Strength grading and the end user – lessons from the SIRT project at Napier University

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ABSTRACT

The paper reviews the research that has been undertaken by the Strategic Integrated Research in Timber (SIRT) project at Napier University, with reference to the technologies, techniques and approaches required to grade the UK's timber resource according to the real needs of the end user. The project has been operating since 2004, and has made significant progress in understanding the nature and variability of UK-grown Sitka spruce.

It has been seen that UK-plantation Sitka spruce can yield timber of grade C24, and that with the right breeding and silviculture it may indeed be economic to aim higher than the current C16 production. Conversely it has also been seen that there are geographic areas where the current resource is of marginal quality for constructional use. In these circumstances it is important to know how to find the best wood within each tree, and how to divert unsuitable material at an early stage. Crucially, it is important to ensure grading of such marginal material is actually delivering what the end user wants.

Indeed a number of important general questions remain about the suitability and robustness of current grading practices. These questions are partly informed by data that has been gathered to-date, but more research is needed and possible approaches are presented for discussion. These include questions around: the variation in the resource and the implications for sawmillers and end users; the potential and pitfalls for resource segregation; and the 'non-mechanical' properties that affect utilisation of graded timber (principally distortion and knots).

INTRODUCTION

Strategic Integrated Research in Timber (SIRT) is a collaborative multi-discipline project involving the Centre for Timber Engineering at Napier University, in partnership with the Department of Chemistry at the University of Glasgow and Forest Research (the research agency of the Forestry Commission). It commenced in 2004 with initial funding provided by the Scottish Funding Council with the intention of creating a UK virtual centre with expertise in timber research; particularly with respect to the UK's principal commercial species Sitka spruce (*Picea sitchensis*). It has undertaken a number of different studies aimed at characterising the resource at a range of scales (from molecular to forest), and understanding the influence of silviculture and genetics on the key constructional properties of timber. Substantial progress has already been made through a combination of fieldwork, laboratory testing and review of existing literature (both grey and published). In addition, significant progress has been made with regard to the application of acoustic-based non-destructive testing for resource assessment and segregation. However, a number of important questions have arisen that give cause to consider whether current UK grading practice is effective from the point of view of the construction industry, and whether resource segregation is feasible in practice. In this paper, the main studies that have been undertaken to characterise the Sitka spruce resource are reviewed, and the implications from this research and future segregation practices on timber grading are discussed.

CHARACTERISING THE PROPERTIES OF UK-GROWN SITKA SPRUCE

It has long been known that there is considerable variation in the physical and mechanical properties of the Sitka spruce timber from UK plantations. However there was little understanding of the sources and extent of this variation. Previous research in a range of species has indicated that factors including genetics, silviculture (i.e., initial planting spacing, timing and intensity of thinning, pruning, rotation length, fertiliser application), and site conditions (i.e., exposure, temperature, rainfall, and soil type) can affect the wood properties of a tree and thus the performance of timber produced from it.

This information is important for wood processors when selecting stands for purchase, as certain combinations of site, genetics, and silviculture could yield timber with substantially poorer physical and mechanical properties, leading to higher rates of strength grading rejects. Similarly, this information is of use to forest managers seeking to grow stands for timber production, as it allows them to manage for improved timber quality.

Four key resource characterisation studies have been undertaken in which the properties of Sitka spruce were investigated at the standing-tree scale right down to the scale of a few microns. These studies have substantially improved the understanding of the impact on mechanical performance of structural timber of factors at the micro-structural level (e.g. cellulose structure and abundance) and at the forest-level (e.g. genetics, the environment and forest management). The relevant conclusions of these studies are summarised below, but more detailed wood properties information can be found in Moore *et al.* (2008).

The studies used a combination of instruments for making time-of-flight and resonant stress-wave velocity measurements, and undertaking pseudo-static mechanical testing. Specifically, they included an IML Hammer (Instrumenta Mechanik Labor, Germany), an ST-300 (Fibre-gen, New Zealand), a HM-200 (Fibre-gen, New Zealand) and a Zwick Z050 universal testing machine (Zwick Roell, Ulm, Germany).

