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# 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 ( $\rho$ ) and speed propagation of a wave ( $v$ ) as shown in Equation 1:

$$MOE_{dyn} = \rho * v^2 \quad (1)$$

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).

$$Speed = Wavelength * Frequency \quad (2)$$

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<sup>2</sup> 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<sup>2</sup>), 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  $3600 \pm 1$  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 ( $MoE$ ). The transducers remained on the board throughout the test until the failure load was reached.

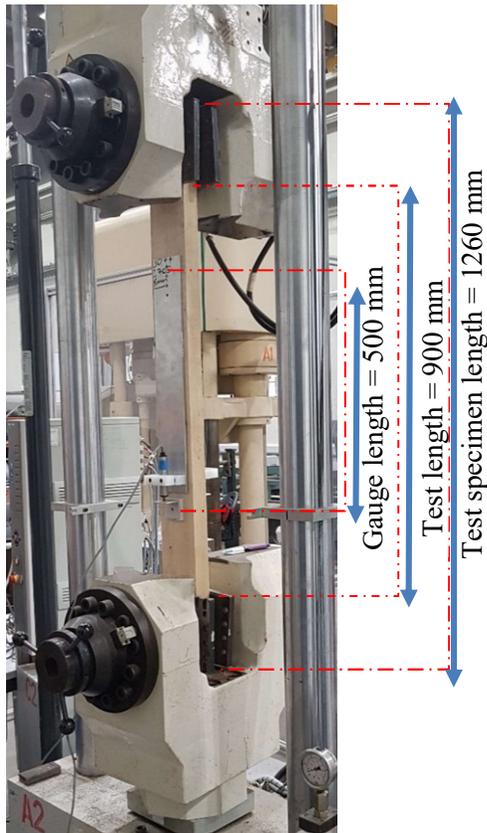


Figure 1—Set up of tension test.

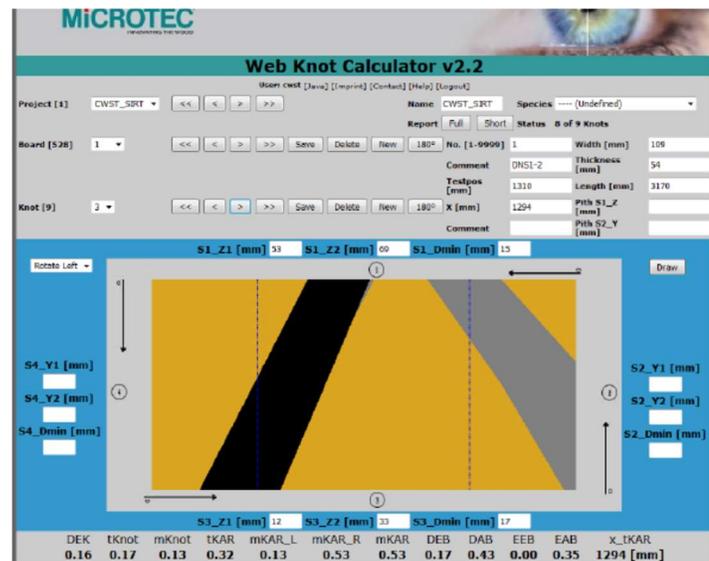


Figure 2—Web knot calculator interface.

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 <sup>1</sup>
	min	mean (CoV)	max	mean
MoE (kN/mm <sup>2</sup> )	5.32	9.44 (23.4%)	13.8	10.6
Tension strength (N/mm <sup>2</sup> )	7.5	22.3 (27.9%)	32.5	26.9
Density <sub>384</sub> (kg/m <sup>3</sup> )	306	418 (13.3%)	538	422
Fmax (kN)	36.7	110.4 (27.7%)	160	
Density test specimen (kg/m <sup>3</sup> )	351	437 (10.5%)	534	
Density board (kg/m <sup>3</sup> )	340	434 (14.1%)	531	
tKAR		0.40 (45.8%)		0.28

