Report on strength and stiffness properties of Biligom lumber samples

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On 22 August 2016 I received four marked pieces of 36x111mm treated Biligom lumber from Mr. Mattie Oosthuizen with a request to possibly do strength tests on them and to comment whether they fulfil the strength and stiffness requirements of this specific product grade.

The following comments on the samples received:

1. All four pieces had various degrees of splitting present. After having tested hundreds of pieces of Biligom I can state that the splitting observed within the four sample pieces are quite normal and to be expected for Biligom.
2. The dimensions of the pieces received were too small for flexural testing. Also, for strength testing of lumber according to the in-grade test method (SANS 6122) one need at least 100 pieces in order to determine the characteristic strength and gauge whether a group of lumber comply with a strength grade. Take note that it is not possible to determine whether a single piece of lumber conform to strength requirements – you can only test a large group of lumber as the characteristic strength is a statistical value (5th percentile) and not a border value.
3. The Biligom process is audited by an independent accreditation body (SATAS) and every piece of lumber is tested in bending during the process while the lumber is still wet. After drying, most of the strength properties will only improve despite splits and deformation that will appear during the drying process.
4. Extensive testing by my own laboratory has been done on this product and we have established that (a) most of the important strength properties are much higher than those of SA Pine Grade 5 and (b) the variability in the flexural properties are much lower than that of SA Pine. The lower variability of bending strength and stiffness mean that an end-user can have a higher degree of confidence in the reliability of structures build from Biligom than from SA Pine when the same safety factors are used.
I attach here a peer-reviewed journal article that appeared in the Southern Forests journal reporting on the results of testing 720 pieces of Biligom lumber. There are no reason to believe that the pieces of Biligom lumber that has been sent to me will behave differently to the lumber described in the journal paper attached.

With best regards,

Dr. C. Brand Wessels
The potential of young, green finger-jointed *Eucalyptus grandis* lumber for roof truss manufacturing

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South Africa is a timber-scarce country that will most probably experience a shortage of structural softwood lumber in the near future. In this study the concept of using young, green finger-jointed *Eucalyptus grandis* lumber was evaluated for possible application in roof truss structures while the timber is still in the green, unseasoned state. Drying will occur naturally while the lumber is fixed within the roof truss structure. The objectives of this study were (1) to investigate the strength and stiffness variation of the finger-jointed *E. grandis* product in both the green and dry state for different age and dimension lumber, (2) to investigate the variation in density, warp and checking in the lumber when dried in a simulated roof-space environment and (3) to evaluate the potential of this finger-jointed product as a component in roof truss structures. Green finger-jointed *E. grandis* lumber of ages 5, 11 and 18 years and dimensions 48 x 73 mm and 36 x 111 mm from Limpopo province were evaluated. The study showed that the young finger-jointed *E. grandis* timber had very good flexural, tensile parallel to grain, and shear properties in both the green and dry state. The mean and characteristic modulus of elasticity and modulus of rupture values of the finger-jointed *E. grandis* product were higher and the variation lower in comparison to currently used South African pine sources. The tensile perpendicular to grain and compression perpendicular to grain strength did not conform to SANS requirements for the lowest structural grade (S5). Both tree age and product dimension were sources for variation in the physical and strength properties. Based on the results from this study the concept of producing roof trusses from green, finger-jointed young *E. grandis* timber has potential.

**Keywords:** checking, green gluing, MOE, MOR, shrinkage, splitting, strength properties, warp

Introduction

In a study completed by Crickmay and Associates in 2004, on the demand and supply of softwood sawlogs and sawn lumber in South Africa, it was predicted that South Africa will face an increasing shortage of structural lumber over the next three decades. Subsequently in 2008, for the first time in nearly half a century, significant volumes of structural lumber was imported from countries such as Argentina, Brazil and New Zealand (Crickmay and Associates 2014). Although lumber demand has decreased since the onset of the global economic recession, it can be expected that supply will again become a constraint with a favourable economic growth rate in South Africa.

Unlike softwood saw logs resources, South Africa produces more *Eucalyptus* logs than our own processing industries can consume, and large volumes of *Eucalyptus* chips are exported each year (Chamberlain et al. 2005). *Eucalyptus* timber is rarely processed into structural lumber in South Africa mainly because of processing problems associated with splitting of the wood due to growth stresses, brittle heart, dimensional stability and collapse after seasoning (Jacobs 1955; Malan 1984, 1993; Vermaas and Bariska 1994; Malan 2003). If these problems can be overcome, *Eucalyptus* timber, and especially *Eucalyptus grandis*, might be a promising raw material for structural lumber products. Apart from the larger volumes available for processing, the mean annual increment of South African *E. grandis* is 24.6 m³ ha⁻¹ y⁻¹, whereas South African pine species shows a mean annual increment of 14.6 m³ ha⁻¹ y⁻¹ (Crickmay and Associates 2005).

