Characterisation of Irish-grown Scots pine timber for structural applications

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ABSTRACT: There is very little knowledge on the timber quality of the native Scots pine grown in Ireland, and its potential to produce timber for structural applications. This paper studied the mechanical performance in tension and bending of 100 specimens with 100mm x 44mm cross-section. Pairs of specimens were established based on the dynamic modulus of elasticity and density, with one specimen destructively tested in tension, and the other in bending. Grade determining wood properties of modulus of elasticity, strength and density were determined in accordance with EN408, with adjustment to reference moisture content and depth according to EN384. The two sets were graded to the tension and bending strength classes defined in EN338. Results showed that Irish-grown Scots pine can produce timber yields above 96% of C20 class. In tension, yields above 90% can be obtained for T11 and T12 classes. These values are slightly higher than those for Sitka spruce in Ireland and therefore show the potential of Irish grown Scots pine for timber production. The study showed that the model given in the European standards to estimate tension strength values from bending strength values underpredicts the values obtained for the Irish Scots pine here studied. A new model describing the relationship between the tension and bending strength properties was developed using the Irish dataset.

KEY WORDS: Scots pine; Structural properties; Timber quality; Grading, Dynamic modulus of elasticity .

1 INTRODUCTION

Sitka spruce (*Picea sitchensis* (Bong.) Carrière) is the main tree species grown in Irish forest and currently covers 334,560 hectares or 52.4% of the forest area in Ireland [1],[2]. In Great Britain (GB), it accounts for 51% of the conifer area [3]. For many years it has been the only species machine graded for structural use in Ireland. Since 2018, based on work carried out as part of the WoodProps programme at the National University of Ireland Galway, Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) can also be machine graded in Ireland and GB using common settings [4], [5]. This is possible due to the similarities in the growing conditions of the two countries, which results in similar timber characteristics.

Having a limited number of commercial species is a risk for the timber industry in the event of outbreak of pests and diseases that could deplete the forest crops, with the consequent economic and environmental impacts. In addition, climate conditions may not be suitable in the future for the species currently commercialised. One way of increasing the resilience of Irish forests is by diversifying the species.

Both Sitka spruce and Douglas fir are originally from North America. In Ireland, there are three native coniferous species: Scots pine (*Pinus sylvestris* L.), yew (*Taxus baccata* L.) and juniper (*Juniperus communis* L.). Scots pine is the only of the three which grows to dimensions that make it a suitable species for the timber market. In Ireland, it currently only covers 8,010 hectares or 1.3% of forest area. Scots pine grows from the mountains of Sierra Nevada in southern Spain to the Scandinavian countries and to the far east of Russia. It is one of the most important commercial species in Europe. The wood is easily worked, it has a good weight to strength ratio, and it is widely graded for use in construction [6]. There is potential to significantly increase the area of Scots pine grown in Ireland and to provide an alternative source of timber for construction purposes if the properties of Irish-grown Scots pine, required for strength classification, are established.

Structural timber with rectangular cross section is graded in Europe based on the standard EN14081 [7] and supporting standards. The ultimate aim of grading is to guarantee the quality of timber, and its safe use for construction. Timber is graded in groups, referred to as strength classes, determined by characteristic values that define minimum requirements of mechanical and physical properties. The characteristic values of the grade determining properties are the mean value of modulus of elasticity (MOE) and the 5th percentile values of strength and density. These values can be used by a structural engineer for the design of a building or structure. A timber population can be graded to satisfy different requirements. To achieve higher grades some of the lower quality timber may need to be rejected. In this paper, the basic grade is defined as the strength class achieved by 100% of the population.

In Ireland, Scots pine can be visually graded as general structural (GS) or special structural (SS) using the standard IS127 [8], but it cannot be assigned to the most common strength classes given in EN338 [9] as machine graded. As a result of the small timber volume available, and limited grading possibilities, it is not currently an attractive species for commercialisation in Ireland.

There has been very little research carried out on the timber quality of Scots Pine grown in Ireland, which inhibits the use this local resource as sawn timber for construction or for the manufacturing of engineering wood products. Scots pine is used more widely in GB, particularly Scotland, where a C20 strength was reported as the basic grade [10].

