Structures and Buildings
Volume 167 Issue SB6

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Raftery and Harte

ice | proceedings

Proceedings of the Institution of Civil Engineers
Structures and Buildings 167 June 2014 Issue SB6
Pages 380–386 http://dx.doi.org/10.1680/stbu.12.00052
Paper 1200052
Received 23/07/2012 Accepted 04/06/2013
Published online 12/09/2013
Keywords: statistical analysis/strength & testing of materials/timber structures

Material characterisation of fast-grown plantation spruce

1 **Gary M. Raftery** PhD, MIEI
Lecturer, Department of Civil and Environmental Engineering, Faculty of Engineering, The University of Auckland, New Zealand

2 **Annette M. Harte** MEngSc, PhD, CEng, FIEI, MIWSc
Senior Lecturer, Civil Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland


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This paper describes a programme of mechanical tests undertaken to assess the relationship between mechanical properties and physical characteristics in the longitudinal direction of fast-grown plantation spruce grown in Ireland. Little published work exists in the literature in relation to characterisation of such fast-grown material. The parameters studied include density, knot area ratio, modulus of elasticity and ultimate strength. Modulus of elasticity is the most highly correlated parameter to the tensile strength for both clear and in-grade specimens. The knot area ratio has a considerable influence on the strength of the timber both in compression and tension. Density is more highly correlated to ultimate compressive strength than ultimate tensile strength in clear wood specimens. The modulus of elasticity in tension has a poor correlation to the density of clear wood and is also poorly correlated to the knot area ratio and the density of in-grade specimens. The information produced is essential in the future development, design and optimisation of engineered wood products using such fast-grown plantation wood.

1. Introduction

In recent years, increased emphasis has been placed on the promotion and development of products manufactured from sustainable materials for use in the construction industry (Harrison, 2006; Harte, 2009; Khatib, 2009). One structural material that is a natural renewable resource with a secure supply, recyclable, has low carbon dioxide emissions and requires low energy in its production in comparison to steel and concrete is timber (Buchanan and Levine, 1999; Sathre and Gustavsson, 2009). Timber is also cost competitive, strong and aesthetically pleasing. As one of the oldest building materials, timber has many applications in the construction industry (Thelandersson and Larsen, 2003). Sitka spruce (*Picea sitchensis*) is the most widely planted tree species in Ireland, where the species accounted for 60% of the forest estate at the start of the century (Treacy *et al.*, 2000). Due to the moist climatic conditions prevalent in Ireland and the UK, this wood is fast grown and is characterised by its low density, large ring widths and high juvenile wood content. Picardo (2000) employed mechanical stress grading on 5000 pieces of Sitka spruce grown in Ireland and observed that 95% of boards sampled, yielded C14 and C16 grade timber. The wood harvested from this species has demonstrated a high susceptibility to distortion when dried to low moisture contents (Bourke *et al.*, 2001). Joyce and O'Carroll (2002) identified that for the foreseeable future, the most lucrative market for the species was to be good-quality structural timber, while applications in the fencing market and production of transmission poles should be secondary to this. Robinson (2007) stated that if Irish timber was to be used as a substitute for imported timber then re-engineering of the material such as defect cutting, finger-jointing and timber lamination to improve the material properties was advisable. Despite the fast-grown nature of this timber with a 35/40-year rotation clear fell stage (Moloney and Bourke, 2004), good-quality bonds were achieved in experimental bond test programmes when using conventional wood laminating adhesives and epoxy adhesives (Raftery *et al.*, 2008, 2009a, 2009b). However, little published work exists in relation to the mechanical testing of this timber. Winandy (2002) previously stated that a better understanding of how to use lower-quality and fast-grown timber was necessary. Winandy further highlighted that an increased volume of smaller diameter wood with higher proportions of juvenile wood would enter the timber market in the USA. An increased focus would, as a result, be directed towards engineered wood products and engineering systems from such timber. In order to develop engineered wood products using such fast-grown material, an assessment of the interaction between the physical properties and material properties in the longitudinal direction is essential.