Many authors agree that growth stresses in *Eucalyptus* trees result in some of the most serious wood quality problems of this genus (Malan and Gerischer 1987; Yang and Waugh 2001; Washusen et al. 2003; Kojima et al. 2012). Growth stresses are the main cause of splitting in logs and lumber from *Eucalyptus*. According to Maree and Malan (2000) splitting-related losses exceed 10% in South African eucalypt sawmills. Another consequence of growth stresses is a condition known as brittle heart. Wood with brittle heart contains numerous fractures and splits, is unattractive, low in strength, and impossible to machine to a smooth surface (Malan 2003). Brittle heart only manifests in large older trees (Yang and Waugh 2001). By harvesting and processing *Eucalyptus* trees while they are still young, some of the negative consequences of growth stresses can be avoided (Yasin and Raza 1992).

About 30 years ago research showed that gluing of green lumber is possible with adhesives such as phenol resorcinol-formaldehyde (Bin et al. 2005). Green lumber is defined here as lumber that has a moisture content above fibre saturation point (FSP). More recently, single component polyurethane (PU) adhesives began to be used commercially for green gluing (Sterley 2012). These PU adhesives enable...
manufacturers to finger-joint green lumber and utilise the final product in construction either in the green state or after drying the glued composite product. Many studies confirmed the structural integrity of green glued joints of softwoods with PU adhesives (i.e. Pommier and Elbez 2006; Bergman et al. 2010; Sterley 2012). However, there has been less attention on green gluing of hardwoods (Karastergiou et al. 2008) and none could be found for Eucalyptus.

It is well known that moisture negatively affects the strength and stiffness properties of wood (Dinwoodie 2000). For that reason, using green lumber as a structural product is not allowed by the South African structural grading code (SANS 1783-1 2009). However, in other countries, such as New Zealand, grading standards include a green grade (NZS 3603 1993). Both the green and dry properties of this grade are included in the standard so that the engineer can use either or both green and dry characteristic stresses as required in the design. It has been shown that moisture affects the various strength properties of wood very differently – whereas compression strength parallel to grain of clear wood can increase by 60% when drying from 20% to 8% moisture content, impact strength is hardly affected (Ranta-Maunus 2003). Importantly, moisture influence high-quality and clear wood much more than low-quality knotty lumber. For instance, Madsen (1992) found that for Douglas-fir moisture had virtually no effect on the 5th percentile bending strength (low-strength lumber) but a huge effect on the 95th percentile bending strength (high-strength lumber). For structural design purposes the characteristic or 5th percentile strength values are used – in other words the low-strength lumber in a population determines the strength values that will be used to design structures.

A small sawmill in Limpopo province recently started production of young E. grandis lumber that was finger-jointed with a one-component PU adhesive while the wood was still unseasoned with a moisture content above FSP. The lumber is sold unseasoned and ungraded into the local informal market. According to the producer, the use of young trees (5–18 years old) and the green finger-jointing of planks, ameliorate many of the problems usually associated with Eucalyptus lumber from mature saw log resources (S Drake, Biligom, pers. comm., 2012). As discussed, young trees have less growth stresses, split less and do not develop brittle heart. In addition, the green finger-jointing apparently help to arrest split development in boards at the joints.

The aim of this study was to determine the suitability of using young, unseasoned, green finger-jointed E. grandis lumber as structural components in roof trusses. According to this concept the lumber will be proof graded while green and will dry naturally while fixed in a roof structure. Drying-related degrade that does not significantly affect the mechanical properties of the lumber and roof truss will, in this case, not be a concern since the truss only has a structural function. According to current South African regulations, structural lumber must be dried to a moisture content of less than 15% (SANS 1783-1 2009). At present, more than 70% of all sawn lumber in South Africa is used in buildings, mainly in the roof structures (Crickmay and Associates 2014). The specific objectives of this study were as follows:

- to determine the characteristic strength and stiffness values of both unseasoned finger-jointed Eucalyptus boards as well as boards that have been dried to equilibrium moisture content and investigate the variation over different ages and dimensions of lumber
- to investigate the variation in density, warp and checking in finger-jointed Eucalyptus lumber when dried in a simulated roof-space environment
- to evaluate the potential of this finger-jointed product as a component in roof truss structures.