The Kershope progeny trial (genetics)

Forest Research led the first known study that has investigated the wood properties, timber yield and timber performance of genetically improved Sitka spruce. This study compared the wood properties of four different 37-year old Sitka spruce 'treatments' within a genetics trial. Three of these treatments contained the first generation half-sibling progeny of selected 'plus trees' (trees that were identified as having superior vigour, straightness or branch characteristics) while the fourth contained trees grown from unimproved seed collected from the Queen Charlotte Islands, Canada (Mochan *et al.* 2008).

Non-destructive acoustic measurements of dynamic modulus of elasticity were made on freshly-felled logs and dried and conditioned structural sized timber using both time-of-flight and resonance-based acoustic tools. The timber was then destructively tested in four-point loading according to EN408 (CEN 2003a) to determine both static global and local modulus of elasticity, as well as bending strength. All timber samples were labelled so that the log, tree and treatment they originated from could be identified.

A variance components analysis (Table 1) revealed that less than 1% of the variation in wood stiffness was actually attributable to differences between the treatments. In fact, most of the variation was attributable to differences between individual pieces of timber within a log and between individual trees within a treatment. Similarly, there was no difference in strength observed between treatments, but, as expected, a moderate correlation was found between strength and stiffness. There was a statistically significant difference in wood density between two of the treatments, but again, the main sources of variation were actually within log and between trees within a treatment. Based on the characteristic bending strength and stiffness values, the timber overall met the requirements for the C16 strength class (CEN 2003b).

Table 1: Sources of variation in selected properties of structural timber from the Kershope progeny trial

Property	Between treatment groups	Between trees within a treatment group	Within a log
Density	4.1%	41.0%	50.8%
Stiffness*	0.6%	38.4%	50.5%
Bending strength	-	49.4%	47.3%

* *Figures are quoted for static global modulus of elasticity*

The high level of tree-to-tree variation is likely to be due in part to the fact that trees in each treatment were half-sib. Indeed the magnitude of tree-to-tree variation within a treatment is evidence that there is considerable scope to improve wood quality through tree breeding, provided that the characteristics of interest are moderately heritable. The current tree-breeding programme has focussed on increasing density, reducing branch size and improving stem straightness as the main means of improving wood quality (Lee, 1999), but strength and stiffness may also be useful targets. Indeed microfibril angle in juvenile wood is thought to have a significant heritability (Donaldson and Burdon, 1995) and hence there is potential scope for selecting trees for lower microfibril angle in order to improve the stiffness of the juvenile core that makes up a high proportion of the converted timber (see Birkley Wood, below).

Overall, while there was a lack of difference observed in the mechanical properties of structural timber between the different treatments, there were considerable differences in the recoverable volume of logs and sawn timber. On a per hectare basis, Mochan *et al.* (2008) predicted that the progeny from the three plus trees would all yield significantly more timber than the control due to a combination of improved growth rates, lower mortality and/or improved stem form.

The Baronscourt re-spacing (pre-commercial thinning) trial

This study, led by Forest Research, examined the effect of early thinning on wood properties and timber performance in a historically-important replicated experiment in Northern Ireland. The experiment consisted of five different re-spacing treatments (5.6 m, 4.6 m, 3.7 m, 2.6 m and an un-thinned control at 1.9 m) and was felled when the stand was 57 years old. Each spacing was replicated five times in a Latin square, and three trees were sampled from each plot for study.

As with the Kershope study, considerable variation in the properties of structural timber was found between trees within a treatment and within the trees themselves. Despite this, significant differences in static modulus of elasticity and bending strength were found between thinning treatments. Both stiffness and strength decreased with increased spacing. The timber from the un-thinned control treatment had characteristic strength and stiffness values sufficient for the C18 strength class, while timber from those treatments where the trees were growing at a spacing of 3.7 m or wider failed to meet the requirements for C16. These findings generally agreed with those obtained by Brazier and Mobbs (1993) who found C16 yields were too low to be economically viable for spacings greater than 2 m (although this limit of 2 m may be a little conservative).