<sup>1</sup>(Stapel and Denzler, 2010); min: minimum value; max: maximum value

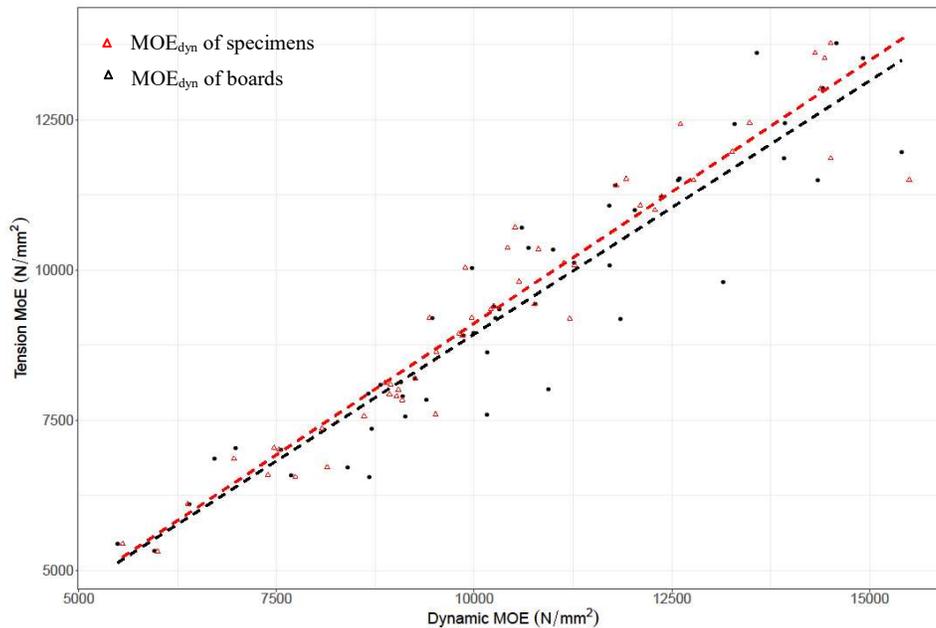
Density was very similar in both datasets, but the mechanical properties were higher in the Gradewood project. On 63 boards of Irish-grown Sitka spruce of 25x96 mm<sup>2</sup>, Raftery (Raftery, 2010) obtained mean values of 7890 N/mm<sup>2</sup> for  $MoE_t$ , 22.8 kN/mm<sup>2</sup> for tension strength and 404 kg/m<sup>3</sup> 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 <sup>2</sup>
Density <sub>384</sub> - MoE <sub>t</sub>	0.70	0.49
Density <sub>384</sub> - Strength	0.63	0.40
MoE <sub>t</sub> - Strength	0.59	0.34
MoE <sub>dyn, specimen</sub> - MoE <sub>t</sub>	0.96	0.92
MoE <sub>dyn, board</sub> - MoE <sub>t</sub>	0.94	0.88
MoE <sub>dyn, specimen</sub> - Strength	0.58	0.34
MoE <sub>dyn, board</sub> - Strength	0.56	0.32

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



**Figure 3**—Relationship between MoE<sub>dyn</sub> of the test specimen and the board with the MoE<sub>t</sub>.

When used to predict tension strength, MoE<sub>dyn</sub> of the test specimens was only able to explain 34% of the variation (RMSE=5.1 N/mm<sup>2</sup>), and 32% if MoE<sub>dyn</sub> was applied to full boards (RMSE=5.2 N/mm<sup>2</sup>). 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<sub>t</sub> as it is influenced by knots. Using Swiss-grown Norway spruce, Steigher and Arnold (2009) reported relationships (R<sup>2</sup>) of 0.80 between MOE<sub>dyn</sub> and MoE<sub>t</sub>, and 0.34 between MOE<sub>dyn</sub> 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/mm<sup>2</sup>).

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<sup>2</sup>). Table 3 shows some of the coefficients of determination investigated.

**Table 3**— Variables for tension strength prediction

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

\*\*\*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).

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

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

## Results for grading

The characteristic values of the dataset were 12.3 kN/mm<sup>2</sup> for strength, 340 kg/m<sup>3</sup> for density and 9435 kN/mm<sup>2</sup> 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<sup>2</sup>. 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<sup>2</sup>. 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<sup>2</sup>, and explained 48% of the strength variation, but only density and tKAR were statistically significant. The  $MoE_{dyn}$  was measured on the board.

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

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

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<sup>2</sup>. 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.