Materials and methods

The sample specimens used in this study were obtained from plantations located in George’s Valley near Tzaneen in Limpopo province, South Africa. Young E. grandis trees of ages 5, 11 and 18 years were felled and left in the forest for approximately six weeks during the summer – also the wet season in this area. The tree stems were cut into shorter logs and processed into 50 × 76 mm and 38 × 114 mm dimension lumber using cant sawing patterns. The worst defects were removed by cross-cutting of the boards. The green lumber was finger-jointed into longer lengths using a commercial PU, Purbond HBS 159. After a curing time of at least 40 min, the boards were planed to structural size lumber of dimensions 48 × 73 mm and 36 × 111 mm. The process followed was the normal production setup in the sawmill resulting in a product spread representative of the usual operation in the mill for the specific log diameter inputs. The green lumber was wrapped in plastic to prevent drying and was transported to the test facilities at Stellenbosch University.

Test specimen preparation

A total of 220 long-length boards were randomly split into two groups: one for testing in the green condition and another for testing after being dried. The original concept for the lumber is that roof trusses will be manufactured in the green condition and will dry when fixed in the truss in the roof space environment (between the roof covering and ceiling of a house). A greenhouse at the Department of Forest and Wood Science, Stellenbosch University, was used to simulate drying in the roof space. The drying conditions in the greenhouse were severe and temperatures of above 50 °C and relative humidity of 30% were measured during March. In comparison, the same measurements were performed inside the roof space of a nearby tiled roof building and, surprisingly, temperatures were always below 40 °C and humidity above 40%. Drying conditions for the sample material could therefore be considered as severe. No data could be found for roof space temperatures and humidity for South African conditions and constructions, but Bin et al. (2005) mentioned roof space temperatures of up to 70 °C in Mediterranean countries. The one group of lumber was dried in the greenhouse until equilibrium moisture content (EMC) was reached after about nine weeks. The 220 long-length boards (green and dried) were processed into 720 test specimens for the different strength and stiffness tests (see Table 1). Due to the limited number of long-length boards available as well as the different lengths
of the long boards, it was not possible to cut an equal number of specimens from each tree age class.

**Warp, checking, splitting and shrinkage measurement**

Deformation or warp of lumber include bow, spring, cup and twist and are defined in SANS 1783-1 (2009) and illustrated in Figure 1. The bending test specimens were used to measure each of these variables according to the SANS regulations after drying in the greenhouse. Surface defects were measured for each laminate in each board after drying. For surface cracks wider than 1 mm, defined as checks, the maximum width, length and laminate position were recorded. Splits in lumber occurred at the end of boards due to the faster drying of the open-grain area and the maximum width, length and position of each split were measured.

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

**Destructive testing**

Bending and tensile parallel to grain tests were done according to SANS 6122 (2008) on both the green and dried specimens. The bending specimens destined for dry testing were also tested in bending while green, but only to a very low stress level of 6.3 MPa so that none of the specimens failed. From these results the modulus of elasticity (MOE) could be calculated in the green state and then, for the same specimens, after drying MOE could also be calculated from the destructive bending tests. The AS/NZS 4063 (2010) standard tests were used for compression parallel to grain, tensile perpendicular to grain, compression perpendicular to grain and shear tests since the SANS standard does not specify methods for most of these tests. For the AS/NZS 4063 (2010) standard, random defect placement is prescribed but not for the tests in SANS 6122 (2008). A newer version of SANS 6122 was in draft format while this study was conducted (subsequently published in 2014) where random defect placement has also been prescribed and it was decided to follow random defect placement in this study.

The density specimens were cut from the complete cross-sectional area of the destructively tested specimens directly after testing. One defect-free specimen of the full cross-section and 20 mm long was obtained from each laminate in a board. The maximum moisture content method for determining basic density for small wood samples was followed for all density calculations (Smith 1954). This procedure also allowed for determining an accurate moisture content determination at the time of testing.

**Data analysis**

Statistical analysis was performed with Statistica 12.6 (StatSoft, Tulsa, OK, USA). F-tests were performed to explain and compare the difference in mean values for various strength properties. When performing the equality of variation analysis, an F-test was used to explain the variability within the various samples and Bonferroni post-hoc tests were performed additionally, to analyse the specific variation between samples.

**Results**

**Warp, checking, splitting and shrinkage**

The 200 bending and tensile parallel to grain specimens were used for analysis of warp, checking and end-splitting after drying. In the green state virtually no checking, end-splitting or warping was observed in the young finger-jointed lumber. Results of twist in the dry sample,
after exposure to quite severe drying conditions in the greenhouse, can be seen in Figure 2. Since the test specimens for bending and tensile tests were of different lengths, twist was expressed as a percentage of that allowed according to the structural grading standard SANS 1783-2 (2012). Very low levels of bow, spring and cup were observed and only a single specimen exceeded the limitations on the cup set by the grading standard.

The checking and end-splitting results can be seen in Table 2. Severe checking occurred in many laminates (see Figure 3) and 35.5% of the boards did not make the checking requirements of SANS 1783-2 (2012). Most of the checking occurred in the 48 × 73 mm dimension lumber boards (54%) and only 17% of the 36 × 111 mm boards were rejected due to checking.

