knot stress calculation)	-15.94	2.47	27.28	24.15	39.74	12.16	100.00	-	-
$KPar_f$ (Knot parameter full board)	-38.13	9.46	42.73	50.76	48.81	10.22	20.53	100.00	-
$KPar_c$ (Knot parameter centre third)	-27.39	12.06	36.04	41.24	41.28	11.17	29.08	71.45	100.00

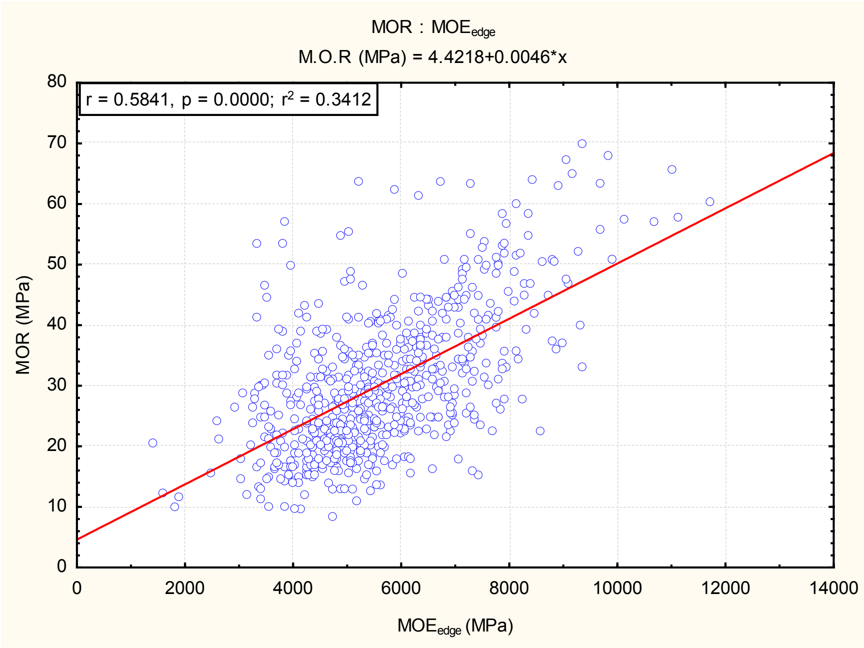

Figure 23: Scatterplot of MOR against MOE_{edge}

Density vs. MOR, MOE and tension

The correlations of MOE, MOR and tension with density (Table 14a) are comparable with results found in other studies where R^2 values of between 20-30% were obtained (Glos, 2004). It is noticed that the manually measured density data (ρ_m) shows better correlations with other properties than the scanner density (ρ_s). The manually measured results will in this case be the most reliable to use. This lack of accuracy from the scanner data is explained in the methods and materials section of the report. The 87.97% correlation between the manual and the scanner measured densities is considerably lower than expected from new technology grading machines (Bacher, 2010).

MOE_{edge} vs. MOE_{flat}

A surprising result is the low correlation between MOE_{edge} and MOE_{flat} (r = 64.2%) from Table 14a. This value is almost the same as between MOR and MOE_{flat} (r = 65.85%). The low correlation might be explained by the fact that the MOE_{flat} value is determined at the weakest point of the timber and on flat, probably including a big knot percentage, as opposed to the random test setup for the determination of MOE_{edge}.

MOE_{dyn} vs. MOE_{edge} / MOR / Tension

A very encouraging NDE property measured is that of MOE_{dyn}. MOE_{dyn} was the best single predictor for MOE_{edge}, MOR and tension (Table 14a). Figures 24, 25, and 26 depict the relationships of MOE_{dyn} with these three characteristic values. The correlation values are even better, although not by much, than the correlation with MOE_{flat} which was calculated from flatwise bending on the weakest point of the samples. The higher correlation values of MOE_{edge} and MOR with MOE_{dyn} compared to MOE_{flat} shows promise when taking into consideration that MOE_{dyn} measurements are simple and cheap compared to the measurement of MOE_{flat}. The effects of MOE_{dyn} and MOE_{flat} grading will be discussed later in the thesis in section 4.2.3.

Other properties

The other variables that were deemed to be statistically influential were: annual ring widths (*ring max, ring min and ring avg*.), the position of the timber piece within the tree (*position*) and knots (*knot avg. knot max, knot area /board, KSC, $KPar_f$ and $KPar_c$*).

It is noticed that the ring average, which is the mean width of the annual rings on each board, has a better correlation with both MOE_{edge} and tension than the individual knot parameters has. This is not such a surprising result for MOE_{edge}, as the knots do not play such a big role as would be expected for MOR and tension. It is, however, surprising that the single knot parameters do not play a bigger role in the prediction of tension. This might be due to the limitations in the tension testing discussed earlier. The correlation between MOR and ring width average is also only slightly lower when compared to MOR vs. knot area per board (Tables 14a and b), which is shown as the best predictor between the different knot parameters. The best predictor for MOE_{edge}, MOR and tension, between the different knot measurements taken, is the total knot area per board. This seems to be a better predictor than the maximum knot size in a board. The knot stress calculation and knot parameters, which was formulated by combining knot sizes and positions, did not show good correlations.

