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Mechanical characterization of green Sitka spruce logs

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ABSTRACT: Timber is by its nature a very heterogeneous material. Many different factors impact its mechanical properties, from tree species to environment (climate, competition, soil...). While a number of studies in the past dealt with sawn timber and its mechanical properties, only a small number of them studied round logs. An even smaller number dealt with logs where moisture content is above fibre saturation point, e.g. green logs. The objective of this study is to investigate and describe the load-deflection response of green Sitka Spruce logs using a four point bending test. The trees for this study were felled at the age of 20 years and consequently the percentage of juvenile wood is relatively high.

Green logs behave differently when stressed in comparison to dry timber. The flexural stiffness is significantly lower and the load-deflection response is highly non-linear. The test results are useful for designing further green round log testing, especially when studying wind throw in standing trees, as they can give a clearer picture of the stresses that can be expected. There are significant differences in static and dynamic modulus of elasticity between bottom and top logs from the same tree. More logs will have to be tested to further characterize the nature of those differences.

KEY WORDS: round logs, Sitka spruce, structural properties, green logs

1 INTRODUCTION

Structural properties of timber are an important factor in design and construction of timber structures. As timber is by its nature a very heterogeneous material where many different factors interact with and/or impact its mechanical properties, a high confidence level when studying the relationships between them is relatively difficult to achieve.

While different sawn timber products such as kiln dried boards are often used in construction and as such have been a subject of many different studies, round logs are a less studied subject. The use of round logs in timber construction is relatively uncommon when compared to other timber products. The biggest potential markets were identified both in small buildings and large engineered structures, while small diameter round logs could also be utilised in footbridges, sound barriers and landscaping [5]. One could argue that the usage is scarce because not enough is known about the behaviour of the material itself. On the other hand scarcity of research might imply that there is no need on the market to know more about using round logs. While that might be true, predicting sawn timber properties from round wood measurements would be very helpful to sawmills, as it would enable the early classification of the logs regarding quality of the expected sawn timber.

This lack of research has had an impact on developed standards – for instance there are standards for testing sawn timber [1]-

[3] and for round poles [4], but there are currently no standards for structural testing of logs. CEN standards written for sawn timber are not directly applicable to round timber, especially to small diameter round timber. For example, a high proportion of juvenile wood would indicate that the strength could be lower when the diameter gets smaller – contrary to EN 384 size adjustments for sawn timber [5]. While there is no universally accepted definition of juvenile wood, it is typically described as the zone near the pith of the log. In Sitka spruce the transition between juvenile and mature wood appears to occur around the age of 12 to 13 years [19]. A proposal for testing round small round timber was developed as a part of a large EU Research project (FAIR CT 95-0091) [5], in which the large proportion of juvenile wood is taken into consideration. This has yet to be implemented in harmonised standards.

A small number of researchers has examined the behaviour of logs in different bending tests [6]-[16], mainly of dry round logs. Sample sizes ranged from 24 to 445 logs tested, while approximately half of the papers examined used a three point bending test and the other half a four point bending test. A cantilever test was used in only one of the papers examined [13]. Span to depth ratios varied from 18:1 to 29:1, while studies [10], [13] and [16] used a fixed specimen length rather than a fixed span to depth ratio. None of the studies found were performed on Sitka spruce logs (*Picea sitchensis* [Bong.] Carr.); the majority of the testing was done on specimens from different species across the *Pinus* genus. The diameters of the logs tested varied between between 10 and 20 cm in most of the previous studies [6]-[16]. Studies [7], [8] and [13] tested green

logs (moisture content above fibre saturation level) using three point bending tests or as a cantilever [13].

The focus of the present work is to establish the mechanical properties of roundwood from Irish Sitka spruce. In this paper, results from a test programme to establish the properties of green timber will be presented. Later studies will investigate the properties of dried logs. This information will inform the identification of possible end uses for the product, contribute to the understanding of the structural behaviour of standing trees and allow sawmillers to sort logs on the basis of structural capacity before processing.

2 MATERIAL AND METHODS

2.1 Material

A total of 37 logs of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) was sourced from a forest plantation near Frenchpark, County Roscommon, Ireland. The trees were planted in 1995 and felled in November of 2015.

After felling, the logs were extracted from the forest and transported to the testing facilities at the National University of Ireland, Galway. All logs were 3000 mm in length.