In Table 3 the twist and checks were analysed for the more problematic 48 × 73 mm dimension according to tree age classes. There was a significant difference between levels of twist and checking between the 5- and 11-year-old specimens. The reject rate of twist and checking for 5-year-old boards was also much higher than the 11-year-old boards. For the 36 × 111 mm boards no statistical significant difference was found in checking and twist results between the 11- and 18-year-old lumber.

The shrinkage measurements were done in the width and thickness directions and were a combination of radial and tangential shrinkage. The mean shrinkage of the boards was 2.83% from green to EMC and there were significant differences between different age groups (Figure 4). This was probably due to the older specimens being more dense (see Table 4). Linear regression analysis was performed with shrinkage as the dependent variable and density as the independent variable and a significant positive relationship was observed at the $\alpha = 0.05$ significance level.

### Density and moisture content

The mean basic density of the sample, which consisted of 720 specimens and 1 556 laminates, was 425.3 kg m$^{-3}$ with a standard deviation of 61.9 kg m$^{-3}$. There was a wide range of density values from 320 to 740 kg m$^{-3}$ (Figure 5). Table 4 shows the mean basic density of laminates for different dimensions and ages. The densities of the two dimension classes (48 × 73 mm and 36 × 111 mm) and the three different age groups (5, 11 and 18 years) all differed significantly at the $\alpha = 0.05$ significance level.

The green sample group, which consisted of 110 full length boards and 582 laminates, had a mean moisture content of 40.1%. There were high levels of variation in moisture content between laminates ranging from 20% to more than 100% (Figure 6). By far the largest part of the laminates' moisture content was above FSP, which is close to 30%.

**Table 2:** Percentage of boards from the dry sample rejected according to the checking and end-splitting requirements of SANS 1783-2 (2012)

<table>
<thead>
<tr>
<th>Checks</th>
<th>48 × 73 mm</th>
<th>36 × 111 mm</th>
<th>End-splits</th>
<th>Combined</th>
<th>48 × 73 mm</th>
<th>36 × 111 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boards rejected (%)</td>
<td>35.5</td>
<td>54</td>
<td>17</td>
<td>1.5</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**Figure 2:** Distribution of twist of the two dimension classes, expressed as a percentage of that allowed according to SANS 1783-2 (2012)

**Figure 3:** Severe surface check (left) and end-split (right)
There were no significant differences between the moisture content of different dimension classes and age groups.

**Destructive test results**

Results from the destructive tests are shown in Table 5. The table also contains the required characteristic stress values of the different structural grades as listed in the timber building code (SANS 10163-1 2003). The minimum, 5th percentile and mean values for each property are listed. According to the design code only the 5th percentile values are of interest as these are the ‘characteristic’ values used to design structures. The only exception is MOE where the mean values are used in design. Since 5th percentile MOE values are used in many other design codes in the world, and the current draft version of SANS 10163-1 also includes 5th percentile MOE values, these were also included in the results.

The majority of failures of the bending test specimens occurred at or close to a finger-joint in the board. This held true for both green and dry specimens and the different dimensions. Figure 7 shows a typical failure of a pith-containing 48 × 73 mm specimen. Note the failure line generally following the finger profiles for the laminate on the right except in the centre of the cross-section where the pith was situated. In the pith area the fingers failed at their base, showing that the pith material was weaker than the bond line. There was a statistically significant difference at the α = 0.05 level between the green and dry samples’ mean MOR values, which were 37.1 MPa and 43.7 MPa, respectively. The green sample characteristic bending strength (20.8 MPa) conformed to grade S7 and the dry sample (25.9 MPa) to grade S10 requirements (Table 5, Figure 8).

In both the green and dry state the 5th percentile MOE and mean MOE of the green finger-jointed E. grandis conformed to the SANS grade S7 requirements (Table 5). It was interesting to note that there was no statistically significant difference between mean MOE of the green and dry specimens and that the mean MOE value of the green group was even slightly higher (9 900 MPa) than the dry group (9 826 MPa). The MOE distribution of green and dry

| Table 3: Percentage of 48 × 73 mm boards of different ages (5 or 11 years) rejected based on twist and checking requirements of SANS 1783-2 (2012) |
| --- | --- | --- | --- |
| Twist | Checks |
| 5 y | 11 y | 5 y | 11 y |
| Rejected (%) | 72.5 | 26.7 | 70.0 | 43.3 |
| n | 40 | 60 | 40 | 60 |

![Figure 4: Mean shrinkage of specimens from green to equilibrium moisture content and their 95% confidence intervals for different age groups](image)

| Table 4: Mean basic density of young Eucalyptus grandis laminates for different dimensions and ages. Values in the same row followed by different superscript letters or numbers are significantly different (p < 0.05) |
| --- | --- | --- |
| Dimension (mm) | Age (y) |
| 48 × 73 | 36 × 111 | 5 | 11 | 18 |
| Mean density (kg m⁻³) | 399.5⁺ | 435.9⁺ | 374.5¹ | 429.2² | 462.8³ |
| n | 360 | 360 | 156 | 391 | 173 |

![Figure 5: Basic density distribution of individual laminates of young Eucalyptus grandis](image)
specimens looked very similar (Figure 9). The MOE was also determined for the dry specimens while they were green so that green and dry MOE could also be compared for the exact same specimens (results not shown in Table 5). In this case the mean green MOE was statistically significantly higher at the $\alpha = 0.05$ level than after drying.