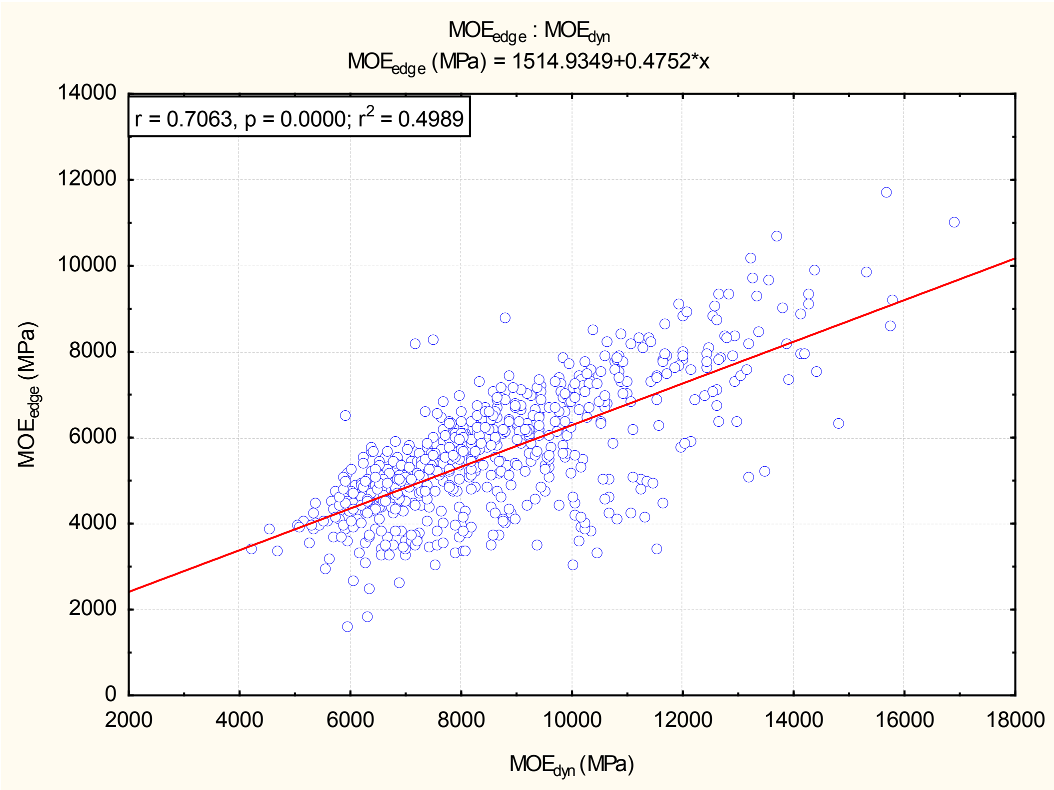

Figure 24: Scatterplot of MOE_{edge} against MOE_{dyn}

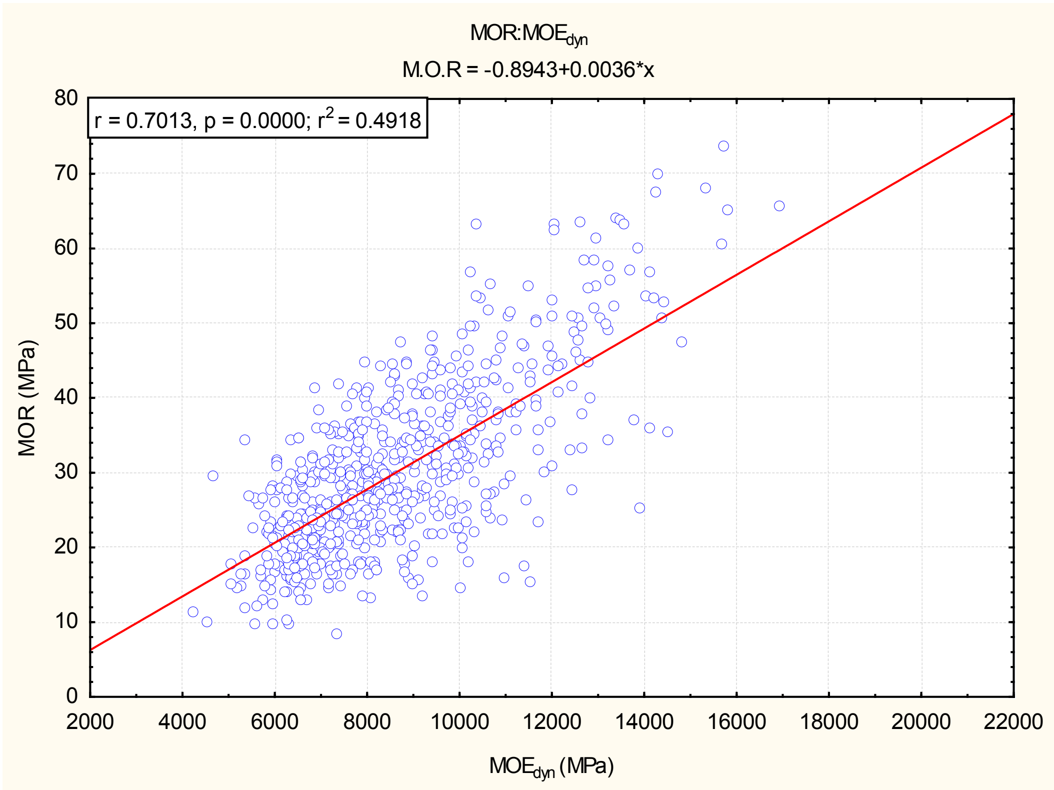

Figure 25: Scatterplot of MOR against MOE_{dyn}

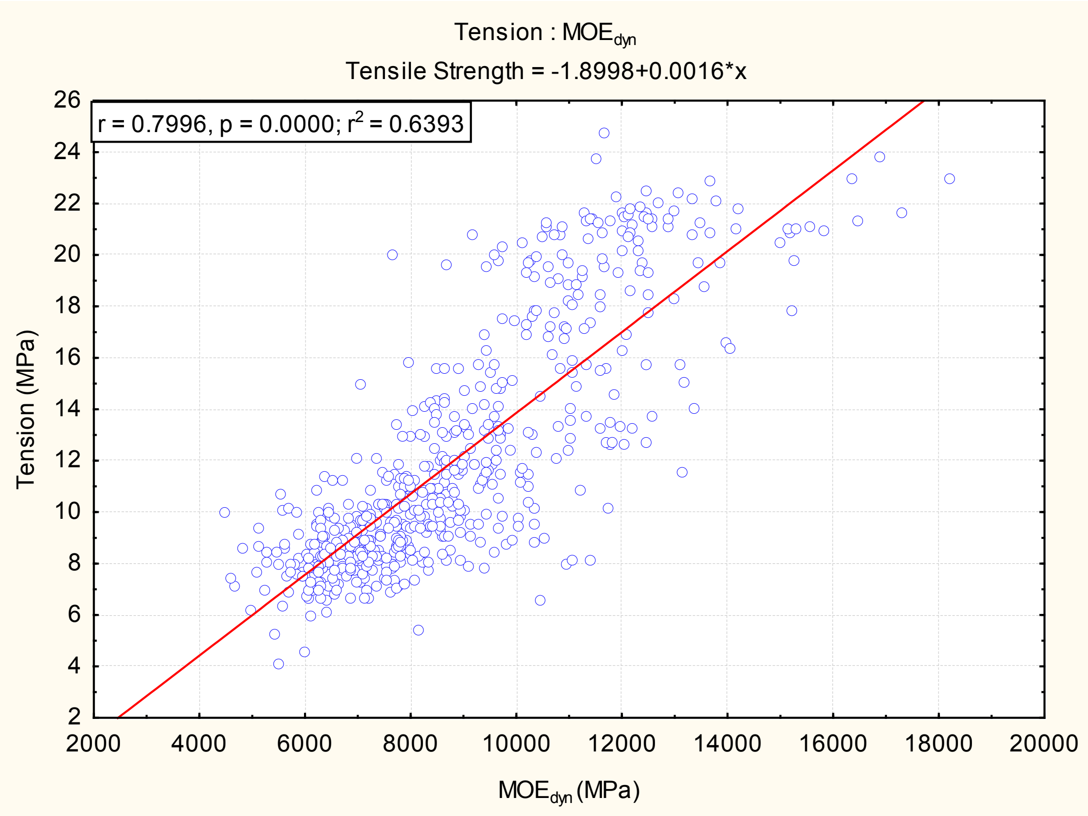

Figure 26: Scatterplot of tension against MOE$_{dyn}$

4.2.2. Using combinations of properties to predict strength and stiffness

Multiple regression analysis was used to determine how well combinations of NDE properties can predict the strength and stiffness of the young *P. patula* timber. A combination of the best subsets, Mallows Cp and forward stepwise regression methods were used to identify properties to include in prediction models. Table 15 depicts the degrees of determination between the destructively tested properties and combinations of indicator properties. These are the indicator properties with the highest influence on the characteristic strength properties of timber. By means of statistical analysis of the co-linearity only the properties that were determined to be influential in the destructive test results are displayed in the table. Note that the r-values for single properties might be slightly different to that in the correlation and determination tables (Tables 14a and b and Table 15) due to higher sample numbers possible when only individual correlations are considered.