1.1 Material characterisation studies involving timber

The definition of accurate and reliable material properties is fundamental to all engineering design and analyses. The findings of several material characterisation studies which have examined the relationships between a number of physical and mechanical properties in different timber species is reported in the literature. Steffen *et al.* (1997) reported that density and modulus of elasticity varied considerably over the cross-section of Norway spruce boards. Larsson *et al.* (1998) found a coefficient of determination of 0·26 between bending strength and density. Johansson *et al.* (1998) reported strong coefficients of determination from 0·51 to 0·73 between density and modulus of elasticity in a comprehensive study on Norway spruce. It is stated by Dinwoodie (2000) that several studies have found high correlations between density and various strength properties in timber. A study was undertaken on spruce and pine, which was sourced in Finland, where coefficients of determination of 0·37 and 0·58 were found to exist between the density of the timbers at 12% moisture content and the bending strength of the timbers (Hanhijärvi *et al.*, 2005). Coefficients of determination of 0·65 and 0·72 for the spruce and 0·50 and 0·58 for the pine were established between the density and local and global moduli of elasticity, respectively.

Several studies report on the significant reduction in mechanical properties of timber when knots are present. Orosz (1969) demonstrated the influence that knots have on the tension properties of 50 mm × 100 mm Southern Pine sections when a coefficient of determination of 0·76 was obtained when modulus of elasticity measured flat-wise was plotted against knot measurements. The coefficient of determination measures the proportion in the dependent variable that is shared with or explained by the independent variable in the regression model. Schniewind and Lyon (1971) reported that the prediction of tensile strength parallel to grain could be considerably improved if information on knots was included with the modulus of elasticity. Kunesh and Johnson (1972) reported that edge knots in timber were associated with lower tensile strengths than those containing centre knots. Knots located near the fingers in finger-jointed connections in timber had a significant negative influence on the tensile strength of the joint (Pellicane *et al.*, 1987). The knot area ratio (KAR) and margin knot area ratio (MKAR) are common measures to quantify the presence of knots and knot clusters in timber. KAR is the ratio of the sum of projected cross-sectional areas of the knots to the cross-sectional area of the piece of timber at a specific location; IS 127 refers (NSAI, 2002). MKAR is the ratio of the sum of the projected cross-sectional areas of all knots or portions of knots in a margin intersected at any cross-section, to the cross-sectional area of the margin. A margin is the area adjacent to the edge of the timber section that occupies one quarter of the total cross-sectional area. Coefficients of determination of 0·32 and 0·32 were determined between KAR and the tensile strength and edgewise bending strength of Norway spruce, respectively, in comparison to 0·20 and 0·34, respectively, for the MKAR, as reported by Johansson *et al.* (1998) and Hoffmeyer *et al.* (1999). Higher correlations were obtained between edgewise bending strength and measurements of KAR and MKAR in another study where coefficients of determination of 0·58 and 0·45, respectively, were found (Johansson and Kliger, 2000). The presence of knots was shown to influence the local longitudinal stiffness of Radiata Pine structural timber in a study undertaken by Xu (2002).

1.2 Objectives of the present study

The objective of this research is to improve the understanding of relationships that may exist between physical characteristics and mechanical properties in fast-grown plantation spruce for both in-grade and clear wood specimens. Studies were undertaken to examine the compressive and tensile behaviour parallel to the grain (Raftery, 2010). Such information will assist in the development and optimisation of engineered wood products manufactured using such timber.

2. Material and methods

All the timber used in the experimental characterisation studies was Irish-grown Sitka spruce, which was sourced from the same stand in the west of Ireland. Consequently, variability in the wood resulting from contrasting environmental conditions during growth was significantly reduced. In the sawmills, the timber was kiln dried to approximately 18% moisture content and machine stress graded to C16 EN 338 (CEN, 2003a), the mostly commonly produced grade in Ireland, before being delivered to the laboratory. The timber stock used in the test programme had an average annular ring thickness of 7·2 mm with a standard deviation of 2·1 mm. All the timber stock and all specimens were initially conditioned in an environment of 65 ± 5% relative humidity and a temperature of 20 ± 2°C prior to testing. Such an environment gave an approximate equilibrium moisture content of 12%. The moisture content of all specimens was determined using the oven-drying method.

2.1 Compression testing of clear specimens

One hundred and twenty five clear compression specimens of Irish-grown Sitka spruce were tested parallel to grain using a 500 kN Denison testing machine according to BS 373 (BSI, 1957). Specimens had an approximate length of 60 mm with a cross-section size of 20 mm × 20 mm. This programme involved testing a minimum of five specimens from 22 boards randomly selected from the delivery, so that a range of specimens with varying density would be tested. The loading faces of the test pieces were sanded smooth and square so that the test piece was parallel to the axis and no eccentricity existed. A loading rate of 0·635 mm/min was used. The specimen dimensions were measured to a precision of 0·01 mm prior to testing using a vernier caliper. The mass of each piece was measured using an electronic balance correct to 0·01 g after the test was complete. The load at failure and the corresponding density of each piece was determined.

