Use of Nondestructive Techniques for Determination of Tension Parallel-to-Grain Properties of Spruce

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Abstract

The paper presents a study of the tension properties of *Irish-grown Sitka spruce*. Fifty timber pieces were destructively tested having resonant frequency and knots measured. The aim was to improve knowledge of the performance of spruce in tension and to check the suitability of the equations given in the European standards to calculate secondary properties from grade determining properties. Static stiffness, which limited the grading of the dataset, was largely predicted using dynamic modulus of elasticity (MoE_{dyn}). Tension strength was modelled using density and tKAR index. It was found also that adding MoE_{dyn} in a linear regression was not useful. The research reveals that the equation given in EN384:2018 for tension strength, based on populations of higher stiffness than Irish spruce, results in values that may not be appropriate for Irish-grown spruce timber.

Keywords: grading, NDT, sawn timber, spruce, tension, wood properties, strength, standards

Introduction

General information

The interest in timber construction has increased in recent years, largely motivated by the demands of society for renewable and more environmentally-sensitive construction materials to mitigate climate change. The WoodProps programme in NUIG is aiming to increase knowledge on Irish timber to support its use in construction.

Sitka spruce (*Picea sitchensis* (*Bong*) Carr.) occupies 51.1% of the forest area in Ireland (Forest Service 2019). More than half of the output from Irish sawmills in 2015 was used in the construction sector

(IFFPA, 2016), and it is also the main commercial species in the UK. It was the only species machine graded until Douglas fir machine grading settings were approved in 2018 (Gil-Moreno et al., 2019). Historically, most of the research in Ireland and the UK have addressed the grading determining properties of bending strength, bending modulus of elasticity (MoE) and density. There is very little information published on tension properties parallel to the grain, and they are typically estimated from bending tests using empirical relationships, which has proved reasonably satisfactory for most cases (Walker, 1993). This is partially due to the difficulties in measuring tension properties as it is not uncommon that test pieces fail out of the prescribed test section as a result of the clamping conditions.

Another empirical approach to predict mechanical properties in tension is the use of non-destructive techniques (NDT). Measurement of density and knots is typically more important for strength prediction than for MoE prediction.

NDT based on acoustic measurements are widely used for prediction of mechanical properties, particularly MoE, due to the direct link between MoE and the acoustic behaviour of a wave travelling through the material (Bucur, 2006). The Newton-Laplace equation calculates dynamic modulus of elasticity (MoE_{dyn}) from density (ρ) and speed propagation of a wave (v) as shown in Equation 1:

$$MOE_{dyn} = \rho * v^2 \tag{1}$$

In particular, the use of the resonance speed to calculate MoE_{dyn} has offered accurate estimations of static MoE (Gil-Moreno and Ridley-Ellis, 2015). This method, generally applied in the longitudinal direction, calculates the speed of a wave measuring the frequency and wavelength (Equation 2).

$$Speed = Wavelength * Frequency \tag{2}$$

The importance of tension properties is reflected in the new European standard EN338:2016 (CEN,2016) which now includes strength classes based on tension tests. Strength classes are defined by characteristic values: fifth percentile strength and density, and mean MoE. The superseded EN338:2009 and EN384:2010 gave an equation ($f_{t,0,k} = 0.6 * f_{m,0,k}$) to calculate the characteristic values of tension strength ($f_{t,0,k}$) from edgewise bending characteristic values ($f_{m,0,k}$). The revised EN384:2018 (CEN,2018) uses a new relationship ($f_{t,0,k} = -3.07+0.73* f_{m,0,k}$) that for $f_{m,0,k}$ below 23,6 N/mm^2 reduces the associated tension strength values, and increases it for those above.

A problem of using a general linear equation for material across different grades is that the relationships between bending and tension properties may vary depending on the timber quality. The Gradewood project agreed that the relationship given in EN338:2009 was generally correct for lower grades (internal document N0832 CEN/TC 124/WG02). Irish timber typically achieves C16 strength class quality ($f_{m,0,k}$ = 16 N/mm^2), and the new relationship in EN 338:2016 was established based on testing of Scandinavian and central European timber, that typically achieves strength classes higher than C16 and for which grading is usually strength limited. Irish and British spruce is typically limited by stiffness, and as a result, the relationship may not adjust well to the Irish and British timber quality.

The aim of this *WoodProps* study is twofold. First, it examines the characteristic grading properties in tension of Sitka spruce grown in Ireland. Second, it examines the suitability of the equation given in EN384:2018 applied to Irish timber to derive bending properties from tension. The research is ongoing, but there is already enough data to make some preliminary recommendations.

