A multidisciplinary study assessing the properties of Douglas-fir grown in the South West region of England

J.M. Bawcombe[1], R. Harris[2], P. Walker[3] & M.P. Ansell[4]

Abstract

This paper presents a review of research assessing the relationship between anatomical and mechanical properties of Douglas-fir grown in South West England. Testing methods being utilised include the mapping of variations in wood density, microfibril angle and ring widths using Silviscan-3, assessment of the radial and longitudinal change in stiffness and strength through three point bending tests of small clear specimens, and the measurement of dynamic modulus on standing trees. In providing a clear description of these methods and the importance of the links between them, a concise overview is given of a repeatable study which has the potential to provide valuable information to the local forestry industry, timber graders, and further the exploitation of local timber resources in high value structural applications.

1 Introduction

The South Western region of the United Kingdom (UK) presents excellent conditions for growing trees due to its mild oceanic climate, good quality soils and topography. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is the most abundant conifer species found in the region, accounting for almost 25% of the growing stock. The species is well established on international timber markets, where its reputation for producing high quality material sees it used in a wide range of structural applications. Despite this, utilisation of material from the South West in these higher value end uses is poor; due in part to a lack of knowledge regarding the quality of the standing resource.

Timber quality is a subjective term, dependent upon both the end product being produced and on the position in the wood supply chain from which it is judged. Principally it can be described in two ways; as the resultant of physical and chemical characteristics that allow a tree to meet the property requirements of different end uses (Mitchell 1961), or as a set of attributes that do not necessarily impact product performance, but which do affect the cost of other operations throughout the supply chain (Zhang 1997).

[1] PhD Research Student, j.m.bawcombe@bath.ac.uk
[2] Professor of Timber Engineering, r.harris@bath.ac.uk
[3] Director BRE Centre for Innovative Construction Materials (CICM), p.walker@bath.ac.uk
BRE CICM, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, England.
[4] Deputy Director BRE CICM, m.p.ansell@bath.ac.uk
BRE CICM, Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, England.

For timber products destined for structural applications, the fundamental properties which affect end user perceptions of quality are typically the modulus of elasticity (MOE), modulus of rupture (MOR), dimensional stability and the availability of section sizes. When converting trees to traditional sawn timber sections it is therefore the values of these intrinsic properties, and the extent of their variations in the stem, that influence the quality of the end product produced and its value to growers and processors. However, with the development of manufactured timber products such as laminated veneer lumber and plywood webbed I-beams, increased use is now being made of material that would have previously been regarded as being of a poorer quality, for reasons such as excessive knottiness, short section size or a low MOE. To some extent, the evolution of available timber products that has occurred with the addition of value added processes into the supply chain has diversified the ways in which the products produced from a resource can be classified as being of a high quality. Despite this, it is likely to remain the case for the forest owner that a raw material possessing superior properties will attract a greater value than one with inferior properties (Barbour & Kellogg 1990).

The MOE and MOR of timber are known to be influenced by a combination of physical and chemical characteristics. There is now much debate over the relative contribution of many of these factors to timber mechanical properties, particularly at the cellular level. Historically, a large emphasis was placed on density being the key anatomic driver responsible for the increase in MOE and MOR observed with increasing cambial age (Zobel & van Buijtenen 1989). This has led to the development of the premise that faster growth, typically observed in the first formed juvenile wood, where growth rings are widest and wood density lowest, is a good indicator of poorer quality material. However, as improved measurement techniques have been developed, a renewed interest has emerged into assessing how other anatomical features such as the proportions of early-/latewood in a growth ring, the angle of cellulose microfibril chains in the cell wall and tracheid size influence timber properties. It is now accepted that in many species variations in the MOE and MOR of clear wood specimens are best explained by considering the influences of wood anatomical features in combination, rather than examining each individually (Downes *et al.* 2002).

This research sets out to further the understanding of the relationship between micro- and macroscopic wood features, to timber mechanical properties in Douglas-fir. These findings will be used to evaluate the efficiency of BS 4978 (BSI 2007), the current UK visual strength grading code, for use with Douglas-fir. In sampling material from across South West England, this work will also help in assessing the properties of a potentially valuable underutilised resource.