2.2 Compression testing of in-grade specimens

One hundred and sixty two in-grade specimens of Irish-grown Sitka spruce were tested parallel to grain using the Denison testing machine in accordance with EN 408 (CEN, 2003b). Test specimens were selected from the delivery of boards such that the most critical strength-reducing KAR was located in the centre of the test specimen. The most critical KAR was selected, as this location would be a weak point in the board. Each test specimen had a thickness of 38 mm and width of 96 mm. The corresponding lengths of the test specimens were 226 mm in accordance with EN 408. Before the test, the dimensions of each specimen were measured using a vernier caliper. The loading faces of the test pieces were sanded smooth and square. Each test piece was positioned parallel to the axis of the loading machine and a preload of 1·5 kN was applied. Load was applied at a constant loading-head movement rate so that the maximum load was obtained within 300 ± 120 s. In general, a displacement rate of 0·8 mm/min was applied to each specimen. The ultimate compressive strength of each specimen was determined by dividing the maximum load by the cross-sectional area. The corresponding density of each piece was determined by cutting a specimen 40 mm long from the section, which was free of knots or other features such as resin pockets that were non-representative of the timber.

2.3 Tension testing of clear specimens

Tension testing of clear Irish-grown Sitka spruce specimens was executed with reference to ASTM D143 (ASTM, 2000). Each specimen had an approximate section size of 9·5 mm × 4·8 mm. The specimen was clamped in the Denison testing machine after it had been ensured that it was perfectly aligned to the vertical. Load was continuously applied during the test at a rate of displacement of 1 mm/min. Over 140 specimens were tested. Each specimen was cut from a different board. The deformation of each specimen was measured using an extensometer over a gauge length of 50 mm in order to determine the modulus of elasticity. The strength of each specimen was determined from the load at failure divided by the cross-sectional dimensions of the fracture area. Pieces of an approximate length of 40 mm and the cross-section of the specimen were cut from locations adjacent to the fracture location so that an estimate of the density could be obtained. The length and cross-sections of these pieces were also measured with an electronic vernier caliper to a precision of 0·01 mm.

2.4 Tension testing of in-grade specimens

The in-grade Irish-grown Sitka spruce tension test programme involved testing parallel-to-grain specimens initially to determine the modulus of elasticity and subsequently to determine the failure strength in accordance with the procedures specified in EN 408 (CEN, 2003b). Eighty-three specimens were tested with each specimen cut from a different board. An approximate section size of 25 mm thick and 96 mm wide was used. The test pieces were carefully selected from 4200 mm long boards so that the most critical knot area ratio was included. The knot area ratio was measured with reference to IS 127 – the specification for stress grading of softwood timber (NSAI, 2002). The specimens tested were a minimum of 1600 mm long, which ensured a free length of 1000 mm from the end grips. EN 408 states that the tension test specimens should have a clear length of the test machine grips of at least nine times the larger cross-sectional dimension. The ends of the specimens were initially clamped in the testing machine with a pressure of 5000 kPa and vertical alignment was checked using a spirit level. An extensometer was positioned centrally on each narrow face of the test piece so that the effects of distortion, arising from the inhomogeneity of the specimen, were minimised when determining the modulus of elasticity. Deformation was measured over a central gauge length of 480 mm (five times the width of the piece) and this gauge length was at least 200 mm clear of the grips. Testing was executed using a constant loading rate of 0·024 mm/s, but at no stage was the specimen damaged or the proportional limit exceeded. After unloading of the test specimen in question and upon removal of the two extensometers, a constant rate of crosshead movement was applied so that failure in the specimens occurred in 300 ± 120 s. The ultimate strength was determined by dividing the failure load by the cross-sectional dimensions, which were measured using a vernier caliper that had a precision of 0·01 mm. Density specimens of approximate length 30 mm and cross-sectional area of the specimen were taken from beside the location of the fracture.