Material and methods

This investigation comprised 50 ungraded pieces of sawn timber of Sitka spruce grown in Ireland, with cross section 100 x 47 mm. Most specimens (42 pieces) were offcuts of a previous study and were between 1346 mm and 2215 mm long (mean of 1724 mm), which was enough for the purposes of this study. The dataset was completed with eight pieces of 3600 ± 1 mm, donated by a local sawmill.

After conditioning the timber pieces to approximately 12% moisture content, the resonance frequency was measured with a grading machine MTG960 (Brookhuis Microelectronics BV, Holland). Density was obtained from mass and average dimensions of three points along the piece, and the MoE_{dyn} calculated using equations 1 and 2. For the destructive testing, the expected weakest section was selected based on the size and location of knots, that were measured using the online software Web Knot Calculator v2.2 (Microtec, Italy) to obtain the tKAR index (Figure 2), and model the mechanical properties. Due to the limitations on the length that the testing machine can accommodate, the pieces were cut to 1.26 m, centring in the test section. The mass and resonance frequency was measured again to calculate the MoE_{dyn}. This paper will use the term specimen to refer to the tested piece, and board to refer to the material before cutting.

The specimens were destructively tested in tension parallel to the grain according to EN408:2010 (Figure 1) using a Dartec 250 kN (Zwick Roell, Germany). One transducer was placed on each face of the specimen, and the average displacement was used to calculate the modulus of elasticity (MoE_t). The transducers remained on the board throughout the test until the failure load was reached.

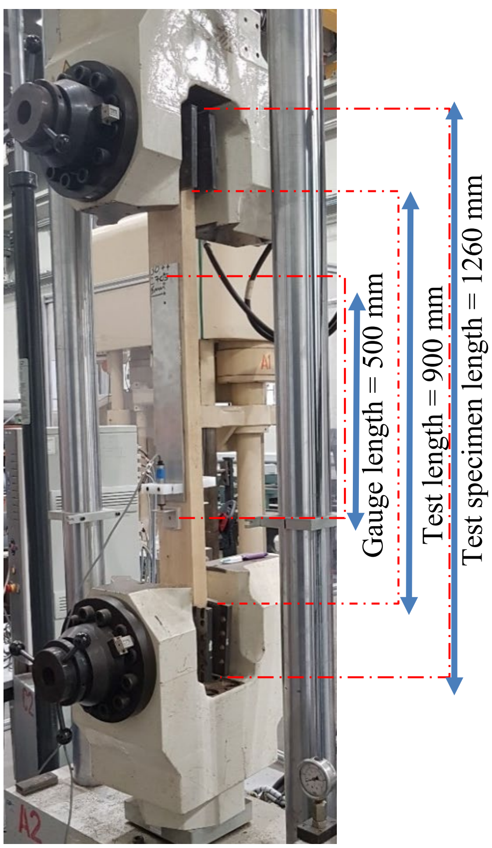

Figure 1—Set up of tension test.

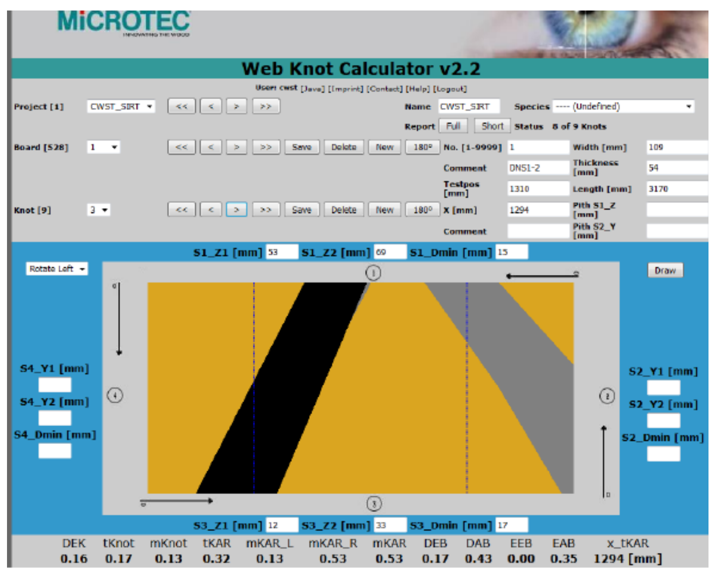

Figure 2—Web knot calculator interface.