The 5th percentile tensile parallel to grain strength of the green (14.9 MPa) and dry (14.1 MPa) groups was relatively similar (Table 5). Mean values were not calculated since the testing machine had an upper limit and not all of the boards were broken. The green sample of the smaller dimension tensile group had one outlier or very weak board (3.3 MPa). Such low strength rogue boards should be removed if proof grading is performed at a processing plant.

Tension perpendicular to grain and compression perpendicular to grain are often considered as less important structural lumber properties (Madsen 1992). For nail plated roof trusses this probably holds true because neither of these properties are utilised in the joint areas. The limited test material available in the project was considered, and it was decided to allocate less sample material to these tests, shear and compression parallel to grain than the bending and tensile parallel to grain properties. The SANS 6122 (2008) in-grade testing standard does not specify test methods for the analysis of tension perpendicular to grain and the AS/NZS 4063 (2010) standards were applied. There was no significant difference between the means of the green and dry sample for the tension perpendicular to grain and compression perpendicular to grain.

Table 5: Characteristic stress values for green and dry young finger-jointed *Eucalyptus grandis* lumber. The required characteristic grade stresses according to SANS 10163-1 (2003) are also indicated. Values in the same row followed by different superscript letters are significantly different ($p < 0.05$)

<table>
<thead>
<tr>
<th></th>
<th>Green specimens</th>
<th>Dry specimens</th>
<th>SANS characteristic grade stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Min.</td>
<td>5th perc.</td>
</tr>
<tr>
<td>Bending strength (MPa)</td>
<td>100</td>
<td>14.9</td>
<td>20.8</td>
</tr>
<tr>
<td>Modulus of elasticity (MPa)</td>
<td>100</td>
<td>5 355</td>
<td>7 041</td>
</tr>
<tr>
<td>Tensile$_{\parallel}$ strength (MPa)</td>
<td>100</td>
<td>3.3</td>
<td>14.9</td>
</tr>
<tr>
<td>Tensile$_{\perp}$ strength (MPa)</td>
<td>40</td>
<td>0.2</td>
<td>0.48</td>
</tr>
<tr>
<td>Compression$_{\parallel}$ strength (MPa)</td>
<td>40</td>
<td>15.4</td>
<td>19.3</td>
</tr>
<tr>
<td>Compression$_{\perp}$ strength (MPa)</td>
<td>40</td>
<td>3.85</td>
<td>4.16</td>
</tr>
<tr>
<td>Shear strength (MPa)</td>
<td>40</td>
<td>1.55</td>
<td>2.21</td>
</tr>
</tbody>
</table>

$^1$ Values from draft version of SANS 10163-1
grain tests. However, the 5th percentile values of the green (0.48 MPa) and the dry (0.3 MPa) groups was quite different.

For compression strength parallel to grain the 5th percentile value of the green sample (19.3 MPa) conformed to SANS grade S5 requirements and the dry sample (24.8 MPa) to grade S7 requirements. Mean values were not calculated because the strength of some specimens was above the machine limit. Moisture content normally has a big influence on compression strength parallel to grain for both high- and low-quality material (Madsen 1992; Ranta-Maunus 2003). In the limit states timber design code SANS 10163-1 (2003), a partial material factor lowers the ultimate compression resistance by 33% when moisture content of lumber is higher than 20%. Madsen (1992) proposed an adjustment factor of 20% lower compression strength for green lumber. In the case of this *E. grandis* lumber the 5th percentile compression parallel to grain value was about 22% lower for the green sample compared with the dry sample, which was roughly in agreement with Madsen’s recommendation.

For compression perpendicular to grain neither the green (4.16 MPa) nor the dry (3.91 MPa) sample groups conformed to the 5th percentile requirement of the lowest structural grade S5. The mean of the dry sample (7.75 MPa) was significantly higher than the mean of the green sample (5.8 MPa), which was in agreement with results on softwoods tested by Madsen (1992). The weak minimum value (2.92 MPa) and the low 5th percentile value of the dry sample were probably caused by severe drying defects such as large checks in some of the young material (see Figure 10). As with tension perpendicular to grain, this property is of limited importance in nail plated roof truss design.