2.2 Methods

Using a crane each log was weighed and the diameters at both ends and in the middle were measured using a diameter tape. The logs were not debarked before testing.

2.3 Non-destructive testing

Using a MTG Timber Grader (*Brookhuis Applied Technologies, Netherlands*) each log was tested to determine its fundamental frequency in the longitudinal direction in order to test the possible usage of the device on logs. Not all logs were measured using the MTG Timber Grader.

The volume of each individual log was calculated as the sum of two conical frustums using the three measured log diameters (both ends and middle). Density was then derived from the volume and weight. Moisture content was measured and was above fibre saturation point in all of the logs, as they were tested fresh, i.e. in green condition.

The dynamic modulus of elasticity was derived from the fundamental frequency (f), log length (l) and density (ρ) (Equation (1)) according to [5].

$$E_{dyn} = 4l^2 f^2 \rho \quad (1)$$

2.4 Destructive testing

After measuring the logs with the MTG Timber Grader, they were set up in the testing machine and prepared for a four point bending test (see Figure 1). As there are no standards for structural testing of round logs, the testing protocol used was based on the proposed standard of small diameter round log testing [5] and the standard for testing dry sawn timber [3].

As the middle diameters of the logs varied and the length was fixed, a constant span-to-depth ratio could not be achieved. Instead a constant span of 2700 mm was chosen. The loading heads were 900 mm apart. After preliminary testing a loading rate of 0.3 mm/s was chosen to ensure the maximum load was achieved in 300s (± 120 s). The testing was stopped when no further log or testing head movement was possible due to size restraints of the testing rig. Displacement was measured at midspan using two string pots mounted at the base of the machine, they were attached to the upper side of the log using a steel plate. Both displacements and the force applied were recorded with the help of LabView software [17] with a sampling rate of one measurement per second.



Figure 1: Four point bending test setup

The static modulus of elasticity, determined using the linear portion of the load/displacement plot, was calculated from the load/displacement linear regression using Equation (2) - the square of the correlation coefficient was greater than 0.99 in all cases.

$$E_{static} = \frac{a(3l^2 - 4a^2)(F_2 - F_1)}{48I(w_2 - w_1)} \quad (2)$$

where

F_1 and F_2 are the loads corresponding to $0.1F_{max}$ and $0.4F_{max}$, w_1 and w_2 are the corresponding displacements, F_{max} is the maximum load recorded during the test, I is the mean second moment of area of the log section, a is the distance between the support and load head.

The bending strength was calculated using Equation (3) as per the round log testing standard proposal [5] using the diameter at the point of failure (d), the maximum load (F_{max}) and the distance between the support and load head (a).

$$f_m = \frac{16F_{max}a}{\pi d^3} \quad (3)$$

2.5 Data analysis

All data analysis was performed with the help of the statistical software IBM SPSS 22 [18]. Gathered data were checked for

normality using Shapiro-Wilk's test and homogeneity of variances was tested using Levene's test. Correlations were assessed using the Pearson correlation coefficient and Spearman's rank correlation coefficient.

3 RESULTS

Ten logs were the bottom logs and 27 were the top logs of the trees. A maximum of two logs per tree was sampled. Logs were randomly selected within trees at the time of extraction to ensure maximum statistical power of the experiment. The sampling groups are unequal, which was accounted for in later stage data analysis, where relevant.

The average tested log diameter was 18.01 cm (calculated as an average of the diameters at both ends and the middle), ranging from 14.1 to 23.7 cm with a standard deviation of 2.6 cm. Some characteristics of the measured variables are listed in Table 1.

Table 1 – Characteristics of the measured variables

	N	Min.	Max.	Mean	Std. Dev.
Volume [m ³]	37	0.05	0.13	0.08	0.02
Density [kg/m ³]	37	703.7	967.1	859.5	62.0
Fundamental frequency [Hz]	29	400.0	571.0	493.0	46.6
M [kg]	37	37.5	110.5	66.9	17.2
DBH [cm]	37	17.6	23.8	20.4	1.8
E _{dyn} [N/mm ²]	29	4882.2	10762.6	7599.4	1722.3
E _{stat} [N/mm ²]	37	1715.9	6875.3	4623.9	1502.6
F _{max} [N]	37	16219.7	74369.0	36691.3	12910.5
Bending strength [N/mm ²]	37	15.5	47.7	36.2	6.0

Some significant correlations were discovered between the measured and calculated variables. The static modulus of elasticity moderately to strongly correlates with all of the diameters measured, most strongly with the diameter at the thicker end of the log (Pearson's $\sigma = -0.872$, $p = 0.000$). It is also in correlation with the density (Pearson's $\sigma = 0.615$, $p = 0.000$) and fundamental frequency (Pearson's $\sigma = 0.790$, $p = 0.000$). Surprisingly, there is no correlation with the diameter at breast height (DBH) and either the static or dynamic MOE.

