Variables affecting the stiffness and distortion of Sitka spruce

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Timothy Nathaniel Reynolds

1965 – 2010

In memory of a most loved husband and devoted father.

We will love you always.

Now you really are Doctor of Wood!

Abstract

Inherent in the structure of timber are features affecting dimensional stability, stiffness and strength. These include knots, compression wood and spiral grain. Physical characteristics such as log shape, density, rate of growth, presence of juvenile wood and microfibril angle also affect these properties and, in turn, utilisation. In this thesis, the relationships between tree, log and board variables to the properties of stiffness and distortion of British-grown Sitka spruce (*Picea sitchensis*) are examined. The research's main aim was to identify variables which could potentially be used to sort timber.

Different behaviour in terms of the relationship between stiffness and variables such as density, knot content, log taper, tree height and axial position were noted between groups of upper log and butt log material, and between the four stands and two sites studied. Relationships between stiffness and these variables were generally weak, notably for density. Overall, variables based on radial position within the stem were not found to be useful sorting parameters. No relationship between batten stiffness and compression wood content or slope of grain was observed. The relatively low stiffness of butt wood material was associated with high microfibril angle.

Batten twist was found to be a function of spiral grain angle and distance from pith. However, practical difficulties with the use of slope of grain measurements to sort timber were noted. Although severe forms of compression wood were seen to be associated with stem-form correction, relatively straight logs and those which were round, or without pith eccentricity, were also observed to contain compression wood and hence yield timber which distorted on drying.

In particular, this work demonstrates the effect of sorting timber using combined variables (*e.g.* log shape and knot content). These findings may be of use to foresters, sawmillers and developers of timber scanning technologies.

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Acknowledgement

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The author is grateful for the assistance provided by many colleagues at BRE who carried out test work and measurements on several hundred of pieces of timber. The author is particularly indebted to Mr Gerald Moore for his careful laboratory work on the shrinkage and mechanical properties of small clear samples. Colleagues at Forest Research (Professor Barry Gardiner, Mrs Elspeth MacDonald and Mr Shaun Mochan) contributed by selecting and harvesting logs, assisting with sawmill operations, and also providing disc images and other data. Programming work on data from an industrial 3D laser scanner was carried out by Mr Paul Dollemore. The author is grateful to Mr Darryl Francis for use of the facilities at Adam Wilson & Sons Ltd sawmill, Troon, Scotland, and to Dr Sven-Olof Lundqvist of STFI-Packforsk for carrying out MFA measurements using SilviScan™. Mr Chris Holland and Mr Clive Benham compiled the BRE Sitka spruce grading dataset analysed as part of this work.

The author would like to thank the Forestry Commission for their sponsorship in respect of course fees; together with his supervisors Dr Daniel Ridley-Ellis, and Professor Philip Turner of Edinburgh Napier University, and also Dr Vahik Enjily of BRE.

Declaration

The contents of this thesis are the results of my own investigations (unless otherwise referenced), assisted by the practical work of colleagues, and conducted under the guidance of my supervisors.

07/06/2010.

Tim Reynolds

Notation

Units, definitions of further variables and other notation used in statistical analysis are detailed in Chapter 3. Note that common abbreviations and statistical notation are not listed (*e.g*. dia., R^2 *etc*). Protocols for measurement are given in Appendix 2.

Variables

b	Batten width in EN 408:2003 bending test *i.e.* smaller cross section
Bow1	Batten bow as defined by BS 4978:1996 at drying stage 1
Bow2	Batten bow as defined by BS 4978:1996 at drying stage 2
Cut ht.	Cut height *i.e.* distance from ground level to the lowest point on the log or batten
CW total, etc.	Compression wood content of battens (detailed in Chapter 3)
CW score	Compression wood content of small clear samples (as detailed in Chapter 12)
d	Batten depth (during machine grading)
DBH	Diameter at breast height (1.3 m)
Density	Defined as oven dry mass divided by volume at 12% moisture content
Dens	Abbreviation for *Density* (as above) used in tables *etc.*
$Dens_{(bulk)}$	Bulk density, defined as sample mass divided by volume at a given moisture content
E_{cb}	Modulus of elasticity derived from a Cook-Bolinder grader
E_{cen}	Modulus of elasticity based on local shear free measurement as detailed in EN 408:2003
$E_{m,g}$	Modulus of elasticity based on the global E test method as detailed in EN 408:2003
E_{plank}	Modulus of elasticity measured in three point bending about the minor axis of a board (in this work equivalent to E_{cb})
EMC	Equilibrium moisture content (%)

f_m	Bending strength (*i.e.* modulus of rupture), as defined by the EN 408:2003 test method
h	Batten depth in bending test to EN 408:2003 (*i.e.* larger cross section)
IP	Indicating Parameter (of Cook-Bolinder machine stress grader)
JW	Juvenile wood content
Knotarea%	Percentage of knot cover on all batten faces
Kn300%	Percentage knot cover over worst 300 mm, on outer batten face
Kn900%	Percentage knot cover over 900 mm central section
Log arc	Log arc or sweep
Log max dev	Log maximum deviation
L	Batten length
m/c	Moisture content
MFA	Microfibril angle
MOE	Modulus of elasticity
MOR	Modulus of rupture
MKAR	Margin knot area ratio (as defined in BS 4978:1996)
Pith Dist	Distance from log pith to centre of batten (radial position)
RH	Relative humidity
Section	Code relating to axial position as defined in Appendix 2
SOG	Slope of grain
Spring1	Spring as defined by BS 4978:1996 at drying stage 1
Spring2	Spring as defined by BS 4978:1996 at drying stage 2
t	Batten thickness (during machine grading)
T	Temperature (degrees Celsius)
TKAR	Total knot area ratio (as defined in BS 4978:1996)
Twist1	Twist as defined by BS 4978:1996 at drying stage 1
Twist2	Twist as defined by BS 4978:1996 at drying stage 2
Whorl no. etc.	Whorl number, spacing *etc.* (as defined in Appendix 2)
ε_L	Longitudinal shrinkage
ε_R	Radial shrinkage
ε_T	Tangential shrinkage
Δ	Deflection

Abbreviations

ANOVA	Analysis of variance
BRE	Building Research Establishment
CW	Compression wood
FPRL	Forest Products Research Laboratory
FR	Forest Research (UK)
GL	Ground level
MRC	Multiple regression and correlation
PRL	Princes Risborough Laboratory

"Out of the crooked timber of mankind
no straight thing can ever be produced"

Immanuel Kant
Idee zu einer allgemeinen Geschichte in weltbürgerlicher Absicht (1784).

1 Introduction

Timber is a useful but naturally variable material. Inherent in its structure, both in log and sawn form, are features which affect dimensional stability (*i.e.* distortion on drying), stiffness and strength. These include knots, compression wood, and spiral grain. Physical characteristics such as log shape, density of clear wood, rate of growth, presence of juvenile wood, and microfibril angle also affect these properties and, in turn, utilisation. Timber which is stronger and stiffer is more suited to more demanding structural applications, whilst distortion on drying can cause problems such as poor fit at connections.

In this work a detailed and extensive dataset was established of tree, log and board variables that could be related to timber properties of stiffness and distortion.

1.1 Objective

The objective of this study was to investigate the relationships between tree, log and board variables (such as taper, ovality and knot content) to the sawn timber properties of stiffness and the development of distortion on drying for British-grown Sitka spruce (*Picea sitchensis*). It was not the intention to quantify these properties or set limits for any particular end uses. Rather, the main aim was to identify variables which would be useful parameters for sorting timber according to required qualities and thresholds. Although some comparison to the property of strength is made, this work principally deals with stiffness.

The research questions are:

- What are the variables that affect timber stiffness and distortion?
- How do these variables interrelate?
- What measurable features on trees, logs and boards can be used as criteria to sort timber?

- What are the practical difficulties in making the measurements?
- What threshold values should be applied?
- What benefits can be gained by combining variables obtained at tree or log stage with those for sawn timber?
- What parts of the trees are more prone to distort on drying?
- Which trees, and which parts of trees, are better for higher grade structural timber?

1.2 Methodology

The overall approach used was to obtain sample batches of timber and relate the potential predictor variables of the logs and boards to the criterion variables of the end-product. By relating both log and batten variables to end-product qualities the worth of measuring these variables in the production process could be evaluated. Batten predictor variables included those based on knot content, slope of grain, ring width, density, juvenile wood content and both radial and axial position in the stem (these measurements are fully defined in Chapter 3). Log predictor variables included taper, diameter, arc, ovality, pith eccentricity and whorl spacing. Tree predictor variables included height and diameter at breast height (*DBH*). In addition, by studying the behaviour of small-scale samples, the effect of variables such as density and compression wood content could be studied without the influence of knots.

The material studied consisted of around 500 battens of Sitka spruce obtained from four stands (denoted “FR1, 2, 3 and 4”) from two localities in Scotland (Lochaline and Benmore, detailed in Appendix 1). In addition, an extensive data set of test work on Sitka spruce, which was used by BRE to establish machine grade settings and BS 5268 strength classifications, was also analysed (this material being denoted here as “BRE grading set”). The BRE grading set of battens was obtained from a number of UK sawmills and is treated as a random sample. The assumption made is that these data represent material which may typically be encountered, and which will display similar relationships between the criterion variables of stiffness and distortion to the predictor variables such as batten knot content and log taper. Thus the usefulness of the measurements could be indicated. However, it is recognised that for the FR1, 2, 3 and 4 material any of the relationships established (for example, between tree height and stiffness) may be site specific and may not necessarily transfer to the "mixed" material in an industrial setting.

Binomial correlation, multiple regression and correlation (MRC) and analysis of variance (ANOVA) was used to analyse the interrelation between variables and produce predictive models. The MRC models illustrated the effectiveness of combined knowledge of these variables. From the inspection of the data, the effect of applying threshold values to sorting criteria could also be evaluated.

1.3 Background

Sitka spruce is the UK's most important commercial species, providing over half the total volume of softwood timber produced, and representing 28% of the total forest area (Forestry Commission, 2008). The supply of softwood timber in the UK is expected to increase markedly over the next twenty years, but with concerns about decreasing wood density, larger proportion of juvenile wood, increased incidence of compression wood and poorer stem form (Achim *et al.,* 2006).

Sitka spruce takes its name from the seaport of Sitka in Alaska and its natural range extends down the seaboard of western America from mid-Alaska to California (Cary, 1922). Most of the trees in this country were grown from seed obtained from the Queen Charlotte Islands in British Columbia. In its native land Sitka spruce grows to immense size; its notable grandeur having been described by the explorer Meriwether Lewis in 1806 who encountered trees that were 12 feet in diameter (3.7 m) and 230 feet tall (70 m), with the first 20 or 30 feet (6 to 9 m) without any limb. British-grown Sitka spruce trees grow relatively quickly and tend to be harvested on short rotations. As a consequence the timber differs significantly from the slower grown softwoods with generally higher density and lower knot content, currently imported or available from North America and northern Europe. British-grown Sitka spruce tends to meet a lower structural grade than imported softwood, which can exclude it from certain markets. For example, none at present is used for trussed rafters; the main UK market for higher grade softwood. Some timber frame manufacturers prefer imported timber because they consider the level of knots in British-grown timber (which can cause problems of nail-fouling) to be too high. Distortion, which is also regarded to be relatively high for British-grown Sitka spruce, can also cause problems with the travel and positioning of boards on automated timber frame production lines.

Domestic Sitka spruce and imported Norway spruce (*Picea abies*) can be compared by reference to the Ministry of Technology Forest Products Research publication Bulletin 50 (Lavers, 1969). On the basis of the small clear samples studied, mean density at 12% moisture content for UK Sitka spruce is given as 384 kg/m^3, whilst the density of Norway spruce is given at 417 kg/m^3. For modulus of elasticity (*MOE*) the values are 8100 N/mm^2 and 10200 N/mm^2 respectively; and for modulus of rupture (*MOR*) 67 N/mm^2 and 72 N/mm^2 respectively. According to Holland (2005), who had extensive experience at BRE testing timber, whilst UK grown Sitka spruce generally grades to Strength Class C16, imported Norway spruce readily grades to C24.

1.4 Quality requirements for structural timber

Probably the biggest limiting factor in timber usage is its lack of dimensional stability on drying. There has been a move in construction away from the use of solid timber joists towards the use of engineered wood products such as I-beams, which exhibit lower cross-grain shrinkage and distortion on drying. Wood is inherently anisotropic in its structure, and is not the only material available for use in construction. Notable are recent developments in competing, alternative construction methods such as large format thin joint masonry, light steel frame and Structural Insulated Panels. There is a move towards off-site production of prefabricated “volumetric” housing units, where dimensional accuracy is particularly important. Man-made composites such as Fibre Reinforced Polymers have also been recently developed as timber alternatives for products ranging from marine piling to ladders, as well as structural units for buildings.

The properties of British-grown Sitka spruce were the subject of extensive study by the Forest Products Research Laboratory (FPRL) during the 1930s, with the overall conclusion that, with suitable silvicultural management, it ought eventually to become more comparable with imported softwood for “utility” purposes. The end uses of timber at that time are in many respects quite different to that of today, with pit props and trench-lining being examples of uses which no longer exist.

Trussed rafters (which were introduced into the UK in the late 1960s) are usually fabricated from higher Strength Class softwood such as TR26 (approximately equivalent to C27 as defined by EN 338:2009). The usage of lower Strength Class timber tends to result in the need for increases in the section size (depth), together with larger area punched metal plate connections, which may not be economic. Nevertheless the possible use of domestic Sitka spruce for trussed rafters has been the subject of some experimentation (*e.g.* Harrod, 1975). BRE recently carried out, on behalf of a commercial client, a number of load tests on trussed rafters fabricated from Sitka spruce which satisfied the requirements of BS 5268-3:2004 Code of practice for trussed rafter roofs. This code stipulates much tighter limits for distortion than those given in BS 4978:1996 for General Structural timber, as well as other quality requirements for defects such as fissures, wane and knots (with particular reference to their effect on connector plates).

Glued laminated elements (“glulam”) also require timber which is not prone to distort on drying, as does timber supplied to other markets, such as the DIY trade, where boards are often stacked unrestrained in heated warehouses. Distortion on drying (as distinct from deformation under load) takes a number of forms (Figure 1.1), the importance of which may be different for various applications. Bow and spring are essentially caused by differences in longitudinal shrinkage across the batten section, whilst twist is driven by the presence of spiral grain. Cup is the result of differences in radial and tangential shrinkage.

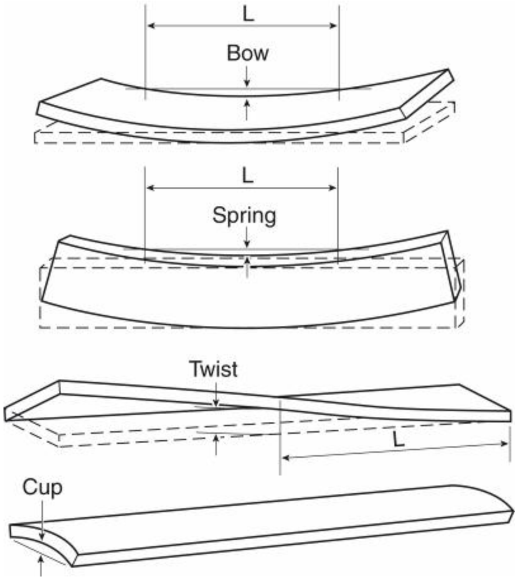

Figure 1.1: Distortion in the form of bow, spring, twist and cup.

Structural designs can be tailored to use timber which is of lower grade (although it may not be economic to do so), but timber that is too distorted to use, or causes problems in service, will struggle to find a market. Mochan (2002) alluded to British-grown Sitka spruce's poor reputation among end-users. Typically a British sawmill producing C16 timber may suffer a reject rate of around 3% at machine grading stage due to inadequate strength parameters, but an additional 7% reject rate due to distortion; usually in the form of twist. In the UK, timber is commonly machine graded at around 18% moisture content following, kiln drying and tends to distort further as it dries down to in-service levels (typically 12%).

Sitka spruce is suited to the oceanic climate of the UK and grows well in upland, exposed areas. Adapted growth responses of trees include the development of spiral grain to make the tree more stable (Ennos, 2001). Changes in the wood microstructure also make the tree more flexible so that it can reconfigure more efficiently away from the wind. Unfortunately for the forester, a successful living tree might not necessarily produce successful processed, dried timber. Trees that were selected and planted decades ago may not produce material that is either suited to, or can compete well with, new construction technologies.

1.5 Application of scanning technologies

The potential of the better quality material within British-grown Sitka spruce has often been highlighted. Sorting of timber in the future is likely to be aided by automatic scanning equipment, but the effects of segregating the better quality resource from the lower, particularly in respect to strength grading, need to be considered. With better information on the material being processed, optimised sorting can be performed without undermining the necessary strictures of the grading system. According to EN 14081-1:2005, timber that is graded shall not be re-graded to the same or different grades unless the method of determining machine settings has made allowances for changes in the population caused by the previous grading. Sorting, for example at log stage, may alter the characteristic properties of the material on which the grade settings are based. Removal of the better quality logs from a production line will have the effect of reducing the average quality of the remainder.

Three dimensional log shape scanners (Figure 1.2) are already used to optimise volumetric yield, and these also have the potential to be used to automatically determine timber quality, for example on the basis of log taper or out-of-roundness. Novel technologies such as tomographic log scanners (Figure 1.3) will undoubtedly become more affordable in the future, and can be used to determine factors such as knot sizes and whorl spacing prior to sawing. This information could be used to determined cutting patterns, directing unsuitable timber away from structural sizes. Computerised log tagging and board marking systems can allow information from the forest such as tree height or axial position within the stem to be linked throughout the wood chain. By investigating the relationships between timber variables the potential worth of these techniques can be indicated.

Relatively simple laser/camera setups can be used to measure grain angle, knot content and other defects on boards. Material likely to distort excessively, or likely to be rejected at machine grader stage, can be segregated prior to the expensive process of kiln drying. Such “green sorting” can both improve efficiency and enable the timber to compete in the more discerning markets such as trussed rafter and metal web beam production which it would not otherwise reach. X-ray graders, in addition to the measurement of clear wood density and knot content, also have the potential to gather information on “rate of growth” (ring width) and compression wood content, and might also be used to determine board radial position and orientation within the stem (Figure 1.4). Knot position data can be used to sort or cross-cut timber so that problems such as knot fouling do not occur during later manufacture of trussed rafters or timber frame panels.

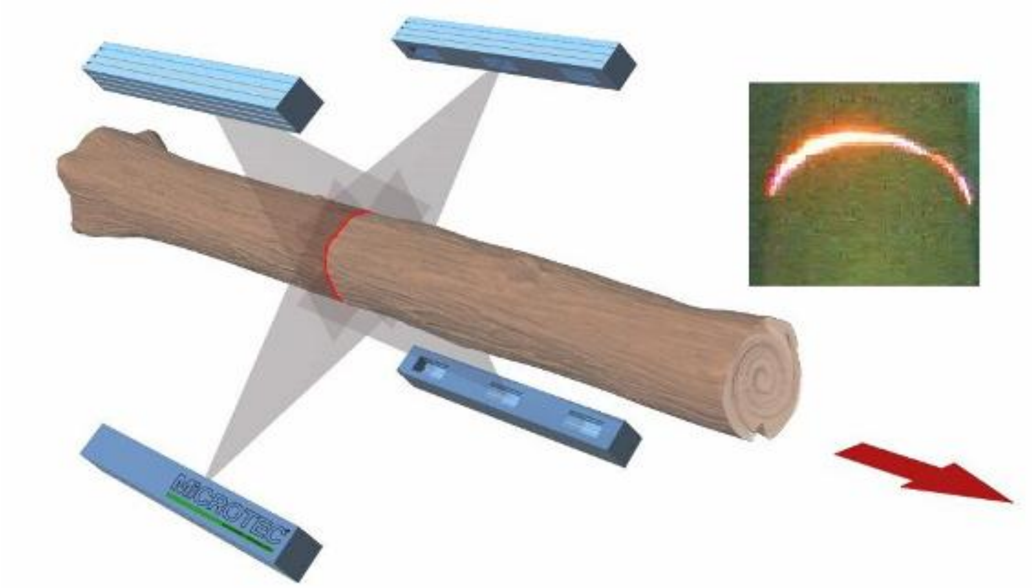

Figure 1.2: Three-dimensional log shape scanner, operating on principle of triangulated measurement of laser sheet of light images (inset).

(picture courtesy of Microtec)

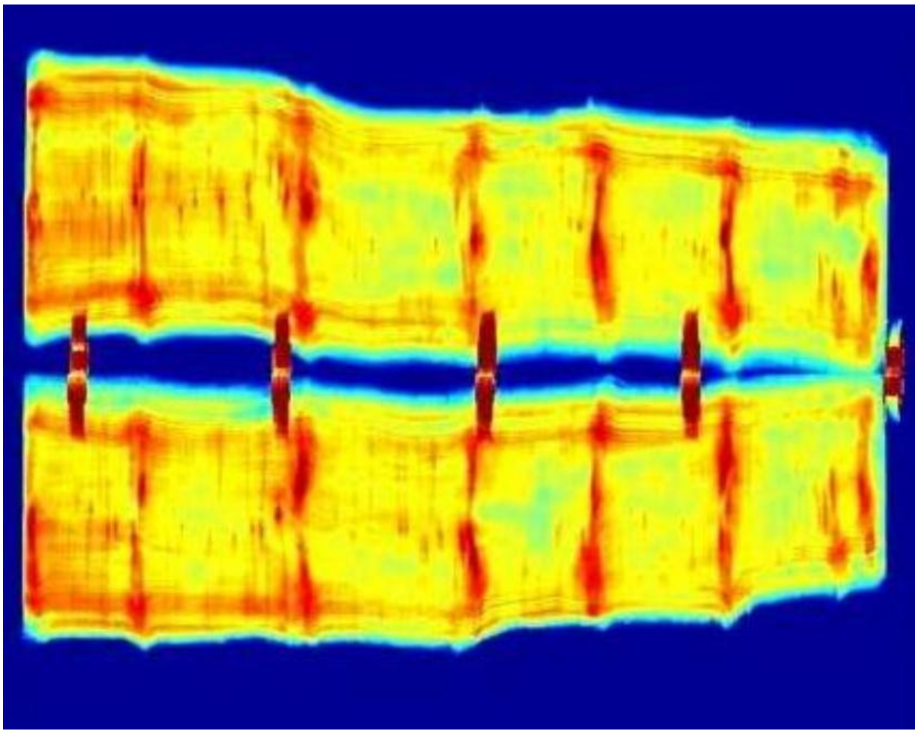

Figure 1.3: Example of X-ray attenuation profile produced by tomographic log scanner, showing knot positions and whorl spacings.

(picture courtesy of Microtec)

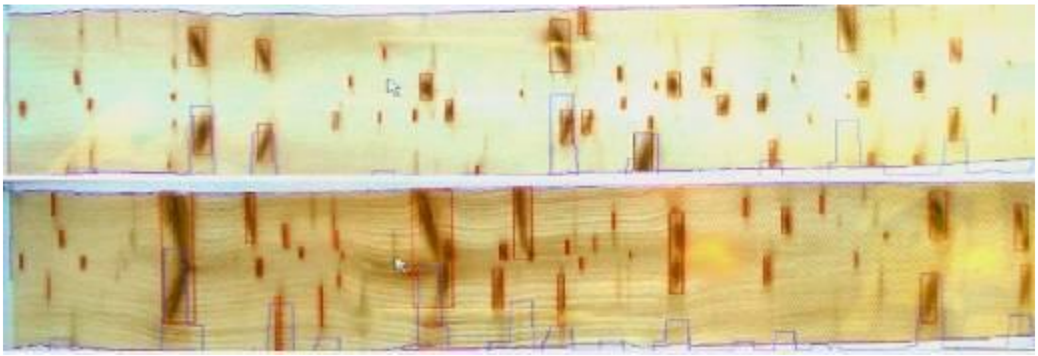

Figure 1.4: Image from X-ray grading machine showing knot positions on boards.

2 Literature review

2.1 Introduction to literature review

Timber is one of the oldest building materials and a great deal has been written on its structure, properties and usage. Concerns over the quality of plantation timber go back to the beginning of the twentieth century. The quality of British-grown Sitka spruce has been the subject of considerable research at BRE (formerly PRL and FPRL) since the 1930s. With timber being a much studied and familiar material, it might appear that there is little left to uncover. Thornquist (1993) produced a comprehensive summary on the effects and properties of juvenile wood. Richter (1932) studied the twisting of telegraph poles. Timell (1986) wrote three volumes on compression wood; referencing within these the observations of many others. Yet, there are concerns that the quality of British-grown timber will diminish further, due partly to changing forestry practice. Hubert (2004) presented stem form data suggesting that future yields of structural quality timber will fall.

Since the 1980s there has been remarkable development of advanced timber grading and scanning techniques (Szymani, 1999). The advent of relatively fast and inexpensive computing power has allowed technologies such as tomographic log scanners and optical board scanners, once limited to research work, to be used industrially. Moves within industry are towards the use of high speed X-ray grading machines. These new types of grader measure different parameters to the bending type machines they replace and base grading decisions on a combination of measurements according to empirical rules. It was the objective of this research to assess the possibility of applying a similar approach to sort timber earlier in the production process. This literature review examines the research already undertaken on the key characteristics.

A comprehensive review on the effects of silviculture on the timber quality of Sitka spruce was produced by MacDonald and Hubert (2002). The following is of particular interest in their report: two pieces of work by Maun (1992 and 1998) the first of which showed that grain angle had a low influence on the stiffness of Sitka spruce battens, whilst the later work showed that it was highly significant. In comparison, Kliger *et al.* (1995) showed that grain angle had little influence on the stiffness of Norway spruce. Possibly unresolved is the effect of spiral grain on stiffness (distinct from the effect of cross grain associated with knots and stem deviation). In the summary of the review by MacDonald and Hubert, density is reported to be a highly significant predictor of batten stiffness; but higher density wood is also stated to have poorer drying stability (this being attributed to its ability to absorb more water and hence exhibit greater shrinkage and swelling).

The following sections deal with juvenile wood, timber distortion and stiffness separately, and in more detail. Work of particular relevance to the findings, or that published during the course of the research, is referred to in greater detail in the sections dealing with summary of results and discussion. A great many reports and papers are pertinent to both distortion and mechanical properties such as those dealing with slope of grain or compression wood. Many, if not all, aspects of tree and wood quality are interrelated. This poses something of a challenge when considering the order in which to deal with them. Early work at FPRL/PRL on Sitka spruce relevant to both distortion and strength are reviewed in a separate section.

2.2 Juvenile wood

A great many articles have been written on the subject of the quality of “young” plantation grown softwood. Brazier’s numerous treatises on juvenile wood are especially illuminating, not least because they tend to summarise the findings on British-grown Sitka spruce. By way of defining the nature and behaviour of juvenile wood he refers (in Brazier, 1970) to the various observations made by others of the changing nature and anatomical structure, such as cell size and alignment, density and microfibril angle, that occurs from the centre of the tree outward, whereas later formed adult wood tends to be more consistent (Figure 2.1). Juvenile wood was defined by Larson (1969) as that formed in close proximity to the foliage and regarded the term to be a misnomer; better described positionally as “core-wood” or “crown-formed wood”.

Trees that grow quickly in their early years, or are harvested at a young age, tend to contain a high proportion of juvenile wood. Because the outer portions of logs are either chipped or converted into falling boards, structural sizes from such trees will be composed either completely or partially of juvenile wood. Significantly they will be composed of material that is of changing nature across their section. Generally juvenile wood has been found to be less stiff than adult wood, and the greater anisotropy also tends to cause distortion on drying. The timber which is obtained from plantations today is, in this respect, inferior to that which has been obtained in the past from natural forests. Trees which are harvested as soon as they are able to yield structural sections such as joists (typically 200 x 47 mm) also tend not to have any of the clear wood, free of branches, that develops at the lower part as the forest canopy rises. Consequently the timber also contains more knots.

As illustrated by Zobel and Sprague (1998) the trees harvested today, at short rotations, are much younger and tend to be a smaller size than those available in the past. Despite this, there is a greater need to utilise as much as possible of this resource against a background of competing, alternative materials as well as a requirement to preserve natural “old growth” forests. The greater proportion of juvenile wood and top wood in the timber produced from plantations today is the very reason why this material is of research interest.

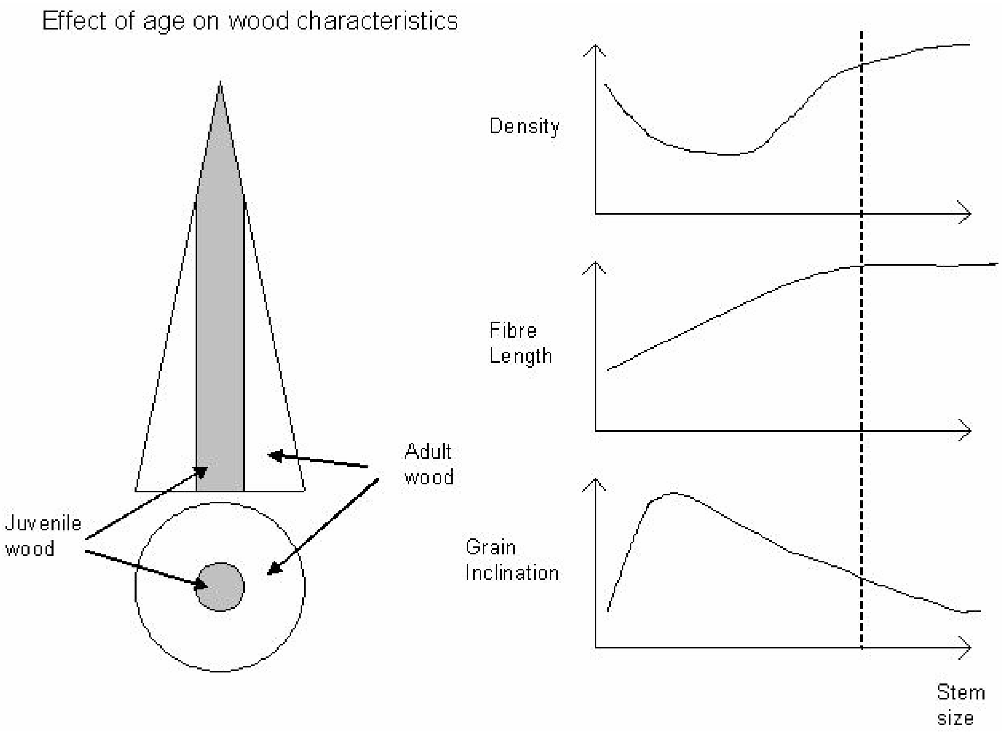

Figure 2.1: Juvenile wood distribution (generalised schematic), with typical patterns from pith to bark for a 30-year-old conifer. (after Brazier *et al.*, 1976). Note that the vertical line appears to represent the juvenile wood/adult wood boundary.

2.3 Spiral grain and twist

Spiral grain is a natural feature of wood in which the grain is at an angle to the major axis of the tree, and may change with age (Figure 2.2).