The Birkley Wood study (rotation length)

A strong storm provided the opportunity to study the timber from an 83-year-old stand of Sitka spruce growing in northern England. Typical rotation lengths for commercial Sitka spruce stands in the UK are between 40 and 50 years. At this age the juvenile core comprises a significant proportion of the volume of harvested log and an even larger proportion of the converted lumber. Juvenile wood generally has poorer mechanical properties than wood formed when the cambium is older (Brazier 1985), and also has poorer dimensional stability, especially with respect to twist due to high spiral grain (Johansson *et al.* 2001).

Thirty trees were sampled and the properties of timber cut from consecutive radial positions within a log (i.e., representing increasing cambial age) were compared. A substantial increase in bending strength and stiffness was observed with increasing distance from the pith. Timber sawn from near the outsides of logs met the requirements for the C24 strength class, while timber from the centre could only meet C14. The site that this stand was growing on was quite wind exposed and it is possible that longer rotations on a more sheltered site may yield a greater proportion of timber that is able to satisfy the requirements for the C24 strength class.

The Benchmarking study (regional variation)

This study investigated the extent of variation in the wood properties of harvest-age (i.e., 35-45 year-old) stands of Sitka spruce throughout Scotland and northern England, and also investigated the effects of selected environmental and management factors on this variation. Sixty-four sites were selected on the basis of elevation, latitude, longitude, yield class, initial planting spacing and whether or not the stand had been thinned. Ten trees per plot were randomly selected and the dynamic modulus of elasticity of the wood in the standing tree was predicted from stress wave velocity.

Predicted dynamic modulus of elasticity of the 640 trees assessed in this study ranged from 3.8 kN/mm^2 up to 12.3 kN/mm^2. The majority of this variation (55%) was due to differences between individual trees within a site, although differences between sites were also found to be important (35%). The remaining 10% of the variation was due to differences between measurements made on the north and south sides of each tree. Stem straightness and dynamic stiffness were found to vary independently. Analyses of site-level data indicate that wood stiffness is significantly influenced by yield class, elevation and initial spacing, as well as by the interactions between elevation, latitude and longitude, and yield class, elevation and initial spacing. The grade recovery and mechanical properties of the timber from the different sites has yet to be compared and related back to predicted values of dynamic stiffness.

LINKING TIMBER GRADING TO RESOURCE CHARACTERISTICS AND END USER REQUIREMENTS

UK grown Sitka spruce is currently graded to a C16/reject scheme and it is generally regarded as uneconomic to aim for C24/reject, as the price differential for the two grades would not outweigh the reduced yield. This research has confirmed that timber cut from the resource currently reaching harvesting age does, overall, have mechanical properties that place it into the C16 class, but it has also shown that there is, potentially, a large amount of variation in wood stiffness between stands. There is also a great deal of variation in stiffness between trees within these sites so for the forester and sawmiller there is considerable scope for segregating the current resource to maximise value and reduce rejects.

In the longer term there does seem to be potential for growing trees that will yield an economic return of C24-class material through a combination of tree breeding, longer rotation and informed silviculture, although this will also require changes in sawmill technology and cutting patterns. It is, perhaps, too early to dismiss this objective on economic grounds.

However, the implications for the end user seem less rosy. Large site-to-site variations and sensitivity of wood properties to forest management give cause to consider whether current grading practice truly delivers what is required of it by the reliability theory behind limit states design. Looking ahead, the use of more effective segregation, changes in silvicultural practice, a reduction in inter-tree variation through tree breeding and the deployment of vegetatively propagated tree stocks may have unintended consequences. Indeed, when examining the reasons why the UK construction sector prefers imported timber a whole spectrum of questions arises.

Non-destructive testing and segregation

The most immediate opportunity for improving the profitability for growers and processors lies in segregation. Stands (and possibly trees) that are unlikely to produce an economically acceptable outturn of structural-quality timber could be identified and diverted to other non-structural end uses; conversely the sale of good quality timber for low value uses could be avoided.

Segregation already occurs to a certain extent through measurements of characteristics such as density, diameter and straightness, and through the experience of timber buyers. However, the current generation of field portable and easy-to-use acoustic tools for measuring stress-wave velocity on standing trees and logs offers a more effective way of directly segregating for mechanical performance. Indeed, thanks in part to the research results obtained through the SIRT project, these tools are already being put into service by the UK's forest and timber industry.