2.5 Density variability study of in-grade timber

An examination of the variability in the density of samples taken along a number of randomly sampled boards was also undertaken in order to maintain a practical approach to determine the density of the wood. The boards were of a cross-section 96 mm × 44 mm and were 4200 mm long. Specimens 50mm in thickness and of the cross-sectional area of the board were cut at regular intervals such that only clear wood that was free of knots and defects was selected. The wood samples were weighed using a mass balance with precision to 0·01 g. The dimensions of the specimens were measured using a vernier caliper with precision to 0·01 mm. The density of each piece was determined from the recorded measurements.

3. Experimental results

The test results from the material characterisation studies are presented in the following sections. Tabulated data of the results are available in Raftery (2010).

3.1 Compression testing results of clear wood specimens

The results from the testing of the clear compression samples of wood are shown in Figure 1, where the compressive strength is plotted against the density of the specimens in question. The linear regression line together with the value for the coefficient of determination, R^2, is also shown. The coefficient of determination is used to measure how well the regression line fits the data, and its value lies between 0 and 1, with high values indicating a good fit. In this case, a strong correlation is obtained in the relationship between the compressive strength and the density, with a coefficient of determination of 0·6968. The compressive strength values varied between 25 N/mm^2 and 49 N/mm^2 over the density range

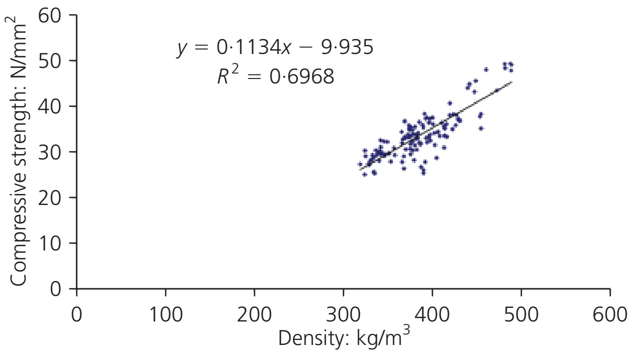

Figure 1. Clear wood compressive strength plotted against density

$319–487\ kg/m^3$. Compression wrinkling was visible in all failed specimens. The specimens had an average moisture content of 11·71% with standard deviation of 0·46%.

3.2 Compression testing results of in-grade timber specimens

The results from the compression testing of the in-grade samples of timber are shown in Figure 2, where the compressive strength at failure is plotted against the KAR and in Figure 3, where the compressive strength at failure is plotted against density measurements from the samples. A coefficient of determination of 0·4151 was determined between KAR and compressive strength, while a value of 0·1614 was determined between the ultimate compressive strength and the density. As expected, the compressive strength values associated with the in-grade testing are significantly lower than the values associated with the clear wood testing and vary between $13\ N/mm^2$ and $34\ N/mm^2$ over the density range $332–554\ kg/m^3$. Typical patterns of failure for specimens comprised compression wrinkling accompanied by longitudinal splitting emanating from a knot. The specimens had an average moisture content of 12·02% with standard deviation of 1·11%.