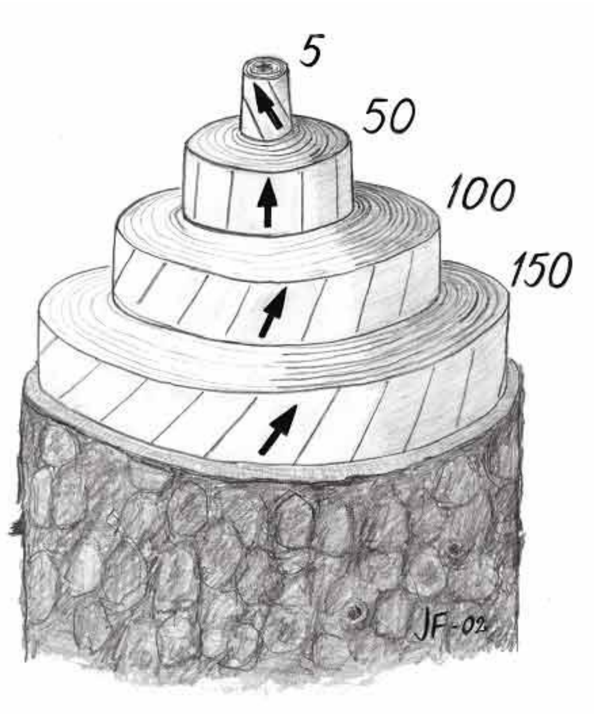

Figure 2.2: Spiral grain development in an old spruce tree, with ring number marked (after Säll, 2002).

Spiral grain has long been known to influence twist (Stevens 1961; Brazier 1965; Preston 1950). Figure 2.3 shows a board containing pith, with spiral grain, which has developed severe twist on drying (notable is the relatively little amount of space between knot groups where grain angle can accurately be assessed). Balodis (1972) noted that twist increased with increasing angle of spiral grain and decreased with increasing distance of the board from the pith. His analysis showed that twist was proportional to the ratio of grain angle to distance from pith; and that the constant of proportionality is a function of the tangential shrinkage component of the wood. Balodis suggested that the effect of twist could be reduced by increasing the vigour (*i.e.* growth rate) of the trees. An increase in stem size, he argued, results in the production of wider boards which can be more effectively restrained during seasoning, and increases the relative proportion of material outside the critical region surrounding the pith.

Figure 2.3: Slope of grain marked on a severely twisted batten containing pith.

Most researchers are in agreement on the influence of spiral grain on twist. For example, Danborg (1994) found in material from young Norway and Sitka spruce that the boards were prone to severe twisting, that the twist was induced by spiral grain, and that it was most pronounced in small dimension boards sawn near the pith. However, there are exceptions: Maun (1998) found that the magnitude of grain angle had little effect on drying distortion in the form of twist.

Danborg (1994) observed that bow and spring (which is caused by differences in longitudinal shrinkage, and is not related to spiral grain) was problematic only for boards near the pith, and on this basis it might be reasoned that all boards close to the pith should be selectively sorted. However, this might involve segregating and discarding an unacceptably large proportion of the timber.

Johansson (2002) described trees in which spiral grain continued to increase with distance from the pith (the inference being that these were a particular problem), whilst for other trees spiral grain increased from zero at the pith, then reversed, becoming negative. Clearly the usefulness of under-bark measurement of spiral grain on home-grown material depends on the relative incidence of each type. Because the direction of spiral grain angle changes with age, trees can also exhibit an axial variation in grain angle on the outside of the stem (Harris, 1989).

Harris (1989) produced a 200 page treatise on spiral grain. However, the effectiveness of industrial sorting for propensity to twist is not dealt with, nor is the influence of stem form on spiral grain angle. The concept of boards cut such that they have balanced spiral grain across their section is not featured, although Burger's (1953) observations on the twisting of telegraph poles are of particular note:

> "In conifers that follow the common pattern of spiral grain, being initially left hand and sometimes changing to straight grain or right hand spiral grain in outer wood, poles that have left hand spiral grain throughout twist more than those with straight grain or right hand spiral grain on the outside"

Nyström (2002) concluded that logs with left handed spiral grain angle larger than 2.5° will yield battens which acquire large left handed twist on drying, whilst logs with right-handed spiral grain over 5° will acquire a moderate right-handed twist. Nyström's explanation for this seemingly inconsistent behaviour is that the absolute majority of trees have a left handed spiral grain close to the pith, and when the spiral grain is right-handed on the outside of the stem, a proportion of the boards produced have balanced spiral grain across their section and thus stay relatively straight after drying. It follows that the trees with right-handed spiral grain (under bark) should be preferentially obtained, where available, and that left hand spiral grained trees of even quite modest spiral grain angle should be avoided. Clearly acute angles or small differences between angles are more difficult to measure than larger ones, particularly so in an industrial setting such as a sawmill log conveyor. Factors such as angle of log axis relative to the axis of measurement together with influences such as taper and stem form will be important.

Harris (1989) commented that spiral grain is seldom consistent from the centre to the outside of the stem. He also refers to Stevens and Johnston (1960) who conceded that the complexity of spiral grain patterns and the influence of internal restraint virtually preclude the accurate estimation of the actual twist that will develop during drying. Harris concludes that both theoretical and practical results indicate that the main structural feature of wood associated with twist in dried boards is the ratio of grain angle to distance from the pith.

In Harris's section on the measurement of spiral grain angle he details two methods which have been proposed to summarise grain angles as a single statistic for each tree. Referring to Kennedy and Elliot (1957), one method involves calculation of a "cumulative absolute spiral grain angle" whereby the direction of spirality is ignored on the grounds that only the absolute degree of spirality affects timber properties. Brazier (1965) aimed to provide some indication of the volume of wood affected by spirality with his "spiral grain index", which aimed to overcome the issue of giving undue weighting to values near the pith which affect a relatively small volume of wood. Both methods of assigning a single value to a tree appear to miss the point later illustrated by Nyström (2002) of battens which distort less owing to the balanced polarity of spiral grain angle occurring across their section, and Balodis (1972) who identified that twist was related to the quotient of grain angle over distance from pith.

In his description of the characteristics of Sitka spruce grown in its native land of North America, Cary (1922) states that spiral grain is found but not to "any great extent", but that it could generally be detected in a standing tree by a twisting of the fluted portions of the lower trunk. Overall the timber was considered to be very strong for its weight and straight grained, hence its use in the aircraft industry and nowadays for guitars. The production of high quality timber for such purposes does not suggest a trend to develop right-hand spiral grain with age. Of interest, in BRE’s wood library, is a sample old “old growth” Canadian Douglas fir (*Pseudotsuga menziesii*), cut well away from the pith but with a spiral grain angle of around 30° and which has twisted remarkably, indicating that it is not only plantation timber which can develop this form of distortion.

It is sometimes assumed that the greater longitudinal shrinkage of juvenile wood is the cause of the twist exhibited by “fast grown” plantation timber. In the model for twist proposed by Stevens (1961) the constant of proportionality is, however, tangential shrinkage. He postulated that for a grain line A-B (Figure 2.4) in a square cut section taken from a tree with spiral grain, tangential shrinkage causes rotation of B relative to A because the grain line is unable to extend (*i.e.* expand longitudinally) as the section faces on which A and B lie contract. Although Stevens made no comment on a possible interaction between twist and compression wood, it follows that if grain line A-B is able to contract (*i.e.* shrink longitudinally) then rotation of B relative to A will be lower.

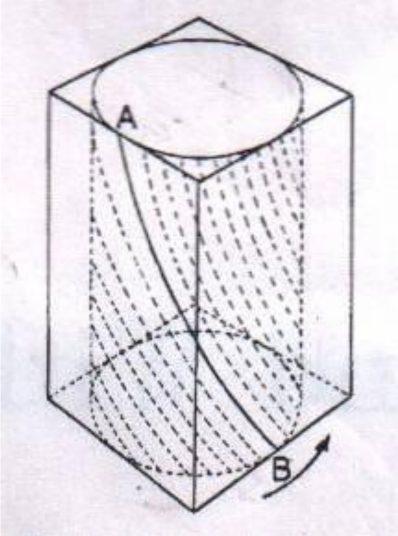

Figure 2.4: Spiral grain (after Stevens, 1961).

By inspecting a twisted batten it can be seen that the rotation is not such that it could be attributed to longitudinal shrinkage of the fibres, *i.e.* this observation is in agreement with Stevens. If it were the case that longitudinal shrinkage of the fibres caused by juvenile wood or compression wood made twist worse, then the direction of twist would tend to be such that the rotation of the batten was in the opposite direction, *i.e.* longitudinal shrinkage along the fibre line AB would pull B in the opposite direction to that indicated above. Thus compression wood and juvenile wood, by virtue of the greater longitudinal shrinkage, might actually reduce twist. Johansson (2002) concluded, following her review of the parameters that influence distortion, that longitudinal shrinkage had only a minor effect on twist and that spiral grain angle followed by distance to the pith were the major parameters. Booker (2005) demonstrated through the construction of a geometrical model, that an increase in longitudinal shrinkage would reduce twist. He concluded that one of the aims of tree breeding should be to reduce tangential shrinkage since an increase in longitudinal shrinkage would tend to cause bow and spring, together with an unacceptable shortening in length after drying.

In recent work (Straže *et al.*, 2007) that involved the measurement of axial, radial and tangential shrinkage of 18 x 60 mm lamellas cut from Norway spruce logs, a governing equation for twist at various drying stages was determined which included an exponential term for distance from the pith (*i.e.* twist rapidly decreasing with increasing pith distance), spiral grain angle in the middle of the lamella, and tangential shrinkage.

In statistical models for the twist of British-grown Sitka spruce battens, as detailed in an internal report for the EU “STUD” project (Maun *et al.*, undated), it was apparently expedient to include a term related to the knot content in addition to slope of grain on the outer face of battens, distance from the centre of the batten to the pith, juvenile wood content and ring width. Knots, because they represent “interruptions” in otherwise straight (or spiral) grained timber, might have an influence on twist. Their relative distribution on batten faces may also be an indicator of both axial and radial position within the stem.

Mattheck and Kubler (1995) describe the formation of spiral grain in certain trees as being the result of the torsional effects of asymmetrical crowns or branches due to prevalent wind loads, but also illustrate the biological advantages of spiral grain in facilitating a more constant circumferential distribution of nutrients and water in case of branch or root loss. However, the advantages of spiral grain are accompanied by certain disadvantages. When stems with spiral grain are subjected to bending they are exposed to potentially damaging shear and tension perpendicular to the grain stresses. Trees which develop mechanically stimulated spiral grain (as distinct from genetically controlled spiral grain) as a result of non-symmetric crowns or branching under prevalent wind conditions, can fail due to changes in wind load. Thus the development of spiral grain, and hence propensity for a tree to yield twisted timber, may be related to factors such as tree size, rate of growth, position within the stem, or branch and hence knot characteristics.

Skatter and Kucera (1998) theorised that the patterns of spiral grain in conifers were a growth strategy in response to the combined effects of bending and torsion as a result of prevalent wind loads. Their hypothesis explaining the development of spiral grain, was that prevalent torque arose from the combination of systematically asymmetric crowns (due to the sun) and prevailing westerly winds within the areas where conifers are grown. Torsional forces in the stem occur when the crown is asymmetric in the plane perpendicular to the wind direction. Spiral grain improves the breakage strength of the tree stem. Even radial distribution of branches (and hence knots) may therefore be a characteristic of trees with low spiral grain. Twist may also be linked to tree size, with taller trees being subject to greater wind forces whilst shorter trees on the same site benefit from shelter. A genetic predisposition to develop spiral grain may also be linked to branching or other characteristics of the tree such as predisposition to form (or not to form) compression wood.

2.4 Compression wood

2.4.1 Formation and characteristics

Compression wood is a type of reaction wood that tends to form in conifers that have been partially blown over, in trees on the windward side of exposed plantations, in the lower part of trees growing on a slope, and below heavy branches (Desch and Dinwoodie, 1996). Compression wood is characterised by its relatively dark brown colour compared with normal wood, together with more highly developed late wood (Figure 2.5).

Figure 2.5: Compression wood (darker bands) in batten with deviating pith.

Jaffe (1973) coined the term “thigmomorphogenesis” to describe the phenomenon in which mechanical stresses influence plant organogenesis (*i.e.* growth behaviour and structure). Mattheck and Kubler (1995) give a plausible explanation for the ability of compression wood to bring about stem correction. The compression wood of gymnosperms expands in the axial direction and pushes the tree into the vertical position (so reducing the lever arm and hence bending stress on the stem). They considered that since the fibrils in the walls of compression wood cells are arranged “quasi-transversely” to the cell axis, under internal cell pressure these cells are able to expand longitudinally whilst lateral expansion is restrained. The cells are shorter than in normal wood because of the higher risk of buckling. In Mattheck and Kubler's modified version of the wood-reinforced concrete analogy, the brittle but pressure resistant lignin chimneys are thickened when exposed to compressive stresses, for example on the lee side of the prevailing wind or on the lower sides of leaning trees. Cellulose (rather like steel reinforcing bar) is characterised by high tensile strength. Thus the high microfibril angle, higher lignin content and thickened cell walls of compression wood are explained. To complete the picture, tangential stresses are controlled by rays (composed of cellulose) which act as transverse interlocks.

A lateral branch taking the place of the leading shoot (Figure 2.6) is another example of negative gravitropism. In both cases the adaptation succeeds in reducing bending stresses. According to Mattheck and Kubler the potential successors' (*i.e.* radial shoots) urge to straighten is suppressed by the lead shoot, this being termed apical dominance, presumably by some chemical stimuli.

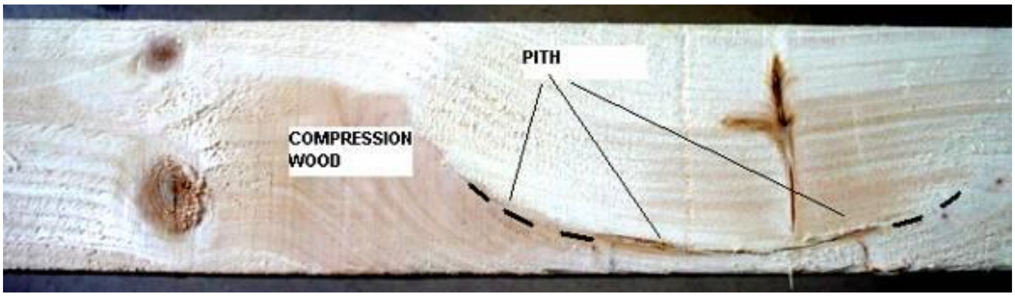

Figure 2.6: Compression wood formed as a result of loss of leader.

Mattheck and Kubler (1995) illustrate a number of theorems on the subject of the mechanical self-optimisation of trees (note only two of these are directly related to the formation of compression wood):

1. The principle of minimum lever arms, whereby the tree minimises external stresses by reducing the length of the loaded lever arm. Minimum lengths can be achieved by changing the shape of the tree through the development of reaction wood, or through the passive yielding of the flexible parts of the tree to achieve sail reduction.

2. The axiom of uniform stress, whereby unavoidable stresses are distributed evenly on the surface of the tree. Stresses on the surface of the tree are uniform at each point on the time average. Knots do not result in weakness, at least not in a tree stem.

3. To minimise critical shear stresses, the wood fibres and tree rings are arranged on the axial or tangential force flow.

4. The strength of the wood depends on the distribution of the mechanical stresses that act in the tree when it is exposed to external loads. The outer shape of the tree and the local internal quality of the wood are optimised and adapted to the degree and type of loading.

5. Unavoidable weak points are counterbalanced by the growth stresses developed by the tree. The growth stresses counteract the critical loads that may cause failure.

2.4.2 Effects on timber quality

The greater longitudinal shrinkage of compression wood compared with normal wood causes bow and spring on drying. It can have a particularly deleterious effect on the drying stability of products which are laminated at high moisture content, particularly if the number of laminations is low (Figure 2.7 and Figure 2.8). Compression wood, although denser than normal wood, is also considered to have inferior bending strength; in particular being brittle.

Figure 2.7: Glue laminated falling boards with pronounced bow on drying caused by compression wood in the outer plies.

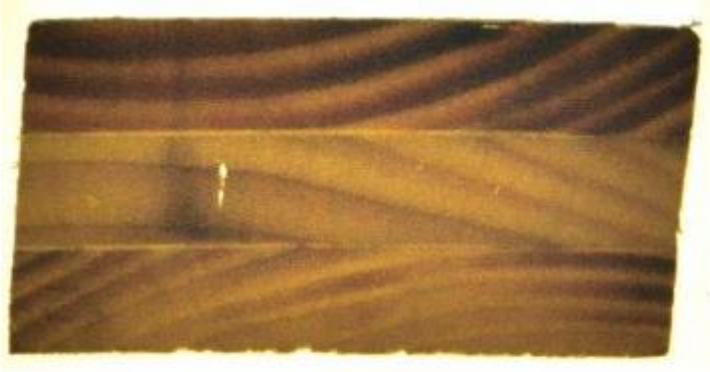

Figure 2.8: Section through distorted glue laminated timber showing compression wood in upper ply (by means of transmitted light on a thin section).

2.4.3 Relation to log shape

Compression wood in logs may be indicated by their shape and form, as shown in work on Scots pine (*Pinus sylvestris*) and Norway spruce (Warensjo, 2003). Since compression wood is associated with stem form correction, it is reasonable to expect that a curved log is likely to contain compression wood. In fact, it is difficult to see how such a change in stem form could be accomplished without some radical change in internal structure. The characteristically thicker growth rings of compression wood can also cause logs to become oval in section (Figure 2.9) or exhibit pith eccentricity.

Figure 2.9: Compression wood in Sitka spruce fence post (centre). The growth ring structure suggests that the log was quite oval in section.

Industrial 3D laser scanners are used in many sawmills to optimise volumetric yield by controlling sawing patterns on the basis of log shape factors, and also have the potential to be used automatically for log sorting on the basis of propensity to distort. Compression wood, however, can also be present in straight trees (Figure 2.10). The log pole shown was 13 m long, straight and round in section, but with a slightly eccentric pith.

Figure 2.10: Compression wood noted in Sitka spruce foundation pile after driving.

Brüchert and Gardiner (2002), in a study of the effect of wind exposure on the spatial distribution of compression wood, noted a remarkable amount of compression wood in the inner core of all the trees tested. It was also reported that close to the edge of the stand the trees grew shorter and thicker than the trees which grew in more sheltered positions. This type of compression wood, which forms throughout the tree section and not just on the leeward side of prevailing winds, has the purpose of reinforcing the stem from compressive forces resulting from wind sway. Such trees are clearly not correcting stem form deviation. This type of compression wood, formed throughout the tree section, might not cause problems with distortion due to its more uniform distribution.

In her PhD thesis Stokes (1994) refers to Teleweski's (1989) definition of "flexure wood", which also forms in trees stems as a result of bending. According to this account, flexure wood forms when the stem returns to vertical, as opposed reaction wood which forms when the stem is permanently displaced; both types act to keep the stem straight. According to Stokes, flexure wood is denser than normal wood, with a smaller tracheid lumen size and microfibrils at angles approaching that of compression wood. Flexure wood tracheids are reported not have a thicker S2 cell wall layer with intercellular spaces, such as those found in reaction wood. Flexure wood is more rigid with a greater inertia and flexural stiffness than normal wood and so is more effective at maintaining the stem in a vertical position during windy conditions. Stokes also refers to Telewiski and Jaffe's (1986) observations that flexure wood results from an increase in the number of tracheids. This type of material, again illustrates that the properties of so-called "clear wood" vary, and are defined by microscopic structure and not, simply, density.

2.5 Stiffness and strength

2.5.1 Influence of density and microstructure

Dense hardwoods such as greenheart (*Guaiacum spp.*) and oak (*Quercus spp.*) are favoured for their strong timber. The grade stresses and moduli of elasticity for the higher strength classes of softwoods tabulated in BS 5268-2 and EN 338 correspond to higher values of average density, compared to those of lower strength classes. On a simplistic level, it might be considered logical to assume that a doubling of density for any similar material will result in a corresponding increase in both stiffness and strength in the same way that two identical timber beams placed side by side will be twice as strong as a single beam. Where this notion falls down, however, is when the denser material is dissimilar; in the case of wood this could be due to differences in micro-structure or chemical composition.

In a review paper on microfibril angle (MFA, defined in Figure 2.11), Cave and Walker (1994) question arguments by others that density has a major effect on the yield and quality of timber, highlighting that changes in stiffness observed from pith to bark cannot be solely attributed to changes in density. Brazier (1986) also questioned the significance of density for the selection for wood quality in improvement programmes aiming to improve strength and stiffness. He identified two features of greater influence, grain inclination and presence of juvenile wood. British-grown Sitka spruce, with its tendency to have a large juvenile core owing to fast growth, is known to tend to produce lower structural grades than imported softwoods with lower rates of growth. The proportion of juvenile wood within battens, and not density, would therefore seem to be (potentially) a reliable indicator of likely grade.

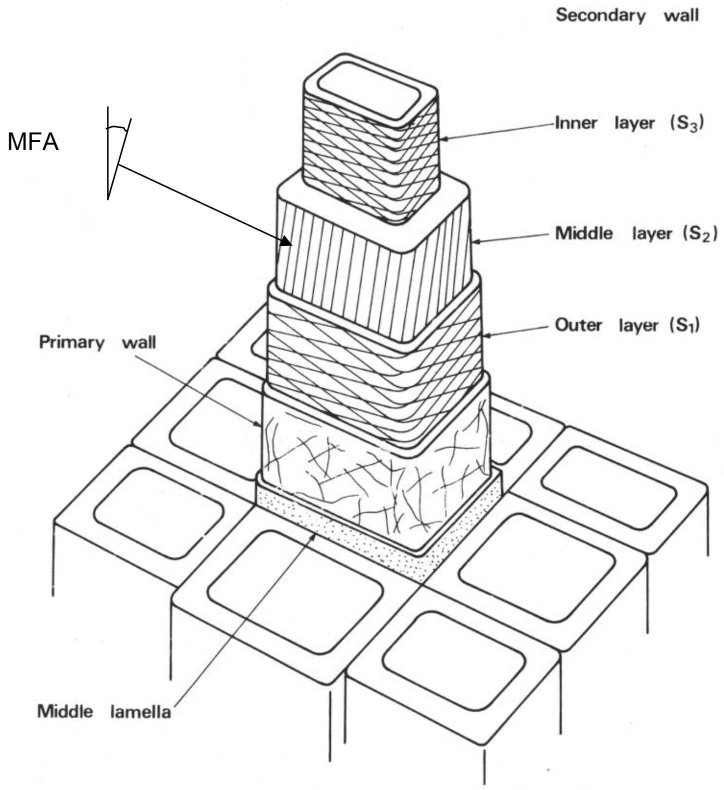

Figure 2.11: Simplified structure of wood cell wall, showing angular arrangement of the microfibrils in the S2 layer (after Dinwoodie, 1981).

Brazier (1986) noted the influence of microfibril angle on stiffness, and was concerned that the strength reducing features he observed were all adversely affected by forest management policies which favoured enhanced rates of growth on short rotations. Brazier illustrated the effect of microfibril angle on stiffness with a linear fit graph (MFA v. MOE). It is significant that in Brazier's graph MOE has not been corrected for sample density – implying that density was not significant for the batch tested. Given the significance of microfibril angle, and the fact that it cannot be measured in an industrial setting, the question then is how closely can its effect be estimated from related variables such as ring width, proximity to pith and percentage of juvenile wood.

Brazier (1991), commenting on the weaker material he observed near to the base of Sitka spruce trees, stated that it occurred in battens cut from both juvenile core and adult wood. Brazier suggested that the reason for the low performance of the near-butt wood might be due to a combination of low density, irregular grain associated with a buttressing effect from the roots, and possibly also "unusual" cell microstructure. In more recent work, Xu and Walker (2004) assembled stiffness profiles from pith to bark and from butt to the upper top logs for radiata pine (*Pinus radiata*), and identified a zone of high microfibril angle and low stiffness within the base of the trees. Like Brazier, they advocated segregating this material. Note that this was apparently the subject of a trial at PRL/BRE, however the work (on material from the Forest of Ae) was apparently not fully reported.

Cockaday (1992) determined the variation of bending stiffness, microfibril angle and dry density throughout four Sitka spruce trees. A large proportion of Cockaday's work, however, concerns the effect of sample size and orientation with respect to growth rings on his measurements; hence the testing of more homogeneous timbers such as the tropical hardwood ramin (*Gonystylus spp.*), together with laminated composites. Cockaday showed that bending stiffness was strongly and inversely related to microfibril angle. He concluded that the relationships observed between MOE and density were either very poor or insignificant, and considered that extremes of density in his samples were associated with compression wood. His samples were carefully selected to be straight grained. The determination of rate of growth was also outside the scope of his work.

Cockaday found no single consistent model to represent the variability of MOE with all four trees studied. Both MOE and MFA were found to vary systematically across the radius of the tree but not axially, whilst density was not found to vary systematically. This suggests that Cockaday did not encounter any markedly low stiffness at the base of the trees studied, which contrasts with the findings of Brazier (who was his PhD supervisor). Since Cockaday's samples were clear of knots, there is no reason to suppose that for full-scale samples with knots there will be any improvement in any observed relationship between bulk density (*i.e.* including knots) and stiffness.

Pendini (1992 and undated) reported, from studies into the variation of MFA in Sitka spruce grown in Denmark, that MFA decreased very rapidly from growth ring number 3 until numbers 9 to 12 where it stabilised. This was found to be more apparent at breast height (1.3 m) than at other sample heights (25%, 50% and 65% of tree height). Within a growth ring it was found that MFA decreased with increasing height in the stem. The fastest growing trees were found to have the highest MFA in both juvenile and mature wood, although it was also observed that the narrow growth rings, formed in some trees when they are suppressed, tend to have tracheids with a high MFA. Overall, the data suggested that fast growth will lower the quality of juvenile wood in Sitka spruce but did not support the theory that the number of juvenile growth rings will increase with increasing growth rate. From the graphical data presented of trends in MFA from pith to bark, greatervalues of MFA were observed at 1.3 m than higher in the stem.

Treacy *et al*. (2001), in a report on the mechanical and physical wood properties of Sitka spruce grown in Ireland, detail inverse relations between both MFA and MOE, and between MFA and MOR; although in the case of the latter MFA accounted for only 34% of the variation.

2.5.2 Influence of knots

Knots are regarded as defects in timber. The assessment of knot area ratio (KAR) forms the basis of the visual grading of softwoods to BS 4978. It would therefore not be surprising if their presence was accompanied by strength and stiffness reductions. However, Brazier (1991) concluded, in a study on Sitka spruce, that they had only a very small to marginal effect on stiffness. Maun (1992), however, stated that there was a strong correlation between stiffness and knots. Holland (2005) also reported that during machine stress grading the grade determining lowest stiffness value frequently occurs at knot positions, and in particular those of large splay knots.

Samson and Blanchet (1991) tested white spruce (*Picea glauca*) battens in bending with a test geometry similar to that used in bending-type grading machines. Experiments showed that the effect of knots was very small. It was reasoned that the low sensitivity to knots was the reason for the quite poor correlation between strength and machine measured stiffness.

In Brazier's earlier report (Brazier, 1986), on the growth features affecting the structural performance of wood, it was shown that the effect of an increase in knot size on Sitka spruce was a reduction in the minimum reaction force of the grader (*i.e.* lower stiffness). For battens from the butt length logs (to 4 m height), for a given knot size the performance of butt material was demonstrated to be poorer than that of battens higher in the stem with the same knot content.

The graphical representations of data presented in Brazier (1991) show that there is a much poorer relationship between average batten density and stiffness for butt logs, than for those from higher in the tree (this might possibly be due to the so-called weak butt effect, as detailed above, occluding any relationship). When comparing average values of stiffness for the mid-900 mm of the battens (obtained by averaging the sequence for the grader output), and combining these batten values for each log, it was found that the most important factor influencing between-log variation was density, with the amount of juvenile wood a lesser, but significant, factor. Knots were found to contribute nothing to the variation in stiffness in second length logs and made only a small contribution to that of the third length logs, however it was noted that knot content did not vary much between logs (for a variable to be found significant it must actually vary within the test sample).

In a study based on the measurement of green heartwood density and percentage of heartwood of Norway spruce logs using computer tomography (Oja *et al*., 2001), it was shown that it was possible to predict stiffness, and hence batten grade, determined by a Cook-Bolinder strength grader. The measured green heartwood density was found to be the most important variable; although high values for the knot related variables had a negative effect on stiffness. The model constructed for large butt logs was the strongest, which suggests a good relationship between density and stiffness for battens at the base of the tree. The exercise involved sorting logs into high strength and low strength groups, which were then graded. From the above, it can be concluded that both density and knots affect stiffness, since stiffness measurement is the operating parameter of the Cook-Bolinder grader.

The volume authored by Bräuner and Poulsson (1997) contains a section on the relationship between strength and visual parameters obtained from a study into the mechanical properties of Sitka spruce grown in two regions of Denmark. Although the precise relationships between MOE and other parameters such as total knot area ratio (TKAR) are not given, relationships between strength and the other parameters are. Since it is reported that MOE is the parameter that best predicts strength it can be reasonably inferred that relationships between parameters such as TKAR and strength will follow relationships between these parameters and stiffness. Density is reported to be second, after stiffness, at best predicteding strength (R^2 = 0.4 and 0.2 for the two sets of data), whilst knots did not seem to play a major role in the prediction of strength. A parameter based on "knot cluster" (not explained in the text) and TKAR are reported to be the best visual parameters to predict the bending strength. However, they only explained 0.14 to 0.24 of the bending strength variation. Wide face knots are stated to show no efficacy for the prediction of mechanical properties.

In *Timber - its nature and behaviour* (Dinwoodie, 2000) there are several useful inclusions of BRE test data showing relationships observed between various parameters such as density, MFA, slope of grain and stiffness or strength. One such inclusion is a graphical representation of MOR versus TKAR for British-grown Douglas fir, showing a marked reduction in MOR with TKAR and a linear fit with R^2 = 0.36. Stated is that, in general, the significance of knots depends on their size and distribution, with knots in clusters and those on the top or bottom edges of beams being more critical.

2.5.3 Influence of axial and radial position

Kliger *et al.* (1995) studied the strength and stiffness of battens in relation to position within "fast grown" trees from two plantations of Norway spruce in southern Sweden. This type of timber was deemed to probably constitute a substantial part of the raw material supply in the future, and has an obvious parallel with the situation in the British Isles. The results indicated that the mean values for strength and stiffness were lowest for the core studs and increased further away from the pith. The radial variation in strength and stiffness appeared to be associated with variation in ring width. Density, alone, did not explain the radial variation but could be used together with either ring width or knot area ratio to explain the stiffness and strength respectively (with an apparent lack of relationship between knots and stiffness). An increase in strength and stiffness from the butt logs to the top logs was found to be significant. Density was found to be the best variable to explain this variation. The magnitude of grain angle and the margin knot area ratio had only a minor effect on strength and stiffness.

In other work (Johansson and Kliger, 2000) the parameters that showed the greatest influence on the bending strength of Norway spruce grown in Sweden, Finland and France, were knot area ratio and grain angle. The 750 battens tested were obtained from 23 different stands, and the ages of the trees varied from 60 to 135 years (in comparison most UK Sitka spruce is felled much younger at around 35 to 50 years). Other variables recorded in the test work included density, ring width, distance to the pith and distortion. From a table of the influence of parameters on strength and stiffness given in the paper it can be seen that density has a strongly positive effect, whilst distance to pith is relatively poor. The biggest influences on twist are reported to be grain angle and distance from pith, whilst the influence of knots and ring width are concluded likely to have been due to association with proximity to pith.

Sonderregger *et al.* (2008) reported, from a study of small clear samples taken throughout the stems of Norway spruce trees grown in Switzerland, that there were clear trends for an increase in both MOE and MOR from pith to bark, but no distinct trends axially. Brüchert (2000), in a study of the effect of wind exposure on Sitka spruce, also reported no significant axial variation in either stiffness or strength.

