DETERMINATION OF WOOD STRENGTH PROPERTIES THROUGH STANDARD TEST PROCEDURES

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ABSTRACT

In this study a review of existing recognised standards for wood mechanical testing was conducted. This review considers tensile, compressive, bending and shear test methodologies from a range of sources. In addition, values for wood mechanical properties were obtained through controlled experimentation using a universal material testing machine. Selected standard procedures were used to obtain wood strength properties both along and across the grain. These consist of a three point bending procedure used to evaluate the wood strength across the grain and a longitudinal shear procedure used to evaluate the wood strength along the grain. Strength properties obtained through controlled experimentation are compared to values available in existing literature with little discrepancy.

Keywords: Mechanical Test Procedures, Universal Testing Machine, Wood Strength Properties

1 INTRODUCTION

Wood is anisotropic and hence some mechanical test procedures are often performed both along and across the grain. Tension and compression tests have been successfully performed both along and across the grain. Compression tests show that wood has much larger strength and modulus of elasticity values along the grain rather than across (Reiterer and Stanzl-Tschegg 2001, Manríquezand Moraes 2009). The trend for tensile tests is the same as compressive (Oh 2011, Galicki and Czech 2005) (larger values along the grain). However, the magnitude of the compressive strengths is significantly larger than tensile, typically ten times larger. Due to the nature of the test procedure, static bending test procedures are mainly implemented to characterise wood strength across the wood grain. Shear test procedures have been implemented in all three wood machining directions (Munthe and Ethington 1968) revealing that only a true shear failure mode occurs along the wood grain.

1.1 Static Bending

Four point bending is recommended by British Standards for wood as failure occurs at the point of maximum displacement between the two loaded anvils (British Standards 2003). This eliminates the excessive compressive forces that would occur with the use of a single anvil and reduces likely-hood of shear along the grain. American Standards for three point bending specifies a span to depth ratio of 1:14 (ASTM 2009). Once again this ensures that the failure mode is bending with no shear along the grain or compressive deformation caused by the loaded anvil.

Previous research into the properties of Finnish birch (Gustafsson 2001) has evaluated both the British and American test procedures. The findings reveal an average modulus of elasticity (**MOE**) of 11.2 GPa for three point bending compared to 14.9 GPa for four point bending, an increase of approximately 25%. Comprehensive records (Bergman et al 1999) reveal an **MOE** value of 13 GPa in static bending which lies between these two values, showing that results from both test procedures are within an appropriate range. The modulus of rupture (**MOR**), commonly referred to as bending strength, is calculated to be the same regardless of the testing procedure.

Despite the discrepancy between the two test procedures for determination of **MOE**, evidence from literature shows that **MOE** has been accurately determined using the three point method. This was used to evaluate Green wood (Coutand et al 2004) and wood plastic composites (Wechsler and Hiziroglu 2007)

$$MOR = \frac{3FL}{2bd^2}, \quad \textbf{At point of fracture} \tag{1}$$

$$MOE = \frac{FL^3}{4bd^3\omega}, \quad \textbf{At elastic limit} \tag{2}$$

1.2 Shear

Shear occurs most commonly along the grain direction hence values in this direction are referred to as longitudinal shear. French standards for longitudinal shear incorporate a test specimen with three separate shear zone where failure can occur (AFNOR 1942). This standard has been used previously to determine the modulus of rigidity for a predictive cutting force model where a tool machines wood along the grain (Eyma et al 2004). Alternatively, American standards have developed a method for accurately measuring the shear strength (**τ**) and modulus of rigidity (**G**) (ASTM 2009). The set-up consists of a test piece that can fail along only one zone of shear.

$$\tau = \frac{F}{A}, \quad \textbf{At point of fracture} \tag{3}$$

$$G = \frac{\tau}{\gamma} = \frac{FL}{Ax}, \quad \textbf{At elastic limit} \tag{4}$$

A previous study on wood shear (Munthe and Ethington 1968) using spruce, applied the American standard methodology and apparatus to all three orthogonal planes of symmetry with respect to the wood grain direction. The results indicate that the wood is much stronger along the grain. Tests both across the fibre direction and growth rings (end grain) yield **τ** values approximately 20% that of along the grain and **G** values of approximately 3%. Furthermore, only true shear was observed along the wood grain. This was illustrated by a uniform fault line propagating along the wood grain. Other failure modes were observed: Buckling of the annual growth rings at the wood end grain and bending of the fibres across the grain which are both referred to as “rolling shear”.