Both the green (2.21 MPa) and dry (2.7 MPa) groups conformed to the 5th percentile requirements of grade S7 for shear strength according to the SANS 10163-1 (2003) code. The mean shear strength of the dry group was significantly higher (4.23 MPa) than that of the green
group (3.6 MPa). Shear strength is important for good joint strength of the nail plated trusses.

In Table 6 the MOE and MOR of $36 \times 111$ mm lumber from five sawmills from different regions in South Africa, obtained from a different study (Crafford and Wessels 2011), was compared with that of the green and dry finger-jointed $E.\ grandis$ lumber. The mean MOE of the $E.\ grandis$ finger-jointed lumber was significantly higher than four of the five South African pine structural sawmills. The standard deviation of MOE was significantly lower than that of all the pine sawmills. The coefficient of variation for MOE of the finger-jointed $E.\ grandis$ was 11.8% compared with between 18.6% and 34.8% for the different South African pine lumber sources.

**Discussion**

**Warp, checking, splitting and shrinkage**

Limitations in warp, checking and end-splitting are included in the SANS 1783-2 (2012) structural lumber specifications. The main reason for these limitations is not strength related but rather the problems caused by these defects when manufacturing structures with lumber. Severely twisted members make jointing in the manufacturing of roof trusses and other structures very difficult or impossible. For certain applications checking and warp might also not be aesthetically acceptable. The concept of building roof trusses with green members, as intended with this young $E.\ grandis$ product, only requires the members to be free of these defects while green. As the roof truss will dry while fixed within the roof structure, possible problems related to these defects that occur during drying should rather be evaluated within the completed structure after drying. The truss structure will presumably restrict movement during drying. It is possible that deformation during drying (especially twist) might result in dislodging some of the nail plated joints and also result in distorted top chord surfaces. However, since truss manufacturing did not form part of this study, it was decided to include the warp, checking and splitting evaluation in the board evaluations.

Nearly 30% of the 200 specimens did not make the twist specifications for structural lumber. About three-quarters of the reject specimens were from the $48 \times 73$ mm dimension class. The main reason was probably that this dimension class came from the younger and smaller diameter trees (see Table 1), and therefore contain more pith/core material. As with lumber from young softwood trees (Wessels et al. 2014), this $E.\ grandis$ product was subject to severe twist during drying, although still considerably better than boards from young $P.\ patula$ trees. The finger-jointing of green laminates would probably have helped to contain the levels of twist. The different laminates will twist in different directions and some laminates will have less twist than others, resulting in full-length specimens having lower twist. The twist results highlight the potential economic benefit of the concept of manufacturing

![Severe checking around the pith in a juvenile tensile specimen (left) and compression specimen (right)](image)

**Table 6:** Comparison of the mean, standard deviation (SD), coefficient of variation (CV) and characteristic stress values of modulus of elasticity (MOE) and modulus of rupture (MOR) of ungraded $36 \times 111$ mm lumber from different sources. The different sawmills process South African pine and are from different regions. Values in the same row followed by different superscript letters are significantly different ($p < 0.05$)

<table>
<thead>
<tr>
<th>MOE (MPa)</th>
<th>E. grandis (green and dry)</th>
<th>Sawmill 1</th>
<th>Sawmill 2</th>
<th>Sawmill 3</th>
<th>Sawmill 4</th>
<th>Sawmill 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>10 627.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9 961.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8 273.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7 898.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8 060.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6 875.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>SD</td>
<td>1 248.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1 853.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2 065.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2 160.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2 490.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2 181.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>CV (%)</td>
<td>11.8</td>
<td>18.6</td>
<td>25.0</td>
<td>27.3</td>
<td>30.9</td>
<td>31.7</td>
</tr>
<tr>
<td>5th percentile</td>
<td>8 419.4</td>
<td>6 732.3</td>
<td>5 488.1</td>
<td>4 533.8</td>
<td>4 511.8</td>
<td>3 437.7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>MOR (MPa)</th>
<th>E. grandis (green and dry)</th>
<th>Sawmill 1</th>
<th>Sawmill 2</th>
<th>Sawmill 3</th>
<th>Sawmill 4</th>
<th>Sawmill 5</th>
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<tbody>
<tr>
<td>Mean</td>
<td>41.26&lt;sup&gt;a&lt;/sup&gt;</td>
<td>39.56&lt;sup&gt;a&lt;/sup&gt;</td>
<td>35.61&lt;sup&gt;a&lt;/sup&gt;</td>
<td>35.56&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>26.34&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>SD</td>
<td>7.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>15.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>15.90&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.06&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.54&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>CV (%)</td>
<td>17.3</td>
<td>35.7</td>
<td>44.0</td>
<td>44.7</td>
<td>42.8</td>
<td>43.8</td>
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<tr>
<td>5th percentile</td>
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<td>21.02</td>
<td>17.16</td>
<td>14.99</td>
<td>19.23</td>
<td>11.06</td>
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trusses with green lumber and then drying the finger-jointed *E. grandis* product within the roof structure. In theory 30% of the lumber would not be suitable for structural lumber if the laminates were dried and graded individually before truss manufacturing. With the proposed concept of manufacturing trusses with green lumber, however, no lumber will be rejected due to twist, which only occurs after drying. However, the possible negative effects of deformation within the truss system after drying will still have to be evaluated in full-scale truss evaluations. If twist still proves to be problematic, increasing the rotation age of plantations might be a management option as the harvesting age clearly had a large influence on the levels of twist present (Table 3).