In this paper, the timber quality of Irish-grown Scots pine for structural applications as a viable option for the timber market is investigated. An analysis of the potential strength classes for the material is carried out. This is normally studied using bending tests (C-classes), but the paper will also address the wood properties using tension tests (T-classes), which were added in the most recent version of the standard EN338 [9]. Using paired sets of bending and tension test results, a model is developed to predict tension properties from bending test results, which is compared with those presented in EN384 [11], [12]. This knowledge is particularly important in timber engineering, for glulam and other timber elements where tension is the dominating load, rather than bending.

2 MATERIAL AND METHODS

2.1 Materials

The material sampled in this study was sourced from a forest plantation in county Laois. The plantation was a mix of Douglas fir and beech (*Fagus sylvatica* L.) with Scots Pine being a minor component. The selection of trees for felling was based on silvicultural criteria and commercial practices and not on timber quality criteria. Logs of 3.6m length were cut from each tree and processed in a sawmill using standard cutting patterns into boards having a 100 mm x 44mm cross-section. A total of 239 boards were obtained, and later kiln dried. Prior to testing, the material was conditioned at 20 °C and 65 % relative humidity so that it would reach a moisture content near 12%.

The 239 boards were assessed non-destructively using a Timber Grader MTG 960 grading machine. This device induces a longitudinal vibration using an internal hammer and records the natural frequency of the acoustic wave generated [13]. The lengths of the boards were measured to the nearest mm allowing calculation of the acoustic velocity. The mass and average cross-sectional dimensions from measurements at three evenly spaced points along the board were recorded to obtain the density. These variables allowed the calculation of the dynamic modulus of elasticity (MOE_{dyn}) using Equation (1).

$$MOE_{dyn} = \rho V^2 = 4\rho f^2 l^2 \tag{1}$$

where ρ is board density, V the acoustic velocity, f the longitudinal natural frequency and l the board length. For the purposes of this paper, it is assumed that the moisture content of the boards was identical after the conditioning.

A representative subsample of 100 boards was selected for further testing. The 239 boards were divided in quartiles based on MOE_{dyn} with density as a secondary variable. From each quartile, pairs of boards were selected with one board from each pair for the tension tests and the other for the bending tests.

2.2 Methods

The two sets of boards, tension and bending, were destructively tested in accordance with EN 408 [14]. The properties determined with these tests include static MOE and strength both in tension and bending. The weakest or critical section was located at the mid-point of the tested length for the tension tests and at mid-span for the bending tests. The critical section for each board was determined initially from analysis of the X-ray images captured by a Goldeneye 702 (MiCROTEC s.r.l. – GmbH) in the sawmill and this was confirmed by visual inspection in the testing laboratory.

Tension tests were carried out in the parallel to the grain direction. Due to the limitations on the length that the test machine can accommodate, the specimens were cut to a 1300mm length centred on the critical position. One transducer on each face of the specimen was used to measure the displacement over a gauge length of 500mm, and the average reading was used to calculate the MOE. The load was applied at a constant loading rate until failure. The equipment used for the tension test was a Zwick/Roell 250kN Servo Hydraulic testing machine. Nine specimens broke or slipped in the clamps. This could have underestimated the strength of the material in the section tested, but it was considered it would be on the safe side for the analysis and due to the relatively small sample size it was decided to include all the specimens in the dataset.

The bending tests were conducted in four-point bending over a simply supported span of 1800 mm. Three properties were determined: local MOE (MOE_L), global MOE (MOE_G) and bending strength. MOE_L is measured along the neutral axis of the specimen, and the deflection measured between the two loading points over a length of five times the depth of the section. In this section the bending moment is constant, and it is considered to be shear free, therefore pure bending. One transducer on each face of the specimen was used to measure the displacement, and the average was used to calculate the MOE_L. MOE_G is determined using the deflection over the entire span and includes the deflection due to the shear forces between the supports and loading points. In this study it was measured in the tension face using a laser. MOE_G is easier to measure and is therefore more frequently measured than MOE_L, but it requires additional adjustments to be used for grading. This paper will use MOE_L for the grading, and MOE_G values will be reported for information. The arrangement for the bending tests is shown in Figure 1.