A density sample approximately 50-mm long, spanning the full cross-section and cut near the failure point, was used to calculate the clear density ($Density_{384}$), and the moisture content using the oven drying method according to EN13183 (CEN, 2002). The MoE_t and density values were corrected to a reference moisture content of 12%, and the strength values adjusted to a reference depth of 150 mm according to EN384.

Results and discussion

The results presented here are the descriptive statistics of the tension properties, the correlations between them, models for prediction of mechanical properties, and the grading performance as well as a comparison with results in the Gradewood project.

Thirty-five specimens broke within the test length, seven others slipped in the clamps, and eight pieces broke as a result of the clamping pressure. The MoE_t was measured in the range of the 10%-40% of maximum load, and therefore was not influenced by the failure of specimens that broke as a result of the clamping pressure or slipped. The strength could have however been underestimated on those pieces that slipped without breaking and those that failed as a result of the clamping pressure. Due to the relatively small sample size, it was decided to include all the specimens in the dataset. The tKAR index was only used for 30 pieces because the measurements were either missed or the test specimens slipped.

Descriptive results

Table 1 summarises some of the properties measured, and shows the Gradewood project for comparison.

Table 1— Summary of properties

Property	WoodProps			Gradewood[1]
	min	mean (CoV)	max	mean
MoE (kN/mm^2)	5.32	9.44 (23.4%)	13.8	10.6
Tension strengh (N/mm^2)	7.5	22.3 (27.9%)	32.5	26.9
$Density_{384}$ (kg/m^3)	306	418 (13.3%)	538	422
Fmax (kN)	36.7	110.4 (27.7%)	160	
Density test specimen (kg/m^3)	351	437 (10.5%)	534	
Density board (kg/m^3)	340	434 (14.1%)	531	
tKAR		0.40 (45.8%)		0.28

[1](Stapel and Denzler, 2010); min: minimum value; max: maximum value

Density was very similar in both datasets, but the mechanical properties were higher in the Gradewood project. On 63 boards of Irish-grown Sitka spruce of 25x96 mm^2, Raftery (Raftery, 2010) obtained mean values of 7890 N/mm^2 for MoE_t, 22.8 kN/mm^2 for tension strength and 404 kg/m^3 for density. Tension strength was slightly higher than in the current study, but the results were not adjusted to the reference depth of 150 mm, which would have reduced the values by about 9%.

The strength of the linear association between the three grading properties, and with MoE_{dyn} was measured with Pearson's correlation. This is shown in Table 2. Regressions between the grade determining properties explained between 34% and 49% of the variations. Raftery and Harte (2014) found that $Density_{384}$ only explained 5% of the variation of MoE_t and 9% of strength, which was 59% explained by MoE_t. In this WoodProps study, $Density_{384}$ had a stronger correlation with strength than any of the MoE measured.

Table 2— Pearson's correlation (r) between variables

Properties	r	R^2
$Density_{384}$ - MoE_t	0.70	0.49
$Density_{384}$ - Strength	0.63	0.40
MoE_t - Strength	0.59	0.34
$MoE_{dyn,\ specimen}$ - MoE_t	0.96	0.92
$MoE_{dyn,\ board}$ - MoE_t	0.94	0.88
$MoE_{dyn,\ specimen}$ - Strength	0.58	0.34
$MoE_{dyn,\ board}$ - Strength	0.56	0.32

The MoE_{dyn}, calculated both in specimens and boards, was very strong with MoE_t. On two different studies on beech, Ehrhart et al. (2016; 2018) reported poor relationships between MoE_{dyn} and tension strength (R^2=0.22 and 0.16). For the same species, Westermayr (2018) reported a moderate relationship between strength and MoE_{dyn} (R^2 =0.51). In this study, the MoE_{dyn} of the specimens explained 92% of the variation in MoE_t (RMSE = 690 N/mm²) using a linear regression, and 88% (RMSE = 874 N/mm²) using the MoE_{dyn} of the boards. The MoE_{dyn} represents the average properties of a piece, and the different lengths measured explains the differences of measuring the MoE_{dyn} of the full boards and the tested specimens. The MoE_{dyn} of the specimens (mean of 10.4 kN/mm²) was slightly smaller than in boards (mean of 10.6 kN/mm²). The relationships of MOE_{dyn} in boards and specimens with MOE_t are shown in Figure 3.