The SIRT project has begun to investigate the potential effectiveness of non-destructive tools for predicting wood properties in combination with other measurements at forest down to board level. Even used in isolation, non-destructive tools have been seen to produce reasonable predictions of the static bending stiffness of sawn timber from measurement made on freshly felled logs. For example, Fig. 1 shows the results gathered for the HM-200 comparing the dynamic modulus of elasticity measured on the log with the static modulus of the timber cut from it ($R^2 = 0.45$, $p < 0.001$). The scatter is largely the result of the radial and circumferential variation in wood properties within a log as well as log-to-log variation in green density (which is assumed to be a constant 1000 kg/m^3 when calculating dynamic stiffness from stress wave velocity). The comparison between static and dynamic stiffness for sawn timber is better (R^2 =

0.91, $p < 0.001$, Fig. 2) although there remains some scatter due to variation in stiffness within the batten length. The relationship between the stiffness of individual pieces of timber and the predicted stiffness of standing trees is not quite as good as for the same relationship with felled logs. It is thought that this is because the measurement is more difficult to make and that it only gives stiffness information for the outer wood rather than the inner core where the majority (if not all) of the sawn timber comes from. In the Birkley Wood study, the dynamic stiffness predicted from standing tree time-of-flight velocity measurements made with the IML Hammer only explained around 13% of the variation in dynamic stiffness of the sawn timber, although these trees were of untypical age and diameter. An initial trial of the ST-300 instrument indicated that standing tree stress wave velocity measurements could explain approximately 25% of the variation in dynamic stiffness of individual pieces of sawn timber (Forest Research, unpublished data). This degree of association is at the lower end of the range of values presented by Chauhan and Walker (2006) for radiata pine, but predictions are likely to improve for Sitka spruce when stress wave velocity is used in combination with other measurements.

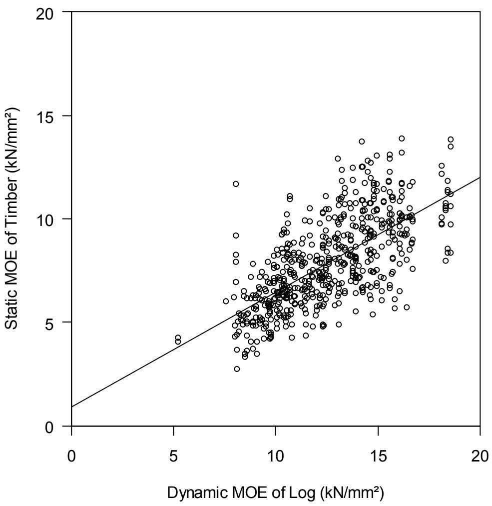

Figure1: Relationship between static stiffness of sawn timber and the dynamic stiffness of the log from which it was cut

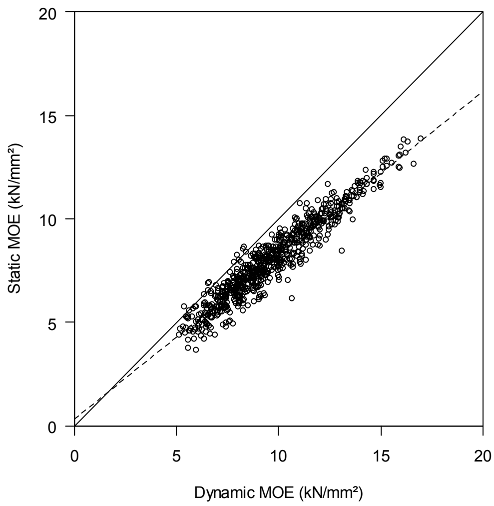

Figure2: Relationship between static and dynamic stiffness of sawn timber

From research on modelling the distribution of wood properties within a tree (e.g., McLean 2008), two particular problems have been identified. For Sitka spruce, the juvenile wood has low stiffness, but not proportionally low density, and so density was found to be a poor indicator for quality on its own. It was also found that 'root-wood' with low stiffness extends for a considerable distance above ground level so that butt logs are affected. It may therefore also be useful to segregate wood within the tree by removing more of the butt during harvesting and altering sawmill cutting patterns so as to avoid as much of the centre of the tree as possible.