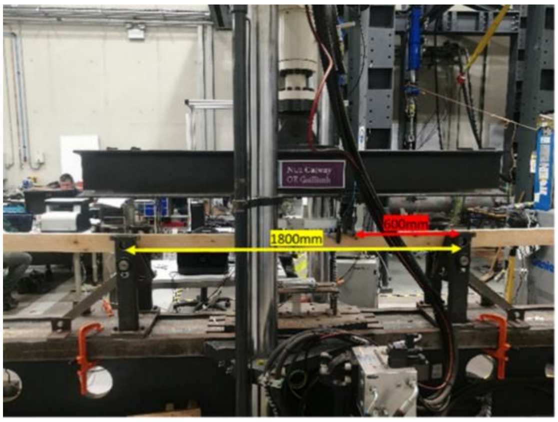

Figure1. Test arrangement of the four-point bending test.

After the destructive testing was completed, a density sample free of knots, resin pockets and other defects, and covering the whole cross-section was cut as close as possible to the fracture location. From the mass and dimensions, the clear density was calculated. This sample was afterwards dried in an oven to determine the moisture content according to EN 13183-1 [15]. The measured MOE_G, MOE_L and density, were then adjusted to 12% moisture content in accordance with EN 384 [11].

Similarly, the bending and tension strength values were adjusted to a reference depth of 150 mm depth in accordance with EN384 [11].

2.3 *Analysis*

After adjusting the properties to the reference conditions, the characteristic values of MOE, strength and density were calculated. This allowed the timber to be graded into strength classes in accordance with EN338 [9]. The bending strength requirements accounted for the factor k_v = 1.12, that reduces the strength requirement of C-classes up to C30 for in-line grading machines [11]. The basic grade, which is that achieved by 100% of the population, was determined. The yields for higher strength classes were also investigated. For assigning a population to a grade, the three properties need to satisfy the requirements set out in EN338 [9].

The relationship between the tension and bending strength properties was also examined. The MOE_{dyn} was used as a reference property. Following this, the suitability of the equations set out in EN384 [11] to convert bending to tension strength characteristic values is investigated.

The standard EN14358 [16], gives statistical methods for the determination of characteristic values. As the populations graded had more than 40 specimens, the 5th percentile values were calculated using the ranking or non-parametric method.

3 RESULTS AND DISCUSSION

3.1 *Acoustic measurements*

This paper only discusses the properties of the 100 specimens destructively tested. For the paired specimens, the average percentage differences in MOE_{dyn} and density were 0.17% and 4.4%, respectively. The distribution of the MOE_{dyn} values of the 100 specimens destructively tested are shown in Figure 2. The values ranged from 5.77 kN/mm^2 to 15.0 kN/mm^2, with an average of 10.4 kN/mm^2 (SD = 2.16 kN/ mm^2). As shown in Table 1, the average value is slightly below that reported in the study by Hassan et al. [17], which used the same acoustic method to determine the MOE_{dyn} of Scots Pine in the Czech Republic. It is typical for trees grown in Central Europe to have higher stiffness relative to timber from Western European regions.

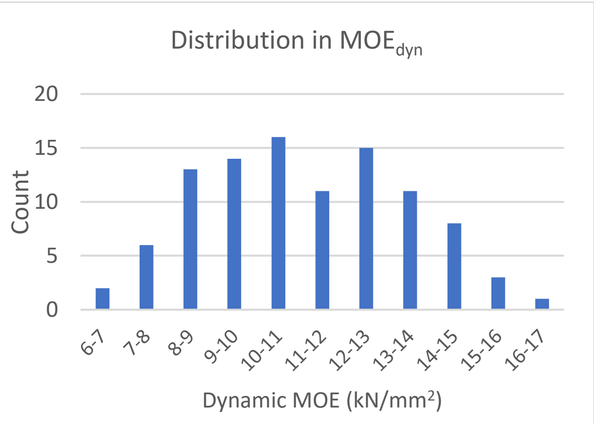

Figure 2. Distribution of the dynamic MOE

In the study by Hassan et al. [17], only 40 specimens were tested.