2 Materials and methods

2.1 Selection and preparation of sample material

The nature of forestry ownership and management practices used within the South West of the UK is diverse. The single largest land manger operating 18%

of the resource is the Forestry Commission (FC). Ownership of the remainder of the resource is highly fragmented and is split between a number of private estates, charities and local authorities. This research is primarily concerned with the relationships that exist within individual trees, rather than quantifying the influences of specific external factors such as stand location and silvicultural practices. However, in order to capture the likely range of variations in wood properties that can be found, sample stands are to be selected so as to reflect the range of yield classes and felling ages typical of Douglas-fir harvested in the region.

Despite only managing a relatively small proportion of the regions forests, the FC was responsible for approximately 45 % of softwood harvesting during 2008 (Ekosgen 2009). Due to this, the first stage of experimental work is to focus on obtaining sample material from FC operated Douglas-fir stands, before moving on to privately operated estates. The nature of the two resources can be very different. Typically, FC operated stands are single species, even aged plantations thinned at five yearly intervals from age 20 until clear felling at an age ranging from 50-55 years. Management practices employed on privately operated estates are much more diverse with mixed species, mixed aged sites common, along with longer rotation lengths resulting in stems that contain a much larger proportion of mature wood.

Within the FC operated resource six even aged stands with ages ranging between 50-55 years and yield classes between 10 (slower growth) to 20 (faster growth) are to be selected for the extraction of sample trees. Within each stand three 0.03 ha (300 m^2) circular survey plots are to be established, with all Douglas-fir found within each plot having diameter at breast height (DBH) recorded, and an assessment made of dynamic modulus taken on the Northern and Southern face of the stem. After calculating the distribution of growth rates present in each stand determined by DBH, six trees from each will then be selected for felling so as to cover the range of growth rates present. This will give a sample size of 36 trees for the first stage of the experimental work.

Prior to felling, all sample trees are to have 5 mm diameter, 100 mm long increment cores extracted from the Northern and Southern faces at breast height, to be used for establishing outer wood density for dynamic modulus assessments. Upon felling the total height and the length of the live crown of each tree will also assessed. Following this, sample stems are to be processed by removing two 0.5 m logs, the first centred on breast height and the second at a height of 8 m. These logs are to be used for the preparation of small clear bending specimens to determine mechanical properties. Adjacent to each log, a disc measuring 100 mm is also to be taken and used to study variations in anatomical properties.

2.2 Dynamic modulus assessment

At present the sorting of trees and logs into quality classes prior to removal from the forest for processing is conducted largely by means of an assessment of characteristics such as their diameter, stem straightness and the size of branches (Moore *et al.* 2009). Today, the precision of acoustic based non-destructive evaluation (NDE) tools used on standing trees has improved to the point where tree quality and intrinsic wood properties can be predicted and correlated to the structural performance of the final products (Wang *et al.* 2007).

Standing tree NDE tools employ the principles of one-dimensional wave theory to determine the dynamic modulus in the outer wood of a stem. Each Douglas-fir tree within the sample plots is to have its dynamic modulus assessed with the use of an IML Hammer developed by Instrumenta Machanik Labor Germany, following the experimental setup illustrated in Figure 1.

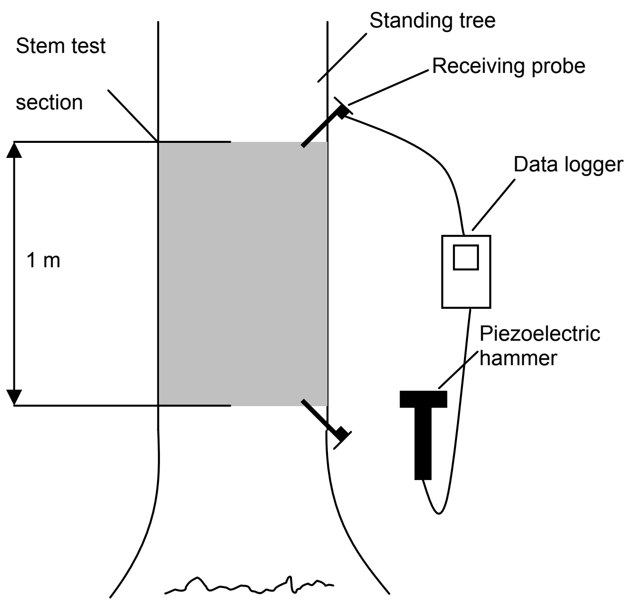

Figure 1: Standing tree dynamic modulus assessment experimental setup, adapted from Wang *et al.* (2001)