Table 15: Coefficients of correlation and determination values (percentages) between destructive tests and both single and combined indicator properties. Pearson's correlation used for single predictors and forward stepwise regression for multiple predictors

Predictors	**MOE_{edge}**		**MOR**		**TENSION**	
	R^2	***r***	***R^2***	***r***	***R^2***	***r***
MOE_{dyn}	48.26	69.47	46.55	68.23	62.93	79.33
MOE_{flat}	46.15	67.93	47.32	68.79	53.69	73.27
ρ_m(Density manual)	30.20	54.95	23.83	48.82	33.71	58.06
Knots1-7F, KSC, Knot max	19.91	44.62	33.67	58.03	31.14	55.80
$\rho_{m,}$ Knots1-7F, KSC	35.94	59.95	42.53	65.22	45.91	67.76
MOE_{dyn}, $\rho_{m,}$ Knots1-7F, KSC	49.89	70.63	54.26	73.67	64.38	80.24

Knot parameters, comprising of knot size and location data and parameter values (Knots1-7F, KSC, Knot max), showed a degree of determination of 33.67% for MOR. This is in the upper range of values found for European timber in the study by Glos (2004). Various combinations of timber properties were statistically evaluated and also tested for co-linearity as explained in the methods and materials section of this report. The fact that MOE_{dyn} (*frequency*) is the best single parameter predictor of both MOE_{edge} and tension, and that combining MOE_{dyn} with density and knots increases the predictability of MOR by almost 7% over the use of MOE_{dyn} alone, suggests that a decent grading criterion can be obtained through only the use of frequency and knot parameters.

The best prediction values for MOE_{edge}, MOR and tension were obtained by combining knot parameters, density and MOE_{dyn}. Statistical analysis showed that the density contributes very little to this prediction value and that the addition of the knot parameters to MOE_{dyn} in the prediction of MOR has a roughly 6% increase compared to MOE_{dyn}. MOE_{dyn} on its own is however the best predictor of MOE_{edge} and tension.

When comparing the R^2 values in this study with that obtained by Glos (2004), it shows that the predictability of MOR using combinations of properties for this resource is quite low. Glos mentions R^2 values of between 55-80% and with a combination of properties the best R^2 value obtained was 53.66%. The predictability of tension strength (despite the limitations in our test setup) is relatively good at 64.13% and of MOE_{edge} quite poor at lower than 50%.

4.2.3. Structural grading according to different NDE properties

In this section test grading rules were developed for illustration purposes for MOE_{dyn} and compared with visual grading and machine grading results. It is a somewhat hypothetical comparison since no grading rules can get results where the current mean MOE_{edge} requirements from SANS 10163-1 are satisfied (Table 12) – simply because it is not possible with the low MOE_{edge} values of this timber resource. Non-strength reducing properties like warp were not considered in these comparisons.

Visual grading was performed as described in SANS 1783 (2005), excluding the non-strength reducing properties like warp but including the density specifications. Mechanical grading was performed according to SANS 10149 (2002), also excluding non-strength reducing properties in the grading process. For acoustic grading according to MOE_{dyn}, the grade allocation rules were developed by simulating different scenarios using the MOE_{dyn} values as the grade limits. There are many combinations of values that can be used, and the efficiency of each set of values will differ. The comparison between these grading methods can be seen in Table 16. Figure 27 shows the results of applying the acoustic grading rules to the samples tested in this study.

The tension sample was not included in this comparison due to the limitations experienced in the test setup.

Because the results cannot be compared against the current SANS 10163-1 requirements (all grading methods will fail based on mean MOE values) this comparison only serves as a crude illustration of how different and new grading methods can be compared. From Table 16 it can be seen that all three grading methods result in fairly similar 5^{th} percentile MOR values for all the grades except that the S10 grade of acoustic grading is lower than the other two methods. There is also a good difference in MOE values between the grades for all the grading methods (although all will fail the SANS requirements). The big difference between the methods in this example is the yield percentages. For mechanical grading nearly 50% of the pieces were rejected whereas only 3.1% of the pieces were rejected using acoustic grading. However, mechanical grading provides results with higher mean MOE values than acoustic or visual grading.

It is fairly difficult to make meaningful comparisons between grading systems with the current resource where nearly any method will provide acceptable MOR values and no method will provide acceptable MOE values. According to the relationships between strength and stiffness values and NDE properties, however, combinations of properties where MOE_{dyn} is used should be more efficient than the current visual and mechanical grading criteria used.