2.5.4 Influence of slope of grain

In an internal PRL report (Brazier, 1954) the percentage loss in strength of cross-grained Canadian-grown Sitka spruce with respect to straight grained timber is tabulated (Table 2.1), indicating that there is a linear relationship.

Table 2.1: Percentage loss in strength of cross-grained Canadian Sitka spruce with respect to straight grained (after Brazier, 1954).

Slope of grain	Reduction in MOR (%)	Reduction in MOE (%)
1 in 25 (2.3°)	6	7
1 in 20 (2.9°)	7	8
1 in 15 (3.8°)	9	11
1 in 10 (5.7°)	15	17
1 in 5 (11.3°)	29	33

In a project report on the influence of spiral and diagonal grain on the mechanical properties of North American Sitka spruce and Douglas fir (USDA Forest Service, 1918) a non-linear relationship between the MOE and slope of grain is illustrated, with rapid reduction in stiffness occurring at a grain angle of 1:15 (approximately 4°). Apparent in the graphical data presented, is that from 0° to 4° the reduction in stiffness is approximately linear (reducing by around 2.5% per degree increase in slope). Hankinson’s non-linear formula for strength property reduction with change of angle of fibre direction is detailed in the USDA Forest Service Wood Handbook (USDA, 1987), together with theoretical graphical representations and a guide to methods of measurements. The methods of measurements of slope of grain are given in the USDA Forest Service (1943) publication “Guide to determining the slope of grain in lumber and veneer”. Notable is that the angle of grain in the radial face is indicated by the direction of annual rings, whereas the angle of spiral grain is made on a tangential face using a scribe.

Booker *et al.* (1997) determined the relative importance of spiral grain angle, density and microfibril angle on the MOE of 44 specimens of radiata pine taken at various points from pith to bark from three trees. Although a negative correlation between MOE and spiral grain angle is presented, it was determined that this relation was not causative, and that the variation was primarily a function of microfibril angle since these parameters (together with density) tend to change with distance from the pith. This does not, however, necessarily preclude the useful estimation of stiffness using slope of grain measurements.

2.5.5 Significance of log shape and tree form

Trees, according to Mattheck and Kubler (1995), “optimise” their performance in the environment not only through changes in external form, but also of internal structure. Thus a feature such as log ovality might have some bearing on the properties of the material within. Trees that are oval probably have adopted that shape for a reason, whilst those on the same site may have remained rounder in cross-section but maintained their strength by some other strategy. By analogy an engineer can choose a more efficient section, opt for a different grade of material, or apply reinforcement.

Jäppinen (2000) used log geometry factors such as taper, out-of-roundness and surface unevenness, together with batten variables based on knot size and grain distortion, to construct models that were reported to be better in predicting batten performance than machine grader stiffness models, or models using batten variables alone.

Watt *et al.* (2006), in a study of the factors affecting the basal stiffness of radiata pine saplings, determined that site had a highly significant influence on stiffness, which exhibited an almost threefold range across the plots studied. Minimum temperature during early autumn, root depth and tree slenderness (tree height/ground-line tree diameter) exhibited the strongest correlations; the latter being consistent with Euler buckling formula, *i.e.* increases in stem slenderness will require increases in material stiffness to reduce the risk of stem buckling. However, findings based on studies of four–year-old saplings may not necessarily transfer well to mature trees, which might develop variations relating to dominance as the canopy closes.

Maun (1998) reported that knots, grain angle and juvenile wood were the key growth characteristics that influenced the machine grade stiffness of Sitka spruce. Together with Tunnicliffe-Wilson (of Lancaster University), he derived a predictive model for average machine grader stiffness based on the variables “mean average grain angle”, “mean maximum grain angle” and “mean weighted knot areas on batten faces” (the precise nature of these variables is not reported). Further “transformed variables” were derived to predict, with some success, the variation of machine grader stiffness along the battens. These transformed variables included “percentage of juvenile wood multiplied by the height of the arc of the log”, “inverse height of arc of the log multiplied by density”, and “natural log[arithm] of the mean average grain angle”. A total of nineteen such variables accounted for 66% of the variance. It is possible that these transformations have the aim of incorporating non-linear relations into a model based on linear multiple regression and correlation. It appears likely that use of variables based on the height of the arc of the log was an attempt at predicting the increase in stiffness with height characteristic of battens exhibiting the weak butt effect (note that Maun appears to have been using the definition of log arc given in the 1993 Forestry Commission Field Book).

2.5.6 Significance of rate of growth

Trees that have grown quickly and are harvested at a relatively young age tend to contain a high proportion of juvenile wood. This is characterised as having relatively high ring width, high microfibril angle, low density and low latewood proportion. Ring width is a criterion used in visual grading (to BS 4978), thus it is logical to assume that this has some relation to batten stiffness, either as an indication of density, association with juvenile wood or other indication of the relative position within the stem.

Although the UK forester and silviculturalist may face criticism for developing a “fast grown” crop, the slower grown material within the British Isles may not necessarily be the better timber in terms of exhibiting lower levels of distortion or reaching a higher strength class. Watt *et al.* (2006), in a study of radiata pine grown in New Zealand, reported that the higher stiffness material contained a greater proportion of latewood as a result of increased growth rates, and that this was linked to higher temperatures in early autumn. However Lasserre *et al.* (2004), encountered a significant negative relationship between tree diameter at breast height and stiffness for eleven-year-old clones of the same species.

Brazier (1991) found, in a study on the effect of spacing on the vigour of 41 Sitka spruce trees, that the timber at the base of the tree was of poorer quality (*i.e.* was less stiff), and that stem size had no apparent effect on structural wood performance. In a between-tree comparison he reported that that the most important wood characteristics were density and juvenile wood. He observed that the effect of increased tree vigour was to reduce density and therefore reduce structural performance, but that the effect on juvenile wood was to reduce its proportion (*i.e.* that the larger trees on the same site had proportionally less juvenile wood). The two effects therefore tended to counteract each other.

Cameron *et al.* (2005), in a study of the influence of selective breeding on juvenile wood formation in Sitka spruce, concluded that the period of formation of juvenile wood appeared to be largely independent of growth rate. In this work the properties of three progenies were compared from the analysis of discs sampled at 1.3 m height taken from selected trees, these progenies being “fast grown”, “slow grown” and a control of Queen Charlotte Islands (QCI) stock (which represents the majority of that planted in the UK and commercially available). The three progenies showed similar trends from the pith to the bark in the variation of ring width, density, tracheid length and diameter, and microfibril angle. In all the treatments, the wood in the first 12 or so rings was associated with high ring width, high microfibril angle, low density and low proportion of latewood, although the tracheid length and microfibril angle showed little evidence of levelling off at 19 rings from the pith. Thus it was considered that the period of formation of juvenile wood, usually considered to be the first 12 rings, was somewhat arbitrary.

From the graphical data presented in the above work, microfibril angle is shown to be higher in both the juvenile core and adult wood of the faster growing progeny, compared to both the slower growing progeny and the QCI stock. Trees from faster growing Sitka spruce progenies were also found to have significantly larger branches, less latewood, more compression wood but lower grain angle (Livingston *et al.*, 2004). Although a distinction needs to be made between findings based on studies of differing progenies and that those which are directly relevant to trees of the same stock, the above suggests that faster grown trees are likely to yield inferior timber in terms of stiffness. However, the lower grain angle (presumably spiral grain angle) of the “fast grown” progeny suggests that these trees will yield timber with lower twist.

In later work, Mochan *et al.* (2008) reported that there was no deterioration in construction strength grade requirements following assessment of improved Sitka spruce compared to QCI origin. In this study (of material from Kershope) for the best progeny, increases of up to 30% green saw log volume were predicted with equivalent properties. Density in the outer portion of the log (as indicated by Pilodyn penetration) was reported to be only marginally lower in the family with the highest rate of growth.

2.6 Early FPRL and PRL studies on Sitka spruce

One of the earliest accounts of the properties of British-grown Sitka spruce is that produced by the Forest Products Research Laboratory (later BRE) in 1933, headed "Project 0. Investigation 67. Investigation to determine whether Sitka spruce is a suitable species for cultivation in the British Isles" (FPRL, 1933). Project 0 included assessment of the timber from four localities: Durris on the Kincardine-Aberdeenshire border, Bedgebury in Kent, Leighton Hall on the Montgomeryshire Border, and Fulmodestone wood in Norfolk. At that time the trees felled they were between 48 and 70 years old. As a reflection of the era, the possible uses considered for such timber included non-tainting boxes for butter and pantry shelving, barrels, trench lining, as well as general boarding.

The above report details several less than favourable comments arising from commercial trials. The timber was characterised as of wide ring growth, coarse grained, with large knots, and did not compare well with similar types of Russian and Swedish timber. Knot content varied significantly between the batches of timber. Of particular interest is the observation that spiral growth was particularly evident in the butts.

Project 18 of the Forest Products Research Laboratory was an investigation into the relation between the structure, chemical composition and physical properties of Sitka spruce. Progress Report 6 of this effort (FPRL, 1936) details the results of a wide range of observations made on samples obtained from the above four sites. It was reported that there was no significant difference in average density of clear specimens between the different localities, and no consistent difference between butt material and that from higher in the bole (in terms of density). The densest wood was found at the outside of the tree but it was observed that the increase in specific gravity from the centre outwards was not as consistently progressive as in the case of the strength figures (note that "strength" refers to compression parallel to the grain tests, whilst bending tests do not appear not to have been carried out). Of particular note are the general observations that wood from the middle of the merchantable bole (around 6 m from the butt) is stronger than that from the butt. It is also noted that within the disc, passing from the centre outwards, there is a tendency for strength to decrease at first and then to increase. Positive relationships were observed between strength and specific gravity, and strength and percentage of latewood; whilst inverse relationships were observed between strength and ring width, and between specific gravity and ring width. The importance of microstructure is evident, in the observation that it appeared that larger cells have a higher strength efficiency (*i.e.* for given values of specific gravity and ring width, higher strength is associated with a larger "calibre" *i.e.* diameter of the tracheids). Of particular note in the above report is the suggestion that some of the unaccounted variance was due to differences in the slope of micellar components of the cell wall (*i.e.* MFA). Such abnormally flat inclination of the cell wall "micellae" was noted in the compression wood encountered, which was regarded as a more efficient type of tissue with respect to compressive strength. One cause of its formation was proposed as the actual compression resulting from leaning of the trunk, although other factors including change in water supply and interruption of growth by frost or defoliation were also suggested.

A more lengthy account of the above FRPL work is given by Phillips (1941) in a Department of Scientific and Industrial Research Report which includes observations on a second set of material from

Glenbranter and Benmore in Argyllshire. This second set was reported to be of slower growth, with rather more numerous but smaller knots. All the logs in the study were cut from the lower 30 feet (9 m) of the stems and were reasonably straight and cylindrical. As with earlier work, compressive strength parallel to grain, density and ring widths were the main variables obtained. From the summary, the following is particularly relevant: wood from near the middle of the merchantable bole was (again) found stronger than that from the butt; likewise strength was found to increase away from the pith. Both differences in strength could not be accounted for by a difference in density alone. Within each disc the specific gravity decreased radially for the first 10 to 15 rings and then increased progressively towards the bark. The differences in specific gravity noted between the top and butt discs were insignificant. It was noted that within each set little variation was evident between the material from different localities.

The report features an account of the methods of measuring microfibril angle, including the method of estimation by using the slit-like pit apertures. The variation in microfibril angle with height in the tree was studied by examination of corresponding rings in each pair of top and butt discs (*i.e.* same year of growth). In the central core it was found that the microfibril angle was larger at the butt than higher up in the same ring. A note is also made that the butt latewood is also less prominent than higher up. The following apparently generalised observation is worth repeating verbatim:

> "For example, the fifth ring from the pith had a [micro]fibril angle of 14 degrees at the 20 foot level and the same ring at the 8 foot level (10 rings from the pith here) had an angle of only 5 degrees. Outside the central 10 rings here were no consistent differences due to the height in the ring."

Thus microfibril angle, and the properties of clear wood onto which one might hope to project the strength reducing affects of measurable features such as grain angle and knots, appear to change markedly throughout the stem both longitudinally and radially. It is important to bear in mind that when trends from pith to bark are reported that these observations include outer material which may not end up in boards used for structural purposes. In Philips' report, and elsewhere, reference is made to Air Ministry requirements for timber (Sitka spruce was used in the Mosquito during WWII and in the Sopwith camel in WWI). Thus considerations on the usefulness of clear wood, away from the butt, and not rafter and joist sizes was perhaps uppermost in the minds of those whose suggestion it was that this timber ought, with good growing practices, yield timber equal to that of Canada.

Of interest because of its assertions on rate of growth, and also because it was published in an era of "make do and mend", the War Emergency Edition of the Handbook of Home-grown Timbers (HMSO, 1941) stated that when Sitka spruce is quickly grown, with large knots and wide rings, the timber is only suitable for the roughest class of packing cases or boarding, but when slower grown (six rings to the inch) the quality improves considerably. The Ministry of Technology (1967) publication "Home-grown timbers Sitka and Norway spruce" contains more detail. Spiral grain in Sitka spruce is described as a commonly observed feature of the timber near to the pith, varying a great deal in intensity between individual trees. It is also reported that the inclination of the grain is usually left of vertical, diminishing with age, and higher in Sitka than Norway spruce. Both spruces are stated to be prone to contain compression wood, particularly in trees that are exposed to westerly gales, however the incidence of this defect is not high and its effect is not serious. Twisting, on drying, is stated as worse in Sitka than Norway spruce, and bow is definitely greater.

A review paper on the quality of Sitka spruce grown in Great Britain (Wood and Bryan, 1960) is illuminating. From this, the following is repeated:

> “One of the characteristics of these young trees is the considerable variation in timber quality from the pith outwards. The density is high near to the pith dropping to a minimum at about 10 to 15 rings from the pith and then increasing gradually to the cambium layer. The higher density near to the pith is not proportionally stronger. The inner zone of the tree is characterised by low density and progressive changes in the dimensions and structural characteristics of the tracheids. Excessive longitudinal shrinkage of the juvenile wood is not a feature of Sitka spruce and the timber is not bedevilled by excessive spring or bow. The timber seasons quickly and well. The major defect, however, is twist, and the twist is always in the same direction. The degree of twist in any one board has been shown to be related to the degree of spirality, and inversely proportional to the distance from the pith.”

FPRL Bulletin no. 48 (FPRL, 1962) details the results of the “Sitka survey” of that period. It is stated that, in the material examined, the spiral grain was almost always left handed and of the trees studied, 60% had maximum grain angle near to the pith with a gradual decrease to the bark, whilst 30% displayed a trend for constant spiral grain angle or with a slight increase to the bark. There was no relationship between the trends observed and region or quality class of log.

BRE Current Paper CP 20/76 (Brazier *et al.*, 1976) detailed the results of a later evaluation of home-grown Sitka Spruce. Of interest (since presumably the trees were not chosen on grounds of peculiar stem-form) in otherwise mundane tables of density data are several which were denoted as having very extensive or severe compression wood. Nine consignments of material planted in the 1920s were studied, from various localities of Scotland (Tarentig, Glenbranter, Dovey, South Stone, Glengarry, Drumtochty, Beddgeletert, Achnasshellach and Castle O’er). The use of Brazier’s spiral grain index occludes the original grain angle values, although index values with heights are given. It is reported that no real trend emerged in these values. However, when reporting the variance of spiral grain index there was a significant difference between trees on the same site, but no difference between diameter class and heights. Spiral grain in the material studied is reported to exhibit a slight but statistically significant reduction compared with the more vigorously grown material studied earlier.

Although the above report (like others) is unflattering on the machining properties of Sitka spruce, it is more sanguine over the high yield of comparatively strong M75 grade timber achieved, as defined in CP112 (BSI, 1967). However it is clear from the tabulated data that reject rates when grading to M50/M75 varied greatly. (Note that for British-grown Sitka spruce M75 is approximately equivalent to C18/C22, whilst M50 is approximately equivalent to C14/C16).

2.7 Automatic board scanning and detection of defects

In his PhD thesis "Automatic inspection of sawn wood" (Åstrand, 1996) reviews the motivation for the use of automatic inspection in the wood industry:

- Expensive labour – the price of labour is getting more expensive, whilst the cost of computers is falling;

- Tedious work – the manual inspection of wood often requires high skill and long experience. However the work is tiresome, tedious and monotonous. The level of personnel turnover is high;

- Speed – manual inspection is slow. Automatic inspection may be carried out without forming a "bottleneck" in the production process;

- Accuracy – human operators make mistakes. A better yield and higher quality may be achieved using an automated system;

- Flexibility and complexity – in an automated environment more complex decisions and situations can be handled. Information about every single defect, its type and position can be taken into account.

The processing speed of computers and memory has increased greatly over recent years, enabling large amounts of image based information to be rapidly analyzed; so-called "machine vision". Lower cost, high resolution digital cameras and laser diodes have also become available. Automatic board scanning systems can measure what cannot be seen by a human operator. X-rays can be used to measure density variations, whilst lasers can be used to measure slope of grain. Computers can be used to rapidly combine and utilise the information available from other instruments such as moisture meters and board dimension scanners, and possibly link these to information available from log shape scanners and forest tagging.

According to Åstrand (1996), the use of automatic board scanning also facilitates a number of production aims:

- Optimising raw material – removal of defects or minimisation of defects. Knots can be removed by processes such as finger-jointing. Boards may be cross-cut or trimmed to remove defects. Boards may be orientated so that knots are hidden or placed non-critical areas on finished products *e.g.* windows.

- Sorting of boards into different quality classes – sorting of boards prior to kiln drying ("green sorting") allows material which would later become rejected or downgraded to be sorted from the production stream so as to avoid unnecessary kiln drying or machining.

- Monitoring of the production line – in particular recording board details facilitates simulation prior to making changes in production.

With clear, straight grained, wood as perhaps the ideal, features such as knots and pitch pockets are termed defects, although they are of course natural features of the wood. Whilst growing, trees develop branches, the base of which become enveloped by the trunk. The form that these branch stubs take on sawn timber depends on the way in which the stub is sectioned. If the knot is cut perpendicular to its growing direction then the knot appears round, whereas if the knot is cut along its direction of length then a splay knot results. A knot which is surrounded by bark is called an encased or bark-ringed knot. Although many knots can be distinguished by virtue of colour or light contrast between knots and sound timber, light coloured sound knots are difficult to detect against background clear wood. Clear wood itself can have darker zones (*e.g.* compression wood). There can also be colour differences between sapwood and heartwood, particularly when freshly cut due to the variation in water content. Other forms of defect include splits, fungal decay and bark pockets, as well as dimensional defects such as wane. Distortion can also be measured by optical scanning techniques, as can board dimensions.

Sawn timber is said to have an inclined or cross grain when the wood elements lie at an angle to the long axis or sides of the piece (Brazier, 1954). The condition can be brought about in a number of ways. It results from the through and through conversion of trees with natural or spiral grain; and from the sawing of a tapered log parallel to the pith rather than the bark. Localised cross grain is produced in the conversion of trees with irregular stem form, butt swellings or heavy branching. The grain patterns and hence slope of grain are highly complex around knots, making characterisation difficult.

In most forms of board scanner the piece of timber passes through an array of cameras (Figure 2.12), with illumination being provided by fluorescent light tubes and lasers.

Line cameras are utilised to detect the position of board edges and knots (Figure 2.13). The image shows light intensity (white dotted line) measured across one face of the board, *i.e*. at right angles to the longitudinal axis. The red line represents the board face corresponding to the white trace line below, whilst the yellow line represents a dark knot, corresponding to a reduction in light intensity.

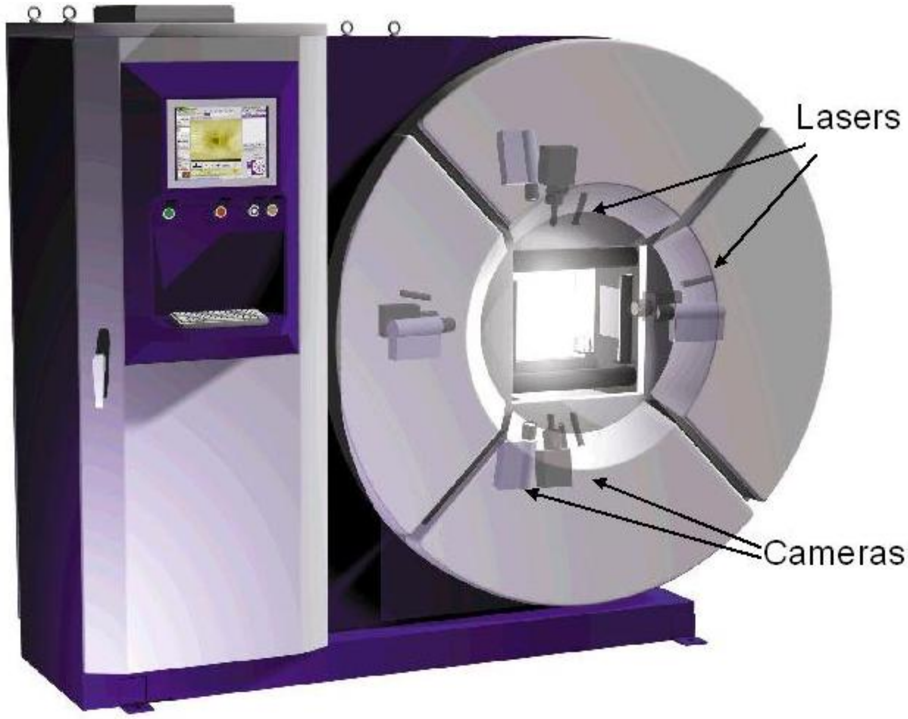

Figure 2.12: Wood Eye^{TM} board scanner, showing array of cameras and lasers.

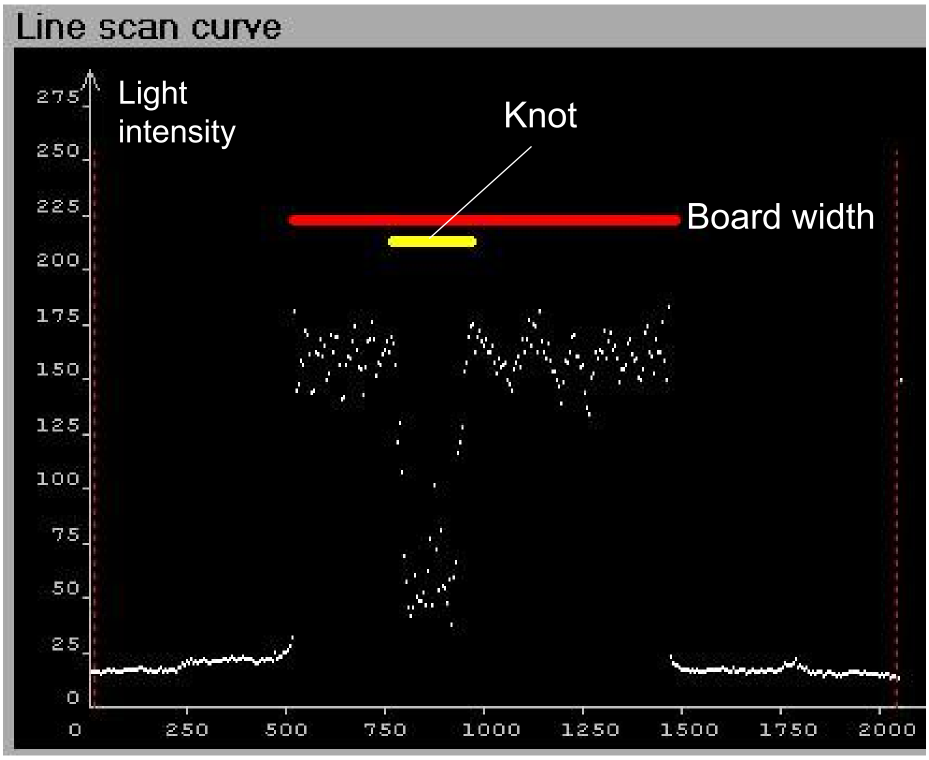

Figure 2.13: Line camera output.
(original in colour)

Note that in Figure 2.13 the horizontal scale is line camera pixel number and represents distance. The vertical scale is a function of light intensity subject to machine settings for gain and automatic camera iris adjustment (in this instance 256 corresponds to a white calibration surface illuminated by the scanners fluorescent tubes).

As the board passes through the camera array, an image or set of data is built up of each face of the board. This form of board movement is lengthways, but it is also possible to process images of boards moving sideways. Algorithms are used to process and analyse the data recorded, for example counting the size and location of knots, together with any dimensional problems with the board. Colour or brightness variation can also be evaluated, as an indication of the nature of the grain pattern.

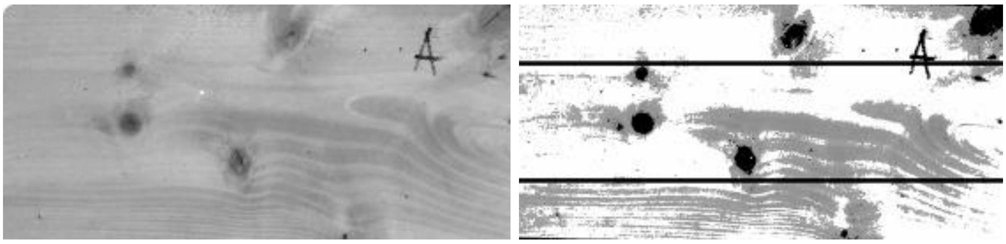

Figure 2.14: Unprocessed image (left) and processed image (right) showing normal wood, compression wood and knots being defined by three tone levels (white, grey and black).

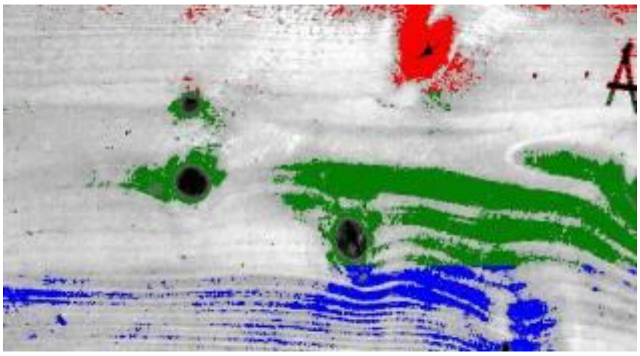

Figure 2.15: Processed image showing compression wood in three zones.
(original in colour)

Figure 2.14 shows the use of image analysis techniques on a piece of wood containing both knots and compression wood. By assigning certain thresholds of pixel brightness to three tonal classes, knots can be set to “dark”, compression wood to “mid-tone” and normal wood to “bright”. Subsequently the area of each group in any portion of the image can be calculated.

Figure 2.15 shows the above board, with areas of compression wood in the edges and central region resolved in colour. Such information might be used to predict distortion.

Image analysis techniques can also be used to measure the rate of growth on batten ends (Figure 2.16). By setting pixels below a certain threshold of brightness to zero and those above to a single brightness value, image information can be "hyper-contrasted". Because the image consists of a computerised matrix of pixel values, mathematical measurements of batten size and features can be performed.

Figure 2.16: Processed image of board end showing ring width and pith position measurements.
Dot indicates calculated pith position. (Note image obtained using experimental program developed by Mr Paul Dollemore and BRE)

By contrasting the particular colour signature of wood (*i.e.* hue), boards moving against a background of sawmill machinery can be distinguished and the knot content measured (Figure 2.17).

Light falling on wood tends to be scattered along the direction of the grain, rather than in the cross grain direction; the so-called "tracheid effect". In compression wood, however, wood the characteristic halo of light scatter is absent (Nyström, 2002; Nyström and Hagman, 1999), see Figure 2.18.

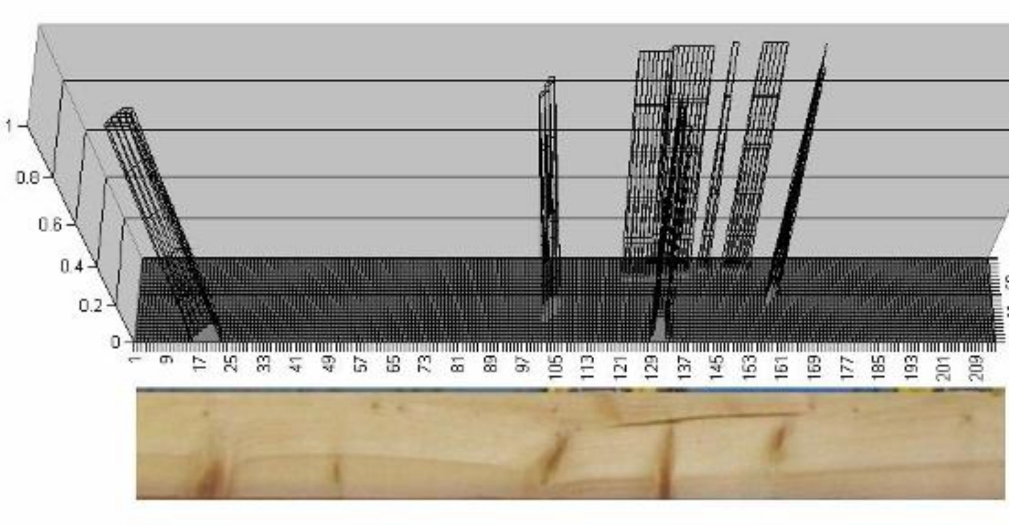

Figure 2.17: Board image obtained in a sawmill showing knots hyper-contrasted from background wood colour, with an algorithimic function of knot hue shown on the vertical scale. The horizontal scale is related to camera pixel number and represents distance. (Note data processed from experimental system developed by BRE and Dr Jeremy Parsons)

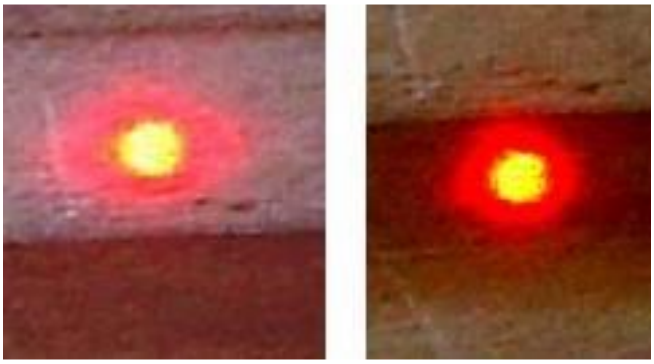

Figure 2.18: Laser tracheid effect, with normal wood (left), and compression wood (right). (original in colour)

The tracheid effect can also be used to measure grain angle (Figure 2.19), and detect knots (Figure 2.20).