Two probes are inserted into the outer wood of the stem, separated by 1 m centred on the breast height. Upon striking the lower probe with a hammer containing a piezoelectric device connected to a data logger, a stress wave is generated in the outer wood of the stem. Measuring the time of flight of the wave between the lower and upper probe, which is also connected at the data terminal, allows the speed of the wave to be calculated. These measurements are to be conducted on the Northern and Southern face of each stem, with the wave speed calculated as the average of three measurements taken on each face. Having determined the wave speed, dynamic modulus can be calculated with the use of Equation (1) below.

$$MOE_{dynamic} = \rho\omega^2 \qquad \text{Equation 1}$$

Where MOE_{dynamic}= dynamic modulus, ρ = density and ω = stress wave velocity

A density value of 1000 Kg/m^3 is typically assumed for the outer wood of a standing tree for use in Equation (1). This value could be susceptible to seasonal variations in moisture content that occur in the stem. In order to get a more accurate assessment of density and therefore dynamic modulus, the bulk density of increment cores taken from the outer wood of all test trees at the time of assessment with the IML Hammer is to be used in place of this assumed value.

2.3 Determination of variations in MOE and MOR

Radial and longitudinal variations in MOE and MOR are to be mapped utilising small clear test specimens (specimens free of defects such as knots and compression wood) measuring 300 mm x 20 mm x 20 mm, to be extracted from each sample log along the North, East, South and West axis of growth. The specimens are to be air-dried to constant mass at 12 % moisture content, prior to being tested in three point bending in accordance with ASTM standard D 143-94 (ASTM 2009). Specimens will be tested in an Instron universal testing machine loading on to the tangential-longitudinal face closest the pith at a rate of 5 mm/min. A record will be kept of the radial position in the log from which each specimen was obtained and the age and number of growth rings present.

2.4 Determination of variations in wood anatomical properties

Pith to bark variations in wood anatomical properties including the microfibril angle (MFA) of cell wall cellulose chains, density, ring width and early-/latewood proportion are to be assessed using Silviscan-3. The Silviscan system was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Melbourne. It allows for the rapid assessment of radial wood samples to a degree of precision and at a level of consistency not possible with alternative methods.

Test pieces are to be obtained from the Northern radial axis of discs extracted from two heights in the 36 test trees, giving a sample size of 72. Following preparation to the final test measurements of 2 mm wide in the tangential direction and 7 mm wide in the longitudinal direction, samples are subject to soxhlet extraction with acetone for 24 hours to remove any extractives present in the cell lumens. This is followed by conditioning at 22 °C and 40 % relative humidity to give a testing moisture content of 7-8 %.

The Silviscan-3 system makes use of three primary measurement tools to assess variations in cellular features, these are:

- Digital optical microscopy: An auto-focusing video microscope is used to measure ring widths and tracheid proportions.
- X-ray densitometry: Wood density is determined by an X-ray area detector by converting X-ray absorption images to density profiles
- X-ray diffractometry: A wide angle X-ray detector is used to measure diffraction patterns, the reflections from the 002 planes of cellulose-I are used to calculate the MFA using the relationship $MFA \approx 1.28S$, where S is the standard deviation of the peak profiles corrected for local dispersion (Evans 1999).

Alongside these direct observations, the radial MOE profile of the samples is also predicted with use of a semi-empirical model based on the available MFA and density information (Keunecke *et al.* 2009). The techniques used in Silviscan-3 assessment are summarised in Figure 2 below.