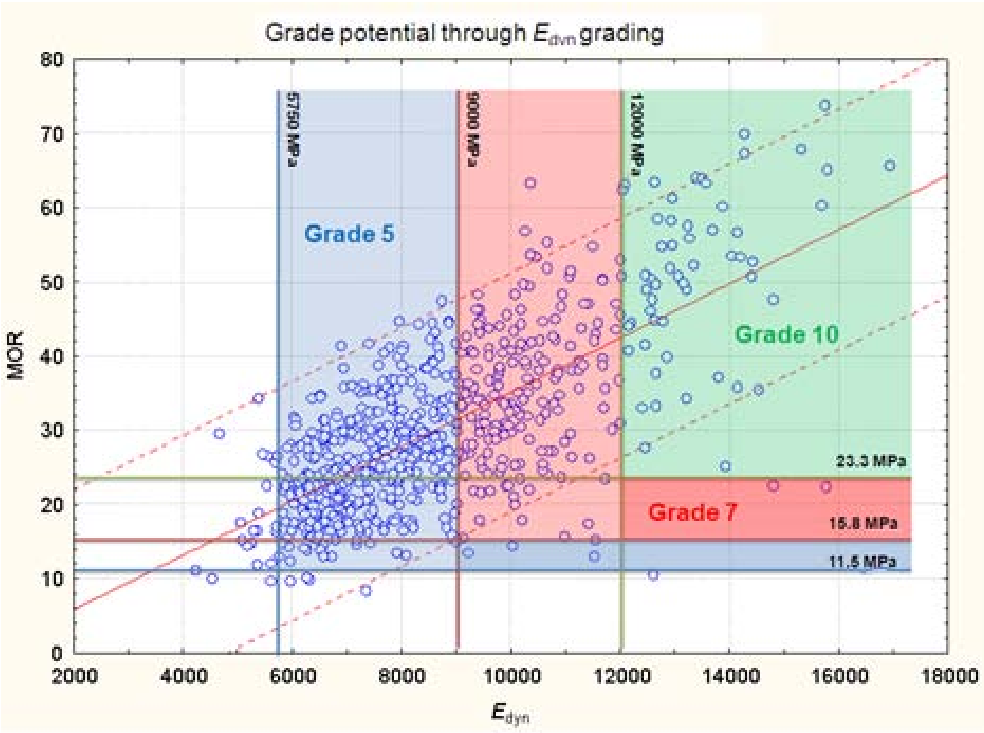

Figure 27: Grade potential using only MOE_{dyn} grading rules

Table16: Comparison of current SANS visual and mechanical strength grading rules with experimental acoustic grading rules (excluding non-strength reducing properties like warp). MOR values are characteristic fifth percentile and MOE are mean values. Values in MPa.

Visual / mechanical grade	**Visual grading**				**Acoustic grading (MOE_{dyn})**				**Mechanical grading (MOE_{flat})**			
	N	**Yield (%)**	**MOR**	**MOE**	**N**	**Yield (%)**	**MOR**	**MOE**	**N**	**Yield (%)**	**MOR**	**MOE**
XXX	122	19.6	12.9	4850	21	3.14	9.96	4648	331	49.6	12.9	4782
S5	377	60.6	15.0	5334	400	59.8	15.0	5023	239	35.8	15.9	6022
S7	94	15.1	17.8	6791	184	27.5	18.0	6331	84	12.6	17.7	7282
S10	29	4.66	27.2	7850	64	9.57	22.4	7884	16	2.40	27.6	8196

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made:

1. The young *P. patula* timber tested in this study has very low stiffness and does not comply with the current SANS 10163-1 (2003) requirements for mean MOE in any of the visual or mechanical grades.

2. The bending strength (MOR) of the timber tested is well above the SANS 10163-1 (2003) requirements for 5th percentile values for all of the visual and mechanical grades. A random placement of the worst defect was used in this study which is in line with some other international testing standards but contrary to the current in-grade testing specifications SANS 6122 (1994).

3. The 5th percentile values for tension strength parallel to grain of the timber tested for both visual and mechanical grades were similar to the requirements as specified in the SANS 10163-1 document for all the structural grades. There were, however, some limitations in our test setup which caused the results to be lower than it should have been if a correct test setup was possible.

4. The mechanical grading rules as contained in SANS 10149 (2002) resulted in consistently better outcomes in terms of strength and stiffness differentiation of grades than the current visual grading rules as contained in SANS 1783-2 (2005).

5. Of all the individual non-destructive predictors of strength and stiffness, the dynamic modulus of elasticity (MOE_{dyn}) shows on average the best correlation with MOR, MOE_{edge} and tension strength. When combinations of NDE properties are used to predict stiffness and strength the degree of determination can be increased in some cases over only using a single predictor such as MOE_{dyn} or MOE_{flat}.

The following recommendations are wider than the scope of this study but are included to provide a holistic picture of the current problems associated with structural grading of the (variable) SA Pine resource. The recommendations are in the order in which they should be implemented:

1. A study should be performed on the market requirements of structurally graded pine products with a focus on the largest market viz. the roof truss industry. The study should provide answers to the following questions:
    a. what is the impact on timber usage and cost in roof truss manufacture if the characteristic values of structural timber grades will be changed to the values determined in this study for young *P. patula* timber; and
    b. what are the most critical strength and stiffness properties for this industry and which properties are less critical?