The quality issues affecting constructional use of Sitka spruce

The majority of the timber used in building and construction in the UK is imported. Where domestic timber is used, this tends to be in non-structural applications such as fencing, or by small builders and the DIY market. At present less than 30% of the structural timber used in this country is produced from UK forests, requiring fewer than 1 in 3 of the UK-grown logs harvested (Forestry Commission 2007). Few timber framers and no trussed rafter manufacturers use home-grown timber, and it is thought that a continued increase in the market share for pre-fabricated timber frame buildings may actually result in a reduction in the amount of home grown structural timber used.

With the increasing popularity of 'room-in-the-roof' construction it seems that the trend for trussed rafters is for higher-grade timber to reduce construction depth. However, C16 timber has perfectly adequate mechanical properties for typical timber frame construction where wall thickness and floor depth are more governed by thermal and acoustic performance than they are by strength and stiffness. The price differential between imported C24 timber and C16 is relatively small, especially when calculated as a proportion of the total cost of the whole construction project. Indeed in some circumstances C24 is a less expensive option due to savings elsewhere, even when used as a direct substitute for C16. Although some timber frame manufacturers prefer C24, the main issue with UK-grown timber does not appear to be simply its strength grade *per se*.

One reason that timber frame manufacturers often give for not using UK-grown timber is dimensional stability. Even though graded timber has limits on bow, spring and twist, the tighter tolerances of factory pre-fabrication appear to be more demanding. There is also a view that UK-grown timber distorts more once in service. It is known that UK timber is indeed particularly prone to twist due to the fact that it is cut from near the centre of smaller diameter logs and therefore has a relatively high percentage of juvenile wood and a high grain angle. Other types of distortion are thought to be linked to the presence of compression wood. It may therefore be possible to improve the dimensional stability of UK timber through a combination of changes in silviculture and processing. In the short term it may be possible to identify and segregate the trees and logs likely to produce timber prone to distortion and to introduce tighter rejection criteria at the point of grading.

Another reason that is given for not using UK-grown Sitka spruce is that it has more knots than imported timber. There may be a certain amount of disregard for knotty timber based on the belief that it will be less stiff and less strong than clear wood, but knots do cause genuine problems in prefabrication due to nail fouling. There is also a similar problem with low-density flaws and lack of nail holding. It may be possible in the short term to remove the sort of knotty material that causes problems through a combination of segregation and grading.

Perhaps the most important issue however, is the poor perception generally of UK-grown timber. There is a certain long-standing cultural tendency in the UK to denigrate anything that is 'made in the UK'. This certainly extends to timber where people look to countries with more of a perceived connection with forestry and wood production. It is common to hear it said that the UK's timber grows too quickly to be any good, and that short rotation plantations are no match for the 'more natural' forests of Scandinavia. It has been suggested that builders prefer to use imported C16 on the belief that it contains a higher proportion of stiffer and stronger material than UK-grown C16, which helps to 'cover any mistakes' in design and construction. It may be that the root cause of the poor perception is a poor understanding of timber grading, and of the real characteristics of UK timber.

These are significant challenges for producers of UK timber. Timber framers have well established supply chains and have a streamlined 'just in time' production that depends hugely on consistency and continuity of supply. Their margins of profitability are low and so have good reason to be resistant to change without a visible, and guaranteed, financial return.

A thorough survey of industry is required to really understand end-user requirements and to separate anecdote from reality. Real concerns need to be identified and addressed and misconceptions that act as an artificial barrier need to be dispelled. What is certain is that any timber that needs to be rejected once it has entered the prefabrication factory has a penalty cost that is much higher than the value of the timber itself.

Challenges for timber grading

A number of questions have arisen from the findings of SIRT that give cause to consider whether grading really delivers the end user with what they want. Processors are concerned with maximising the amount of timber that is produced and, other things being equal, will select a grading technology that grades their product most favourably, over one that grades most correctly. Users assume that a package of timber that is graded C16 will have an overall range of properties representative of the grade, but are they correct in this assumption and whose responsibility is it to ensure they are – now and into the future?