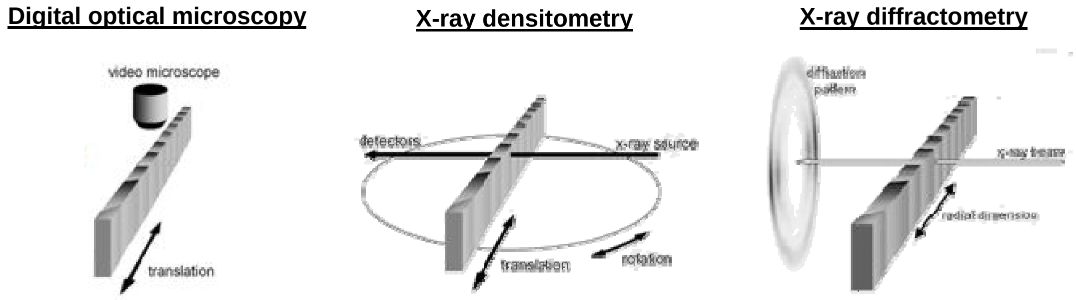

Figure 2: Silviscan-3 measurement principles

Upon completion of testing the data collected is processed and presented in the form of tables relating measured properties to radial position and the average of the properties for growth rings and early-/latewood bands.

3 Analysis of results

3.1 Relating dynamic modulus measurements to the MOE and MOR of small clear specimens

The relationship between the speed of an induced stress wave, density and dynamic modulus given in Equation (1) was developed through the use of one-dimensional wave theory, typically applied to homogeneous or isotropic materials. Its application in assessing the properties of timber, an anisotropic material, with the use of standing tree NDE tools has been the subject of a number of previous studies. Results have shown that a good correlation exists between dynamic modulus and the MOE derived through static bending tests of both small clear specimens, and larger sawn sections in the juvenile and mature wood of a number of species (Lindstrom *et al.* 2002, Ishiguri *et al.* 2008). However, no significant relationship has been found between time of flight measurements and MOR (e.g. Ishiguri *et al.* 2008).

By assessing the values of dynamic modulus evaluated in sample Douglas-fir trees and correlating these results with those obtained for the MOE and MOR of small clear specimens, this work aims to further the understanding of the ability of acoustic NDE tools to predict the properties of standing Douglas-fir trees. It is expected that the correlation between dynamic and static modulus will be highest when evaluating bending specimens taken from the outer portion of the stem, through which induced stress waves pass. In assessing how static MOE and MOR vary in test specimens closer to the pith, an empirical model will be developed allowing the dynamic modulus of outer wood to be related to the properties of core wood.

3.2 Relating variations in anatomical properties to those in MOE and MOR

The influence of anatomical properties including MFA, density, ring width and early-/latewood proportion on MOE and MOR will be determined through analysis of results from three point bending tests of small clear specimens, and the variations in cellular properties evaluated in pith to bark radial samples taken in adjacent discs. Results will be analysed with the use of simple correlation coefficients and path analysis in order to better understand both the dependent and independent relationships that exist between the variables.

A recent study of Douglas-fir mature wood examining the influence of anatomical variations on mechanical properties, found that the best predictor of static MOE in defect free specimens was the proportions of latewood within the growth rings present in test pieces (Lachenbruch *et al.* 2010). This was attributed to latewood being denser and having a lower MFA than earlywood and therefore contributing a larger proportion to the samples stiffness. This finding could have important implications for BS 4978 (BSI 2007) the current softwood visual strength grading code utilised in the UK, in which ring width is one of the criteria assessed during grading. If it can be shown that in juvenile, as well as mature wood, that the proportion of latewood in a ring has a larger impact on timber properties than ring width, more efficient visual grading methods for Douglas-fir could be established in the future.

4 Continuing work

The work outlined in this paper has summarised testing to be conducted on material extracted from Forestry Commission Douglas-fir sites in the South West of the UK. Following completion of this, similar test methods are to be employed on older sample trees with ages greater than 80 years. Results gathered from these older trees, more reflective of material harvested from privately owned sites, will be used alongside previously gathered data in the development of empirical methods to predict anatomical and mechanical properties at different locations within the stem. It is expected that these trees will exhibit superior outer wood properties due to the greater proportions of mature wood in the stems.

Future testing including an evaluation of the efficiency of visual grading techniques is also to be conducted on structurally sized Douglas-fir sections. This will allow the magnitude of the effects of anatomical properties on MOE and MOR studied in earlier work to be evaluated in sections containing defects such as knots and a sloping grain.

5 Concluding remarks

It is anticipated, that alongside the primary aim of this research to gain a greater understanding of the factors that may influence timber quality in South West Douglas-fir, that further knowledge may be developed in a number of areas of interest to timber growers, processors and graders.