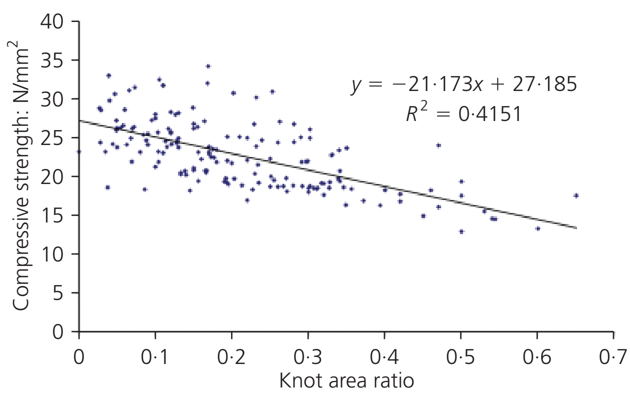

Figure 2. In-grade compressive strength plotted against knot area ratio

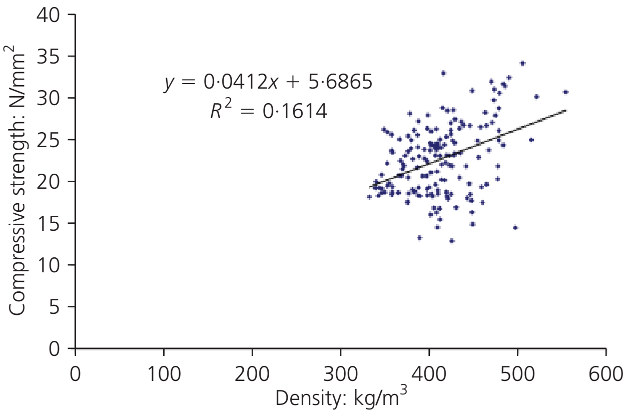

Figure 3. In-grade compressive strength plotted against density

3.3 Tension testing results of clear wood specimens

The tensile strength of the clear wood specimens varied between $23\ N/mm^2$ and $104\ N/mm^2$ over the density range $312–550\ kg/m^3$. The relationship between strength and density obtained from the testing of small clear wood specimens of timber in tension is shown in Figure 4. A value of 0·2576 was determined for the coefficient of determination for this relationship. It should be noted that density measurements were taken as close to the fracture as possible but were not on the fracture. As can be seen from Figure 5, the coefficient of determination between clear tensile strength and modulus of elasticity was 0·3844. Figure 6 shows a plot of clear wood modulus of elasticity against density. Only data from specimens which fractured within the 50 mm gauge length are used in this plot. The specimens had an average moisture content of 11·67% with standard deviation of 0·86%.

3.4 Tension testing results of in-grade timber specimens

The results of the in-grade timber tension testing programme are shown by means of a series of plots in Figures 7–11. The relationship between tensile strength and modulus of elasticity is strong, as seen in Figure 7, where a coefficient of determination of 0·5945 is obtained. The data included in this plot correspond to 32 specimens in the test programme where failure occurred in the range of the transducers only. Figure 8 illustrates a plot of