Significant correlations were also found between bending strength and (1) the diameter at the failure location (Pearson's $\sigma = -0.548$, $p < 0.000$), (2) the static modulus of elasticity (Pearson's $\sigma = 0.386$, $p = 0.019$) and (3) the dynamic modulus of elasticity (Pearson's $\sigma = 0.400$, $p = 0.031$). With the exception of the fundamental frequency, all of the correlations

stated above have a higher Pearson's Rho when compared to Spearman's Rho, which indicates a more linear type of relationship.

The static modulus of elasticity also significantly correlates with the dynamic modulus calculated from fundamental log frequency and log dimensions (Pearson's $\sigma = 0.790$, $p = 0.000$), which indicates that the MTG Timber Grader could also potentially be used on green logs. The same applies for any similar devices that can measure the fundamental frequency of the logs, which can then be used to calculate dynamic modulus of elasticity.

One-way ANOVA was performed on the data to study the impact of log position within the tree on the measured characteristics. The results show that there are significant differences ($p = 0.000$) between the bottom and top logs in density (ρ), bending strength, fundamental frequency, static modulus of elasticity (E_{stat}) and the dynamic modulus (E_{dyn}) derived from fundamental frequency. The static modulus of elasticity by log position is displayed in Figure 2.

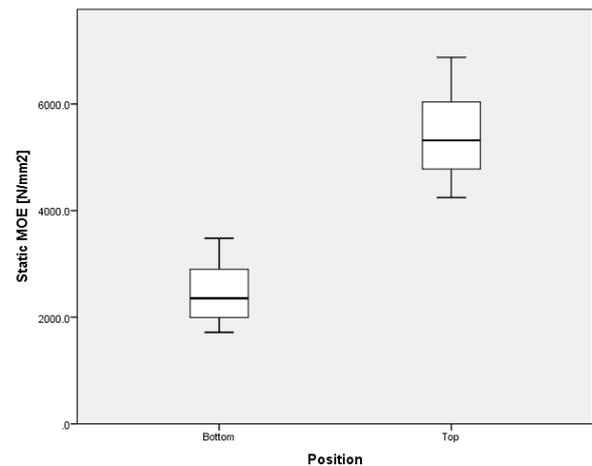


Figure 2: Static MOE distribution by log position

The measured bending strength values ranged between 15.5 N/mm² and 47.7 N/mm² for the 37 logs tested. This compares well with values reported for Irish Sitka spruce boards tested at 12% moisture content in tension and compression [20]. In that study, the tensile strength values of the dry boards ranged between 10 N/mm² and 45 N/mm² and the compressive strength values ranged between 25 N/mm² and 49 N/mm².

The tested green round logs have a mean static modulus of elasticity of 4624 N/mm², which is significantly lower than the typical value of 8000 N/mm² for Irish Sitka spruce dry sawn timber. The mean dynamic modulus of elasticity, on the other hand, is much higher and has an average value of 7600 N/mm². Further testing is required in order to develop an accurate relationship between the dynamic and static moduli of elasticity.

Another noticeable difference in the structural response is that the load-deflection behaviour is highly non-linear whereas dry sawn timber is typically more brittle and linear elastic to failure. Typical green log load-deflection curves are shown in Figures 3 and 4.

Post hoc analysis of the gathered data showed that the logs could be classified into two groups in relation to the typical shape of the load-deflection curve after reaching maximum stress. As shown in Figures 3 and 4 the fibres can either yield very quickly (54% of the logs tested, resulting in Figure 4 shaped peak) or slowly (46% of the logs tested, Figure 3 shaped peak).