2 METHODOLOGY

A programme of work was completed using the American standard test procedures for three point bending and longitudinal shear. These determined wood properties across and along the grain respectively. Eight wood species including both hardwoods and softwoods were selected. The American test standards were favoured as they were easier to implement in the universal testing machine. Hence the question must be asked; does this more simple approach produce results comparable to results obtained via other well established methods?

2.1 Three point Bending

All tests were performed using the American standard methodology described in sub-sections 1.1 and 1.2. The span (**L**) of all of test specimens was kept at 300mm with a 20mm depth (**d**); this is in keeping with the specified 14:1 minimum span to depth ratio. An additional criterion that was also specified by the standard was a 1.3 mm/min crosshead maintained throughout testing until failure. The wood was placed into the experimental set-up in the universal testing machine (Figure 1) where the apparatus was placed between a moving crosshead and a 10 kN load cell. Force vs. Displacement plots were initially

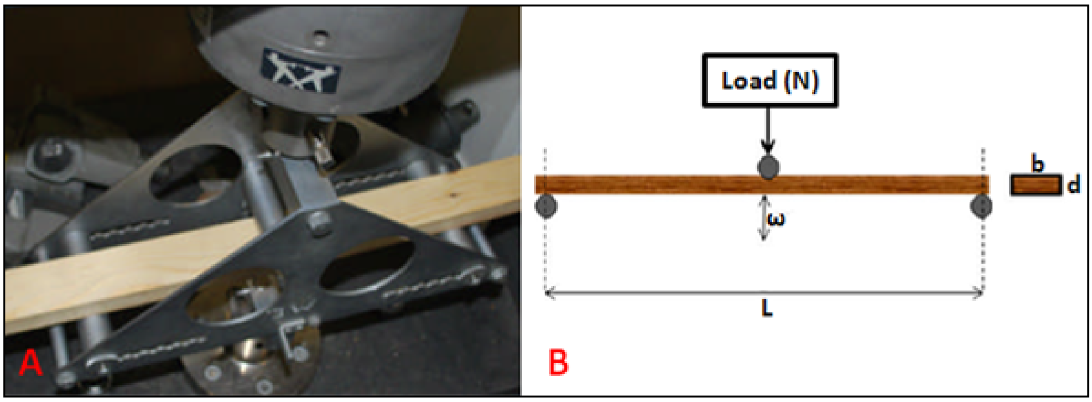

Figure 1: A) Three point bending set up in universal testing machine. B) Schematic diagram

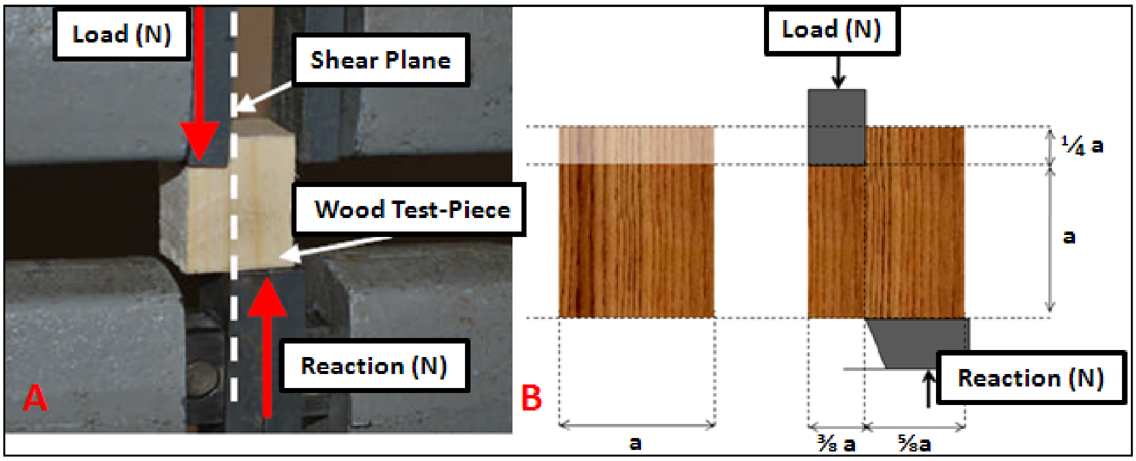

Figure 2: A) Longitudinal shear set up in universal testing machine. B) Schematic diagram