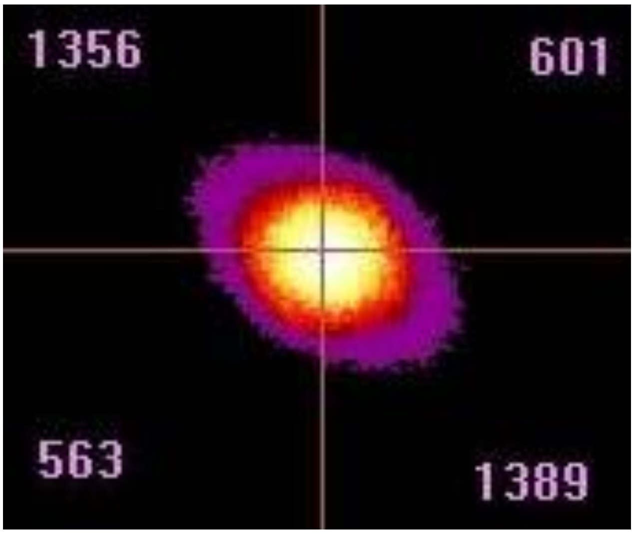

Figure 2.19: Processed image of laser halo indicating wood grain angle, with number of "bright" pixels in each quadrant. Image obtained using BRE / Mr Paul Dollemore developed software. (original in colour)

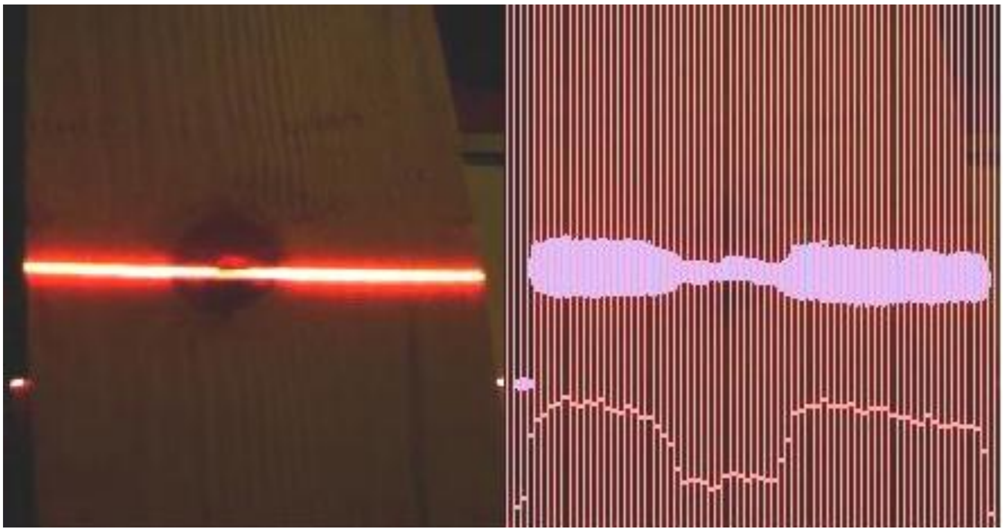

Figure 2.20: Laser tracheid effect used to detect knots. Laser line is projected onto board with knot (left), with processed image with light levels in each vertical column (right). Note experimental system developed by Mr Paul Dollemore and BRE. (original in colour)

Techniques for non-destructive testing and internal imaging of logs are under constant development. For example, Schad *et al.* (1996) detail the use of sound wave transmission, computed tomography, and impulse radar. The techniques are reported to be capable of detecting zones of high and low water content, density, decay and knots. Sepulveda *et al.* (2003) report on experimental work using an X-ray scanner to detect fibre orientation in Norway spruce logs. Stated is that earlier studies showed that a CT scanner could be used to accurately measure spiral grain in logs, on the basis of detection of directional vectors. In the work reported, significant variables used to predict spiral grain angle on boards cut from the logs were green heartwood density, knot volume and a measure of the asymmetrical distribution of knot volume. Although, despite the title of the paper, no significance was found using any of the 39 variables established based on predominant directional vectors derived from the simulated X-ray image. Brüchert *et al.* (2008) demonstrated that industrial CT scanning was capable of detecting knots, whorl spacings and growth rings in green Norway spruce sawlogs, although loss of information in saturated sapwood zones was evident.

A sawmill production line (Figure 2.21 and Figure 2.22) presents many opportunities, particularly at canted log stage, to make an assessment of the quality of the timber being processed, for example by measurement of knot content or grain angle. However, a limitation for existing sawmills is lack of mechanical sorting capacity in terms of number of conveying lines and storage bins. Handling more than one quality of timber, as well as variations in length and size, may not be practical.

Figure 2.21: Canted logs presenting faces upon which knot content and spiral grain angle could potentially be measured.

Figure 2.22: Boards with compression wood (red patches) indicating severe cross grain defects.
(original in colour)

2.8 Discussion and conclusions on literature survey

From the literature review it is not clear which variables, and hence which sorting criteria, will be useful for British-grown Sitka spruce. Work carried out on different species and of timber which is grown under differing circumstances and geographical conditions, may not be directly relevant. For example, studies on slow grown timber may not be relevant to faster grown material. Experimental work carried out for some other purpose (*e.g.* a within stand comparison) may not necessarily transfer to an industrial sawmill setting, where “mixed” timber from a wide range of sources would be encountered. Results based on the study of small clear samples from pith to bark may not be relevant for large section sizes cut predominately from the central portion of logs. Findings have tended to differ in research work; for example in Maun (1992) and Maun (1998) regarding the influence of slope of grain on stiffness. In any case, to determine the overall effect on any sorting process a dataset would need to be established encompassing all of the log and board variables required. No such dataset existed, or was available to the author, at the beginning of the work.

Because of the various findings of Maun (1998), Brazier (1986), Stevens (1961) and Nyström (2002) measurements based on the laser tracheid effect appear promising for indicating batten stiffness, propensity to twist and compression wood content respectively. From the work of Bräuner and Poulsson (1997), detection of edge knots rather than face knots appears likely to be more useful for sorting sawn timber on the basis of strength. Although there is little doubt that distortion in the form of twist is caused by spiral grain, variation of twist with height and batten size is worth investigation, as is the possible interaction between knots (which are associated with disturbed grain). Although Harris (1986) describes methods of measurement of slope of grain, the practical difficulty within an industrial sawmill setting is not discussed. Both Brazier (1986), and Maun (1998, 1992) based their measurements of stiffness on the output of the Cook-Bolinder grader – with no comparison being made to static bending tests about the major axis of the board such as that prescribed in EN 408:2003. These grader derived values of “plankwise” stiffness may be more sensitive to certain defects such as knots.

In the same way that it was clear that extremes of knot size and slope of grain are likely to affect timber stiffness and strength, it also seems likely that extremes of log form such as pith eccentricity, ovality and curvature will also be significant. As demonstrated by Mattheck and Kubler (1995) and Watt *et al.* (2006), trees adapt their shape according to mechanical principles, thus it is logical that the shape attributes of logs can be used as sorting criteria. It may be supposed that logs that grossly lack straightness are unlikely to produce good quality timber. However, within the limits of log deviation acceptable by a typical sawmill, some other factor may be more significant.

From Cockaday's (1992) observations of the radial variation in stiffness, and from Maun's (1990) work on predictive modelling, investigation of sorting on the basis of batten position also appears worthwhile. Brazier's (1991) observation that there was no (or a very poor) relationship between stiffness and log diameter within the stand studied is worth verification – since this suggests that forestry practice which aims at higher rates of growth is not detrimental. Whilst his observation of the negative relationship between stiffness and juvenile wood content, suggests that batten sorting on this basis would be worthwhile although, notably, data for butt logs is excluded. This relationship may not be significant when considering mixed material from both butt and upper logs.

Since microfibril angle cannot be measured industrially, yet is highly significant, it would be useful to determine the effectiveness of sorting based on other parameters such as position of piece in the tree stem. The precise cause of the weak butt effect noted by Brazier (1986) was not apparent at the start of this work, although there are indications in FPRL work that this is due to high microfibril angle. However, in the predictive models created by Maun (1990) a factor for butt logs was still required even though MFA was stated to have been measured. It is notable that this feature has been found present in Sitka spruce (grown in the UK) and radiata pine (grown in New Zealand) but does not appear to have been reported in Norway spruce (grown in northern Europe). Xu and Walker (2004) concluded that the causal effect is abnormally high MFA, and significant only with fast grown short rotation plantation species.

Above all, from the literature study, clear wood appears to be anything other than simply defect free wood of a consistent nature, for which only an assessment of density is needed to indicate its properties, and onto which the strength reducing effects of knots and sloping grain can be merely projected. Highly significant micro-structural and chemical variation occurs in clear wood, and the extremes this is evident in so-called “butt wood” and compression wood.

3 Method and sources of material

The overall method of this work was to obtain sample batches of timber and relate the tree, log and board variables (such as *DBH*, ovality and knot content) to batten performance in terms of stiffness and distortion. By relating both log and batten variables to end-product qualities, the worth of measuring these variables in the production process, together with the practical difficulties of their determination, could be indicated. In addition, by studying the behaviour of small clear samples (*e.g.* longitudinal shrinkage and stiffness), the effect of batten variables, such as density and compression wood content, could also be evaluated, free of the influence other variables such as knots. The nature of butt wood material could also be assessed.

The bulk of the practical work comprised the testing and assessment of around 500 battens of Sitka spruce obtained from four stands (FR1 to FR4) in two forests in Scotland: Lochaline and Benmore (see Appendix 1). This material was selected by Forest Research as part of the EU Compression Wood project (Gardiner and MacDonald, 2005), with the overall aim of including a variety of log shapes. The material from Benmore is considered by Forest Research to more typical of that likely to be available in the future *i.e.* timber which is harvested at relatively young age on short rotations. The assumption made is that this material will show similar relationships between variables (*e.g.* knot content to stiffness) to that which might be encountered at any sawmill. However, it is recognised that certain relationships (*e.g.* tree height to stiffness) may be site specific and may not necessarily transfer to the mixed material in any sorting yard *i.e.* that which has be obtained from a number of sources, including trees of differing age. Relationships observed between certain variables (*e.g.* log size to stiffness) may be influenced by factors such as inclusion of butt wood material. However the primary objective is to identify measurements which would be useful in industrial sorting. It is recognised that this approach may be invalid or unsatisfactory for other purposes. It is not necessarily the objective of this work to determine causal relationships.

Probably the most significant aspect of the timber is that FR1 and FR2 (Lochaline), having been planted earlier and at lower stocking density, yielded larger logs than FR3 and FR4 (Benmore). Ninety logs of 3 m nominal length from the four stands were characterised with variables such as top and bottom diameter, whorl spacing, and log deviation being manually recorded. Figure 3.1 shows a schematic of the typical log height positions. In this work butt logs are defined as those from (nominally) 0.5 to 3.5 m above ground level, whilst all logs above this height are termed upper logs. Cut height refers to the lowest point of the batten or log. No consideration has been given to the position of these logs relative to the live crown of the tree.

The logs were scanned by a Pronyx^{TM} 3D laser scanner in a sawmill before conversion, enabling further log shape variables to be extracted and also allowing the log shapes to be subsequently viewed using software tool developed by Mr Paul Dollemore. Measurements of log ovality and pith eccentricity were also obtained from scanned disc images supplied by Forest Research. Measurements of disc compression wood content and outer log slope of grain are not reported in this work.

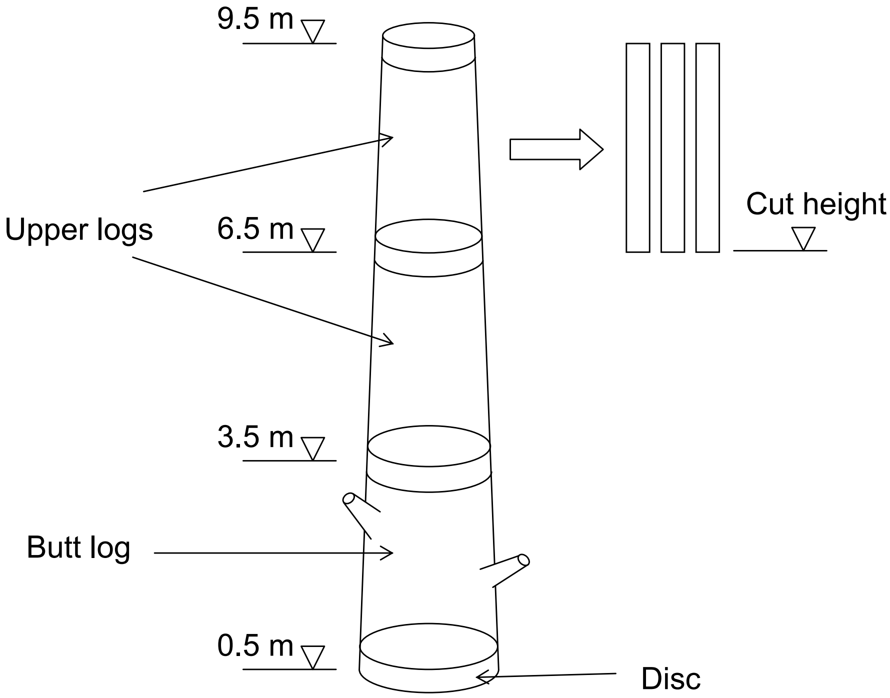

Figure 3.1: Schematic showing typical log height positions (relative to ground level), with definition of batten cut height.

The logs were coded according to stand number, tree number and cut height. For example FR1 - 44 - 3.87 corresponds to stand = FR1, tree number = 44 and cut height (i.e. lowest point) = 3.87 m. Figure 3.2 and Figure 3.3 show the system used to number logs and battens. The log ends were indented with multiple numbers or symbols, and marked with a colour code. Thus each batten has a unique identification code. For example batten “1 B A” originated from a log stamped on the upper end with the symbol “1” which was also colour coded Blue, likewise with battens B, C etc. from the same log. The numbering system involving a unique code and a robust system of marking enabled traceability of each batten to axial and radial position within each tree. The logs from each stand were selected and processed in three separate batches (FR1, FR2 and FR3/4).

Figure 3.2: Log marking. Top (or upper end) of log is marked with an indented stamp and colour code. The 12th growth ring is also highlighted. (original in colour)

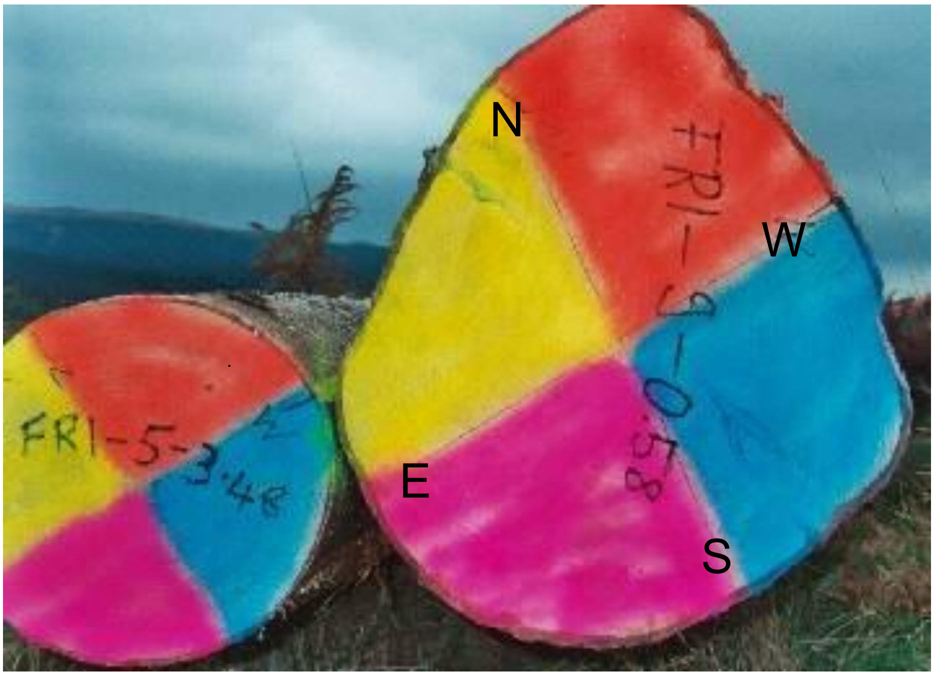

Figure 3.3: Butt (or lower end) of the log marked with site, tree code and height.

The colour quadrants representing compass orientation *i.e.* NSEW. (original in colour)

Figure 3.4 shows an example of 3D log shape data.

Figure 3.4: Example of 3D log shape data.

The timber was “curve sawn” into three nominal sizes: 200 x 47 mm, 150 x 47 mm, and 100 x 47 mm. This process involves orientating the log and adjusting the blades to enable curved logs to be processed, whilst avoiding wane, thus maximising recovery. Over the 3 m log lengths the maximum tolerable degree of curvature for the sawmill concerned was 40 to 45 mm (although this was exceeded in a few instances). For more typical 4.9 m length logs the maximum tolerable curvature is 75 mm; however this tends to cause blade wear. Other details pertinent to the use of the 3D log shape data are that the logs by necessity were passed through a butt reducer before conversion. The effect of this is evident in photographs that were taken of most of the logs as they passed both through the scanner and into the saw blades, and appears minimal, but cannot be quantified precisely. For this reason the manually made measurements of certain log dimensions are more reliable in absolute terms, but it does not necessarily follow that the sawmill scanner measurements are without use.

Aside from the site, tree, log and batten number identification numbers and sawn timber dimensions, the following variables were determined (see Table 3.1 to Table 3.3) as per the protocols and definitions given in Appendix 2. Note that where these variables appear in the text they are in italics with the first letter capitalised (*e.g*. *Ovality, Pith X.*), and that these variables refer to the measurements described unless otherwise stated.

Table 3.1: Tree variables – notation and units.

	Notation	**Units**
Tree height (ground level to tip)	*Tree ht.*	m
Tree diameter at breast height (1.3 m)	*DBH*	cm
Tree taper (*Tree ht./DBH*)	*Tree taper*	m/cm

Table 3.2: Log variables – notation and units.

Log variables	**Notation**	**Units**
Bottom diameter (sawmill scan)	*Bot dia.*	mm
Top diameter (sawmill scan)	*Top dia.*	mm
Log taper (*Bot dia*/*Top dia* over 3 m)	*Log taper*	ratio
Log arc (sawmill scan data)	*Log arc*	mm
Ovality (manual from disc)	*Ovality*	ratio
Pith eccentricity (manual from disc)	*Pith X*	ratio
Whorl number per log	*Whorl no.*	number
Whorl mean spacing	*Whorl mean*	m
Whorl max spacing	*Whorl max*	m
Whorl min spacing	*Whorl min*	m
Log dia. Top (manual overbark)	*Log dia top (man)*	cm
Log dia. Mid (manual overbark)	*Log dia mid (man)*	cm
Log dia. Butt (manual overbark)	*Log dia butt (man)*	cm
Log max deviation (manual)	*Log max dev*	cm/m
Log taper (*Log dia butt* / Log dia. mid)*	*Log taper (butt/mid)*	ratio
Log taper (*Log dia butt* / *Log dia top*)*	*Log taper (butt/top)*	ratio
Log taper (Log dia. mid / *Log dia top*)*	*Log taper (mid/top)*	ratio
*based on manual measurements before sawmill.		

Table 3.3: Batten variables – notation and units.

Batten variables	**Notation**	**Units**
Cut height (*i.e.* distance from ground level at the base of the tree to the lower end of batten)	*Cut ht.*	m
Density (oven dry mass/volume at 12% moisture content)	*Density / Dens*	kg/m^3
Distance from pith to batten centre	*Pith Dist*	cm
Ring width (mean)	*Ring width*	mm
Juvenile wood content (expressed as a decimal)	*JW*	none
Section code (0=contains pith, 1 = pith on edge, 2 = no pith)	*Section*	None
Compression wood content:		
CW face difference (causing bow)	*CW face diff (bow)*	Rank
CW edge difference (causing spring)	*CW edge diff (spring)*	
CW av. both faces	*CW av both faces*	
CW total (adjusted for area)	*CW total (adj)*	
Slope of grain:		
Outer face	*SoG outer*	degrees
Inner face	*SoG inner*	degrees
Knot area ratios (to BS 4978:1996):		
KAR TOP*	*KAR TOP*	ratio (decimal)
KAR MID	*KAR MID*	
KAR BOT*	*KAR BOT*	
MKAR**	*MKAR*	
TKAR	*TKAR*	
*Note that these designations are effectively arbitrary. **MKAR refers to the worst margin.		
Total knot coverage =(total knot area/total batten face and edge area) x 100	*Knotarea%*	ratio (%)
Knot concentration =(knot cover over worst 300 mm length on outer faces/face area) x 100	*Kn300%*	ratio (%)
Knot coverage over mid 900 span =(total knot area/batten face and edge area over central 900 mm span) x 100	*Kn900%*	ratio (%)
Note that knots <10 mm dia. were ignored.		

Variables relating to the number of knots and area of knots over the upper third, middle and lower third batten sections on all faces and edges were also determined.

The battens were machine strength graded using a Cook-Bolinder grader (Figure 3.5) to obtain detailed Indicating Parameter (*IP*) values along the board lengths, performed at around 15% to 18% moisture content. A description of the operation of the grader is given by Boström *et al.* (2000). In this work the machine is simply used as a convenient method of measuring relative stiffness along the entire length of the board (values of *IP* were recorded every 100 mm), and obtaining an indicative structural grade. It is recognised that the variation in moisture content introduces a random error (of a few percent) into the relationships observed within sub-groups of battens, but it is not considered necessary or particularly valid for the purposes of this work to attempt to normalise all the results to 12% moisture content. The adjustment given in EN 408:2003 is for groups rather than individual battens. The boards were fed into the grader with the highest end of the batten (as in the living tree) last, this being the tagged end.

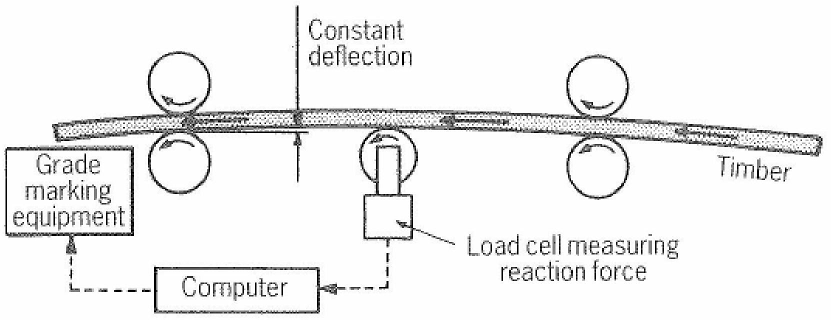

Figure 3.5: Cook-Bolinder grader - schematic of operating principle (after Benham *et al.*, 2003).

Since the machine set-up, in terms of roller span and applied deflection, remains constant for given board sizes, *IP* is effectively a measure of “flatwise” bending stiffness, but more precisely is the reaction load in kN. Values of *IP* normalised for nominal batten size (relative to 100 mm depth) were determined using standard principles of mechanics. Because the position of every batten is known within the tree stiffness profiles both axially and radially could be established.

The following batten properties, normalised for batten size, were determined (Note that the units of *IP* are kN):

- *IP* *i.e.* the grade determining lowest value
- *MOE* (*i.e.* $E_{m,g}$) and *MOR* (*i.e.* f_m) from bending tests to EN 408:2003

E_{cb} (in N/mm^2) was calculated from the *IP* values using Eqn. 1:

$$E_{cb} = \frac{IP_{(\min)} \times 900^3 \times 1000}{4 \times d \times t^3 \times \Delta} \qquad \text{Eqn. 1}$$

where:

Δ = 5.4 mm deflection for 47 mm nominal thickness boards.
$IP_{(min)}$ = Indicating Parameter of Cook-Bolinder (kN)
d = batten depth (mm)*
t = batten thickness (mm)*
900 = distance between supports in the grader (mm).

*Note that because batten dimensions were not precisely measured during machine grading, these are based on nominal sizes.

IP (and hence E_{cb}) is determined on the basis of the average of two passes of the batten through the Cook-Bolinder *i.e.* the batten is bent in both directions about the minor axis, with the objective of removing error due to inherent bow. E_{cb} is based on three-point bending (Figure 3.6) and involves assessment of the whole batten length, although the first and last 450 mm are not subject to the full bending moment.

The EN 408:2003 test method involves a four-point loading arrangement dependent on the depth of the beam. For the 150 mm deep 3 m long battens there was no set-up possible other than to place the batten centrally. For consistency, and to tally with the CW variables recorded, the 100 mm deep 3 m long battens were also placed centrally (Figure 3.7), in which case the ends of the battens are effectively untested. In both cases the batten orientation was kept random relative to the position of knots, and the position of test was not deliberately aligned to the lowest reading of the Cook-Bolinder, as would be the case in work which has the objective of determining machine settings. This approach was adopted to avoid the EN 408:2003 tests being dependent on the output of the Cook-Bolinder.

It is normal in the EN 408:2003 test to bend the batten about the major axis in one random direction, since this represents “real life” usage (although it is also possible to measure stiffness in both directions if the sample is not taken beyond the elastic limit on the first test, and also to deliberately place defects such as knots on the tension or compression face depending on the objective of the work). The Cook-Bolinder grader, because it measures the lowest stiffness within the batten length, is likely to be more sensitive to the so called weak butt effect encountered by Brazier (1991) than the EN 408:2003 tests. Thus, differences between the stiffness measurements, and the method by which they were carried out in respect of deliberate placement of defects such a large knot groups within the test zone, are important considerations. Because E_{cb} values are available for the whole dataset, and in particular all of the butt log material including

200 mm depth battens, this work concentrates on the analysis of these grader derived values.

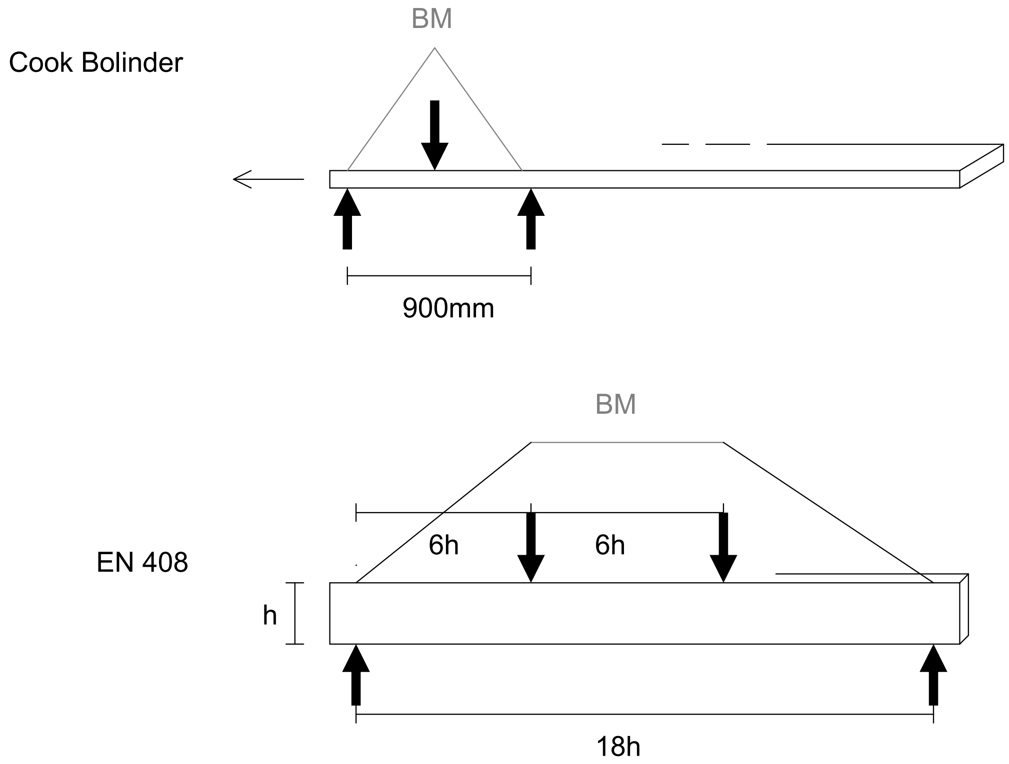

Figure 3.6: Cook-Bolinder and EN 408 bending set-up showing applied bending moment (general case).

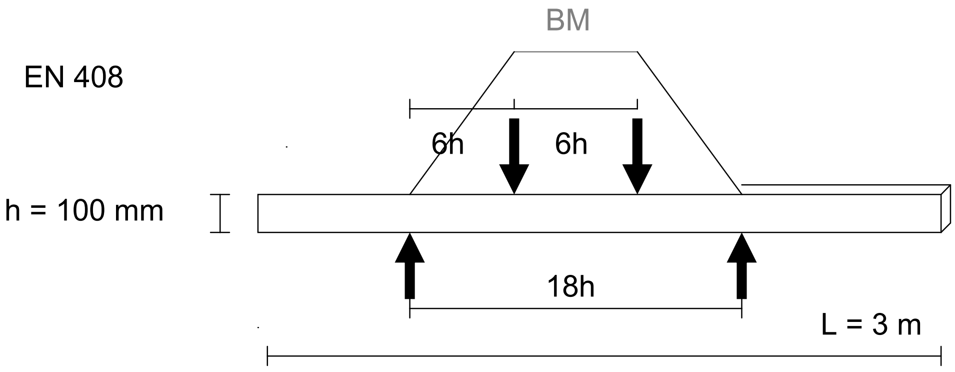

Figure 3.7: EN 408 bending set-up showing applied bending moment for battens with *h* = 100 mm and *L* = 3 m.

Distortion measurements of bow, spring twist and cup as defined by BS 4978:1996 (see Figure 1.1) were generally obtained at two stages:

- After kiln drying (denoted *Twist1*, *Bow1 etc.*)
- After conditioning in a climate controlled laboratory at 20 Celsius, 65% relative humidity, unrestrained without top loading, stored vertically (denoted *Twist2*, *Bow2 etc.*), with a target m/c of 12%.

Measurements of distortion in the green condition (*i.e.* immediately after sawing) were made but are not considered in this work, and neither are measurements of cup made at any stage. Only actual rather than increases in distortion are considered in this work. Distortion measurements were made both manually (with the simple use of a rule and a flat granite table), and with the aid of a frame incorporating displacement transducers, which was developed by Mr Geoff Cooper as part of other work at BRE. Unfortunately because of operator error, a number of the measurements made by this device must be discarded from statistical analysis (the operator appears not to have noticed that the displacement transducer has reached the limit of its range in some instances). Nevertheless, these over-range values still indicate instances where high levels of distortion have occurred.

The timber from FR1 was kiln dried at the sawmill with the battens placed towards the top of a stack of other timber in order to minimise restraint, then transported in packs to BRE. The material from FR2, 3 and 4 was kiln dried at BRE using a rack without any form of restraint from top loading. Details of the kiln schedules are given in Appendix 3. Because of the possible effects of variation in restraint afforded during transport and handling, and known differences in moisture content (which were recorded at each measurement stage), analysis and derivation of models based on certain combined groups of battens from each stand would be invalid. It is possible, however, to carry out between-group comparisons of the influence of variables to look for similarities in behaviour. These considerations are clarified in Chapters 4 and 5.

Table 3.4 contains information on the numbers of battens within sub-groupings of stand number, size and axial position within the stem in terms of upper log and butt log.

Table 3.4: Batten sub-groups.

Main batten sub-groups (stand, batten depth, log)	No. of battens
All Battens (100, 150, 200 mm)	483
All Battens from upper logs (100, 150, 200 mm)	310
All Battens from butt logs (100, 150, 200 mm)	173
FR1 100 upper log	31
FR1 150 upper log	37
FR1 200 upper log	21
FR1 100 butt log	2
FR1 150 butt log	29
FR1 200 butt log	19
FR2 100 upper log	37
FR2 150 upper log	42
FR2 200 upper logs	0
FR2 100 butt log	12
FR2 150 butt log	23
FR2 200 butt log (note: not fully tested)	9
FR3 100 upper log	46
FR3 150 upper log	34
FR3 100 butt log	15
FR3 150 butt log	35
FR4 100 upper log	52
FR4 150 upper log	10
FR4 100 butt log	12
FR4 150 butt log	26

4 Observations on compression wood and batten distortion.

This work involved relating log shape characteristics (such as curvature or arc, ovality and pith eccentricity) to compression wood occurrence in battens and subsequent distortion on drying. A particular aim was aim to establish whether log shape scanners could be used to determine batten propensity to distort at an early stage in the conversion process.