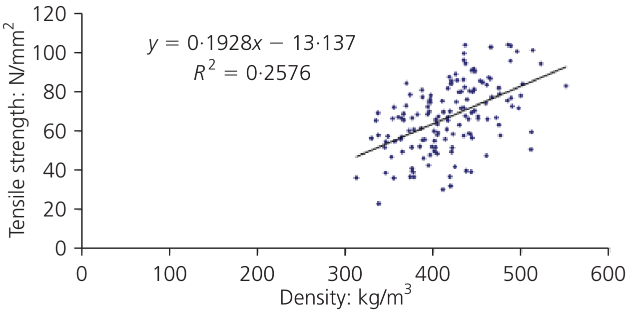

Figure 4. Clear wood tensile strength plotted against density

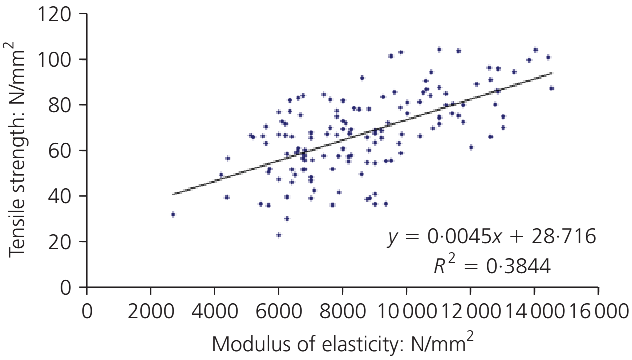

Figure 5. Clear wood tensile strength plotted against modulus of elasticity

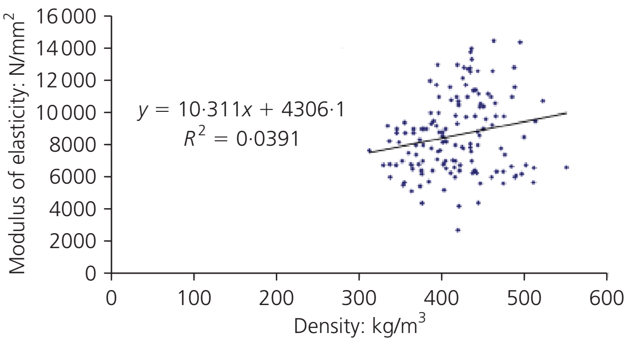

Figure 6. Clear wood modulus of elasticity plotted against density

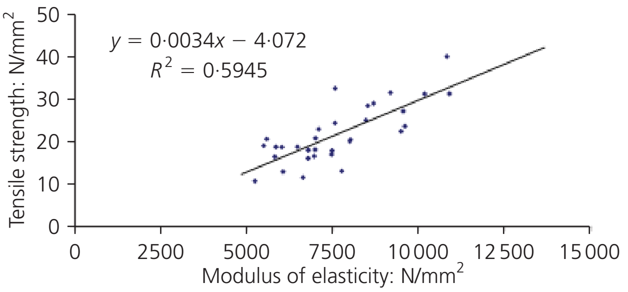

Figure 7. In-grade tensile strength plotted against modulus of elasticity

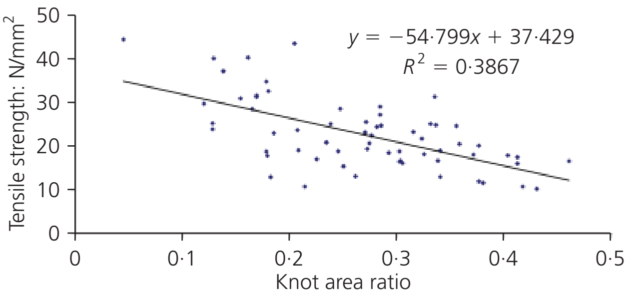

Figure 8. In-grade tensile strength plotted against knot area ratio

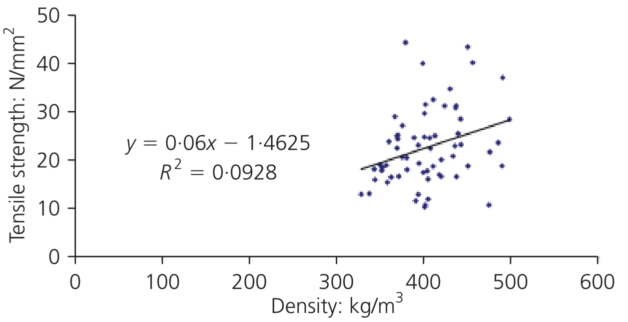

Figure 9. In-grade tensile strength plotted against density

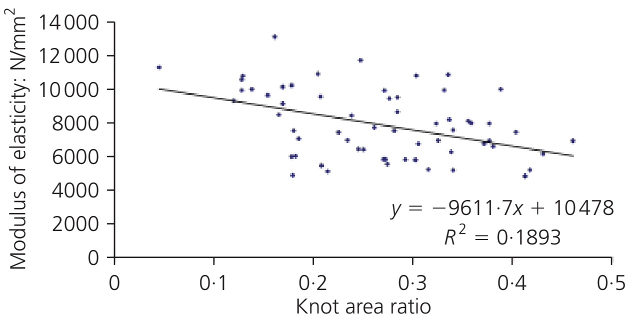

Figure 10. In-grade modulus of elasticity plotted against knot area ratio

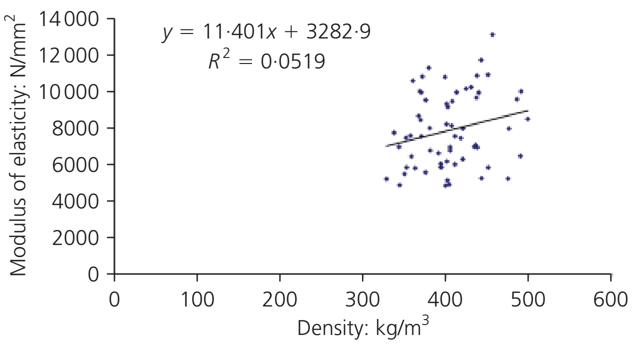

Figure 11. In-grade modulus of elasticity plotted against density

tensile strength against KAR and a coefficient of determination of 0·3867 was achieved for the 63 specimens in the sample size. Only failures which occurred at knots away from the grips are included. A number of failures occurred at the grips and are excluded. Density was found to have a poor correlation with the ultimate tensile strength of the in-grade timber, as shown in Figure 9. In-grade modulus of elasticity has a weak correlation with knot area ratio and density as shown in Figure 10 and Figure 11, respectively. Fractures in the specimens initiated at knot locations. The maximum tensile strength achieved was 45 N/mm^2 compared to 104 N/mm^2 for the clear wood specimens. The specimens had an average moisture content of 12% with standard deviation of 0·3%.

3.5 Density variability study of in-grade timber

The mean and standard deviation of the density variability results as well as the number of samples taken along the 4200 mm board length can be seen in Table 1.

4. Conclusion

A number of conclusions can be drawn from the test results in this study.