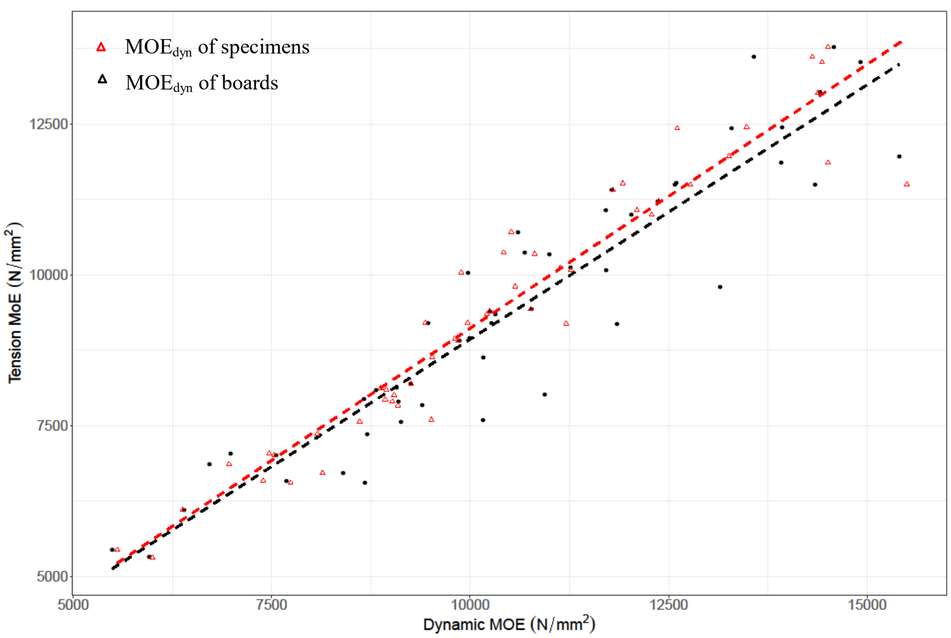

Figure 3—Relationship between MoE_{dyn} of the test specimen and the board with the MoE_t.

When used to predict tension strength, MoE_{dyn} of the test specimens was only able to explain 34% of the variation (RMSE=5.1 N/mm²), and 32% if MoE_{dyn} was applied to full boards (RMSE=5.2 N/mm²). Using only the boards that broke in the test length, the relationship did not improve. The prediction of strength presented more difficulties compared to MoE_t as it is influenced by knots. Using Swiss-grown Norway spruce, Steigher and Arnold (2009) reported relationships (R^2) of 0.80 between MOE_{dyn} and MoE_t, and 0.34 between MOE_{dyn} and tension strength, similar to this WoodProps study.

Based on Pearson's correlation in Table 2, board and specimen density were assessed as an independent variable for prediction of tension strength, explaining 44% of the variation (RMSE=4.7 N/mm²).

Including MoE_{dyn} did not usefully improve the relationship. Applying a stepwise regression, the best model used the board density and tKAR index as variables, explaining 52% of the variation of the strength (RMSE=4.6 N/mm^2). Table 3 shows some of the coefficients of determination investigated.

Table 3— Variables for tension strength prediction

Model	Variables and p-values	R^2 and RMSE
1	MoE_{dyn} specimen***	R^2 = 34%, RMSE=5.1 N/mm^2
2	MoE_{dyn} board***	R^2 = 32%, RMSE=5.2 N/mm^2
3	$Density_{384}$***	R^2 = 40%, RMSE=4.9 N/mm^2
4	Board density***	R^2 = 44%, RMSE=4.7 N/mm^2
5	Specimen density***	R^2 = 44%, RMSE=4.7 N/mm^2
6	Board density** + tKAR*	R^2 = 50%, RMSE=4.7 N/mm^2
7	Specimen density** + tKAR*	R^2 = 52%, RMSE=4.6 N/mm^2

***p-value<0.001; **p-value<0.01; *p-value<0.05;

In practical terms, the prediction of tension strength will use the full length of boards. The following models have been developed based on the dataset studied (50 and 30 boards for equations 3 and 4, respectively).

$$f_{t,0} = -15.9 + 0{,}088 * Density\ board\ (kg/m^3) \tag{3}$$

$$f_{t,0} = -3.7 + 0{,}07 * Density\ board\ \left(\frac{kg}{m^3}\right) - 13.3 * tKAR \tag{4}$$

Results for grading

The characteristic values of the dataset were 12.3 kN/mm^2 for strength, 340 kg/m^3 for density and 9435 kN/mm^2 for stiffness. Therefore, the MoE achieved values of T11 strength class, whereas strength and density achieved T12 and T13, respectively. The limiting factor was stiffness, which favours the use of MoE_{dyn} as an indicating property.