Checking was the worst in pith-containing boards, which were more prevalent in the 48 × 73 mm products from the small-diameter trees. The larger thickness of these boards would also result in more stresses during drying-related shrinkage. The effect of checking on strength and stiffness was included in the mechanical test results discussed later. Aesthetically, checking will not be acceptable for many users where lumber members are visible. For roof truss applications, however, members will normally not be seen by the inhabitants of a house.

Surprisingly, only 1.5% of the dry boards had end-splitting above the SANS 1783-2 (2012) restrictions (Table 2). End-splitting might still be a problem in roof trusses, especially on the lower ends of top-chords, which are sometimes used to fix facia boards. There are many practical ways in which this could be resolved, i.e. nail plates to restrict splitting on top-chord member ends or applying brackets on the ends for fixing facia boards. Designers and erectors of roof trusses will need to be aware of this challenge and solve it in a practical way where necessary.

Shrinkage during drying for this *E. grandis* resource was, as expected, relatively high (Figure 4) with boards from older trees showing higher shrinkage. This was most probably due to the higher density of boards from older trees. Linear regression analysis showed a significant positive relationship between shrinkage and density, as is generally true for most wood species (Tsoumis 1991; Simpson and TenWolde 1999; Walker 2010). Although tangential and radial shrinkage can cause various problems in structures it is not expected to have a significant impact on the truss constructions. The possible negative effect on joint strength due to gaps opening up in the nail plated joints should be evaluated in full-scale truss tests.

**Density and moisture content**

The density differences between age classes were expected as density usually increases sharply with age in the juvenile section of the stem. The difference between the two dimension classes can also be explained by the age differences – 48 × 73 mm lumber was sawn from the smaller diameter 5- and 11-year-old trees and 36 × 111 mm lumber from the larger diameter 11- and 18-year-old trees (see Table 1). Density usually has a positive relationship to the strength and stiffness properties of wood and the specifications for structural softwood grades prescribe minimum density boundaries for individual grades (i.e. SANS 1783-2 2012).

Moisture content was reported to be a critical variable in the green gluing, using PU adhesives, of some softwood species (i.e. Bergman et al. 2010; Sterley 2012). Sterley (2012) mentioned, for instance, poor bonding strength for low-density wood with high moisture content. Despite the extremely high levels of variations in moisture content (Figure 6), it did not seem to result in high variation in bonding strength of joints (Table 6). Even the 5th percentile values, which come from the weak portion of the strength distribution curve, were relatively high for bending strength and tensile strength parallel to the grain – properties where joint strength is critical.

**Destructive tests**

The characteristic bending strength values for both the green and dry specimens were surprisingly high compared with SANS requirements for structural lumber. The minimum values for both the green and dry groups were also relatively high, which indicates that the green finger-jointed lumber do not pose high risks, even in situations where little load sharing occurs and individual member strength is important. Take note that this lumber was not graded. The intention is to proof grade the green finger-jointed product if it is found to be technically and commercially viable. In other studies on softwoods it was found that the bending strength increased significantly as moisture content decreased for high-strength wood but low-strength wood was less sensitive to moisture differences (Madsen 1992). The same trend could be observed here where there was less difference between green and dry specimens in the weaker tail section of the MOR histogram than in the remaining part of the strength distribution curve (see specimens with MOR ≤ 25 MPa; Figure 6).