Furthering the understanding of relationships that exist between the dynamic modulus obtained using acoustic NDE tools on standing trees and the properties of timber sections produced from a tree could allow for increased future usage of NDE equipment within the forestry industry. This will enable more accurate preliminary estimations of timber quality to be made prior to felling, ensuring that material is sent to the most appropriate end use, potentially improving the grade outturn of a forest and therefore profitability. An improved understanding of the relationships that exist between mechanical and anatomical properties could lead to the development of more efficient visual grading standards for UK grown Douglas-fir, making home-grown material more competitive in a marketplace currently dominated by imported wood products.

Acknowledgments

This research is funded by the Silvanus trust through donations from the South West forest industry, Great Western Research and the University of Bath. Thanks goes to Jez Ralph from the Silvanus trust and Barry Gardiner from Forest Research for their support with the project to date.

References

ASTM (2009) “Annual book of ASTM Standards”. American Society for Testing and Materials, West Consohocken, Vol. 04.10 Wood.

Barbour, R. & Kellogg, R. (1990) “Forest management and end-product quality: a Canadian perspective”. Canadian Journal of Forest Research, Vol 20(4), pp 405-414.

BSI (2007) “BS 4978: Visual strength grading of softwood”. British Standards Institution.

Downes, G., Nyakuengama, J., Evans, R., Northway, R., Blakemore, P., Dickson, R. & Lausberg, M. (2002) “Relationship between wood density, microfibril angle and stiffness in thinned and fertilized Pinus radiata”. IAWA Journal, Vol 23, pp 253-266.

Ekosgen (2009) “Strategic economic study of South West England woodland and forestry”.

Evans, R. (1999) “A variance approach to the X-ray diffractometric estimation of microfibril angle in wood”. Appita Journal, Vol 52, pp 283-289.

Ishiguri, F., Matsui, R., Iizuka, K., Yokota, S. & Yoshizawa, N. (2008) “Prediction of the mechanical properties of lumber by stress-wave velocity and Pilodyn penetration of 36-year-old Japanese larch trees”. Holz als Roh-und Werkstoff, Vol 66(4), pp 275-280.

Keunecke, D., Evans, R. & Niemz, P. (2009) “Microstrucutral properties of common yew and Norway Spruce determined with Silviscan”. IAWA Journal, Vol 30(2), pp 165-178.

Lachenbruch, B., Johnson, G., Downes, G. & Evans, R. (2010) “Relationships of density, microfibril angle and sound velocity with stiffness and strength in mature wood of Douglas-fir”. The Canadian Journal of Forest Research, Vol 40(1), pp 55-64.

Lindstrom, H., Harris, P. & Nakada, R. (2002) “Methods for measuring stiffness of young trees”. Holz als Roh-und Werkstoff, Vol 60(3), pp 165-174.

Mitchell, H. (1961) “A concept of intrinsic wood quality, and non-destructive methods for determining quality in standing timber”. U.S. Forest Products Laboratory, Report No. 2233.

Moore, J., Lyon, A., Searles, G. & Ridley-Ellis, D (2009) “The use of acoustic-based NDT to predict the wood propertied of UK-grown Sitka Spruce at different stages in the wood supply chain”. The 16th International Non-destructive Testing and Evaluation of Wood Symposium, Beijing.

Wang, X., Carter, P., Ross, R. & Brashaw, B. (2007) “Acoustic assessment of wood quality of forest raw materials – a path to increased profitability”. Forest Products Journal, Vol 57(5), pp 6-14.

Wang, X., Ross, R., Erickson, J., Forsman, J., McClellan, M., Barbour, R. & Pellerin, R. (2001) “Non-destructive evaluation of standing trees with stress wave methods”. Wood and Fibre Science, Vol 33(4), pp 522-533.

Zhang, S. (1997) “Wood quality: Its definition, impact, and implications for value-added timber management and end Uses”. In: CTIA/IUFRO International Wood Quality Workshop – Timber Management Toward Wood Quality and End-Product Value, pp 117-139.

Zobel, B. & van Buijtenen, J. (1989) “Wood variation: its causes and control”. Springer-Verlag Berlin.