For the thirty boards on which tKAR values were measured, the mean tension strength was 21.3 N/mm^2. Equation 5 explained 69% of tension strength in the Gradewood project (Ranta-Maunus, 2009), and applied to WoodProps dataset gave a mean tension strength of 19.7 N/mm^2. The model predicts a negative value for a piece of low MoE_{dyn} and density and a high tKAR value. A specific model for the dataset in this study (Equation 6), using the same variables as the Gradewood model, gave a mean tension strength of 21.3 N/mm^2, and explained 48% of the strength variation, but only density and tKAR were statistically significant. The MoE_{dyn} was measured on the board.

$$f_{m1} = 6.85 - 0.0078\text{b} - 0.0057\text{h} - 0.0286 Den_{384} - 29.7\text{tKAR} + 3.648 * 10^{-3} MoE_{dyn} \tag{5}$$

$$f_{m2} = -153.3 + 2.007\text{b} + 0.667\text{h} + 0.0531 Den_{384} - 13\text{tKAR} + 1.774 * 10^{-5} MoE_{dyn} \tag{6}$$

Timber grading operates on the basis of the properties of a population rather than the individual boards. The values resulting from equations 5 and 6 were used for simulating a sorting exercise based on tension strength comparing the performance of both equations against the measured values. For illustration, this process used the mean of the population instead of the fifth percentile. The specimens were ranked in ascending order by f_{m1} and f_{m2} values, and their means and the mean of the corresponding measured tension strength values calculated. Subsequently, the lowest f_{m1} and f_{m2} values were removed from the population and the means recalculated. This process was repeated until only the highest value was left in the population. Figure 4 shows the mean tension strength of the population on the y-axis and the proportion of pieces that achieve a certain mean value on the x-axis. For example, the mean tension strength measured on all pieces (100% boards passing) is 21.3 N/mm^2. As the lower quality boards are removed, the mean of the population increases but the proportion of boards is lower. The Gradewood model, would sort the boards in an order that would not correspond with the real quality of timber, resulting in poor sorting of the timber, far from the real quality. The model generated for the WoodProps dataset represents the quality better, although it is, of course, based on the same dataset and further testing is needed.

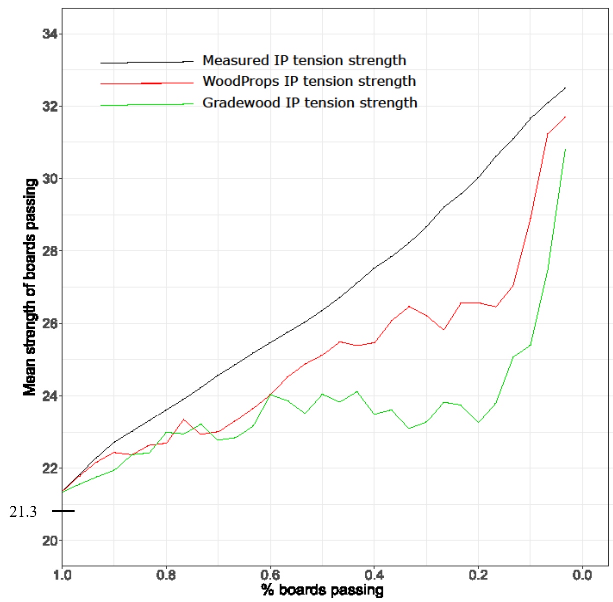

Figure 4—Grading simulation

Conclusions

The dataset examined in this WoodProps study had lower mechanical properties than the Gradewood project. The relationship to predict MoE_t was very strong both using MoE_{dyn} of the tested specimen and the full board. Stiffness limited the grading of the timber studied, hence the use of tools measuring MoE_{dyn} are relevant in grading timber.

For tension strength prediction, density and tKAR index resulted in stronger relationships than MoE_{dyn}. Further specimens will be tested to complete a larger dataset and measure knots, but preliminary results indicate that the equation given in EN384:2018 may not be suitable for use on lower grade timber.

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Abstract

The 21st International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the Forest Research Institute Baden-Württemberg (FVA) in Freiburg, Baden-Württemberg, Germany, September 24–27, 2019. This symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many international researchers, NDT/NDE users, suppliers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, structural lumber, engineered wood products, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 21st symposium is captured in these proceedings. Full-length, in-depth technical papers for the oral presentations and several of the poster presentations are published herein. The papers were not peer reviewed and are reproduced here as they were submitted by the authors.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood projects

Contents

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