The old 'permissible stress' approach to design worked simply by ensuring that stresses remained below a certain threshold to cover a range of performance criteria that included deflection as well as strength. The 'limit states' approach in the new Eurocode suite of standards is very different in that it attempts to address separately various concepts of failure through rules based on reliability theory. In the past it was strength that governed design, but now stiffness and density are also important for both ultimate and serviceability limit states.

The purpose of grading machines is to sort timber according to a set of requirements that includes, but is not limited to, strength. No grading technology can measure strength directly and so instead, it must be predicted from at least one other indicating parameter than can be measured. Bending stiffness and density can be directly measured (and indeed serve as indicating parameters for bending strength) but several other properties are attached to strength classes that are never measured and may not be correlated to indicating parameters. For example, research at Napier University on torsional behaviour of Sitka spruce has shown no correlation between modulus of elasticity and shear modulus (Khokhar *et al.* 2008). The question arises therefore whether graded timber will necessarily have the shear properties that are used for the design calculations. The uncertainty is not only whether grading works, but also whether design rules correctly apply grade properties. For example, Sitka spruce has a notably weak correlation between density and mechanical properties and yet design values such as embedment strength are calculated from the characteristic density values for the particular grade.

The original work to calibrate grading machines for UK Sitka spruce was undertaken in the 1970's and it is possible that the resource has changed since this time, either in terms of its properties or the way the properties are related (reduced rotation lengths are a particular concern in this respect). At the time, the UK Sitka spruce resource was treated as a whole, yet the benchmarking study has shown that there is significant variation from one forest to the next. In general, sawmills have a designated wood supply catchment and so it is possible that they can produce packages of graded material that do not contain enough high stiffness and high strength timber for the packages to have the same characteristic properties as the grade specifies. Grading calibration, and hence the reliability basis of design, assumes that the timber that makes up a single structure is a randomised sample from the whole grade population, yet in practice that may not happen. A low strength member in a building cannot be compensated for by a high strength member in a building in another county. The high level of tree-to-tree and within-tree variation seen in the current resource will go someway to ameliorate this and there is no problem with failing buildings in practice, but the unintended consequences in this regard of tree breeding, silvicultural changes, and more effective segregation need to be understood. Safety factors built into design mean that it is unlikely that this is a problem that reduces safety, but there may well be an increase in site problems and serviceability failures requiring remedial work. Engineered wood products are already displacing solid wood because they have more uniform properties and better dimensional stability, and any increase in snagging problems with solid wood may further reduce the market share for this product.

There is also the matter of the reliability of grading and calibration itself. There is some question as to whether strength graders work effectively in industrial situations and whether they are correctly calibrated and maintained. It has also been seen that, even when undertaking laboratory testing to the standard (CEN 2003a) it is possible to get variation in measurement of modulus of elasticity depending on whether deflection is measured relative to the top, bottom or middle of the timber. In addition the global and local modulii of elasticity are not interchangeable, although they are often treated as though they are. There is a tendency to pick whichever setup is most favourable, irrespective of what makes the most scientific sense.

The rise of non-destructive testing causes some of these problems, but it also brings some of them to light. Crucially it also provides the potential to investigate them in the timber yard, as well as in the forest and sawmill.

CONCLUDING REMARKS

The SIRT project has made significant progress in understanding the nature and variability of the wood properties of UK-grown Sitka spruce. It has been seen that, with appropriate tree breeding, silviculture and segregation, it may be possible to economically produce C24 grade material. Conversely, it has also been seen that there are geographic areas where the current resource is of marginal quality for constructional use. In these circumstances it is important to know how to find the best wood within each tree, and how to divert unsuitable material to other end uses at an early stage.

However, segregation and tree breeding may have unintended consequences in causing graded timber to become unrepresentative of the grade in some regions. Indicating parameters may become less indicative, and forest level factors may cause the proportion of higher quality wood to diminish in some areas. Indeed there are reasons to question whether this may already be the case.

It needs to be ensured that the interests of the end user are truly represented both in terms of setting what is defined by a grade, but also in terms of the impact of future changes in timber production. This is not just a UK problem, but the UK is a case in point as there is a fine balance between imports and home grown material, between solid wood and engineered products, and between wood and materials such as brick, concrete and steel. If users become dissatisfied with the product, they will no longer buy it.

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