- The effect of knots on the strength of fast-grown spruce is significant. Stronger correlations were established in this study between knot area ratio and strength for both compression and tension specimens in comparison to the density of the specimens. These results are in agreement with studies undertaken for other species which are reported in the literature. However, the relationship between strength and knot area ratio is stronger than that reported for uniaxial tests undertaken with other species as stated in Section 1.1.
- Modulus of elasticity is the most highly correlated parameter to the tensile strength of the fast-grown spruce for both clear and in-grade specimens. A stronger correlation was established when testing in-grade specimens in comparison to testing clear specimens.
- Density is a much more accurate predictor of the compressive strength of clear wood specimens of fast-grown spruce than the tensile strength of the clear wood specimens, but still not strong and further investigation is recommended.
- A very weak correlation was found between the tensile modulus of elasticity and the density of clear wood. Weak correlations also exist between the modulus of elasticity of the in-grade specimens and the knot area ratio as well as the density samples cut from the specimens.
- The deviations between the density readings for the boards studied are not deemed to be significant. It is considered appropriate that a good approximation of the density of clear wood in each board can be determined by cutting a specimen from the board under examination.
- The test results will be useful for the further development of engineered wood products manufactured from fast-grown spruce such as reinforced laminated timber (Raftery and Harte, 2011, 2013). The relationships and data can act as useful input for numerical models which can be used to optimise such products.

Board	Number of specimens	Mean density: kg/m^3	Std dev.: kg/m^3	Mean MC: %	Std dev.: %
1	14	387	14	11·91	0·31
2	11	410	19	12·39	0·19
3	8	363	14	12·41	0·22
4	15	350	11	12·33	0·23
5	18	399	12	12·31	0·25
6	15	394	17	12·21	0·18

MC, moisture content.

Table 1. Variability of density in timber boards

Acknowledgements

The primary author would like to thank the Irish Research Council, Science, Engineering and Technology (IRCSET) for the financial support provided. The authors are most grateful to COFORD (National Council for Forest Research and Development) (Ireland), Coillte and the National University of Ireland, Galway for the financial assistance which was provided to support this research.

REFERENCES

ASTM (2000) D13: Standard test methods for small clear specimens of timber. ASTM International, West Conshohocken, PA, USA.

Bourke M, Redington M and Moloney S (2001) Sitka spruce dried to low moisture content for predictable in-service performance as construction elements. *Proceedings of the 3rd Cost Action E15 Workshop, The Drying of Softwood Species, Helsinki, Finland*.

BSI (1957) BS 373: Methods of testing of small clear specimens of timber. BSI, London, UK.

Buchanan AH and Levine SB (1999) Wood-based building materials and atmospheric carbon emissions. *Environmental Science and Policy* **2(6)**: 427–437.

CEN (Comité Européen de Normalisation) (2003a) EN 338: 2003. Structural timber. Strength classes. CEN, Brussels, Belgium.

CEN (2003b) EN 408: 2003. Timber structures – structural timber and glued laminated timber – determination of some physical and mechanical properties. CEN, Brussels, Belgium.

Dinwoodie JM (2000) *Timber: Its Nature and Behaviour*, 2nd edn. Taylor & Francis, London, UK.

Hanhijärvi A, Ranta-Maunus A and Turk G (2005) *Potential of Strength Grading of Timber with Combined Measurement Techniques*. VTT Publications, Helsinki, Finland, vol. 568, pp. 1–81, Report of the Combigrade-project – phase 1, Espoo.

Harrison J (2006) Sustainable materials for the built environment. In *Advanced Civil Infrastructure Materials: Science, Mechanics and Applications* (Wu HC (ed.)). Woodhead Publishing, Cambridge, UK, pp. 271–338.

Harte AM (2009) Timber engineering: an introduction. In *ICE Manual of Construction Materials* (Forde M (ed.)). Thomas Telford, London, UK, vol. 2, pp. 707–715.

Hoffmeyer P, Bräuner L, Boström L and Solli KH (1999) Tensile strength of glulam laminations of Nordic spruce. *Proceedings of PTEC '99, Rotorua, New Zealand*, pp. 223–230, Forest Research Bulletin No. 212.

Johansson CJ, Boström L, Holmqvist C, Hoffmeyer P and Bräuner L (1998) *Laminations for Glued Laminated Timber – Establishment of Strength Classes for Strength Grades and Machine Settings for Glulam Laminations of Nordic Origin*.

Swedish National Testing and Research Institute, Borås, Sweden, SP Report 1998: 38, pp. 1–71.