The method and definitions of variables were given in Chapter 3, with measurement protocols described in Appendix 2. Note that where variables appear in the text they are in italics with the first letter capitalised (*e.g. Ovality*, *Pith X*), and that these variables refer to the measurements described. It is recognised that there are other definitions possible for these characteristics.

4.1 Correlations between compression wood and log variables

Table 4.1 shows the correlations observed using SPSS software (SPSS Inc., version 16.0.2, April 2008) between the compression wood content of the battens (*i.e. CW total adj*), *Cut ht*, *Log arc* (as measured by the sawmill scanner), *Log max dev* (measured manually in the field), *Ovality* and *Pith X* (which were both measured manually from scanned disc images corresponding to *Cut ht.*). *CW total (adj)* is the total compression wood score as per the protocol given in Appendix 2, *i.e.* for both batten faces, adjusted to take into account differing relative sizes of the defined edge and central face zones. As detailed in the protocol, no actual measurement of compression wood on the batten edges was made although these zones where visually examined. The batten compression wood variables are based on the middle 2 m section over which the distortion measurements were made, and not the whole length of 3 m. No attempt to classify the compression wood in terms of colour intensity or underlying distribution within the ring structure of the batten was made.

Although the compression wood distribution on the batten faces was recorded by an experienced wood scientist (Mr Gerald Moore), it is regarded as a basic measure of the compression wood content of the battens, but probably corresponds to that likely to be achieved by some form of automatic scanner. Although the compression wood variables are on a numeric scale, they are essentially qualitative.

In Table 4.1 correlations with $R > 0.4$ are shown shaded (it is recognised that at this level such correlations are weak). Note that the Pearson correlations shown are the coefficients of correlation (R) and not the coefficients of determination (R^2). The significance level (or p-value) is the probability of obtaining results as extreme as the one observed by random chance.

Table 4.1: Correlation table for batten compression wood score (all data).

R	*CW total (adj)*	*Cut ht.*	*Log arc*	*Log max dev*	*Ovality*
Cut ht.	0.20**				
Log arc	-0.04	-0.39**			
Log max dev	-0.06	-0.23**	0.55**		
Ovality	0.06	-0.31**	0.14**	0.24**	
Pith X	-0.04	-0.18**	0.21**	0.17**	0.34**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

N = 459 to 474 (due to occasional missing values) except for *Log max dev* which is based on N = 330.

From Table 4.1 it can be seen that there is no correlation between compression wood score and any of the log shape variables. As might be expended *Log arc* correlates quite strongly to *Log max dev.* No meaningful correlation exists between the variables *Ovality* and *Pith X*, indicating that log shape scanners cannot be used to indicate pith eccentricity. No relation between batten radial position (*i.e. Section* or *Pith dist*) and compression wood content was observed. None of the batten slope of grain variables were found to correlate significantly to any of the compression wood variables. Similarly compression wood score was not found to be related to any of the extensive knot variables. Around half of the battens assessed had nil or very little visible compression wood on the surface.

Figure 4.1 shows the 3D log shape of FR4-554-0.55 which yielded the batten with the highest compression wood score. It is a notably straight butt log.

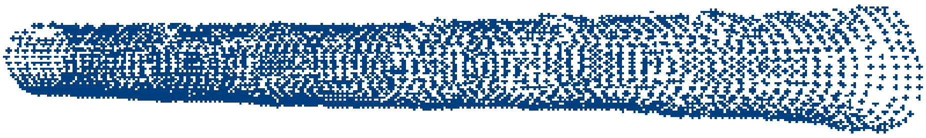

Figure 4.1: Three dimensional grid of log FR4 - 554 - 0.55.

4.2 Observations on log shape

To further aid investigation into compression wood distribution and the effect on distortion, the battens were re-assembled into their original position within logs with reference being made to the 3D sawmill scanner and other data. The following details a compression wood summary for a number of notable logs and battens:

- FR2 - 44 - 3.87: a curved log, compression wood noted at curve, two out of four battens from the log were badly bowed.
- FR2 - 127 - 0.5: a log with large butt sweep, no compression wood recorded on the battens. Two out of three battens were notably twisted.
- FR2 - 79 - 0.51: a log with large butt sweep, no compression wood on the battens, one batten was very twisted, whilst the other remained relatively straight.

- FR2 - 210 - 0.45: a straight log, compression wood was on the edge of the battens. Three out of four battens developed spring, one was also bowed.
- FR2 - 44 - 7.09: a straight log with high level of compression wood, all battens bowed or developed spring.
- FR2 - 133 - 6.7: a straight log with curved base, compression wood was noted at the straight end of the log. Both battens from the log twisted.
- FR1 - 9 - 0.58 / 3.78/ 6.96 /: these logs came from the tree with the most compression wood of all - it was quite straight, with a slight butt sweep.
- FR1 - 70 - 6.8: a curved log, with high compression wood content
- FR1 - 133 - 3.52: straight log, but flattened profile (ovality = 1.14), high compression wood content.
- FR1 - 97 - 6.72: yielded a pair of battens (COB and COA) which exhibited wandering pith, and which subsequently bowed significantly. This was similarly noted for battens 8BA and 8BB which originated from FR1 - 70 - 6.8. Figure 4.2 shows the 3D representation of these logs.
- FR4 - 558 - 3.54: a log with pronounced bow, with high compression wood content.
- FR4 – 238 - 0.7: a log with high consistent bow, but low compression wood content.
- FR3 - 148 - 7.01: an upper log, straight and round, yielded 1 batten with second highest compression wood score of all.

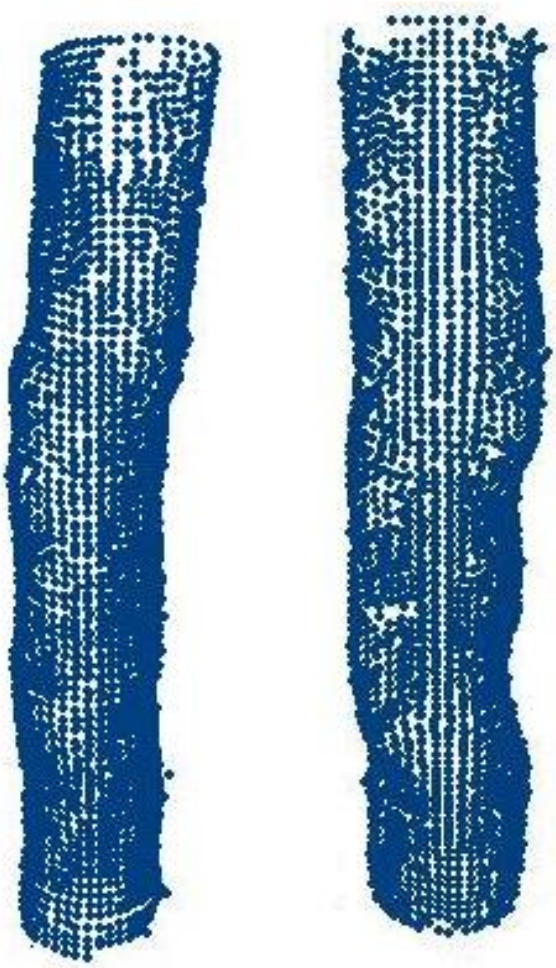

Figure 4.2: Logs from FR1 which yielded pairs of 100 mm battens which were observed to have deviant or wandering pith and which bowed on drying.

Figure 4.3 shows the 3D representation of log FR1 58 - 0.43, which yielded three battens which were without significant compression wood and which remained straight on drying.

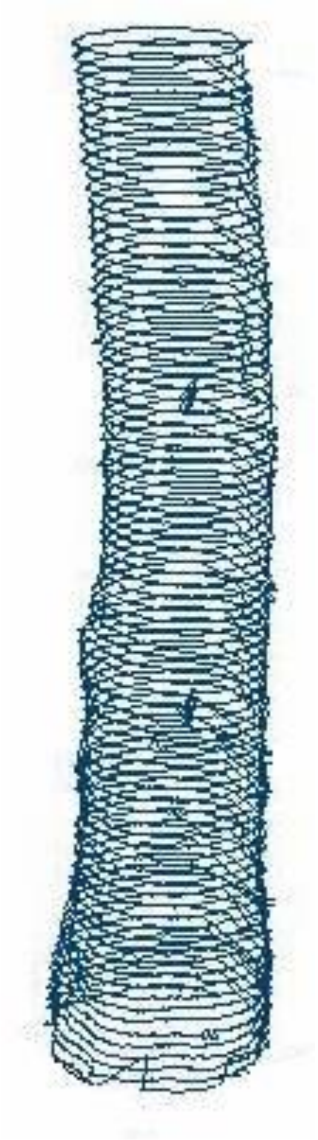

Figure 4.3: Three dimensional representation of log FR1-58-0.43.

Figure 4.4 shows batten FR4-NWA which was noted to have highly wandering pith and high compression wood content which resulted in significant bow on drying. This batten originated from log FR4 - 478 - 3.7, the 3D representation of which is shown in Figure 4.5.

Figure 4.4: Batten FR4- NWA with wandering pith, which bowed on drying (and also twisted).

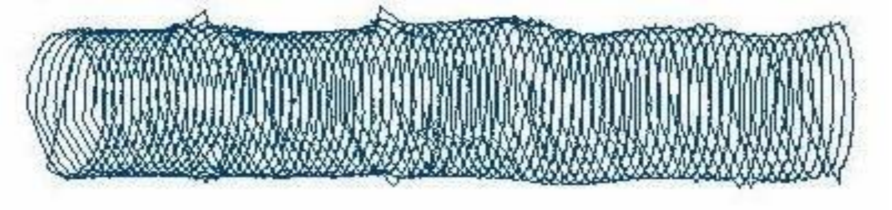

Figure 4.5: Log FR4-478-3.7, which yielded the above batten.

Figure 4.6 shows the 3D representation of log FR2 - 105 - 6.73 plotted as two overlapping grids (upper and lower sets of data), using Surfer^{TM} surface interpolation software (Golden Software Inc., v. 8.02 Oct 2002). This image shows branch swellings which corresponded to field measurements of whorl positions, together with an abrupt change in curvature. Figure 4.7 shows the two battens which came from the above log reassembled (*i.e.* FR2 8NA and 8NB), with compression wood shown in red hatching. Notably compression wood was observed in the relatively straight part of the log, and appeared to have formed in later growth rings as a response to likely asymmetric loading from the upper part of the tree.

Figure 4.6: Three-dimensional representation of log FR2-105-6.72. (The poor image quality on the right hand side is probably due to noise or missing data).

Figure 4.7: Battens reassembled, with compression wood shown hatched.
(original in colour)

Figure 4.8 shows batten FR3-ONB which developed a high level of spring on drying. Notably the compression wood is consistently along one edge of the board. This batten came from log FR3 - 25 - 9.18, which was without pronounced ovality or pith eccentricity and only a slight degree of overall curvature (Figure 4.9). This log exhibited shape characteristics suggesting stem form correction. Although these and similar features may be recognised by the human eye, such subtleties are not reflected in the overall log arc measurements made by the 3D log scanner. This log also yielded two other battens which distorted considerably.

Figure 4.8: Batten FR3 ONB with compression wood consistently along one edge, which developed pronounced spring on drying.

Figure 4.9: Log FR3 - 25 - 9.18 which yielded battens which distorted on drying.

Figure 4.10 shows the disc image from FR1 - 9 - 3.68 (which is the tree with the most compression wood according to the batten assessment method). It is quite round and without pith eccentricity. The distribution of compression wood observed suggests a response to wind loading.

Figure 4.10: Log disc showing darker compression wood rings. (note image produced by Forest Research)

Aside from finding that straight, round logs without pronounced pith eccentricity can yield battens containing relatively large amounts of compression wood; a number of practical problems were identified when evaluating the use of 3D log scanner data for in-line sorting:

- The true axis of the log is indeterminable. It is not possible to tell from 3D scanner data alone which part of a crooked log was originally vertical and which was out of vertical.
- Features such as branch swellings may affect other measurements such as taper and ovality.
- Site information such as degree of lean is, of course, absent.
- Compression wood may form in relatively straight parts of the tree as a reaction to asymmetric loading.

- Features that are associated with compression wood, such as a kink in an otherwise straight tree, may get separated from one log to another.
- Compression wood formation in early tree life may be covered by later growth, effectively hiding log shape details such as wandering pith.
- Straight logs with compression wood were found quite likely to produce battens that bow and spring because of the consistent gross difference of compression wood content between one side of the batten and another.
- Butt reduction before scanning can affect log shape data.
- Compression wood can also form below large branches due to the weight of the branch.
- Compression wood can also form as a response to wind loading.

4.3 Correlations for batten bow and spring

Table 4.2 shows the correlations observed between batten bow and spring after kiln drying unrestrained to around 15% moisture content for FR3 and FR4 100 x 47 mm battens.

Table 4.2: Correlation table for *Bow1* and *Spring1* of FR3 and FR4 100 x 47 mm battens.

R	*Bow1*	*Spring1*	*CW face diff (bow)*	*CW edge diff (spring)*	*Log arc*	*Ovality*
Spring1	0.03					
CW face diff (bow)	0.22*	0.02				
CW edge diff (spring)	-0.04	0.40**	0.26**			
Log arc	0.11	0.10	-0.08	0.06		
Ovality	0.05	0.15	0.11	-0.05	0.13	
Pith X	-0.09	0.23**	-0.06	0.17	0.04	0.33**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

N = 121 to 125.

From Table 4.2 (note that correlations with R > 0.4 are shown shaded) it can be seen that seen that batten bow (*i.e. Bow1*) does not correlate to any of the log shape variables (*Log arc*, *Ovality* or *Pith X*), nor to the batten compression wood distribution variables (*CW edge diff* and *CW face diff*). *Spring1* correlates to *CW edge diff*, which is logical, and also *Pith X*, but only very weakly. No correlation was observed between batten bow or spring and either *Density* or *Section*, nor was there any correlation observed between these forms of distortion and twist at any stage.

Table 4.3 shows the correlations observed between batten bow and spring after kiln drying unrestrained to around 15% moisture content for FR3 and FR4 150 x 47 mm size battens.

Table 4.3: Correlation table for *Bow1* and *Spring1* for FR3 and FR4 150 x 47 mm battens.

R	*Bow1*	*Spring1*	*CW face diff (bow)*	*CW edge diff (spring)*	*Log arc*	*Ovality*
Spring1	0.16					
CW face diff (bow)	0.06	0.24*				
CW edge diff (spring)	0.12	0.08	0.40**			
Log arc	0.13	-0.12	-0.18	-0.07		
Ovality	0.10	0.27*	-0.09	-0.01	0.24*	
Pith X	0.18	0.04	-0.05	-0.07	0.27**	0.55**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

N = 86

From Table 4.3 (note that correlations with R > 0.4 are shown shaded) it be seen that, similarly with the 100 x 47 mm size battens from the same site, there is no correlation between *Bow1* and any of the log shape variables, nor any correlation to the batten compression wood distribution variables. Unlike the case with the 100 x 47 mm battens, there is no correlation between *CW edge diff* and *Spring1*, but there is a weak correlation between *CW edge diff* and *Bow1*. A weak correlation is evident between *Pith X* and *Ovality* for this group of data.

Since the *CW edge diff* values for the FR3/4 100 x 47 mm battens are grouped into a limited number of categories, these can be plotted as a box plot (Figure 4.11). Table 4.4 shows the descriptives.

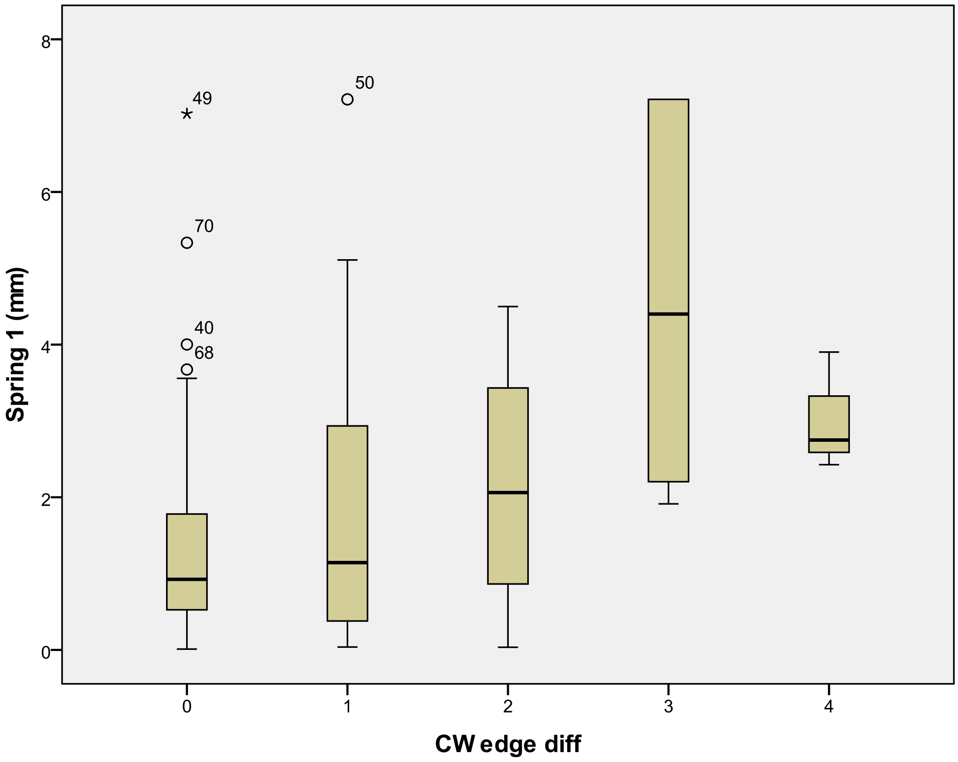

Figure 4.11: Box plots of *Spring1* for groups of *CW edge diff* (FR3/4 100 x 47 mm battens)

Table 4.4: Descriptives, *Spring1* grouped by *CW edge diff* (FR3/4 100 x 47 mm.

Descriptives

Spring 1 (mm)

CW edge diff =	N	Mean	Std. Deviation	Std. Error
0	83	1.3	1.19	0.13
1	22	1.8	1.92	0.41
2	12	2.2	1.58	0.46
3	5	4.6	2.58	1.15
4	3	3.0	0.78	0.45
Total	125	1.6	1.59	0.14

In Table 4.4 it can be seen that there are only eight battens with high values of *CW edge diff*, although the values of *Spring1* for these tend to be high. The low number of battens in *CW edge diff* = 3 and *CW edge diff* = 4 groups invalidates the use of 1 way ANOVA inclusive of these data, however by inspection of the multiple comparisons, (not shown) it could be determined that there are no statistically significant differences between the population means for the other groups (*i.e*. $p > 0.05$). From this, together with inspection of the data, it can be deduced that sorting timber on the basis of the *CW edge diff* variable will be ineffective. A scanner operating on this principle is capable of intercepting only a very few battens out of many which would also spring to similar levels. A similar conclusion was drawn from analysis of the FR 3/4 150 x 47 mm batten group.

The extent by which a growth ring containing compression wood apparent on the surface goes through the section of a batten is indeterminable, unless it is clearly evident on an opposing face (Figure 4.12). Together with the results of the statistical analysis detailed in Table 4.2 and Table 4.3, this suggests that sorting battens by virtue of the amount of compression wood visible on the surface, or apparent differences between face or edge content, would be largely ineffective.

Figure 4.12: Compression wood in battens (darker bands). (original in colour).

In the above figure, the sample on the left shows a wide band of compression wood on the top surface, but little inside. The extent by which the compression wood bands pass through in the sample on the right is indeterminable - unless a cross cut is performed.

In some cases compression wood can be prominent or extensive on the surface of batten, but because it is evenly distributed throughout the section there is little tendency to distort on drying. The prediction of compression wood within a batten based on viewing faces only was found to be problematic for the following reasons:

- The pith position must be known to determine the structure of the growth rings.
- The batten may have wandering pith or be from a curved log making a prediction of pith position difficult.
- The battens may be cut off axis with the log, and the true axis unknown.
- Rate of growth (and hence thickness of compression wood rings) varies with the age of the tree.
- The growth rings may be eccentric about the pith.
- Grain tends to be wild around knots.

4.4 Discussion and summary of findings on compression wood and distortion

Systematic relations between log shape characteristics (in terms of the variables *Log arc*, *Ovality* and *Pith X.*), and the extent of compression wood visible on the central portion of batten faces (in terms of the variable *CW total adj*) were not observed. However, it is possible that the variable *CW total adj* is an inadequate descriptor of the compression wood content. In particular, the variable does not distinguish between milder and more severe forms of compression wood. The absence of any strong correlation between log ovality or pith eccentricity and compression wood content of battens is in agreement with Ohman (2001), for Norway spruce.

Compression wood was noted to form in certain straight, round logs as well as those showing the characteristics of stem-form correction. These characteristics could be subtle, and were not well reflected in values of *Log arc* determined automatically by 3D scanner. Notable is that large amounts of compression wood were also observed by the author in a perfectly straight Sitka spruce log pole which was used in a pile driving test (Figure 2.10).

Logs with wandering pith were noted to yield battens prone to develop bow on drying, but such logs could be quite straight overall. More complex log shape variables might be better able to indicate timber which is prone to distort on drying.

Straight logs with compression wood were noted to yield battens that were prone to distort on drying because of the consistent difference in longitudinal shrinkage of compression wood and normal wood that could occur from one face or edge of the batten along the whole length.

The above results (*i.e.* presence of compression wood in straight logs and logs that are round in section or without pith eccentricity) are in broad agreement with Warensjö (2003) who looked at the distribution of compression in discs taken from Scots pine and Norway spruce logs grown in Sweden. Referenced within Warensjö (2003) is work by several other researchers who noted the development of sinuously shaped stems due to overcorrection; a further indication that compression wood may not readily be indicated by overall log curvature or arc.

Gardiner and MacDonald (2005) determined that compression wood formation in Sitka spruce was related to the degree of stem lean, and local ground slope. This indicates that site specific factors may determine the compression wood content of battens. These factors may have little or no relation to log shape.

Systematic relations between log shape characteristics (*Log arc*, *Ovality* and *Pith X*) and batten distortion in the form of bow or spring were not observed in the dataset. By inspection of the ANOVA Multiple Comparisons it could be determined that there are no statistically significant differences between the population means of *Spring1* for the groups of *CW edge diff* examined (*i.e*. $p > 0.05$). From this is can be deduced that sorting timber on the basis of the *CW edge diff* variable will be ineffective.

No correlation between bow or spring, and batten axial or radial position was observed, in agreement with findings on Norway spruce reported by Johansson (2002). This suggests that a simple sorting strategy based on segregation of log type (*e.g*. butt or upper logs), or mechanical sorting of battens during sawing (*e.g*. centre cut or outside centre cut) will be ineffective.

No correlation between batten twist and compression wood was noted, or between twist and either bow or spring. Note that the absence of a relation between batten compression wood content and twist for Sitka spruce is in agreement with other work on a random timber sample carried out at BRE as part of the EU Compression Wood Project (Gardiner and MacDonald, 2005).

Based on the inspection of individual battens, the compression wood variables derived (as detailed in A2.15) are considered to be poor descriptors of the often intricate distribution of this form of reaction wood. Potentially much more complex descriptors might be determined and used as sorting parameters.

5 Observations on batten twist.

5.1 Relation to slope of grain and radial position.

Figure 5.1 and Figure 5.2 show *Twist1* (*i.e.* twist at stage 1, after kiln drying) plotted against the slope of grain on the batten outer face (*SoG outer*), and distance from pith to the centre of the batten (*Pith Dist*), respectively, for the FR1 100 x 47 mm size battens.

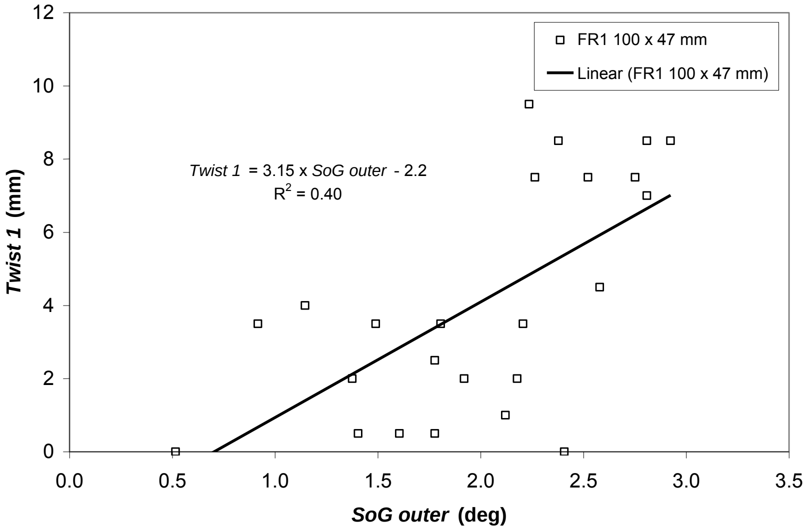

Figure 5.1: *Twist1* plotted against *SoG outer* (FR1 100 x 47 mm).

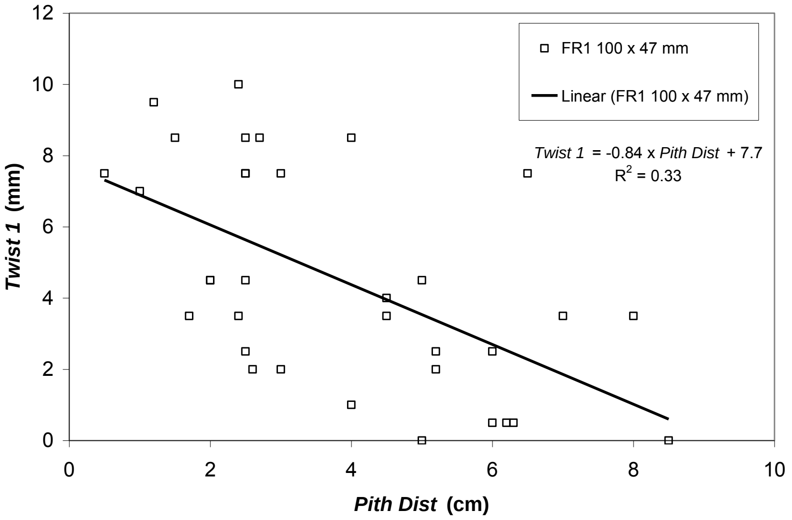

Figure 5.2: *Twist1* plotted against *Pith Dist* (FR1 100 x 47 mm).

It can be seen from Figure 5.1 and Figure 5.2 that twist increases with increasing slope of grain, and decreases with increasing distance from the pith in agreement with Balodis (1972). These relationships were observed to be similar for other sub-groups of batten size and stand. Note that the *SoG inner* values have been discarded from this analysis since, by inspection, they do not correspond to spiral grain angle when measured on a radial face. This aspect of spiral grain measurements is discussed in Section 5.4.

5.2 Correlations and models for twist

Table 5.1 shows the correlation table for *Twist2* (*i.e.* twist at stage 2 after conditioning at 20 °C, 65% RH) for the FR1 100 x 47mm battens.

Table 5.1: Correlation table for *Twist2* (FR1 100 x 47 mm)

R	*Twist 2*	*SoG outer*	*Pith Dist*	*Ring width*	*Section*
SoG outer	0.68**				
Pith Dist	-0.70**	-0.45*			
Ring width	0.39*	0.10	-0.51**		
Section	-0.73**	-0.56**	0.70**	-0.53**	

** Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed). N=34

From Table 5.1 (note that correlations with R > 0.4 are shown shaded) it can be seen that *Twist2* (similarly with *Twist1*) correlates positively to *SoG outer*, and negatively to *Pith Dist*. As would be expected *Twist2* also correlates negatively to the *Section* variable.

No relationship was observed between *Twist2* and any of the knot content variables (*Knotarea%*, *KAR*, *TKAR*), nor *Cut ht.*, *Tree ht*. or *DBH*. Nor was any relation observed between batten twist and compression wood content (*i.e. CW total adj*.)

Twist2 was observed to correlate negatively with batten size (*i.e.* depth) for all groups, suggesting that for larger batten sizes there was a restraining effect (possibly this is caused by inclusion of material further away from the pith, or of lower spiral grain angle, as batten size increases).

Table 5.2 and Table 5.3 detail the multiple regression and correlation model (using SPSS software) for *Twist2* (*i.e.* twist at Stage 2) following unrestrained conditioning to around 15% moisture content for the FR1 100 x 47 mm battens. This method of analysis is useful in determining the relative significance of variables which can be utilised in a predictive linear equation of the following form:

$$Y = \beta_0 + (\beta_1.X_1) + (\beta_2.X_2)\ldots etc. \qquad \text{Eqn. 2.}$$

where Y is the criterion variable, X_1, X_2 *etc.* are predictor variables, and β_0, β_1 *etc.* are factors. For a full description of MRC see Grimm and Yarnold (1995).

Table 5.2: Model summary for *Twist2* (FR1 100 x 47 mm).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.85(a)	0.72	0.70	2.74

a Predictors: (Constant), *Pith Dist*, *SoG outer*

Table 5.3: Model coefficients for *Twist2* (FR1 100 x 47 mm).

Model		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	t	Sig
1	Constant	7.31	2.83		2.58	0.017
	SoG outer	3.37	1.01	0.424	3.33	0.003
	Pith Dist	-1.31	0.291	-0.575	-4.52	0.000

a Dependent variable: *Twist2*

Note that the unstandardised coefficients are the coefficients of the estimated regression model. The standardised coefficients (or beta values) are included for completeness but are only used to make the regression coefficients more comparable, since the variables have different units. The t-statistics detail the relative importance of each variable in the model, (note that the t-values for each variable change depending on the significance of related variables which are included in the model). From the above t-statistics it is evident that both *Pith Dist* and *SoG outer* contribute significantly to the model. The predictive equation for *Twist2* is:

$$Twist2 = 7.311 + (3.37 \times SoG\ outer) + (-1.318 \times Pith\ Dist). \quad \text{Eqn. 3}$$

Where *Twist2* = mm, *SoG outer* = deg, *Pith Dist* = cm

Figure 5.3 shows the model fit (note that the equation for the line of best fit has been omitted since this equates to y = x).

A similar MRC model could be constructed for the FR3 and FR4 100 x 47 mm battens.

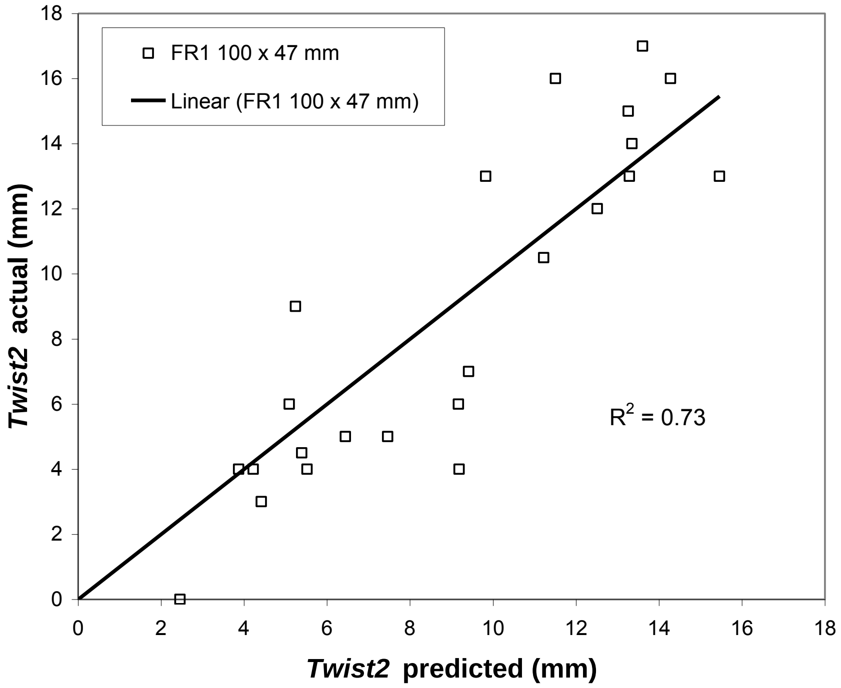

Figure 5.3: Model fit for *Twist2* based on *SoG outer* and *Pith Dist*.