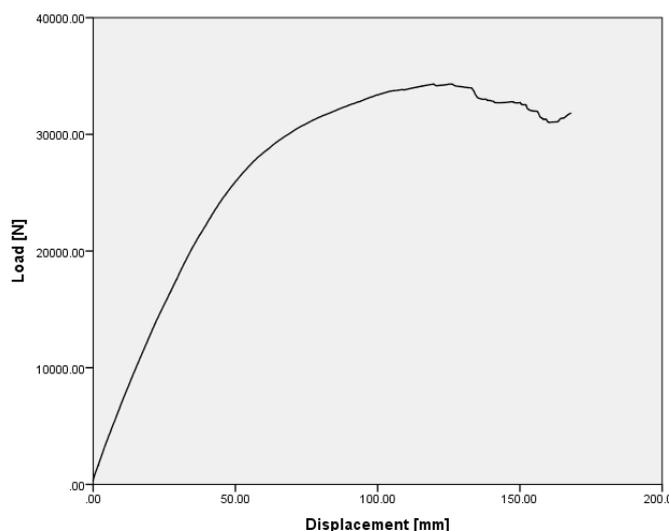


Figure 3: Typical load-deflection response (compressive failure)

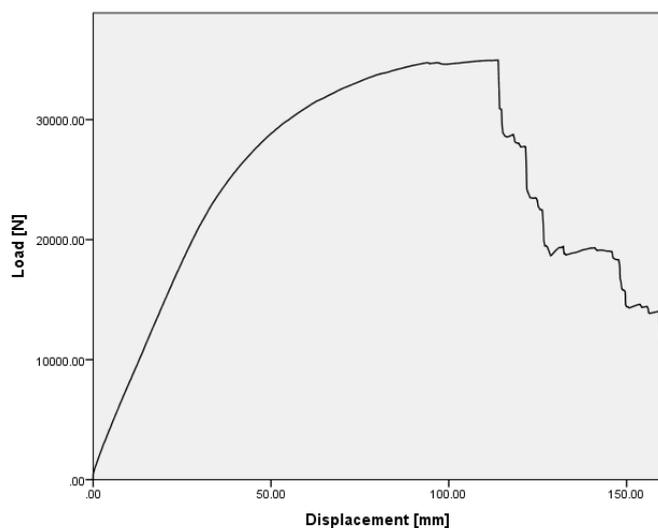


Figure 4: Typical load-deflection response (tensile failure)

The difference between the post peak load-deflection response demonstrated in Figures 3 and 4 is associated with the type of failure. The failure mode associated with the Figure 3 type

response is the result of compressive yielding of the top surface of the log. On the other hand the failure mode associated with the Figure 4 response is the result of tensile failure in the bottom half.

4 DISCUSSION

Testing of 37 green logs of Irish Sitka spruce was carried out to determine the mechanical behaviour. The measured strength values were comparable with measurements on dry boards. The static modulus of elasticity measured in a four-point bending test was however significantly lower than for dry boards. Dynamic modulus of elasticity measurements from the vibration tests were distinctly higher than those from static bending tests. Further investigation on the influence of the moisture content on the frequency measurement is required to explain this difference and a larger sample is required to develop a robust relationship between the dynamic and static moduli.

The discovered correlations between the static modulus of elasticity and various diameters are of interest to further studies regarding both using round logs in construction and when studying the load response in standing trees, for example in wind throw investigations.

The non-existent correlation between breast height diameter (DBH) of the tested trees and the static or dynamic MOE, while both of them correlate with the log diameters, shows that the log taper should not be disregarded when studying either round logs or standing trees of Sitka spruce.

The strong correlation between static and dynamic MOE shows that methods or devices based on the relationship between the fundamental frequency and its elasticity, such as MTG Timber Grader, have potential in grading green logs as well as dry boards. In industrial conditions the correlation coefficient would probably be lower, as the same relationship was observed on boards in several previous studies [5].

The comparison of different mechanical properties between top and bottom logs is interesting, as the results are counter intuitive. One would expect a higher density and higher static MOE in lower, thicker logs. On the other hand, the relationship between the thick end diameter and E_{stat} is negative when taking all log samples into account. To gather any definitive conclusions a more balanced sample is needed, as the statistics tests performed on bottom and top logs did not control for effect of log diameter on account of the small sample size of bottom logs.

Based on the results of this study, the testing protocol used was deemed to be successful and will be used in future structural testing of green round logs.

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