2. The in-grade testing standard SANS 6122 (1994) should be reviewed giving specific attention to the placement of defects during testing. The current version prescribe biased placement of defects which might be an unnecessary strict requirement and is contrary to many other international standards.

3. An in-grade testing program should be performed on a representative sample of structural timber in South Africa using this reviewed SANS 6122 document as a basis.

4. All standards and specifications impacting on the structural grading of SA Pine should be reviewed so that the strength and stiffness potential as well as the financial returns from our current sawlog resource can be maximised. The review should take the following into consideration:
    a. the findings of (1) above, in terms of market requirements for grading. Grade determination and quality control should focus on the most critical properties for the end-use market;
    b. the findings of (2) above, in terms of the variability of the current resource available in South Africa;
    c. the ease of implementation of new grading rules and systems;

d. a system where individual sawmills are responsible for proving the strength and stiffness of their own products on a continuous basis should be evaluated also taking into consideration commercial aspects; and
e. the system should ideally allow each sawmill to maximise the potential of its own resource in terms of strength and stiffness properties.

6. REFERENCES

AS 2858 (2003). Australian Standard. Timber softwood - visual stress-grading rules for structural purposes.

Bacher, M. (2008). Comparison of different machine strength grading principles. Conference COST E53, Delft, The Netherlands.

Bacher, M. (2010). Grading of structural timber, unpublished presentation at Sawmilling SA meeting on 14 July 2010, Johannesburg, South Africa.

Bailleres, H., Hopewell, G., Boughton, G. (2009). MOE and MOR assessment technologies for improving graded recovery of exotic pines in Australia. Forest and wood products Australia limited. Report. PNB040-0708. 92pp.

Barnett, J. R., Bonham, V. A. (2004). Cellulose microfibril angle in the cell wall of wood fibres. Biological Reviews, Cambridge University press 79 (2): 461-472.

Bendtsen, B. A., Senft, J. (1986). Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood and Fiber Science 18 (1): 23–38.

Bengtsson, C. C., Perstorper, R. (1998). Dynamic tests of Norway spruce wood: influence of moisture conditions. Proceedings of the 11th International Symposium on Nondestructive testing of wood, Wisconsin, p 63-74.

Blass H. H., Gard, W. (1994). Machine strength grading of timber. Proceedings of Pacific Timber Engineering Conference, July 11-15, Gold Coast Australia, p 598-603

Bodig, J. (2000). The process of NDE research for wood and wood composites (key-note speech). Proceedings of the 12th international symposium on nondestructive testing of wood. 13-15 September, University of Western Hungary, Sopron, p 7-9

Boström, L. (1994). Machine strength grading. Comparison of four different systems. SP Report 49. Swedish National Testing and Research Institute.

Brazier J, D. (1985). Juvenile Wood. In: Kucera L. J. (ed.). Xylorama, trends in wood research. Basel: Bukhauser Verlag, p 25–32.

Bucur, V. (2005). Acoustics of wood (second edition). Springer, Heidelberg. 393pp.

Burdzik, W. (2004). Grade verification of SA pine. Southern African Forestry Journal 202: 21-27.

Cave, I. D., Walker, J. C. (1994). Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. For Prod J 44(5): 43-49.

Crickmay & Associates. (2009). South African Lumber Index, Feb 2009.

Dinwoodie, J. M. (2000). Timber: Its nature and behaviour. E & FN Spon, London and New York, 257pp.

Dowse, G. P. (2009). Determination and analysis of variance during transverse vibration testing and evaluation of microtec's goldeneye X-ray scanner. Unpublished honours report. Department of Forest and Wood Science, Stellenbosch University.

EN 518 (1995). European Standard. Structural timber. Grading requirements for visual strength grading standards.

Evans, R., Ilic, J. (2001). Rapid prediction of wood stiffness from microfibril angle and density. For Prod J 51(3): 53-57.

Falcon engineering. (Undated). Report retrieved from www.falcon-eng.co.nz

Gaunt, D. J. (1999). Machine stress grading revisited. NZ Timber Design Journal 1(8): 10-18.

Giudiccandrea, F., Verfurth, P. (2006). Combined strength and appearance lumber grading by multisensor technology. Wood SA and Timber Times 31(9): 50-53.

Glos, P. (2004). New grading methods. Proceedings of COST E29 Symposioum, Florence October 27-29. CNR-Ivalsa, San Michele all'Adige, Italy, p 1-8.

Görlacher, R. (1984). Ein neues Messverfahren zur bestimmung des Elastizitätsmoduls. European Journal of Wood and Wood Products (42). p 219-222.

Green, D. W., Kretschmann, D. E. (1997). Properties and grading of Southern pine timbers. For Prod J 7(9): 78-85.