Table 1. MOE_{dyn} values comparison

	Irish Scots Pine		Hassan et al. [17]
	Tension	Bending	
MOE (N/mm^2)	10,415	10,432	11,026
CV (%)	21	20.7	13.4
Min. (N/mm^2)	5,767	5,783	8,304
Max. (N/mm^2)	14,962	14,976	14,654

3.2 *Timber characterization - Tension*

The average tension MOE was 9.56 kN/mm^2 (SD = 2.47 kN/mm^2). The minimum and maximum tension MOE values were 4.44 kN/mm^2 and 15.0 kN/mm^2, respectively. The average tension strength was 24.0 N/mm^2 (SD = 9.18 N/mm^2). The minimum and maximum tension strength were 8.50 N/mm^2 and 44.5 N/mm^2, respectively. The average density of tension boards was 523 kg/m^3 (SD = 42 kg/m^3) and 46% of the specimens fell within the bracket 500-525 kg/m^3. The density ranged from 435 to 592 kg/m^3.

3.3 *Timber characterization - Bending*

The mean MOE_L value in bending for the population was 9.24 kN/mm^2 (SD = 2.36 kN/mm^2). The minimum MOE_L value was 2.78 kN/mm^2 and the maximum 14.5 kN/mm^2. The mean MOE_G was 9.07 kN/mm^2 (SD = 1.84 kN/mm^2) and ranged from 4.72 kN/mm^2 to 12.4 kN/mm^2. A study of Pine grown in Poland and Sweden [18] reported mean MOE_G values ranging from 9.10 kN/mm^2 to 12.4 kN/mm^2 for different parts of the countries. These higher MOE values are expected as Central European and Nordic trees are typically stiffer. A report on the wood properties of British grown Scots pine reported a mean value for MOE in bending of 9.31 kN/mm^2 [19]. This in line with the results found in the present study. The mean strength value of the population was 38.0 N/mm^2. Moore et al. [10] reported a bending strength for British-grown Scots Pine of 44.5 N/mm^2. These results show that there are some similarities between the two studies although British grown Scots Pine was higher in strength than Irish.

The mean density value was 521 kg/m^3 (SD = 47 kg/m^3), with values between 423 kg/m^3 and 656 kg/m^3. The density values do not depend on the type of testing, and both datasets showed similar values. A study in North Scotland gave a mean density of 504 kg/m^3 [10], whereas Lavers [20] reported for Scots pine grown in the United Kingdom 510 kg/m^3. These values are very similar to those observed in the present study and confirms the similar characteristics in wood quality between Ireland and GB for timber production.

3.4 *Timber grading.*

The characteristic values for the tension and bending datasets are presented in Table 2.

Table 2. Characteristic values in bending and tension.

	Bending	Tension
MOE (kN/mm^2)	9.24	9.56
Strength (N/mm^2)	15.3	9.35
Density (kg/m^3)	443	438
Basic grade	C16	T9

The basic strength grade for tension was T9. The tension strength was the critical parameter as it performed comparatively worse than the other two grade determining properties. A 98% yield would achieve T10 grade (i.e. by rejecting the worst two percent of boards, the remaining population would achieve T10 values). Grades T11 and T12 were achieved by 94% and 90% of the population, respectively.

For bending sample, the strength class achieved for 100% of the population was C16. Strength was again the critical parameter. When the worst performing board was excluded from the population, 98% of the boards achieved a C18 strength class. If the two worst performing boards were removed from the population, the strength class increases to C20 for 96% of the population. The lower grades were limited by the comparatively lower performance of strength compared to MOE and density. Furthermore, stiffness became the limiting factor for higher grades. Density was the least limiting property, both in tension and bending.