Johansson M and Kliger R (2000) Variability in strength and stiffness of structural Norway spruce timber – influence of raw material parameters. *Proceedings of the 6th World Conference on Timber Engineering, Whistler Resort, British Columbia*.

Joyce PM and O'Carroll N (2002) *Sitka Spruce in Ireland*. COFORD (National Council for Forest Research and Development), Dublin, Ireland.

Khatib JM (2009) *Sustainability of Construction Materials*. Woodhead Publishing, Cambridge, UK.

Kunesh RH and Johnson JW (1972) Effect of single knots on tensile strength of 2-by 8-inch Douglas-fir dimension lumber. *Forest Products Journal* **22(2)**: 32–36.

Larsson D, Ohlsson S, Perstorper M and Brundin J (1998) Mechanical properties of sawn timber from Norway spruce. *European Journal of Wood and Wood Products* **56(5)**: 331–338.

Moloney S and Bourke M (2004) Adding value to fast grown Irish Sitka spruce through drying and re-engineering. *Proceeding of the COST E15 Conference, Athens, Greece*. Hamburg University, Hamburg, Germany.

NSAI (National Standards Authority of Ireland) (2002) IS 127: 2002. Structural timber –Visual strength grading –Sawn softwoods with rectangular cross section. NSAI, Dublin, Ireland.

Orosz I (1969) Modulus of elasticity and bending strength ratio as indicators of tensile strength of lumber. *Journal of Materials* **4(4)**: 842–864.

Pellicane PJ, Stanfill-McMillan K and Tichy RJ (1987) Effects of knots near the fingers of finger jointed dimension lumber. *Forest Products Journal* **37(5)**: 13–16.

Picardo V (2000) *Quantification of the Yields of Irish Grown Sitka Spruce in the New CEN Strength Classes*. COFORD (National Council for Forest Research and Development), Dublin, Ireland.

Raftery G (2010) *The Use of Advanced Composite Materials in the Flexural Reinforcement of Low-Grade Glulam*. PhD thesis, Civil Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland.

Raftery GM and Harte AM (2011) Low-grade glued laminated timber reinforced with FRP plate. *Composites Part B: Engineering* **42(4)**: 724–735.

Raftery GM and Harte AM (2013) Nonlinear numerical modelling of FRP reinforced glued laminated timber. *Composites Part B: Engineering* **52(September)**: 40–50.

Raftery GM, Harte AM and Rodd PD (2008) Qualification of wood adhesives for structural softwood glulam with large juvenile wood content. *Journal of the Institute of Wood Science* **18(1)**: 24–34.

Raftery GM, Harte AM and Rodd PD (2009a) Bond quality at the FRP–wood interface using wood laminating adhesives. *International Journal of Adhesion and Adhesives* **29(2)**: 101–110.

Raftery GM, Harte AM and Rodd PD (2009b) Bonding of FRP materials to wood using thin epoxy gluelines. *International Journal of Adhesion and Adhesives* **29(5)**: 580–588.

Robinson B (2007) *Engineered Wood Products in Ireland*. COFORD (National Council for Forest Research and Development), Dublin, Ireland.

Sathre R and Gustavsson L (2009) Using wood products to mitigate climate change: external costs and structural change. *Applied Energy* **86(2)**: 251–257.

Schniewind AP and Lyon DE (1971) Tensile strength of redwood dimension lumber – II. Prediction of strength values. *Forest Products Journal* **21(8)**: 45–55.

Steffen A, Johansson CJ and Wormuth EW (1997) Study of the relationship between flatwise and edgewise moduli of elasticity of sawn timber as a means to improve mechanical strength grading technology. *Holz als Roh- und Werkstoff* **55(4)**: 245–253.

Thelandersson S and Larsen HJ (2003) *Timber Engineering*. Wiley, London, UK.

Treacy M, Eversten J and Ni Dhubháin Á (2000) *A Comparison of Mechanical and Physical Wood Properties of a Range of Sitka Spruce Provenances*. COFORD (National Council for Forest Research and Development), Dublin, Ireland.

Winandy JE (2002) Emerging materials: what will durable materials look like in 2020? *Proceedings of the Enhancing the Durability of Lumber and Engineered Wood Products Conference*, Kissimme (Orlando), Florida. Forest Service, Forest Products Lab, Madison, WI, USA, pp. 13–18.

Xu P (2002) Estimating the influence of knots on the local longitudinal stiffness in radiata pine in structural timber. *Wood Science and Technology* **36(6)**: 501–509.