5.3 Relation between slope of grain and radial position.

No relationship between *SoG outer* and *Pith Dist* was observed for any sub-groups of timber. Furthermore, by inspection, the following was deduced:

- The values of grain angle are quite low (the majority are below 5° absolute).
- The fact that battens have all twisted positively indicates that they have all twisted in the same direction.
- The values of outer face slope of grain are all positive

Thus the majority of battens have come from trees (or sections of trees) that have left hand spiral grain.

According to Nyström (2002) trees which start off left hand and change to right hand spiral grain with age may yield a proportion of battens which have balanced spiral grain angle across their width and thus do not distort on drying (shown conceptually in Figure 5.4), whilst those trees which remain with left handed spiral grain produce timber which is prone to develop twist; with a particular problem being that they all twist in the same direction. Säll (2002) states that it has been well-known for centuries that left hand spiral grain trees are inappropriate for building constructions. From data presented by Maun *et al.* (undated) and recently by Ioanna (2007) the trends in spiral grain angle from pith to bark in British-grown Sitka spruce are highly varied, with few logs exhibiting a trend for reversal in grain angle with age.

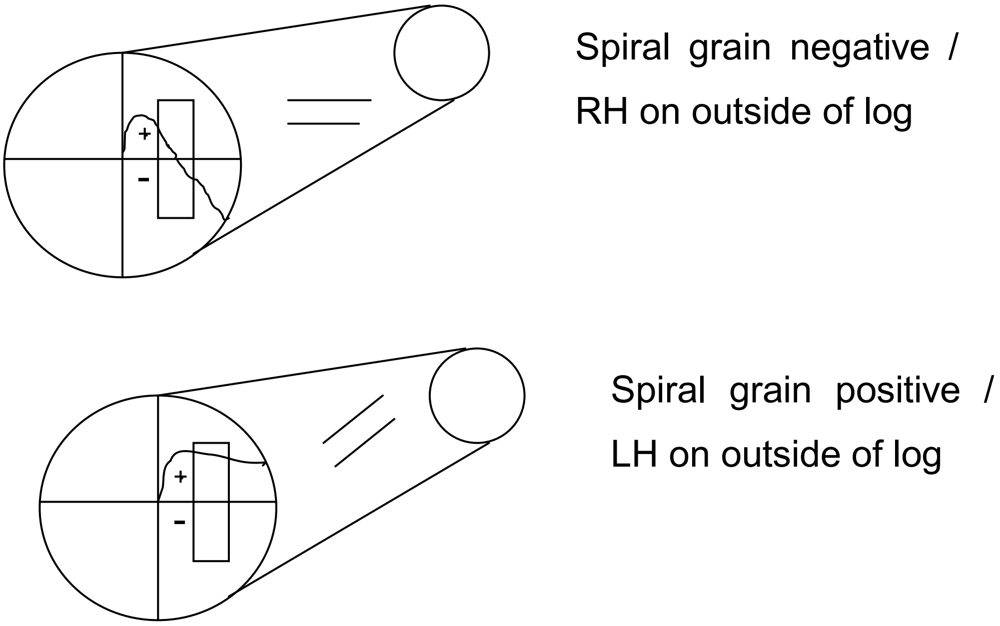

Figure 5.4: Log exhibiting a change from left to right-hand spiral grain angle, when looking from the butt upwards (top). Log which has remained with left hand spiral grain (bottom).

5.4 Practical difficulties of spiral grain measurement

Although grain angle can be measured on any face or edge of a batten, spiral grain angle can only be measured on a tangential face (Figure 5.5).

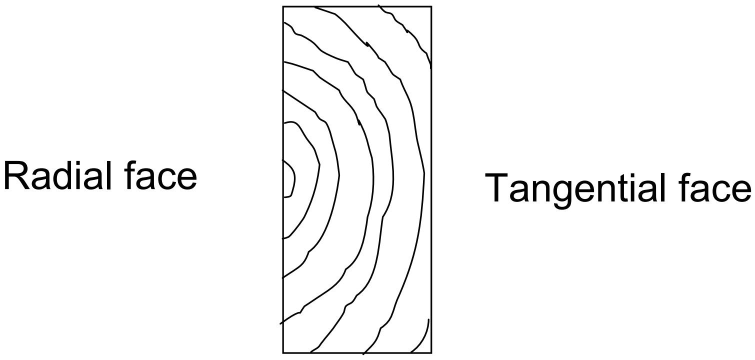

Figure 5.5: Radial and tangential batten faces.

Battens with central pith (termed "boxed pith") present a tangential surface on edges, whilst pieces cut away from the pith present a tangential surface on the wide faces. Where battens have been cut such that one face is radial and the other tangential, and which become randomly orientated about the minor axis in a sawmill (*e.g.* after falling from the saw-line onto a lateral conveyor) will, 50% of the time, present a face which upon which it is not possible to measure spiral grain. Measurement of slope of grain on the outside of canted logs, which present a relatively clean tangential face, would appear more promising; particularly since at this stage some decision on whether to convert into structural or non-structural board sizes could potentially be made.

The presence of knots is also very likely to affect the ability of an automatic scanner using the laser tracheid effect to measure spiral grain angle. Such a scanner would have to be programmed to ignore or otherwise contend with the rapidly fluctuating measurements that occur around knots. It was observed that there was very often limited clear wood between knots and knot clusters where slope of grain could be measured.

The influence of pith position on twist and the difficulty with the use of slope of grain measurements alone to sort timber is illustrated in Figure 5.6. Batten A, which has twisted the most, has a central “boxed” pith and a slope of grain on the upper face measured as zero because it has been erroneously made on a radial surface. Batten B and C have been cut further out from the pith and present tangential faces, with batten C twisting more due to the higher spiral grain angle. For Batten A measurement of spiral grain angle on the edge would have been more appropriate.

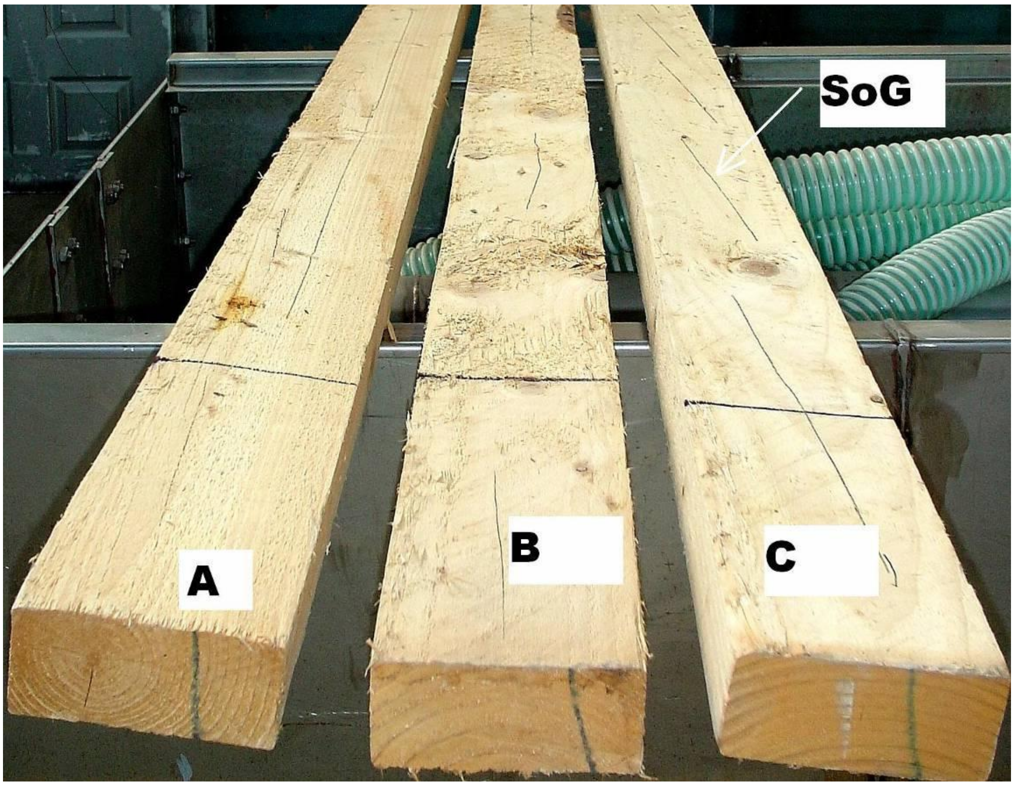

Figure 5.6: Three battens from a set which was dried from green without restraint, exhibiting varying degrees of twist, and on which slope of grain is marked.

5.5 Variation in slope of grain

Figure 5.7 shows box plots of absolute values of batten outer face slope of grain for the respective forest stands.

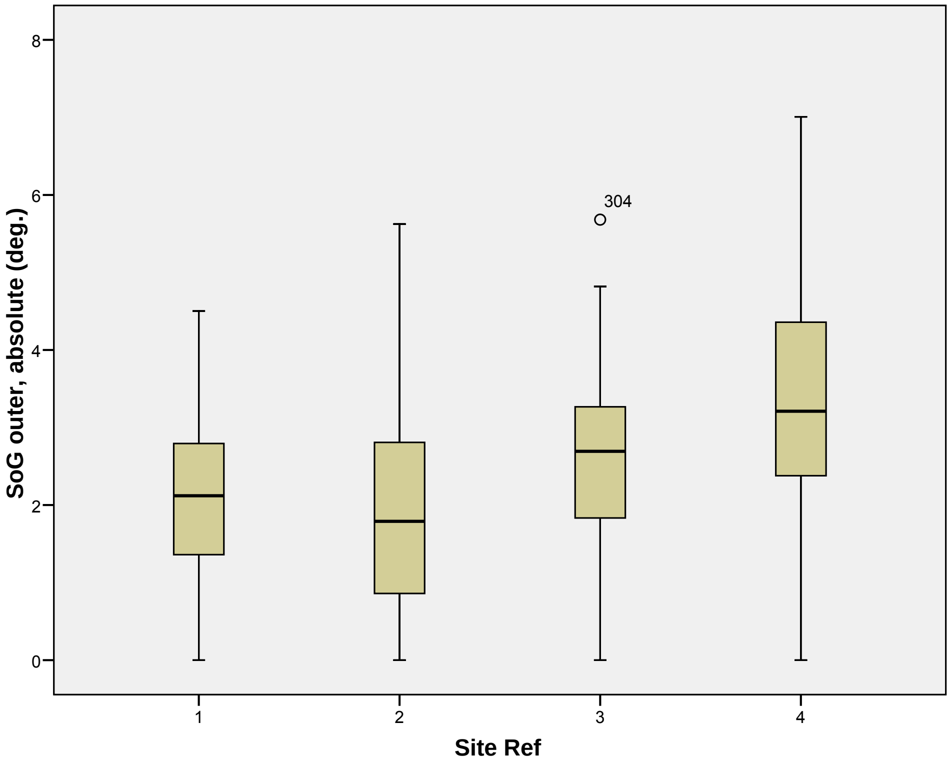

Figure 5.7: Box plots of absolute values of *SoG outer* grouped by stand.

From Figure 5.7 (which shows the lower and upper observations, lower quartile, median 50th percentile, and upper quartile, together with any values considered to be outliers), it can be seen that the majority of the values of slope of grain for all groups are in the range 1 to 5 degrees. This has implications for the resolution of any measurement system.

One-way analysis of variance (ANOVA) determined that the differences in the population means for *SoG outer* for the groups of stand (*i.e.* FR1-4) are statistically significant ($F_{3,465} = 32.6$, $p < 0.001$). Table 5.4 and Table 5.5 show the descriptives and results of the *post hoc* tests (*i.e.* multiple comparisons), respectively.

Table 5.4: Descriptives, *SoG outer* for groups of stand FR1-4.

SOG outer (abs)	**Descriptives**			
Stand	N	Mean	Std. Deviation	Std. Error
FR1	120	2.3	0.87	0.079
FR2	125	1.9	1.24	0.111
FR3	124	2.5	1.10	0.099
FR4	100	3.4	1.33	0.133
Total	469	2.5	1.25	0.057

Table 5.5: ANOVA multiple comparisons, *SoG outer* for groups of stand FR1- 4.

SoG outer (abs)		**Multiple Comparisons**		
(I) Stand ref	(J) Stand ref	Mean Difference (I-J)	Std. Error	Sig.
FR1	FR2	0.35	0.136	0.063
	FR3	-0.26	0.126	0.238
	FR4	-1.12	0.155	0.000
FR2	FR1	-0.35	0.136	0.063
	FR3	-0.61	0.149	0.000
	FR4	-0.15	0.173	0.000
FR3	FR1	0.26	0.126	0.238
	FR2	0.61	0.149	0.000
	FR4	-0.86	0.166	0.000
FR4	FR1	1.12	0.155	0.000
	FR2	1.47	0.173	0.000
	FR3	0.86	0.166	0.000

Method = Tamhane

Note that where Sig. is shown as 0.000 this value is not actually zero

From Table 5.5 it can be seen, for example, that the difference in the population mean of *SoG outer* (absolute) for stand FR4 compared to all other stands is statistically significant at the p < 0.001 level. This is in agreement with observations on discs obtained from the same trees reported by Ioanna (2007).

Table 5.6 shows the correlation table for batten outer faces slope of grain (*SoG outer*) with a series of tree and batten variables for FR1 100, 150 and 200 mm batten sizes as a combined group.

Table 5.6: Correlation table for slope of grain (FR1 all batten sizes).

R	*SoG outer*	Batten size (*depth*)	*Cut ht.*	*Section*	*Ring width*	*JW*	*DBH*
Batten size (*depth*)	0.20*						
Cut ht.	0.03	-0.27**					
Section	-0.06	0.08	-0.05				
Ring width	0.23*	0.05	0.42**	-0.21*			
JW	0.03	-0.41**	0.50**	-0.45**	0.44**		
DBH	0.18*	0.83**	0.01	0.11	0.13	-0.30**	
Tree ht	0.14	0.60**	0.02	0.07	-0.01	-0.25**	0.60**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed). N = 131

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that for this dataset *SoG outer* does not correlate significantly with any variable. In particular the absence of a correlation with *DBH* and *Tree ht*. is noteworthy, suggesting that larger, faster growing, trees do not yield battens with high spiral grain angle and hence yield timber which is especially prone to twist. The strong correlations observed between *DBH* and *Tree ht.*, and between these variables and batten size (*i.e. Depth*) are as would be expected. The quite strong correlation between *JW* and *Cut ht.* indicates that, as expected from the schematic shown in Figure 2.1, batten juvenile wood content tends to increase with height. The absence of a relationship between batten spiral grain angle and axial position (*i.e. Cut ht.*) is in agreement with Brüchert (2000).

Table 5.7 shows the correlation table for batten outer face slope of grain (*SoG outer*) with a series of tree and batten variables for FR2 100, 150 and 200 mm batten sizes.

Table 5.7: Correlation table for slope of grain (FR2 all batten sizes).

R	*SoG outer*	Batten size *(depth)*	*Cut ht.*	*Section*	*Ring width*	*JW*	*DBH*
Batten size *(depth)*	-0.50**						
Cut ht.	0.05	-0.27**					
Section	-0.15	-0.00	-0.10				
Ring width	-0.02	0.15	0.39**	-0.19*			
JW	0.35**	-0.19*	0.44**	-0.59**	0.47**		
DBH	-0.35**	0.53**	0.06	0.04	0.18	-0.16	
Tree ht	-0.30**	0.39**	0.04	0.01	-0.17	-0.12	0.33**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N = 115

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that batten slope of grain (*SoG outer*) correlates negatively with batten size (*depth*), indicating that the smaller battens tend to have higher spiral grain angle. No correlation is observed between *SoG outer* and *Section*. In this dataset a weak negative correlation with *DBH* and *Tree ht*. is evident. As with the FR1 data group correlations shown in Table 5.6, the strong correlations observed between *DBH* and *Tree ht.*, and between these variables and batten size are as would be expected.

Similar correlations were observed for the FR3 and FR4 data groups.

5.6 Influence of cutting pattern

To further explore the effect of radial position on distortion, two logs with similar under-bark grain angles (around 3°) were cut into a series of 40 x 40 x 700 mm billets and allowed to dry unrestrained from green to around 10% m/c (see Figure 5.8). For the sections on the left a cutting pattern representing conventional conversion was used, whilst for the samples on the right a smaller size batten was obtained encompassing the pith (Figure 5.9).

Figure 5.8: Samples after being allowed to dry unrestrained.

Figure 5.9: Close up of centrally cut samples.

Note that in the above figure the pieces are clamped square at the far end so as to be square to the frame of the picture.

From inspection, it was evident the direction of twist was the same throughout the samples regardless of which side of the pith they originated. Whilst the small sized central billet developed a very high degree of twist on drying, the pieces either side of this still twisted. Thus the effect of batten size on twist is due to the inclusion or exclusion of material less or more prone to twist within its section. Joist sized (200 mm deep) pieces taken from the same logs also developed twist on drying (Figure 5.10). Some of the other small-scale billets were observed to bow and spring due to the presence of compression wood (generally the battens either side of the pith were worst affected). It was noted that the grain angle was difficult to determine for many of the pieces due to the presence of disturbed grain around knots. Many of the pieces developed combined bow, spring and twist. No particular trend in the level of distortion axially was evident (*i.e.* from the butt upwards). Thus these observations on small-scale samples are in agreement with those from the FR1-4 batten dataset.

Figure 5.10: Twist of large section timber.

Although Booker (2005) demonstrated, through the construction of a geometrical model, that quarter sawn boards exhibit lower twist on drying than through-and-through cut boards, battens from relatively small size logs tend to consist of a combination of these types.

5.7 Discussion and summary of findings on twist

Batten twist was positively correlated to batten slope of grain (*i.e SoG outer*) and negatively correlated to distance from the centre of the batten to the pith (*i.e. Pith Dist*), as detailed in Section 5.1. This is in agreement with Balidos (1972). These relationships were observed to be similar for other sub-groups of batten size and stand.

MRC models based on slope of grain and radial position explained up to 70% of the variance in twist (Section 5.2). It is probable that a portion of the unexplained variance is due to experimental inaccuracy such as the effect of handling and transport. Better relationships between twist and these variables might have been obtained if radial position was based on an average value for each batten, rather than based on the value for one end only, or if the measurements of slope of grain could be made without the influence of knot content. No attempt has been made to correct the slope of grain measurements (made relative to the batten axis), to values relative to the true axis of the tree. This may be particularly significant for curved logs.

No relationship was observed between twist and knot content, compression wood content (in terms of the variable *CW total adj.*), axial position (*i.e. Cut ht.*), or tree size (*i.e. Tree ht.* and *DBH*) for any group. This indicates that these variables cannot be used as sorting criteria for propensity to twist. The absence of a relationship between batten twist and compression wood content is in agreement with Ohman (2001), for Norway spruce.

Twist was correlated negatively with batten size (*Depth*) *i.e.* twist was observed to be lower in larger battens, suggesting that for larger batten sizes there was a restraining effect (possibly this is caused by inclusion of material further away from the pith, or of lower spiral grain angle, as batten size increases.)

To correctly interpret the slope of grain measurements the type of face (radial or tangential) needs to be known. The measurement of slope of grain can also be difficult due to the presence of frequent knot groups. This would greatly complicate automatic measurement of spiral grain angle, *e.g.* by use of the laser tracheid effect.

Using ANOVA it was determined that there were statistically significant differences in the population means values of *SoG outer* between the individual stands FR1,2,3 and 4 (Section 5.5). This indicates that some stands have greater tendencies to yield timber which is prone to twist. This is worth further investigation. Moore *et al.* (2007) report encountering spiral grain values up to 10° in some stands of UK grown Sitka spruce.

Relationships observed between tree size (*DBH* or *Tree ht.*) and batten slope of grain (*SoG outer*) were either non-existent or weak for all forest stands. This indicates that the faster grown trees within individual stands do not yield battens with higher spiral grain angle. The absence of a relation between batten spiral grain angle and axial position (*i.e. Cut ht.*) is in agreement with Brüchert (2000).

It was evident for the small-scale samples studied (Section 5.6), that the direction of twist was the same throughout regardless of which side of the pith they originated. Whilst the small sized central billet developed a very high degree of twist on drying, the pieces either side of this still twisted, as did a joist sized batten cut from the same log. Thus the effect of batten size on twist is due to the inclusion or exclusion of material less or more prone to twist within its section. No particular trend in the level of distortion axially was evident (*i.e.* from the butt upwards). Thus these observations on small-scale samples are in agreement with those from the FR1 - 4 batten dataset.

Although Booker (2005) demonstrated, through the construction of a geometrical model (for radiata pine), that quarter sawn boards exhibit lower twist on drying than through-and-through cut boards, battens from relatively small size logs tend to consist of a combination of these types. On the basis of the above observations, it appears that in terms of a cutting pattern appropriate for British grown Sitka spruce, the choice is between obtaining either a greater number of small sized battens prone to twist, and obtaining a fewer number of large sized battens which also twist but to a lesser degree, but which will probably used for more demanding applications such as floor joists. Only by discarding the centrally cut “boxed pith” batten could a reduction in the average twist of the remaining battens be achieved.

6 Observations on variables affecting batten stiffness (E_{cb})

The following Section (6.1) details general observations on the results of machine grading. Relationships between grade determining minimum stiffness as measured by the Cook-Bolinder grader (E_{cb}) and a succession of board and log variables are examined to determine the consistency and usefulness of the measurements as sorting parameters (Sections 6.2 to 6.14). In particular, these sections detail the differing relationships observed between upper log and butt log material, together with differences observed between forest stands and batten sizes. It will subsequently be shown that without such discrimination into batten sub-groups, important and useful observations could not have been made. A summary of the findings is given in Section 6.15.

MRC models, based on combined data (*i.e.* treating FR1-4 material as one data group) are detailed in Chapter 7. Further MRC models for the Lochaline (FR1 and FR2) and Benmore (FR3 and FR4) datasets are explored in Chapters 8 and 9. Correlations based E_{cb} , $E_{m,g}$ and f_m are detailed in Chapter 10.

Comparison of the above results with earlier test work at BRE on the “Sitka spruce grading set” is made in Chapter 11.

6.1 General observations

Table 6.1 shows the machine strength grader results for all the battens from stands FR1-4 in terms of percentage reject (R) and pass rates for C16/R and C24/C16/R combinations[*].

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[*] Note that the machine settings utilised in the above table were derived by BRE as part of other work (Holland, 2005).

Table 6.1: Strength grader reject and pass rates for sub-groups of stand and batten size.

FR1 100 x 47 mm		%	FR1 150 x 47 mm		%	FR1 200 x 47 mm		%
C16/R	C16	100	C16/R	C16	97	C16/R	C16	98
	R	0		R	3		R	2
C24/C16/R	C24	38	C24/C16/R	C24	40	C24/C16/R	C24	25
	C16	32		C16	27		C16	25
	R	30		R	33		R	50

FR2 100 x 47 mm		%	FR2 150 x 47 mm		%	FR2 200 x 47 mm		%
C16/R	C16	92	C16/R	C16	93	C16/R	C16	78
	R	8		R	7		R	22
C24/C16/R	C24	60	C24/C16/R	C24	40	C24/C16/R	C24	0
	C16	18		C16	25		C16	11
	R	22		R	35		R	89

FR3 100 x 47 mm		%	FR3 150 x 47 mm		%
C16/R	C16	98	C16/R	C16	100
	R	2		R	0
C24/C16/R	C24	57	C24/C16/R	C24	73
	C16	28		C16	12
	R	15		R	15

FR4 100 x 47 mm		%	FR4 150 x 47 mm		%
C16/R	C16	97	C16/R	C16	89
	R	3		R	11
C24/C16/R	C24	77	C24/C16/R	C24	50
	C16	10		C16	14
	R	13		R	36

From Table 6.1 it can be seen that most of the timber meets the C16 strength class when graded at C16/R combination, but that when grading using the C24/C16/R combination the level of rejects increases markedly. This is particularly evident for the 200 x 47 mm battens. There are, however, significant numbers of battens which could be reach grade C24, particularly from FR3 and FR4.

Figure 6.1 and Figure 6.2 shows box plots and histograms, respectively, of E_{cb} values for the individual stands.

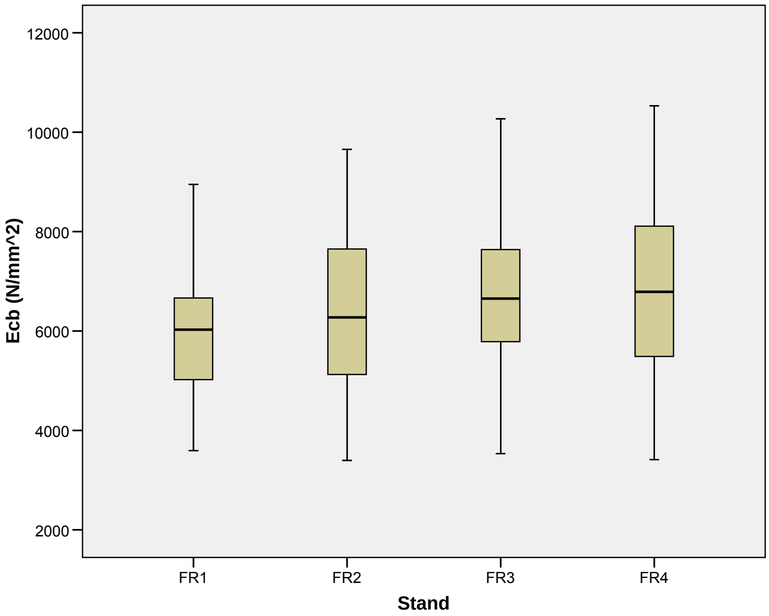

Figure 6.1: Box plots of E_{cb} for each stand.

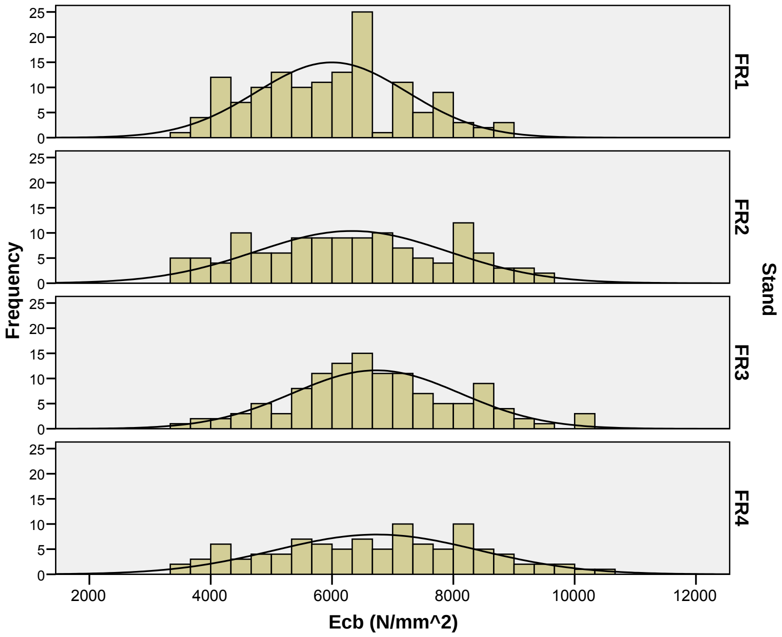

Figure 6.2: Histograms of E_{cb} for each stand (with normal distribution curves).

Although this work is not a particular study into the effects of silviculture on timber quality, from Figure 6.1 and Figure 6.2 (and with reference to the site and stand characteristics given in Appendix 1) it can be seen the stand with the widest initial spacing (FR1) appears to have yielded the least stiff timber. Of interest is that FR3 and FR4 although yielding higher stiffness timber than FR1 and FR2, did not yield any 200 x 47 mm size battens. It can also be seen that within each stand the range of timber stiffness is high, with some battens being over three times as stiff as others. Using 1 way ANOVA it was determined that the difference in the population means of E_{cb} for FR1/2 (Lochaline) and FR3/4 (Benmore) is significant at the $p < 0.05$ level, whilst the difference in the population means of E_{cb} within each locality (*i.e.* between stand FR1 and FR2, and between stand FR3 and FR4) is not statistically significant *i.e.* $p > 0.05$ in both cases.

Figure 6.3 shows a histogram for E_{cb} for a combined group FR1-4 battens, from which it is evident that the distribution is approximately normal. Note that this was confirmed by inspection of the Q-Q plot. (*i.e.*quartile-quartile plot, which is a graphical method for comparing probability distributions).

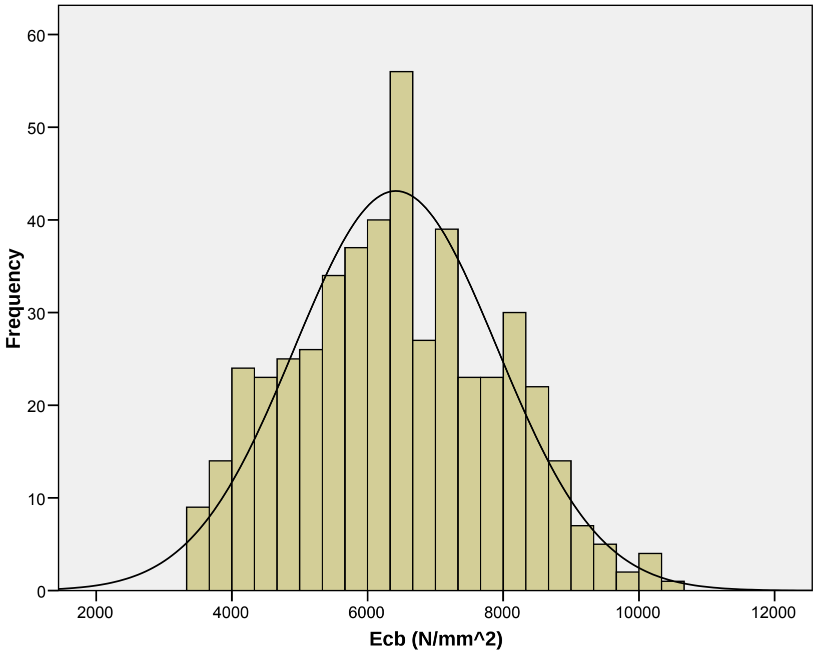

Figure 6.3: Histogram of E_{cb} for FR1- 4 (all battens), with normal distribution curve.

Although Table 6.1 presents ten basic groups in terms of stand and batten size, when considering subdivisions involving butt logs and upper logs (as defined in Chapter 3), there are several more main sub-groupings possible within the dataset (Table 3.4), as well as numerous other possible combinations of stand, batten size and position both radially and axially within the tree. Certain sub-groups, however, contain too few battens to be worth including in the analysis, or were not fully characterised.