Scots Pine grown in GB was shown to achieve a basic strength class of C20 [10]. The study had a sample size of 321 compared to 50 in this study. The results in Table 3 show comparable properties to those in GB, differing more in strength. The dataset in the current study is much smaller, which has a large effect on the calculated percentiles and therefore in the characteristic strength value. The difference in strength is possibly due to a different forest management, but the information to confirm this assumption is not available. When comparing Scots Pine with Sitka spruce, there is a difference in timber quality, with Scots pine achieving a higher strength class. Table 3 compares the results in bending from the present study with three other studies to show the differences in strength grades between the two species by countries.

Table 3. Comparison between species.

	Scots Pine		Sitka spruce	
Mean values	Ireland [Present study]	GB [10]	Ireland [21]	GB [22]
MOE (N/mm^2)	9242	9310	8980	8300
Strength (N/mm^2)	38	44.5	36	32.7
Density (kg/m^3)	521	504	335	387
Strength class	C20	C20	C16	C16
Pass rate	96%	100%	97%	95%

The relationship between the mechanical properties and the MOE_{dyn} determined from acoustic measurements was investigated and the coefficients of determination for each case are given in Table 4. As expected, the relationship of MOE_{dyn} and MOE is strong, both in tension and bending. The relationship with strength is moderate. The relationship between MOE_{dyn} and density is weaker than for the other properties.

Table 4. Coefficient of determination between MOE_{dyn} and the properties in bending and tension.

	MOE_{dyn} (R^2)	
	Tension	Bending
MOE_L	0.80	0.63
Strength	0.50	0.43
Density	0.46	0.28

3.5 *Relationship between tension and bending properties*

The relationship between the tension and bending strength was examined by comparing values obtained for the specimens paired based on their MOE_{dyn}. Figure 3 shows this relationship, and Equations (2) and (3) give the relationships:

$$f_t = -6.91 + 0.0028 \cdot MOE_{dyn} \tag{2}$$

$$f_m = -8.00 + 0.0042 \cdot MOE_{dyn} \tag{3}$$

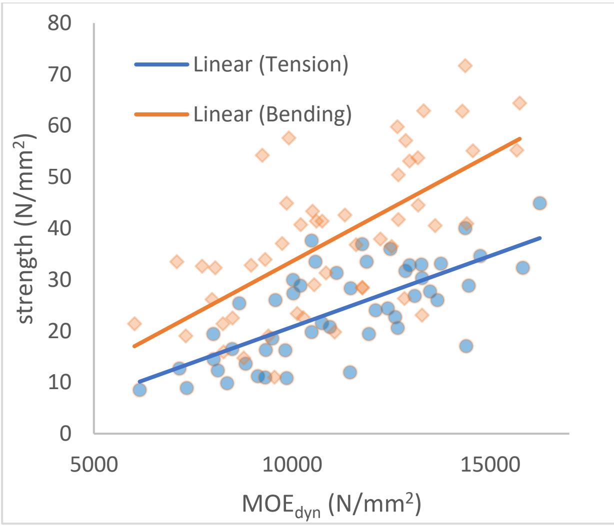

Figure 3. Relationships between MOE_{dyn} and strength in tension and bending.

Bending strength is higher than tension strength. The differences are larger as the MOE_{dyn} increases. This could be the result of a relatively small number of pieces in the upper range of values, but it could also be due a change in the relationship as the timber quality increases.

The conversions in the standards between the tension and bending classes is based on the characteristic values of the strength properties. For the current dataset, the conversion equation given in EN384 [11] conservatively estimates the characteristic tension strength from characteristic bending strength (Equation (4).

$$f_{t,k} = -3.07 + 0.73 \cdot f_{m,k} \tag{4}$$

Comparing the experimentally determined characteristic bending strength of 15.3 N/mm^2 with the characteristic tension strength of 9.35 N/mm^2, using Equation (4) the predicted characteristic tension strength is 8.10 N/mm^2. Equation (4) replaced an earlier model given in the 2004 version of EN384 [12] and this is given in Equation (5).