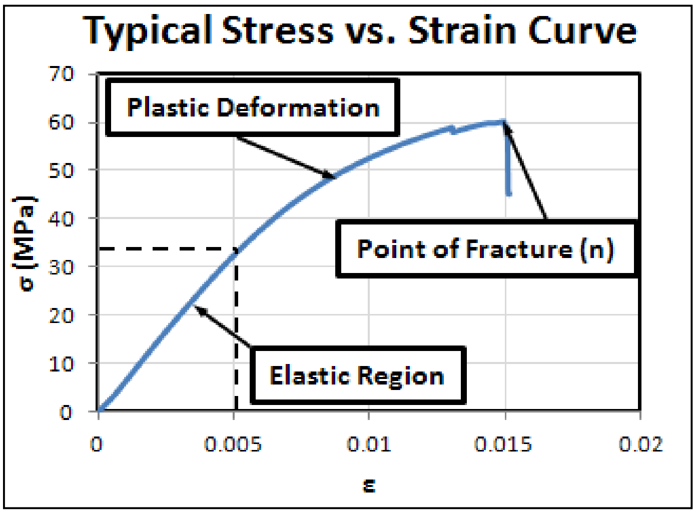

Figure 3: Deformation zones on a typical stress vs. strain curve

generated by the test machine data acquisition system. The linear region where Force was directly proportional to Displacement was taken to be the elastic region where no permanent deformation occurs. Force and Displacement measurements from this region are used to calculate **MOE**. The Force measurement at the point of fracture was subsequently used to calculate **MOR**.

2.2 Longitudinal Shear

As with three point bending, all tests were performed using the American standard methodology. The experimental set up also used the 10 kN load cell. All proportions for the test piece used in experimentation are detailed (Figure 2). A 0.6 mm/min crosshead was maintained throughout testing until failure. As the shear zone was approximately square, both the length and width were taken to be $\boldsymbol{a}$. Equations 3 and 4 could be modified to accommodate the standard test specimen. Once again Force vs. Displacement plots were acquired to determine the elastic region and the point of fracture $\boldsymbol{\tau}$ and **G** were calculated using equations 5 and 6 respectively.

$$\tau = \frac{F}{a^2}, \qquad \textbf{At point of fracture} \tag{5}$$

$$G = \frac{Fa}{a^2 x} = \frac{F}{ax}, \quad \textbf{At elastic limit} \tag{6}$$

2.3 Toughness

Toughness was calculated as the area under the stress ($\boldsymbol{\sigma}$) vs. strain ($\boldsymbol{\varepsilon}$) curves (Figure 3) generated from the universal testing machine force extension plots. The stress strain curve was in the form of a quadratic polynomial. Toughness (**U**) was obtained by taking the definite integral of the quadratic function between zero and the point of facture (**n**) (equation 7).

$$U = \int_n^0 f(\varepsilon) = \int_n^0 (a\varepsilon^2 + b\varepsilon + c) \tag{7}$$

3 RESULTS

In general the average strength of the wood species tested across the grain (denoted by **MOR**) obtained through the three point bending tests (table 1) was measured to be over eight times greater than the strength along the grain (denoted by $\boldsymbol{\tau}$) obtained through the longitudinal shear tests. However, the average elasticity of the wood across the grain (denoted by **MOE**) was measured to be nearly 40 times greater than along the grain (denoted by **G**).

3.1 Bending

For all moisture levels evaluated, values for mean **MOR** for the wood species evaluated range from 50-90 MPa with a linear decrease in strength observed for increased moisture content. The values for mean **MOE** of the wood species evaluated ranges from 4-8 GPa with a linear decrease in elasticity also observed for increased moisture content. The results from the force extension plots show there is no discernible pattern to suggest that the hardwoods yield higher **MOE** values than the softwoods.