Hanhijärvi, A., Ranta-Maunus, A. (2008). Development of strength grading of timber using combined measurement techniques. Report of the Combigrade-project - phase 2. VVT Publications 686. Espoo: VTT. ISBN 978-951-38-7106-2. Available at http://www.vtt.fi/publications/index.jsp

Hanhijarvi, A., Ranta-Maunus, A., Turk, G. (2005). Potential of strength grading of timber with combined measurement tecniques. Report of the Combigrade project - phase 1. VTT Publications 568. Espoo: VTT. ISBN 951-38-6647-5. Available at http://www.vtt.fi/inf/pdf/publications/2005/P568.pdf.

Hankinson, R. L. (1921). Investigation of crushing strength of spruce at varying angles of grain. Air Force Information Circular No. 259, U.S. Air Service.

ISO 13910. (2005). Structural timber - Characteristic values of strength-graded timber - Sampling, full-size testing and evaluation.

Jayne, B. A. (1959). Indices of quality: Vibrational properties of wood. For Prod J 9(11): 413-416.

Johansson, C. J., Bostrom, L., Brauner, L., Hoffmeyer, P., Holmquist, C., Solli, K. H. (1998). Laminations for glued laminated timber. Swedish national testing and research institute, SP REPORT 1998:38.

Knuffel, W. E. (1983)., In-grade testing of SA pine visual grades. Hout 240, CSIR.

Knuffel, W. E. (1984). An improved visual and mechanical stressgrading system for SA pine timber. Hout 318, CSIR.

Larson, P. R., Kretscmann, D. E., Clark III, A., Isebrands, J. G. (2001). Formation and properties of juvenile wood in southern pines, a synopsis. USDA Forest Products Laboratory technical report. FPL-GTR-129

Larsson, D. (1997). Mechanical characterization of engineering materials by modal testing. Doctoral thesis, Chambers University of Technology, Gothenburg, Sweden.

Leicester, R. H., Breitinger, H., Fordham, H. (1998). A comparison of in-grade test procedures. International Council for Building Research Studies and Documentation working commission W18 - timber structures. Meeting thirty-one, Savonlinna, Finland: CIB-W18/31-5-2.

Madsen, B. (1992). Structural behaviour of timber. Timber Engineering Ltd, North Vancouver, Canada. 405pp.

McKeever, D. B. (1997). Engineered wood products: A response to the changing timber resource. Pacific Rim wood market report, Gig harbour, WA. P 5, 15.

Moschler, W. W., Dougal, E. F., McRae, D. D. (1989). Density and growth ring characteristics of *Pinus taeda* following thinning. Wood and Fiber Science 21 (3): 313-319.

Nyström, J., Grundberg, S. (2007). Industrial measurement of spiral grain on debarked sawlogs and prediction of twist on centre planks after drying. In: Modelling the Wood Chain: Forestry - Wood Industry - Wood Products Markets. Ghent University p 87-93

Pearson, R. G., Ross, B. E. (1984). Growth rate and bending properties of selected loblolly pines. Wood and Fiber science 16: 37-47.

Pellerin, R. F., Ross, R. J. (2002). Nondestructive evaluation of wood. Madison: Forest Products Society. 201pp.

Rais, A., van de Kuilen, J. W., Stapel, P. (2010). The influence of knot size and location on the yield of grading machines. 'The Future of Quality Control for Wood & Wood Products'.The Final Conference of COST Action E53. 4-7th May 2010, Edinburgh.

Rayda, R. R. (2003). Non-destructive evaluation of lumber from cull and suppressed growth trees. Laramie, Wyoming: M.S., Deparrtment of Civil and Architectural Engineering.

SANS 10163 (2003). South African national standard. The structural use of timber - Part 1: Limit-states design. Edition 2.3.

SANS 10149 (2002). South African national standard. The mechanical stress grading of softwood. Edition 1.2.

SANS 1783-1 (2004). South African national standard. Sawn softwood timber, Part 1: General requirements.

SANS, 1783-2 (2005). South African national standard. Sawn softwood timber Part 2: Stress-graded structural timber and timber for frame wall construction.

SANS, 6122 (1994). South African national standard. Qualification testing of solid structural timber and laminated structural timber (glulam) for verifying timber grading systems in accordance to a given standard.

Schajer, G. S. (2001). Lumber strength grading using X-ray scanning. For Prod J. 51 (1): 43-50.

Thelandersson, S., Larsen, H. J. (eds) (2003). Timber Engineering. John Wiley & Sons Ltd. 445pp.

Vinopal, G. W., Bryant, P. A., Simon, J. A. (1978). Investigation of the distribution of strength and other properties of SA pine structural timber. Hout 142, CSIR.

Walford, B., & Gaunt, D. (2006). Experience with performance-based visual grading of dimension lumber. NZ Timber Design Journal 2 (14).

Walford, G. B. (2002). Comparison of various standards for the characteristic strength and stiffness of structural timber. NZ Timber Design Journal 2 (11): 13-18.