A very unexpected result was that the mean MOE of the dry boards group was significantly lower after drying than before drying (where MOE was measured on the same boards before and after drying). The mean MOE of the dry boards group was also slightly lower than the green boards group, although not significantly (Table 5). This was completely contrary to findings of other studies on softwood lumber where the mean MOE increased with a decrease in moisture content (Ranta-Maunus 2003). This result could possibly be explained by the deformation that occurred during drying. Nearly half of the dry boards, which had a higher MOE value in the green condition than in the dry condition, had developed twist and checking values above the SANS 1783-2 (2012) limits after drying. When testing a deformed board such as one with twist, the load in the first part of the bending test helps to orient the support surfaces to become parallel with the board edges and possibly also straighten the board slightly. For checked boards some of the load could possibly first compress and close splits rather than bend a board. This will result in lower MOE values than when no twist and checks were present. The MOE of this product was high compared with young South African pine such as *Pinus elliottii × P. caribaea* (Wessels et al. 2011) and *Pinus patula* (Dowse and Wessels 2013). The MOE values were relatively high even compared with mature South African pine where a relatively low volume of S7 grades can usually be recovered by sawmills.
The 5th percentile tensile parallel to grain strength of the green (14.9 MPa) and dry (14.1 MPa) groups was high compared with South African pine (Table 5). Both the green and dry groups conformed to grade S10 requirements for tensile strength. The results were in agreement with Madsen (1992) who concluded that moisture content did not affect the characteristic tensile strength parallel to grain for full-sized Canadian softwood species. Tensile stress in the axial direction is an important property for roof truss lumber material, especially for the bottom-chord of a truss. In the tension parallel to grain tests all the finger joints in a board were loaded within the test span. The results showed that the green finger-joint strength was sufficient in both the green and dry sample for the highest structural grade (S10). Despite the high variation in moisture content and density between laminates, good finger-joint bonds were obtained and tensile strength parallel to grain was evidently a very good property for this product.

The green perpendicular to grain tensile samples’ 5th percentile value (0.48 MPa) conformed to SANS requirements for grade S5 but not the dry sample (0.3 MPa). The lower characteristic strength value of the dry sample was most probably a result of pith checking that was present in some of the perpendicular tensile specimens (Figure 10). There was no significant difference between the means of the green and dry sample, indicating that only some specimens were adversely affected. Unlike our results, tests on Canadian softwood species showed that moisture content affects tensile perpendicular to grain strength severely (Madsen 1992). The low tensile perpendicular to grain characteristic value of this product will probably not have a big influence in roof truss applications where nail plates are utilised as a connection method. Where other connectors such as bolts are used, the checking after drying might cause poor connection strength.

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

Currently, only pine structural lumber from five different species is used in South Africa. The lumber is not specified in terms of species, but is loosely referred to as South African pine. In a study evaluating the relative influence of the different mechanical properties in South African roof truss designs, it was found that bending strength (MOR) was the most important property and that MOE was also an influential property for some members (Petersen and Wessels 2011). The MOE of the E. grandis finger-jointed lumber was clearly superior to that of South African pine, having higher mean values as well as lower variation (Table 6). The 5th percentile MOR of the E. grandis, which is the value used in designing structures, was much higher than that of any South African pine sawmill’s lumber. As with MOE, the variation in MOR of the E. grandis was much lower than that of South African pine. In fact, the coefficient of variation for E. grandis was less than half that of any of the pine sawmill’s lumber. The bending properties of the E. grandis finger-jointed lumber in the green or dry state were much better than typical South African pine sources. These are also the most important properties in roof truss design. The reason for the superior bending properties was probably related to the small knots present in young E. grandis lumber as well as the inherent higher stiffness of the wood related to its anatomical structure.

The ratio between different strength properties for this product was very different to that of South African pine. For instance, the characteristic bending strength:characteristic tension perpendicular to grain strength for South African pine is 1:32 compared with 1:86 for the dry finger-jointed E. grandis. It will therefore be very inefficient to use the South African pine softwood grade requirements in terms of characteristic values for this lumber resource. For structural design purposes a different table of characteristic values and grades with the values typical for this resource should be created.

The potential risks regarding this product that were not investigated include the effect of warp, splitting and checking on nail-plate or mechanical joints within full-scale trusses, the load capacity of nail plates on this lumber, the effect of lumber shrinkage within the truss system, and the possible need for treatment of the sapwood against Lyctus beetles.

Conclusions

The young E. grandis finger-jointed lumber product tested in this study had very good flexural properties in both the green and the dry condition compared to current South African pine lumber resources. The tensile parallel to grain, compression parallel to grain and shear strength were also comparatively good properties for this product. The 5th percentile values of tensile perpendicular to grain and compression perpendicular to grain strength, however, did not conform to SANS requirements for the lowest structural grade. These two properties are of lesser importance in nail plated roof truss structures. Both tree age and product dimension were sources for variation in the physical and strength properties.

Based on the results from this study the concept of producing roof trusses from green, unseasoned and finger-jointed young E. grandis lumber has potential. However, additional research on a number of issues not covered in this study is still required. The effect of deformation, splitting and checking on nail-plate or mechanical joints within full scale trusses, the load capacity of nail plates on this lumber, and the effect of lumber shrinkage within the truss system should be investigated. Further research is also required on the application and strength of nail-plate connections onto the young finger-jointed product, and the possible need for treatment of the sapwood against Lyctus beetles.
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References


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