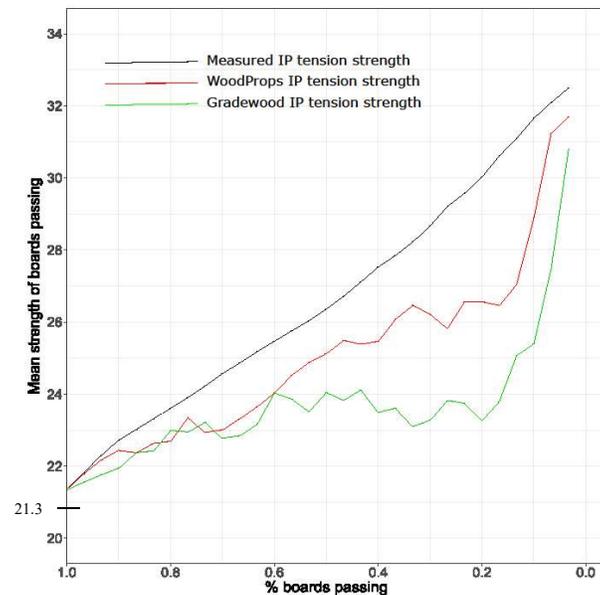


Figure 4—Grading simulation

## 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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## References

Bucur, V. 2006. Acoustics of Wood. 2<sup>nd</sup> Edition. Springer, Germany.

- CEN. 2002. Moisture content of a piece of sawn timber—Part 1: Determination by oven dry method. EN 13183-1:2002. European Committee for Standardisation, Brussels, p.5.
- CEN. 2016. Structural timber - strength classes. EN338:2016. European committee for standardisation, Brussels. p. 11.
- CEN. 2018. Structural timber-determination of characteristic values of mechanical properties and density. EN 384:2016 + A1:2018. European committee for standardization, Brussels, p 22.
- Ehrhart T, Fink G, Steiger R, Frangi A. 2016. Experimental investigation of tensile strength and stiffness indicators regarding European beech timber. Proceedings of the World Conference on Timber Engineering (WCTE 2016), Aug. 22-25, 2016, Vienna, Austria.
- Ehrhart, T., Steiger, R., Palma, P., & Frangi, A. 2018. Estimation of the tensile strength of European beech timber boards based on density, dynamic modulus of elasticity and local fibre orientation. World Conference on Timber Engineering (WCTE 2018), Aug. 20-23, 2018 Seoul, Rep. of Korea.
- Forest Statistics Ireland 2019. 2019. Department of Agriculture, Food and the Marine, Ireland. Available at:<https://www.agriculture.gov.ie/media/migration/forestry/forestservicgeneralinformation/ForestStatisticsIreland280519.pdf>.
- Gil-Moreno, D., & Ridley-Ellis, D. 2015. Comparing usefulness of acoustic measurements on standing trees for segregation by timber stiffness. Proceedings of 19<sup>th</sup> International Nondestructive Testing and Evaluation of Wood Symposium, Sep. 22-25, 2015 Rio de Janeiro, Brazil.
- Gil-Moreno, D., D. Ridley-Ellis, and A. M. Harte, 2019, Timber grading potential of Douglas fir in the Republic of Ireland and the UK: International Wood Products Journal, p. 1-6.
- IFFPA. 2016. An overview of the Irish forestry and forest products sector 2016. Irish Forestry and Forest Products Association. Dublin.
- Raftery G. 2010. The use of advanced composite materials in the flexural reinforcement of low-grade glulam. PhD Thesis. National University of Ireland, Galway.
- Raftery G, Harte AM. 2014. Material characterisation of fast-grown plantation spruce. Structures and Buildings 167: 380-386.
- Ranta-Maunus, A., 2009, Strength of European timber: Part 1. Analysis of growth areas based on existing test results. VTT Publications 706. Finland.
- Stapel P, Denzler J. 2010. Influence of the origin on specific properties of european spruce and pine. Final Conference COST Action E53, May 4-7, 2010 Edinburgh, UK.
- Steiger R, Arnold M. 2009. Strength grading of Norway spruce structural timber: Revisiting property relationships used in en 338 classification system. Wood science and technology. 43(3-4):259-278.
- Walker JC. 1993. Primary wood processing: Principles and practice. 1<sup>st</sup> Edition. Chapman and Hall, UK.
- Westermayr, M., P. Stapel, and J. W. van de Kuilen, 2018, Tensile strength and stiffness of low quality beech (*Fagus sylvatica*) sawn timber. World Conference on Timber Engineering (WCTE 2018), Aug. 20-23, 2018 Seoul, Rep. of Korea.