Walker, J. C. (1993). Primary wood processing. London: Chapman & Hall. 595pp.

Wang, X., Carter, P., Ross, R. J., Brashaw, B. K. (2007). Acoustic assessment of wood quality of raw forest materials - a path to increased profitability. For Prod J 57(5): 6-14.

Wimmer, R. (1991). Relations between growth ring parameters and density of Scots pine wood (in German). Holzforschung und Holzverwertung 43 (4): 79-82.

Zobel, B. J., Van Buijtenen, J. P. (1989). Wood variation. Its causes and control. Springer, Heidelberg, 363pp.

ADDENDUM A - Deflection measurement during bending testing

The deflection measurement for a four-point bending test can be done at two positions according to SANS 6122 (1994). The first position is the measurement at the loading head (that is at a third of the span) – see d2 in Figure 28. The second position where deflection can be measured is at the centre of the span shown as d1 in Figure 28.

A comparison was done between the two testing setups, using the two different measurement positions and the appropriate formulas. The testing procedure is explained below.

Methods and materials

The main test setup was similar to the setup used during destructive testing for the project, with the only difference being the measurement positions.

The distance between the supports was 1950 mm with a third-point distance of 650 mm. The testing speed was set at 14 mm/min. A sample of 30 boards with nominal dimensions of 120x40 mm was tested.

All of the tests were performed in a temperature and humidity controlled testing laboratory at the University of Stellenbosch.

The testing machine automatically measures the deflection at position d2 as shown in Figure 28. Additionally, the deflection at position d1 was also measured with the use of a portable caliper secured in a stationary jig placed underneath the centre of the board on the bed of the testing machine. The boards were all tested to destruction, after which the two different formulas provided in SANS 6122 (1994) were used to calculate the MOE_{edge}. The MOR was also determined and correlated with the two sets of MOE_{edge} values.

The following formulas were used:

MOE_{edge} and MOR according to SANS 6122 (1994)

Deflection at a third of the span (crosshead movement)

$MOE_{edge} = FL^3/5.4*bh^3D$, 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, measured at a third of the span, under the increment in load *F*, in millimetres.

Deflection at mid-span

$MOE_{edge} = F \cdot L^3/4.7 \cdot b \cdot h^3 \cdot D$, where:

MOE_{edge} is the static modulus of elasticity measured on edge at mid-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, measured at mid-span, under the increment in load *F*, in millimetres.

MOR

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

MOR	is the characteristic bending strength (modulus of rupture), 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.

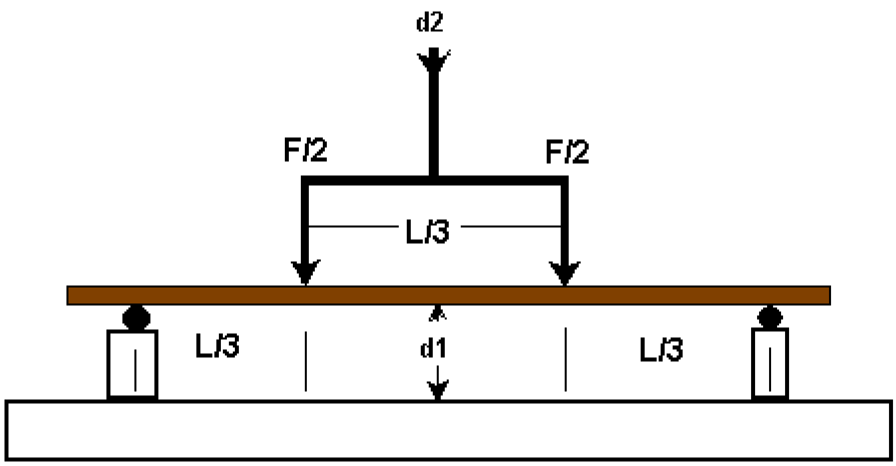

Figure 28: Bending test setup for deflection measurement comparison

Results and analysis

Table 17 shows the R^2 percentages for the correlations between the MOE and MOR values for both the measurement methods. The tests showed no significant difference between the two MOR vs. MOE_{edge} values (34.93 and 32.56%). There is also a very good correlation between the MOE_{edge} values calculated from the two different deflection measurement positions (R^2 = 96.91%).

Table 17: Degrees of determination (R^2 percentages) between two different testing methods

	MOE (3rd point deflection)	**MOE (mid- point deflection)**	**MOR**
MOE_{edge} (3rd point deflection)	100	96.91	34.93
MOE_{edge} (mid-point deflection)	96.91	100	32.56
MOR	34.93	32.56	100

Conclusion

The test results show a very good correlation between the values obtained between the two testing methods, granted that the correct formulas are applied. The correlations with MOR for the two testing methods are also very similar. The measurement of deflection at a third of the span is, therefore, seen as a reliable method for use in this study.