By virtue of the number of batten subsets and number of predictor variables, there are a very large number of individual relationships which potentially could be explored. To aid this, predictor variables such as knot area were normalised for batten size (*i.e.* into knot area/batten face area). Variables such as slope of grain, percentage of juvenile wood, knot area ratio and log ovality do not require normalisation. Absolute as well as raw values of slope of grain can also be examined. The transformation of raw grader *IP* values into E_{cb} (as detailed in Chapter 3) normalises for differences in batten dimensions. However, the use of nominal rather than precisely determined batten dimensions places a limit on the reliability of these results (this aspect of the work is further discussed in Section 13.3).

The aim of the examination of the relationships apparent between variables and batten properties (which may or may not be causal) is to determine which measurements will be useful as sorting criteria. For example, where stiffness (*i.e.* E_{cb}) is correlated against *TKAR*, the position of measurement of the two variables may not have actually coincided (this may be particularly evident with certain butt logs), but this is the situation which is faced in the industrial setting. A study into the relation between knots and strength might be better carried out in some other way; for example with matched specimens of differing knot content, eliminating as far as possible the influence of other variables, and with the load always applied over the knot. In this work, the aim is to demonstrate the effect of sorting, based on the usage of a predictor variable that could reasonably be taken to be the *modus operandi* of the scanner or other operation. Where significant relationships are found between variables, there may be reason to suspect these could be sample specific, or some facet of the combination of sub-groups, or due to random effects, but nevertheless these are of interest and could not be determined without such a detailed dataset.

6.2 Axial position

By inspection of Cook-Bolinder derived E_{cb} values with height in the stem for each tree, *i.e.* continuous values recorded along the length of the board (Figure 6.4 and Figure 6.5 show examples), a trend for increasing stiffness with height in the butt logs of many of the trees is evident. This observation is in agreement with Brazier (1991). It can also be seen that the stiffness profiles for individual battens in the same log tend to correlate strongly, suggesting the limited influence of radial position (note that the influence of variables relating to radial position are examined in Section 6.3). Since the machine grade of each batten is determined by the lowest value of stiffness, this feature is grade-determining for many of the battens. However the feature appears to be variable both between sites and individual trees with some trees hardly exhibiting the effect at all. In particular for upper logs, the variation in stiffness along individual battens suggests an influence of features such as knots.

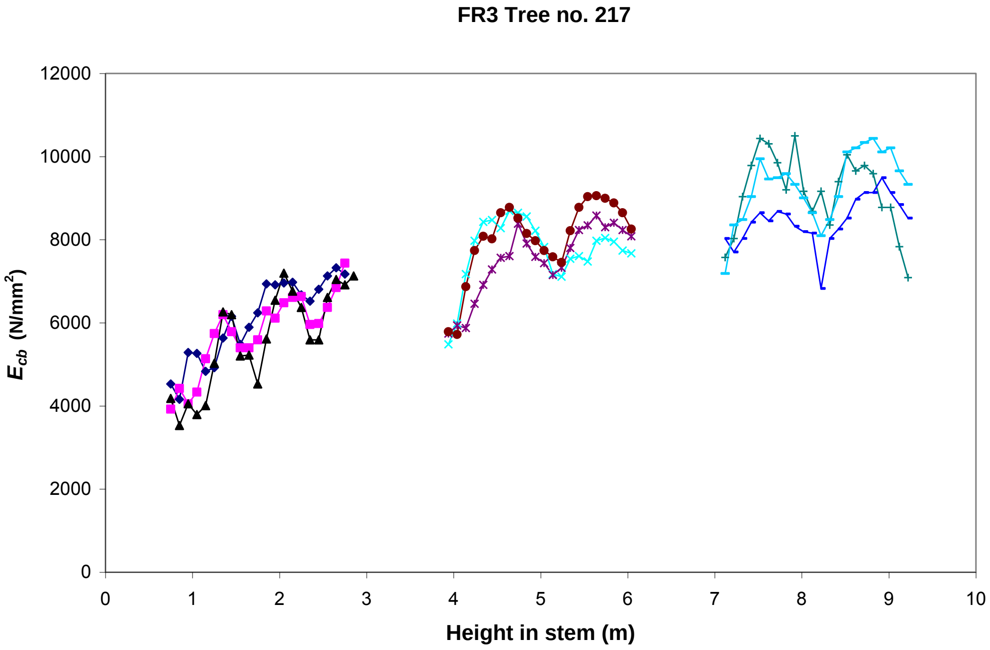

Figure 6.4: Continuous E_{cb} data plotted against height in stem for FR3 tree 217.

(original in colour)

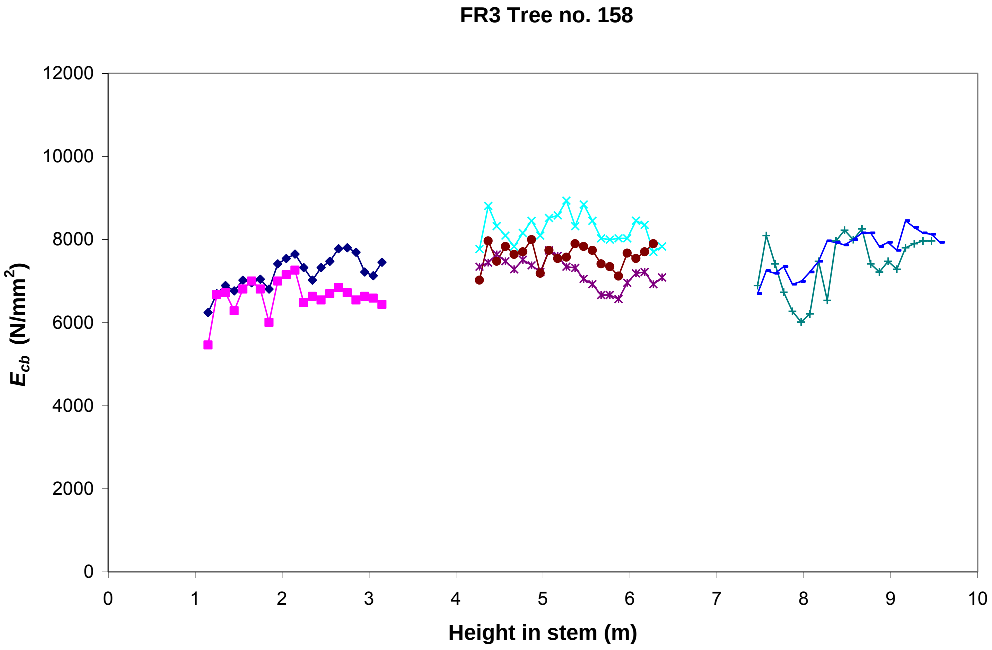

Figure 6.5: Continuous E_{cb} data plotted against height in stem for FR3 tree 158.

(original in colour)

Figure 6.6 below shows continuous IP data for several individual FR3 and FR4 150 x 47 mm size battens from butt logs, together with the threshold values for C16/Reject and C16/C24/Reject grade combinations (note that the selected batten IP data is representative of the range and variation of the whole group and that the other battens in this group have been omitted for clarity.

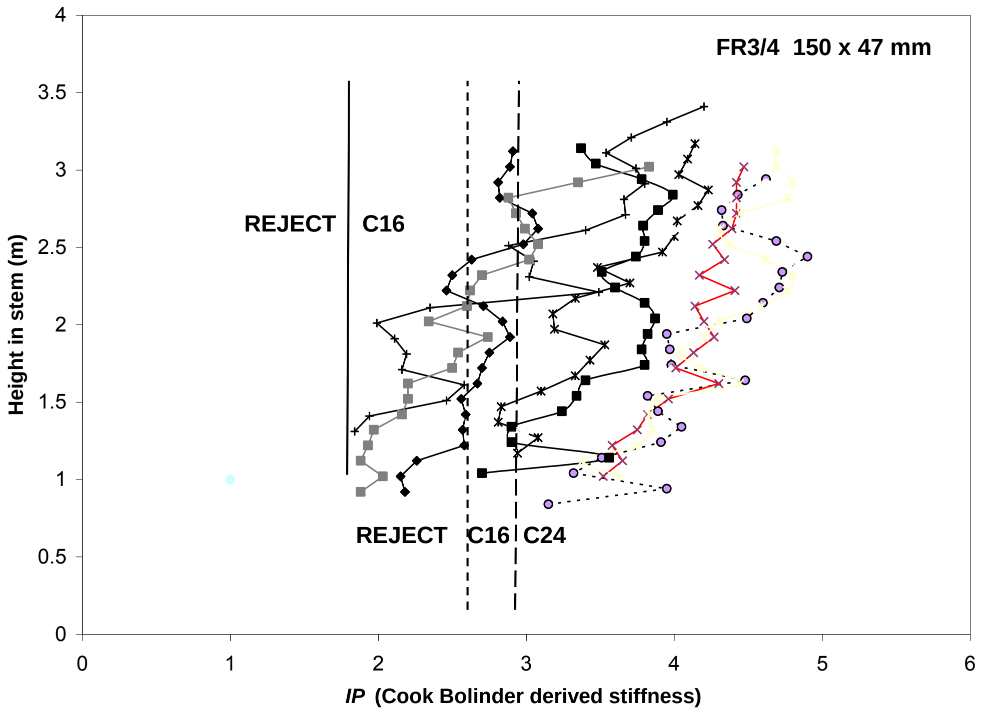

Figure 6.6: ***IP*** **data for selected FR3 and FR4 150 x 47 mm butt log battens.**

(original in colour)

Figure 6.6 shows that there was a wide variation in batten stiffness, even for battens of the same size and from the same locality. There are (from inspection of the whole dataset) many battens, or portions of these battens, that are well above the threshold for C24 material, whilst few battens in the dataset are below C16 level when grading at C16/Reject combination. It would, however, be a misconception to consider that there were large amounts of C24 material in the group that are being under utilised. The relatively low threshold for C16 when grading to C16/R compared with C16 at C16/24 is possible only because, in the former combination, the average batten stiffness is maintained by inclusion of all of the better quality material, and this naturally includes all of that which might have been C24 if the higher grade combination had been opted for. From the above figure it is also clear that a policy of directing all butt logs away from structural timber production would under-utilise large quantities of otherwise suitable material.

Although it is obvious that larger battens such as 200 x 47 mm tend to come from butt logs rather than higher in the tree, smaller battens such as 100 x 47 mm can be cut from any height in the tree. The conversion process usually optimises production in terms of volume, with, for example, the decision to cut either three 100 x 47 mm battens or two 150 x 47 mm battens based on small differences in log size and shape, or end user demand. A 150 x 47 mm size batten could, for example, originate from the upper log of a large tree, or from the butt of a smaller tree. Thus represented in the dataset are 100 and 150 mm deep battens that originate from both butt logs and upper logs, although the numbers of 200 mm deep battens from upper logs are low. Any batten of any size may therefore exhibit low stiffness due to the “weak butt” effect. It would, of course, in an industrial sorting process, be possible to introduce some form of batten marking or tagging system; or to separate butt logs from upper logs during some other stage in the process.

Figure 6.7 shows E_{cb} (*i.e.* the grade determining minimum vale) plotted against batten *Cut ht.* as defined in Chapter 3 for all battens from FR1-4. Figure 6.8 shows E_{cb} plotted against *Cut ht.* for the FR3 150 x 47 mm butt log sub-group.

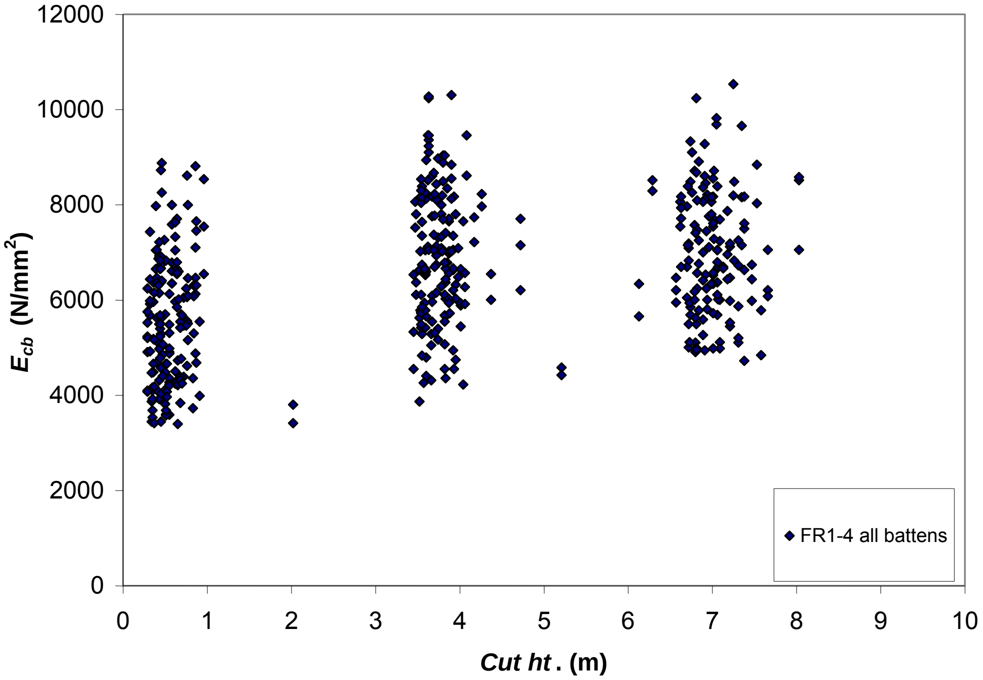

Figure 6.7: E_{cb} plotted against *Cut ht*. (FR1-4 all data).

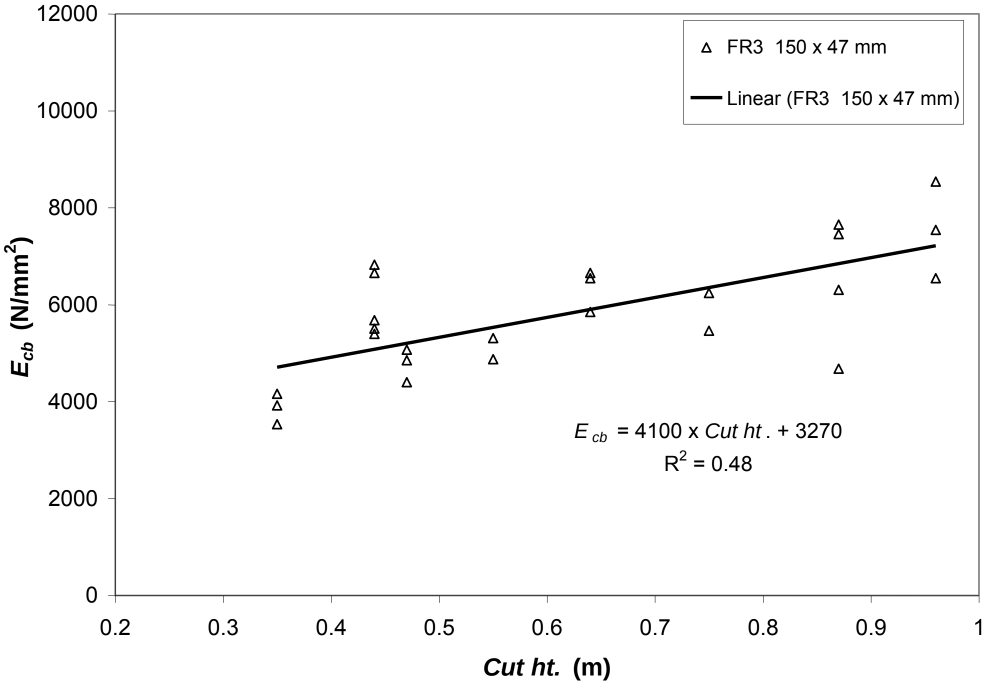

Figure 6.8: E_{cb} plotted against *Cut ht.* (FR3 150 x 47 mm butt logs).

Notable in Figure 6.8 are close groupings of battens which are obviously cut from the same log (*i.e.* they have common values of *Cut ht.*) indicating consistency within the E_{cb} measurements, but also suggesting that batten radial position is relatively insignificant. Although this line of best fit suggests that large gains in stiffness are possible, just by felling trees a few tenths of a metre higher than current practice, no similarly strong correlations were observed in the FR4 150 x 47 mm, FR3 100 x 47 mm or FR1 200 x 47 mm sub-groups of butt log battens. The overall relation between E_{cb} and *Cut ht.* for FR3 and FR4 as a combined group was found to be very weak (R^2 = 0.1). It can therefore be concluded that certain relations which are observed within sub-groups of battens may not be evident when considering a wider, combined sample. Such within-group or site-specific correlations may therefore not be relevant when considering the mixed material entering a sawmill.

By inspection of the correlations between *Cut ht.* and other tree variables for FR3 and FR4 butt log battens, it was evident that (as would be expected), *Cut ht.* is strongly related negatively to *Log taper* , but apparently is not a function of tree size *i.e. DBH*, or *Tree height*, nor *Tree taper* (*i.e*. *Tree ht/DBH*). A strong positive correlation between *Tree height* and *Tree taper* was observed, indicating that the taller trees are more slender.

Figure 6.9 shows box plots for E_{cb} for grouped by *Cut ht.* (*i.e.* 0.5 m, 3.5 m and 7.0 m) for the FR1-4 all battens data set. Using 1-way ANOVA it was determined that there were statistically significant differences in the population means between the groups ($F_{2,483}$ = 56.7, $p < 0.001$). This test does not in itself identify which group is different, and it cannot be assumed from the box plots that it is the *Cut ht.* = 0.5 m group, even though this would be entirely consistent with other observations.

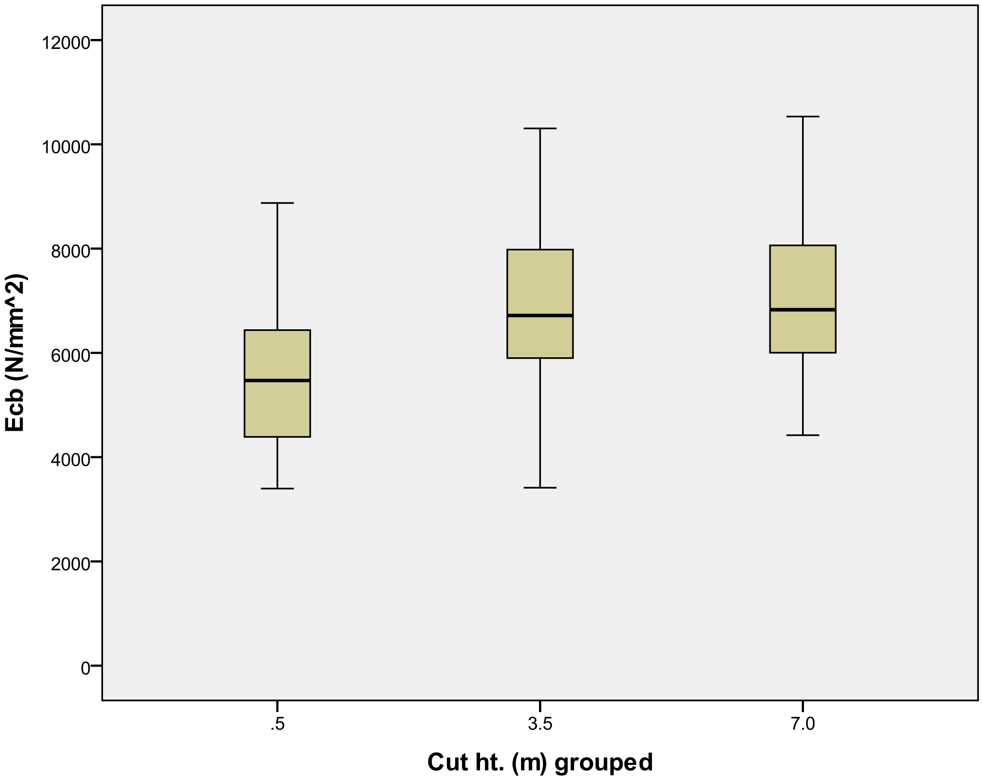

Figure 6.9: Box plot of E_{cb} for battens grouped by *Cut ht*. (FR1-4 all battens)

Table 6.2 and Table 6.3 show the descriptives and multiple comparisons (*i.e.* results of the *post hoc* tests), respectively, which shows that the difference in the population means of the 0.5 m *Cut ht.* group are statistically different at the $p < 0.001$ level, whereas there is no statistically significant difference between the 3.5 m and 7.0 m *Cut ht.* groups.

Table 6.2: ANOVA descriptives, E_{cb} for battens grouped by *Cut ht.*

E_{cb}		**Descriptives**		
Cut ht. =	N	Mean	Std. Deviation	Std. Error
0.5	174	5520	1300	99
3.5	165	6820	1500	117
7	147	6980	1300	107
Total	486	6400	1520	69

Table 6.3: ANOVA multiple comparisons, E_{cb} for battens grouped by *Cut ht.*

E_{cb}		**Multiple Comparisons**		
(I) *Cut ht.* group	(J) *Cut ht* group	Mean Difference (I-J)	Std. Error	Sig.
0.5	3.5	-1300	153	0.000
	7	-1460	145	0.000
3.5	0.5	1300	153	0.000
	7	-1560	158	0.692
7	0.5	1460	145	0.000
	3.5	1560	158	0.692

Method = Tamhane

6.3 Radial position

No relationship was evident between E_{cb} and the variable *Pith Dist* (*i.e.* the distance from the centre of the batten to the pith, as defined in Appendix 2) for any of the individual sub-groups of FR1-4 100 x 47 mm and 150 x 47 mm battens.

A similar lack of relationships between E_{cb} and *Section* (as defined in Appendix 2) was also determined. This finding is in agreement with recent work on Sitka spruce reported by Moore *et al.* (2007), on trees of a similar size. In other work on an uncommon 83-year-old stand of much larger trees (Moore and Lyon, 2008), strong trends for increasing stiffness and strength from pith to bark were established.

It follows that a scanner operating on the principle of measurement of *Pith Dist* or identification of *Section* on sawn timber (should this be technically possible) will be ineffective. This does not necessarily mean that there is no radial variation in stiffness within individual trees. Notable is that the variables *Pith Dist* and *Section* were strongly related to distortion in the form of twist (Section 5.1). The measurements on battens that are useful for predicting distortion may therefore be of little value, overall, in predicting stiffness.

Figure 6.10 shows box plots of Ecb for groups of Section (note that this graphic does not necessarily represent the radial variation of stiffness within trees, rather it represents sorting timber into groups based on the Section variable).

Table 6.5 and Table 6.4 show the descriptives and multiple comparisons, respectively. Note that the use of 1 way ANOVA determined that there are statistically significant differences between the groups ($F_{2,473} = 5.25$, $p < 0.006$).

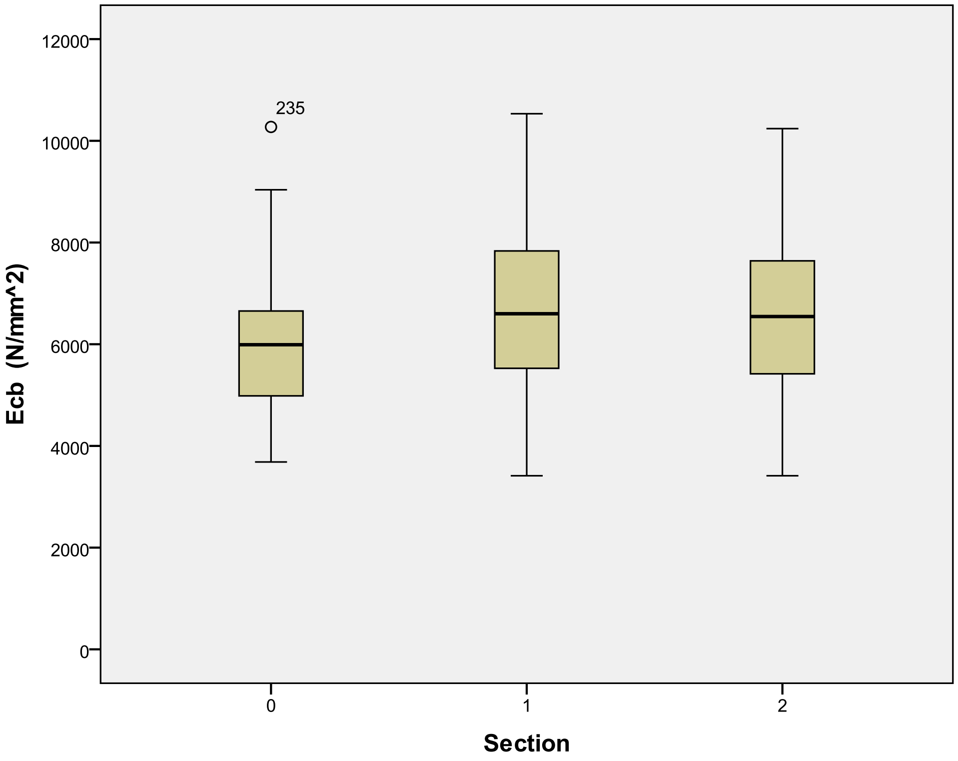

Figure 6.10: Box plot of E_{cb} for groups of *Section* (FR1-4 all battens)

Table 6.4: Descriptives, E_{cb} for groups of *Section* (FR1-4 all battens)

E_{cb}		Descriptives		
Section =	N	Mean	Std. Deviation	Std. Error
0	94	6030	1360	140
1	172	6660	1540	117
2	210	6450	1510	104
Total	476	6440	1510	69

Table 6.5: Multiple comparisons, E_{cb} for groups of *Section* (FR1-4 all battens)

E_{cb}		Multiple Comparisons		
(I) *Section*	(J) *Section*	Mean Difference (I-J)	Std. Error	Sig.
0	1	-620	183	0.002
	2	-414	174	0.055
1	0	620	183	0.002
	2	205	157	0.469
2	0	414	174	0.055
	1	-205	157	0.469

Method = Tamhane

From Table 6.5 it can be seen that differences in the population means values of E_{cb} are statistically significant at the $p < 0.005$ level between *Section* = 0 and *Section* = 1 groups, whilst, in comparison, there is no statistically significant difference between the mean values of E_{cb} for the *Section* = 2 and *Section* = 1. Such small differences between the mean stiffness of the groups are almost certainly of no practical value, but the result does indicate that battens containing pith *i.e. Section* = 0 (which were shown in Chapter 5 to have a greater tendency to develop twist) could be segregated without any particular effect on the average stiffness of the remainder.

6.4 Juvenile wood content

No relationship was evident between E_{cb} and *JW* (as defined in Appendix 2), for sub-groups of FR1-4 100 x 47 mm and 150 x 47 mm battens, *i.e.* combined upper log and butt log material.

Figure 6.11 and Figure 6.12 show E_{cb} plotted against juvenile wood content (*JW*) for the FR2 and FR3 100 x 47 mm butt log sub-groups.

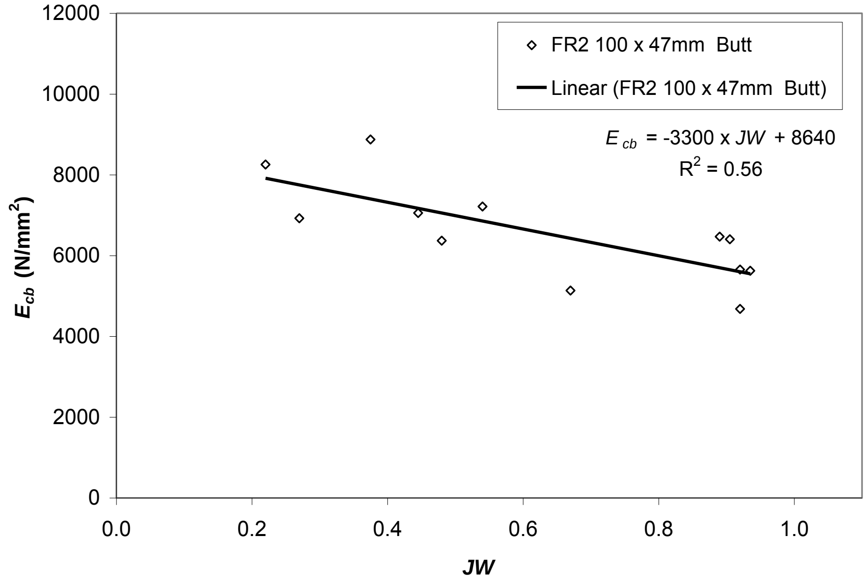

Figure 6.11: E_{cb} plotted against *JW* (FR2 100 x 47 mm butt log).

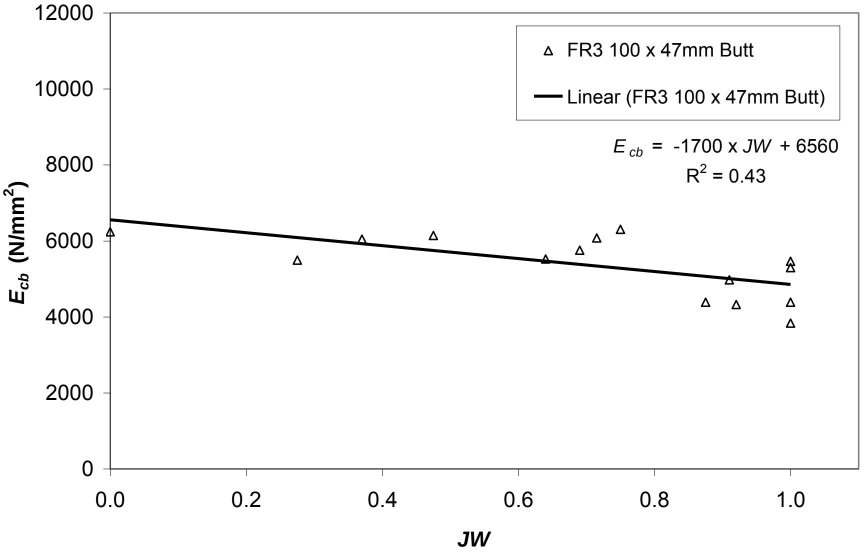

Figure 6.12: E_{cb} plotted against *JW* (FR3 100 x 47 mm butt log).

From Figure 6.11 and Figure 6.12 it can be seen that for these sub-groups of butt log battens stiffness consistently decreases with increasing juvenile wood content.

Table 6.6 shows the correlation table for the sub-group of FR3 100 x 47 mm battens from butt logs.

Table 6.6: E_{cb} correlation table (FR3 100 x 47 mm butt log battens).

R	E_{cb}	*JW*	*Ring width*	*Dens*	*Cut ht.*	*Kn300 %*	*Knot Area%*
JW	-0.66**						
Ring width	-0.44	0.73**					
Dens	-0.63*	0.34	0.23				
Cut ht.	-0.19	0.55*	0.45	-0.04			
	-0.06	-0.38	-0.18	-0.04	-0.29		

Kn300%							
Knotarea%	-0.77**	0.28	0.37	0.54*	-0.11	0.45	
Pith Dist	0.58*	-0.85**	-0.53*	-0.52*	-0.48	0.46	-0.20

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N=12

From Table 6.6 (note that correlations with R > 0.4 are shown shaded) it can be seen that for these battens E_{cb} correlates negatively to *JW* and the knot content variable *Knotarea%*. Variables relating to log diameter (*i.e. Bot dia*, *Top dia*), *Log taper*, *Ovality* and *Pith X* were not found to be significantly related to E_{cb}, for this group, nor was *Tree ht*., *DBH*, *Section*, or *SoG outer*. As would be expected it can be seen that *JW* and *Ring width*, and *JW* and *Pith Dist* correlate strongly.