3.2 Shear

The average $\boldsymbol{\tau}$ values range from 5-12 MPa. The highest values represent the three hardwoods tested which have values approximately 45% greater than the softwoods. Furthermore a linear decrease in strength is observed with an increase in moisture content. The average **G** values of the wood species evaluated range from 15-230 MPa with the larger values once again representing the hardwoods. These values are approximately 50% greater than the softwoods. **G** exhibits a negative linear trend with respect to moisture content.

Table 1: Properties obtained through mechanical testing

	Species	MOE (GPa)	MOR (MPa)	Ub (J/m^2)	G (MPa)	τ (MPa)	Us (J/m^2)	ρ (kg/m^3)	MC (%)
DRY (NOMINAL)	Scots Pine *(SW)*	6.28	79.21	33250	151.47	9.53	26650	576.64	6.00
	Yellow Pine *(SW)*	5.08	47.72	24910	286.27	6.28	17100	484.80	6.00
	Douglas Fir *(SW)*	6.92	72.01	49000	236.51	7.58	34080	496.62	8.00
	Western Red Cedar *(SW)*	9.15	99.28	40600	52.78	8.62	31730	671.57	6.00
	Siberian Larch *(SW)*	7.33	65.24	49020	260.16	9.31	54000	638.46	8.00
	Ash *(HW)*	5.75	105.57	84000	277.03	17.06	94300	912.87	6.00
	Beech *(HW)*	8.89	127.44	61750	363.83	15.55	86400	669.00	6.00
	Sapele *(HW)*	7.80	92.73	58050	219.11	18.17	57200	819.08	6.00
	AVERAGE	**7.15**	**86.15**	**50070**	**230.90**	**11.51**	**50180**	**658.63**	**6.50**
	RANGE	**4.07**	**79.72**	**59090**	**311.05**	**11.89**	**77200**	**428.07**	**2.00**
	STANDARD DEVIATION	**1.44**	**25.24**	**18350**	**94.06**	**4.65**	**28200**	**148.44**	**0.93**
10% (NOMINAL)	Scots Pine *(SW)*	5.83	61.99	21000	152.64	7.97	25200	559.04	14.00
	Yellow Pine *(SW)*	4.03	47.62	19200	91.30	5.69	16120	436.15	11.00
	Douglas Fir *(SW)*	6.14	58.57	24750	43.32	3.97	26850	478.93	14.00
	Western Red Cedar *(SW)*	3.95	54.60	22100	268.98	4.76	26250	460.96	11.00
	Siberian Larch *(SW)*	6.70	88.62	28840	208.32	10.34	27280	615.38	11.00
	Ash *(HW)*	8.23	119.09	61740	123.21	14.20	84000	850.73	10.00
	Beech *(HW)*	11.36	95.04	47250	211.37	14.15	60750	696.65	11.00
	Sapele *(HW)*	9.11	113.05	45500	691.02	14.31	28600	759.75	8.00
	AVERAGE	**6.92**	**79.82**	**33790**	**223.77**	**9.42**	**36880**	**607.20**	**11.25**
	RANGE	**7.41**	**71.47**	**42540**	**647.70**	**10.34**	**67880**	**414.58**	**6.00**
	STANDARD DEVIATION	**2.54**	**27.77**	**15670**	**202.15**	**4.43**	**23080**	**151.22**	**1.98**
20% (NOMINAL)	Scots Pine *(SW)*	6.49	53.85	8750	128.55	10.85	15260	546.36	20.00
	Yellow Pine *(SW)*	3.24	30.57	3840	46.22	2.22	11700	416.88	25.00
	Douglas Fir *(SW)*	4.47	40.92	20470	152.23	4.85	21000	462.60	25.00
	Western Red Cedar *(SW)*	4.69	56.63	10330	138.98	3.74	16640	434.53	25.00
	Siberian Larch *(SW)*	4.08	48.80	22500	136.96	5.76	24080	604.35	20.00
	Ash *(HW)*	7.76	103.94	42750	84.88	7.32	70950	714.17	24.00
	Beech *(HW)*	5.11	78.47	42000	209.07	7.17	35500	737.15	27.00
	Sapele *(HW)*	3.15	62.47	38740	195.14	10.64	28250	632.64	23.00
	AVERAGE	**4.87**	**59.46**	**23670**	**136.50**	**6.57**	**27920**	**568.59**	**23.63**
	RANGE	**4.61**	**73.37**	**38910**	**162.85**	**8.63**	**59250**	**320.27**	**7.00**
	STANDARD DEVIATION	**1.58**	**22.93**	**15730**	**53.23**	**3.08**	**18980**	**124.04**	**2.50**
SAT (NOMINAL)	Scots Pine *(SW)*	4.41	47.00	15400	6.21	5.70	9100	530.23	32.00
	Yellow Pine *(SW)*	2.49	26.65	10200	7.75	2.31	7100	407.70	35.00
	Douglas Fir *(SW)*	3.66	29.69	22000	25.20	4.42	11600	448.67	35.00
	Western Red Cedar *(SW)*	4.33	43.84	21930	19.91	3.49	11000	354.88	30.00
	Siberian Larch *(SW)*	4.45	40.83	22800	7.71	4.71	14200	575.65	32.00
	Ash *(HW)*	5.62	73.15	45990	18.45	6.34	40000	708.26	45.00
	Beech *(HW)*	5.84	76.76	45600	16.20	8.35	31200	787.75	40.00
	Sapele *(HW)*	4.78	69.15	45000	19.54	11.39	21000	595.21	31.00
	AVERAGE	**4.45**	**50.88**	**28610**	**15.12**	**5.84**	**18150**	**551.04**	**35.00**
	RANGE	**3.35**	**50.11**	**35790**	**18.99**	**9.08**	**32900**	**432.87**	**15.00**
	STANDARD DEVIATION	**1.06**	**19.64**	**14610**	**7.02**	**2.89**	**11760**	**147.96**	**5.13**