$$f_{t,k} = 0.6 \cdot f_{m,k} \tag{5}$$

Using Equation (5), the predicted tension strength is 9.18 N/mm^2, slightly below the experimental value of 9.35 N/mm^2. Due to the strong relationships between MOE_{dyn} and the mechanical properties shown in Table 4, artificial grade classes were created using MOE_{dyn} to facilitate the development of a new conversion equation based on the data from this study. Subsamples were created using different MOE_{dyn} thresholds, and the characteristic strength values were calculated for the tension and bending pieces below and above those thresholds. This gave a set of characteristic tension and bending strength values from which a regression equation was derived. Thresholds were established based on quartiles. The MOE_{dyn} thresholds used were: <9350; >9350; 9350-10950; >10950; <10950; 10950-12900; >12900; <12900 (N/mm^2). The new relationship is given in Equation (6) and is plotted in Figure 4 together with the model in the current and previous versions of EN384.

$$f_{t,k} = -1.05\dot{4} + 0.66 \cdot f_{m,k} \tag{6}$$

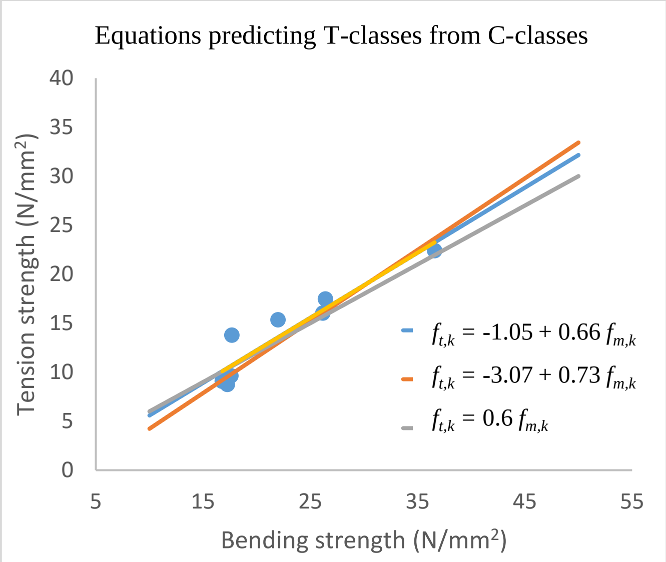

Figure 4. Bending to tension strength prediction model

When the characteristic bending strength value from this study is entered into Equation (6), a characteristic tension strength of 9.04 N/mm^2 is predicted, which is only marginally different from that predicted by the older EN384 model. Figure 4 shows that for timber grades below C24, the old EN384 model is less conservative that the new EN384, whereas for grades above C24 the opposite is the case. As the new model presented in Equation (6) includes a negative intercept, it is more conservative than Equation (5). However, for the dataset studied the new model represents the relationship between bending and tension better than Equation (4). Also, for the higher range of strength classes, Equation (6) give marginally lower conversions but is not as overly conservative compared to Equation (5).

There are a few limitations to be aware of regarding the relationship obtained. The total number of pieces is relatively small, 50 pieces per dataset, covering a relatively broad range of values. As a result, the calculation of the characteristic strength values is significantly influenced by each test result. This also limited the number of points with which to establish the relationship. Finally, the study showed that the grading was limited by the strength property. The MOE_{dyn} was used to derive the relationship, and it may not have captured the mechanical performance fully. The use of other parameters, like knot area ratios would be a good complement to include more data points in the relationship.

4 CONCLUSIONS

This paper has shown that Irish-grown Scots pine properties are slightly lower than those obtained for the species in Scandinavia or Central Europe, but it can produce timber of comparable quality to Sitka spruce in Ireland, and based on similar rejection rates it can produce higher yields of C20. The study showed that the model given in the European standards to estimate tension strength values from bending strength values underpredicts the values obtained for the Irish Scots pine here studied. A new conversion model was developed using the Irish dataset. While this model needs to be carefully considered due to the relatively small sample size, it is closer to the older EN384 conversion model than the current one. Further research is needed to improve the model including increasing the number of specimens and species, accounting for prediction intervals and including different predictor variables.

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