3.3 Toughness

The average toughness values (**Ub** and **Us**) range from 18000-50000 J/m^2. These values are not as significantly affected by the grain direction as the materials strength (**MOR** and **τ**) or elasticity (**MOE** and **G**). The mean values obtained by **σ** vs. **ε** plots in three point bending (**U**b) yielded approximate values only 10% greater than the mean values obtained by **σ** vs. **ε** plots in longitudinal shear (**U**s).

4 DISCUSSION

Established values in literature (Bergman et al 1999) are compared to the obtained mechanical properties in this study (for woods of low moisture content ≈ 6-12%):

- The **MOR** values in this study are 5% lower than the values in literature for the hardwood and 8% lower for the softwoods.
- The **MOE** values are 14% lower for the hardwoods and 41% lower for the softwoods.

- The **Ub** values are 28% lower for the hardwoods and 41% lower for the softwoods.
- The **τ** values in this study 20% higher for the hardwoods and 7% lower for the softwoods.

There were no readily available values of **Us** or **G** from literature to compare to the obtained values documented in this study. **MOE** and **Ub** recorded values collate less well to established values in literature than **MOR** and **τ** recorded values. Both **MOE** and **Ub** are dependent upon strain however **MOR** and **τ** are not. The source of this discrepancy must hence originate from different measurements of strain. A possible cause of this could be variations in the crosshead speed of the universal testing machine. American standards (ATSM 2009) specify speeds of 1.3 mm/min and 0.6 mm/min for the bending and shear tests respectively. Crosshead speeds in the comparable study (Bergman et al 1999) are not specified.

5 CONCLUSION

In general, the American standards for testing (ATSM 2009) were accurately able to determine strength properties, i.e. **τ** and **MOR** (although a small percentage of error in **τ** was observed for the hardwood species evaluated). A larger degree of error was however noticed for the elastic and toughness properties. The values for the bending toughness values (**Ub**) and elastic modulus (**MOE**) documented in this study are noticeably lower than values from literature (Bergman et al 1999). Documented values of shear toughness (**Us**) and modulus of rigidity (**G**) were not readily available from literature to compare to the values recorded in this study. Hence further work is warranted to investigate how values of **Us** and **G** (obtained using the American standard) compare to values using other test methodologies.

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