Table 6.7 shows details the values of E_{cb}, *JW*, *Density*, *Pith Dist*, *Section*, *Knotarea%*, *Log taper* and *Cut ht*. for the FR3 100 x 47 mm battens. Note that, as detailed in Chapter 3, groups of battens numbered consecutively (*e.g.* 2BA, 2BB, 2BC) originate from the same log.

Table 6.7: FR3 100 x 47 mm butt log battens data (grouped by log).

FR3 Log ID	Batten ID	E_{cb} N/mm^2	*JW*	*Dens*	*Pith dist*	*Ring width*	*Section*	*Knotarea%*	*Log taper* (butt / top)	*Cut ht.* m.
31	2BA	5490	0.28	366	6.3	3.6	2	1.25	1.36	0.43
	2BB	4970	0.91	406	1.7	6.0	0	1.50		
	2BC	6140	0.48	386	4.5	4.1	2	0.81		
87	5NA	5530	0.64	338	7.4	4.1	2	1.45	1.23	0.29
	5NB	5750	0.69	345	5.1	6.6	0	0.73		
	5NC	6240	0.00	333	11.5	3.6	2	1.30		

155	8BA	6050	0.37	358	6.8	4.5	2	1.02	1.27	0.72
	8BB	4390	1.00	381	1.7	8.0	0	1.50		
	8BC	5460	1.00	359	3.5	13.0	2	1.54		
214	NNA	3830	1.00	397	0.9	8.0	0	1.99	1.23	0.68
	NNB	4390	0.88	350	5.4	6.6	2	1.49		
	NNC	4320	0.92	402	4.9	8.0	2	1.43		
194	TNA	6300	0.75	335	4.9	5.7	2	0.55	1.12	0.84
	TNB	5300	1.00	340	0.9	6.6	0	0.83		
	TNC	6080	0.72	329	5.6	5.8	2	0.80		

From Table 6.7 it can be seen that three 100 x 47 mm battens have been cut from each log and that the batten with the lowest stiffness in three out of four log conversion instances is the centre one containing pith (*i.e. Section* = 0), although *Section* was not found a significant variable for the whole group. It can also be seen that the least stiff batten out of the whole group is the one with the highest knot content (in terms of the *Knotarea%* variable), which also happens to be a centre cut batten. The stiffest batten is the one with the lowest knot content, which is also *Section* = 2 (*i.e.* pith outside section). The two stiffest battens are actually the two with the lowest density. Thus the stiffness of this group of battens is a function of both radial position in terms of juvenile wood content and knot content.

Figure 6.13 shows the trends in Cook-Bolinder derived stiffness (E_{cb}) with height for the butt log battens from FR3 log 31, showing the influence of radial position (and also height in stem).

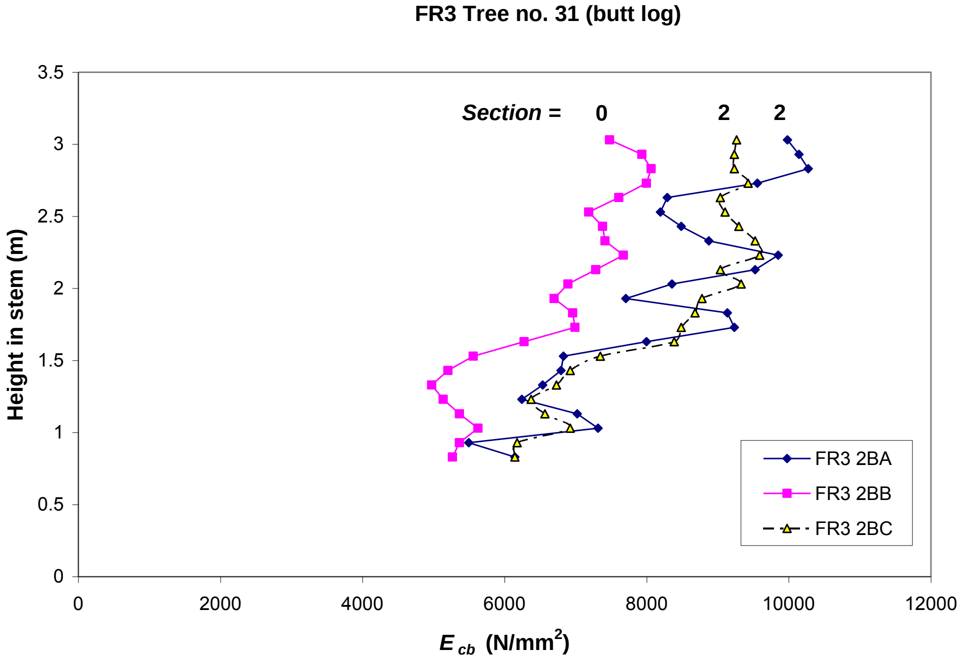

Figure 6.13: E_{cb} trends with height for the butt log battens from FR3 log 31, showing the influence of radial position. (original in colour)

From inspection it can be seen that where three 100 x 47 mm battens have been cut from the same log, this tends to result in a centre cut batten with a high proportion of juvenile wood (shown graphically in Figure 6.14), whereas by comparison the alternative conversion into two 150 x 47 mm results in two battens with *Section* = 1, for which the juvenile wood content does not vary. Note that for upper logs the “2 X” conversion pattern typically results in battens which are mirror images of each-other; hence there is also no variation in juvenile wood content.

Brüchert (2000) also observed a similar radial variation in stiffness for butt log battens, which, in her work, had been cut in a specific pattern as part of a study into the effects of wind exposure.

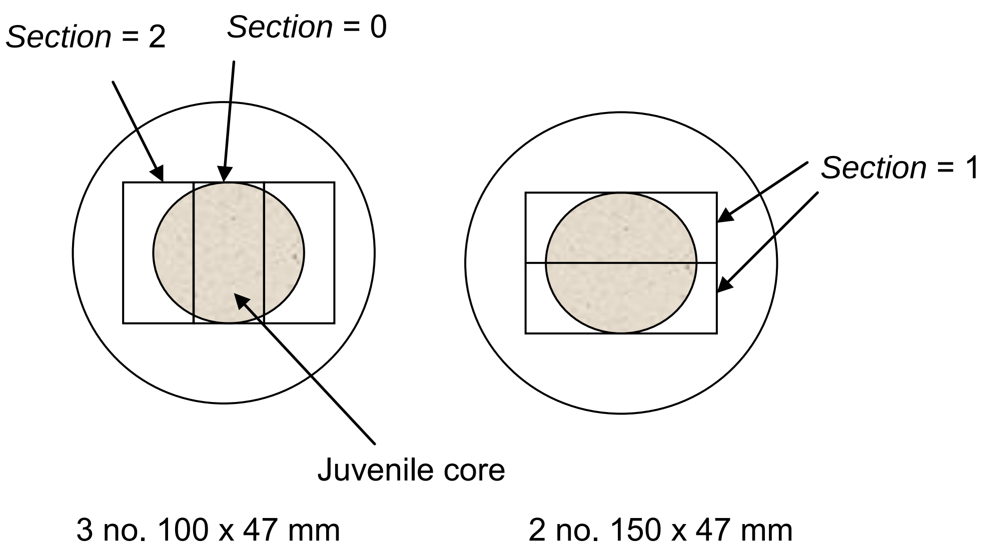

Figure 6.14: Log conversion and juvenile wood content.

Table 6.8 shows the MRC model summary for FR3 100 x 47 mm butt log battens, utilising the variables *Knotarea%* and *JW*. Table 6.9 shows the model summary (note that the t-values indicate that knot content had a greater influence than juvenile wood content).

Figure 6.15 shows the model fit, which is clearly for a relatively small group of 12 battens, and likely to be site specific. However, a similar result was noted for the FR2 100 x 47 mm butt log battens.

Table 6.8: E_{cb} model summary (FR3 100 x 47 mm butt log battens).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.90(a)	0.80	0.77	385.3

a Predictors: (Constant), *Knotarea%*, *JW*

Table 6.9: E_{cb} coefficients (FR3 100 x 47 mm butt log battens).

Model	Unstandardised Coefficients		Standardised Coefficients		
	B	Std. Error	Beta	t	Sig.
1 (Constant)	7765.7	363.1		21.38	0.000
JW	-1231.0	350.2	-0.473	-3.51	0.004
Knotarea%	-1266.1	268.1	-0.636	-4.72	0.000

a Dependent variable: E_{cb}

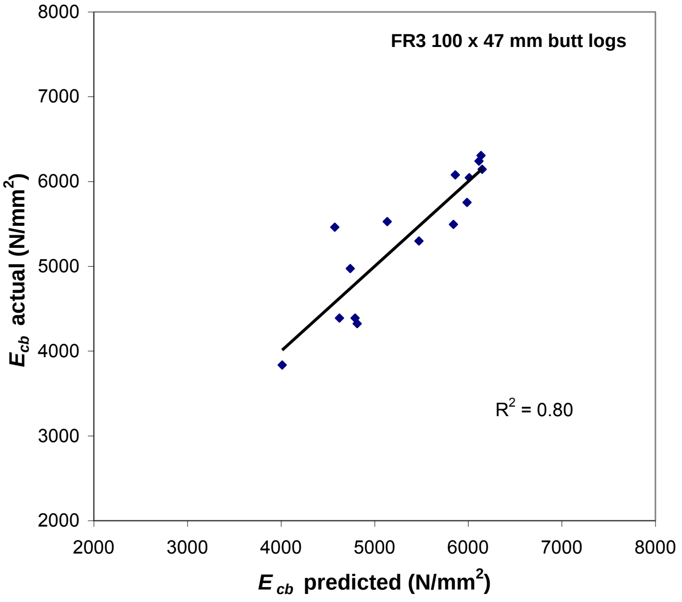

Figure 6.15: E_{cb} model fit (FR3 100 x 47 mm butt log battens).

6.5 Ring width

Figure 6.16: *Ecb* plotted against *Ring width* (FR3 and FR4).

shows the relation between E_{cb} and *Ring width* for the FR3 and FR4 upper and butt log material. Notably the lines of best fit for the two groups are offset, consistent with the generally lower stiffness of buttlogs observed in Figure 6.9.

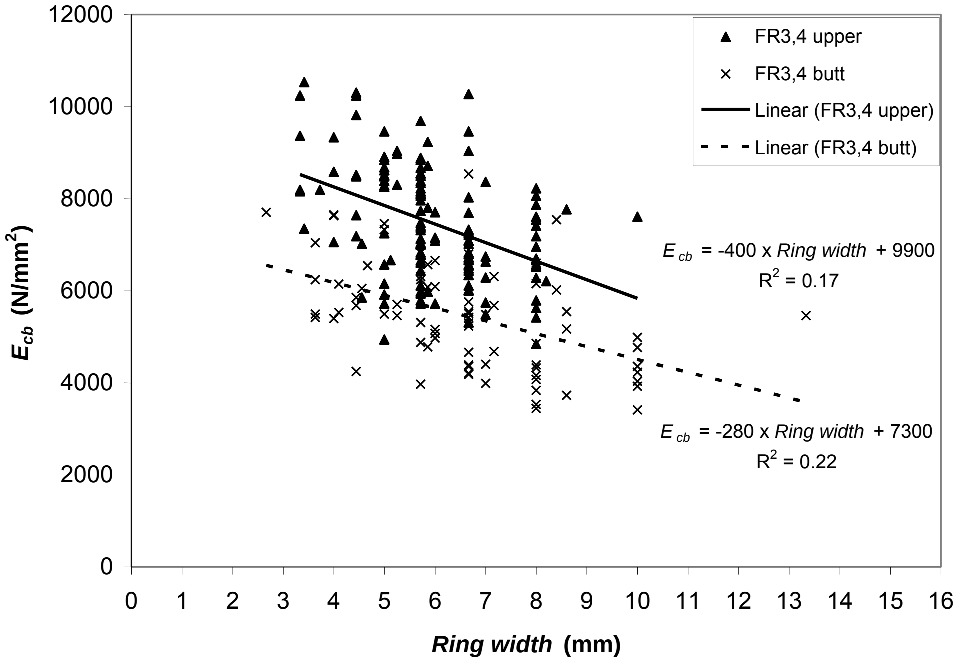

Figure 6.16: *Ecb* plotted against *Ring width* (FR3 and FR4).

In contrast, Glos and Denzler (2007) obtained a quite strong relation between stiffness and ring width (R^2 = 0.31) as part of work to determine the machine settings for the GoldenEye^{TM} X-ray grader for British-grown Sitka spruce.

6.6 Knots and whorl spacing

Figure 6.17 and Figure 6.18 show E_{cb} plotted against *Knotarea%* (*i.e.* the percentage knot cover over the faces and edges of the boards), for sub-groups of upper log battens and butt log battens, respectively.

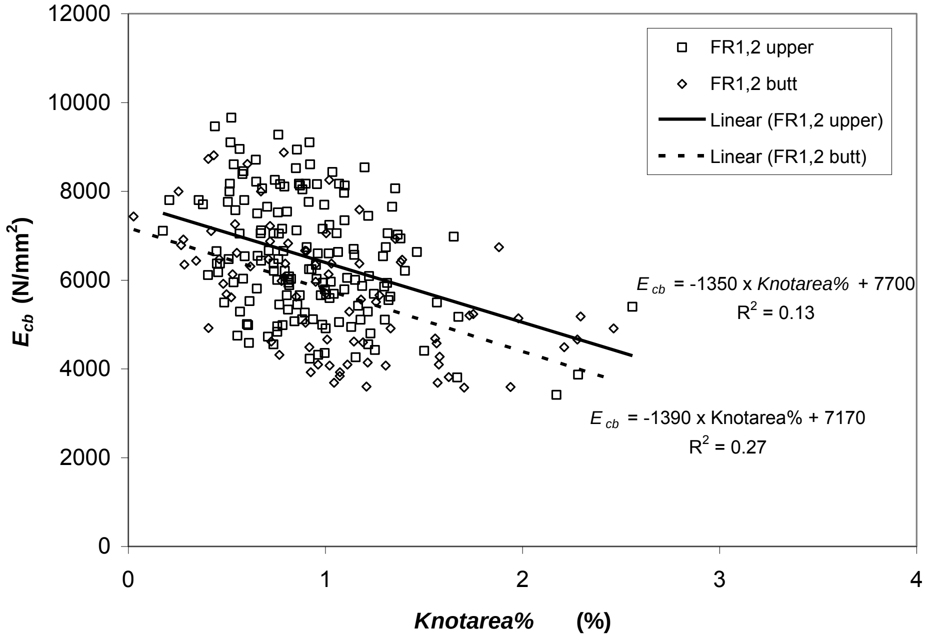

Figure 6.17: E_{cb} plotted against *Knotarea%* (FR1 and FR2).

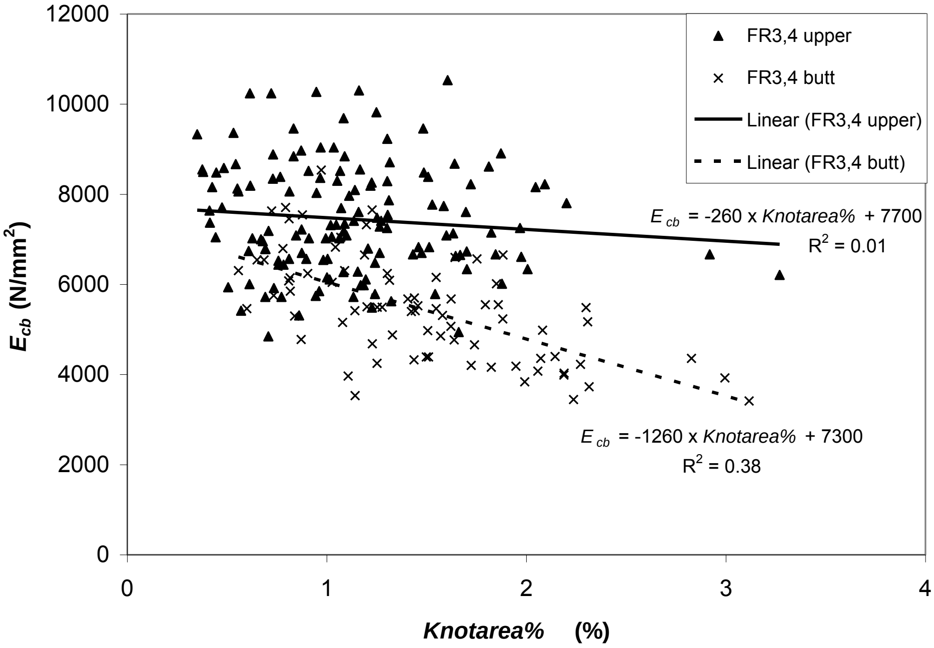

Figure 6.18: E_{cb} plotted against *Knotarea%* (FR3 and FR4).

From Figure 6.17 and Figure 6.18 it can be seen that for butt log material there is, consistently, a negative but weak relationship between E_{cb} and *Knotarea%* for both FR1/2 and FR3/4 butt log groups. For the upper log material from FR1/2 only a very poor relationship is evident between knot content and stiffness, whilst for FR3/4 upper log material there is no relationship at all. This is similar to the findings reported by Brazier (1991). Relationships observed between E_{cb} and either *TKAR* or *MKAR* were found to be non-existent for sub-groups of upper log and butt log material.

Table 6.10 shows the correlation table for E_{cb} with knot and whorl variables for the combined FR1-4 all data group.

Table 6.10: Correlation table for E_{cb} with knot and whorl spacing variables (all data).

R	E_{cb}	*Whorl mean spacing*	*Whorl min spacing*	*Whorl max spacing*	*Kn300%*	*Knot area%*
Whorl mean spacing	0.49**					
Whorl min spacing	0.46**	0.88**				
Whorl max spacing	0.40**	0.82**	0.59**			
Kn300%	-0.24**	-0.06	-0.08	0.01		
Knotarea%	-0.37**	-0.12**	-0.12*	-0.08	0.49**	
TKAR	-0.18**	-0.05	-0.04	-0.02	0.26**	0.27**

** Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed). N ~ 461 except for *TKAR* where N~ 360 due to missing values.

From Table 6.10 (note that correlations with R > 0.4 are shown shaded) it can be seen that E_{cb} correlates positively to all of the whorl spacing variables and negatively to all of the batten knot variables, although in the case of *TKAR* there is no meaningful relationship. There appears to be little correlation between whorl spacing variables and the batten knot variables, but as might be expected the batten knot variables tend to correlate quite strongly between each other, as do the whorl spacing variables. For a scanner capable of detecting knots either in logs or sawn timber, combined usage of the above variables could of course take place.

Table 6.11 and Table 6.12 show the correlations for E_{cb} with the number and total area of knots in batten upper, middle and lower third outer face zones (as defined in A2.17) for FR1/2 and FR3/4 150 x 47 mm size butt log battens, respectively.

From Table 6.11 and Table 6.12 (note that correlations with R > 0.4 are shown shaded) it can be seen that for both groups of FR1/2 and FR3/4 150 x 47 mm butt log battens, E_{cb} correlates negatively to all of the knot variables (albeit very weakly). For FR1/2 the knot variables appear to be marginally more significant than those for FR3/4, however there is no particularly marked tendency for knot variables for the upper, middle and lower sections to be more significant than each other. In both cases there is a tendency for the knot variables to correlate positively to each other.

Table 6.11: Correlation table for E_{cb} with batten upper, middle and lower third zone knot variables (FR1 and FR2 150 x 47 mm butt log battens).

R	E_{cb}	Upper 3rd outer face No. of knots	Upper 3rd outer face AREA of knots	Middle Outer face No. of knots	Middle Outer face AREA of knots	Lower 3rd outer face No. of knots
Upper 3rd outer face No. of knots	-0.44**					
Upper 3rd outer face AREA of knots	-0.49**	0.64**				
Middle Outer face No. of knots	-0.62**	0.53**	0.48**			
Middle Outer face AREA of knots	-0.51**	0.37**	0.63**	0.72**		
Lower 3rd outer face No. of knots	-0.46**	0.35*	0.35*	0.30*	0.32*	
Lower 3rd outer face AREA of knots	-0.43**	0.29*	0.37**	0.27	0.47**	0.74**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N=53

Table 6.12: Correlation table for E_{cb} with batten upper, middle and lower third zone knot variables (FR3 and FR4 150 x 47 mm butt log battens).

R	E_{cb}	Upper 3^{rd} outer face No. of knots	Upper 3rd outer face AREA of knots	Middle Outer face No. of knots	Middle Outer face AREA of knots	Lower 3rd outer face No. of knots
Upper 3rd outer face No. of knots	-0.34*					
Upper 3rd outer face AREA of knots	-0.36**	0.57**				
Middle Outer face No. of knots	-0.40**	0.57**	0.31*			
Middle Outer face AREA of knots	-0.38**	0.23	0.62**	0.50**		
Lower 3rd outer face No. Of knots	-0.37**	0.44**	0.39**	0.27	0.24	
Lower 3rd outer face AREA of knots	-0.45**	0.28*	0.58**	0.24	0.56**	0.73**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed). N= 51

6.7 Density

Figure 6.19 and Figure 6.20 show E_{cb} plotted against *Density* for groups of upper log and butt log material for FR1/2 and FR3/4 respectively.

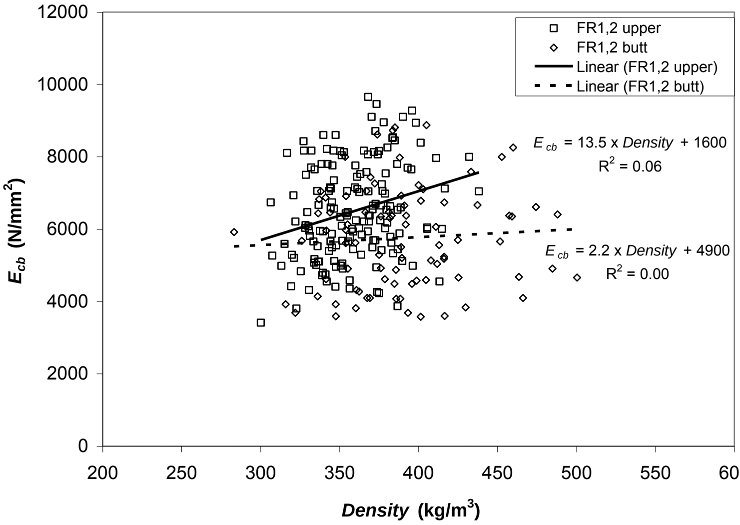

Figure 6.19: E_{cb} plotted against *Density* (FR1 and FR2).

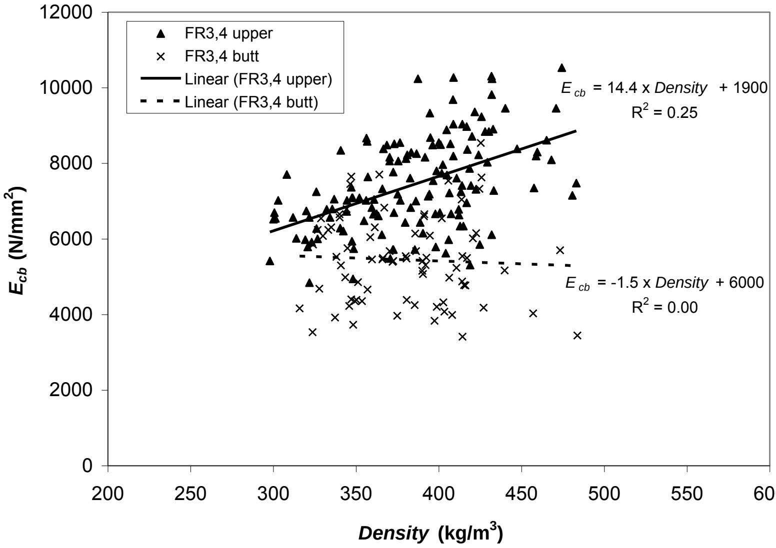

Figure 6.20: E_{cb} plotted against *Density* (FR3 and FR4).

From Figure 6.19 it can be seen that for FR1/2 there is no relationship between E_{cb} and *Density* for either butt or upper log groups. From Figure 6.20 it can be seen that for the FR3/4 upper log group there is a very slight relationship between stiffness and density, but that there is no relationship at all for the butt log group (this observation is similar to that observed by Brazier, 1991). Notable is the lower variance in *Density* for the FR1/2 group compared to the FR3/4 group, and that there are instances of butt log battens with relatively high density which exhibit low stiffness. In particular for FR3/4 the least stiff battens tend to come from butt logs.

6.8 Slope of grain

No significant relationships between stiffness E_{cb} and *SoG outer* were observed for any of the individual sub-groups of batten size and stand. This indicates that slope of measurement (*e.g.* by laser tracheid effect), although found useful for determination of propensity to develop twist on drying (as detailed in Chapter 5) will not be useful for sorting on the basis of stiffness and hence structural grade. The variables that affect batten distortion are therefore different to those affect stiffness. This result is similar to that obtained for Sitka spruce by Moore *et al.* (2007).

6.9 Compression wood

No significant relationships between stiffness E_{cb} and compression wood content (in terms of the variable *CW total adj.*) were noted in any of the individual sub-groups of batten size and stand, nor was any relationship observed between the other compression wood distribution variables as defined in Chapter 3 *(i.e. CW edge diff*, *CW face diff.*). This is probably due to the quite low incidence of compression wood in the sample, or the overriding influence of other factors such as knots or the weak butt effect. It is also possible that the CW variables are poor indicators of batten compression wood content.

6.10 Log ovality and pith eccentricity

No consistent pattern was evident in the individual relationships between E_{cb} and *Log ovality* (as defined in Chapter 3) for the various sub-groups of upper log and butt log material. For the FR3 100 x 47 mm and 150 x 47mm battens (see Figure 6.21) the relationships are similar, but very weak.

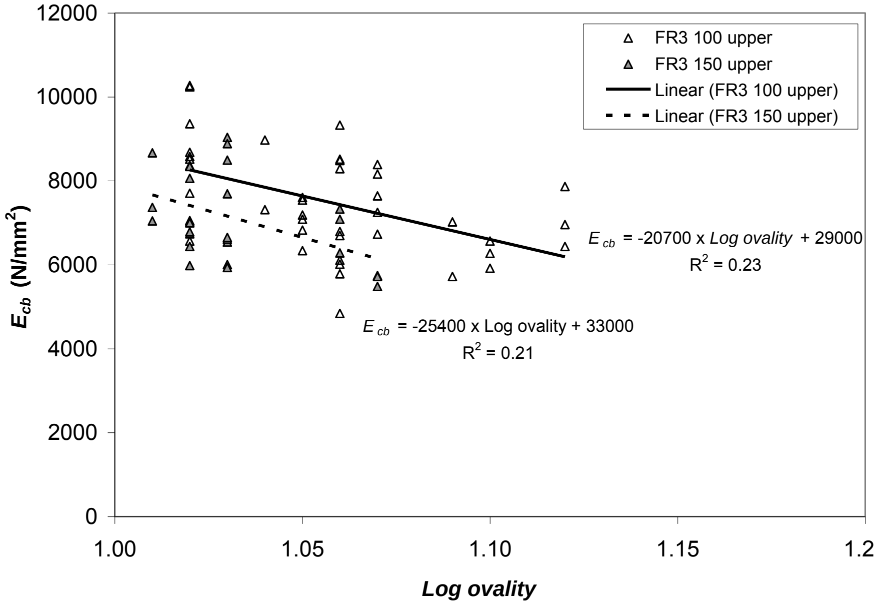

Figure 6.21: E_{cb} plotted against *Log ovality* (FR3 upper logs).

For combined groups of FR1-4 upper log and butt log material no overall relationship between Ecb and Log ovality was evident.

No significant relationship between Ecb and Pith X was noted in any of the sub-groups of data. This indicates that, although readily obtainable by use of 3D scanner, Log ovality is not a useful sorting criterion for stiffness.

6.11 Log taper

Figure 6.22 and Figure 6.23 show E_{cb} plotted against *Log taper* for groups of upper log and butt log material for FR1/2 and FR3/4.

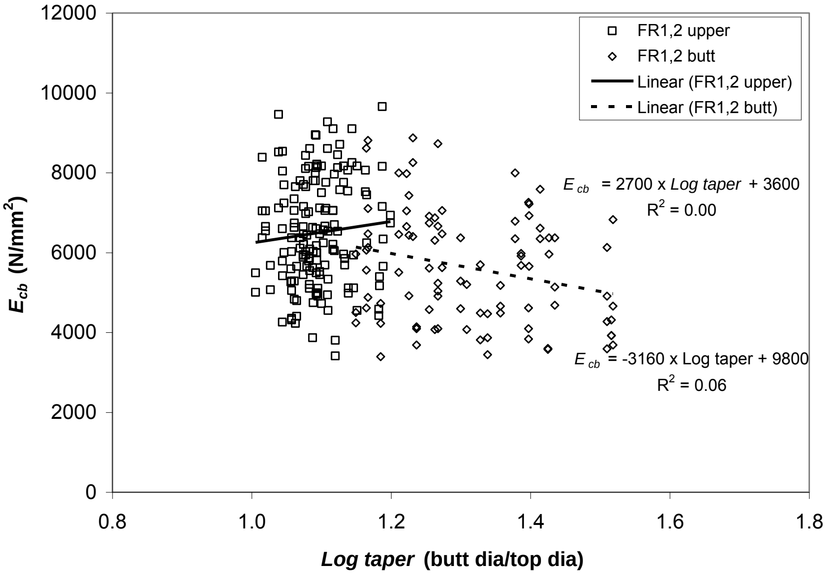

Figure 6.22: E_{cb} plotted against *Log taper* (FR1 and FR2).

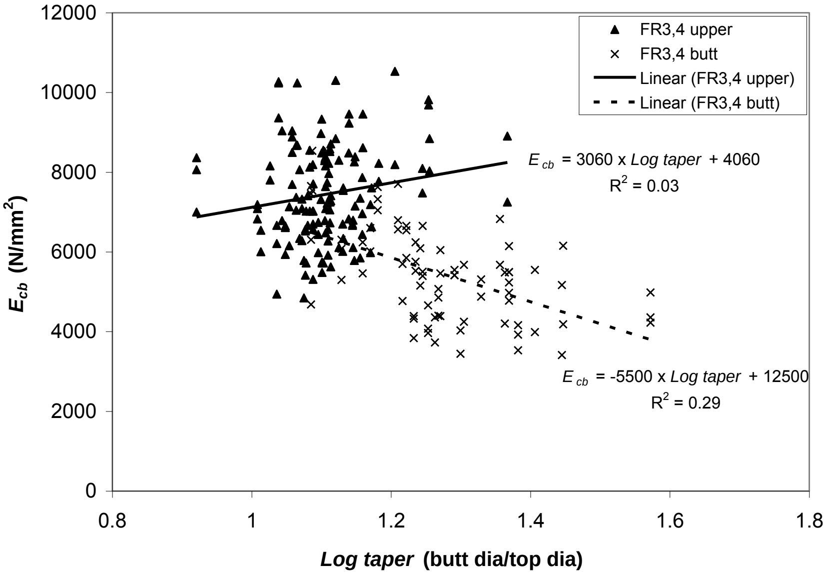

Figure 6.23: E_{cb} plotted against *Log taper* (FR3 and FR4).

From Figure 6.22 and Figure 6.23 it can be seen that for FR3 and FR4 butt log material there is a weak negative relationship between batten E_{cb} and *Log taper*, but that for the FR1 and FR2 group there is no indication of a similarly strong relationship.

Figure 6.24 shows histograms for the combined FR1-4 data separated into two groups of *Log taper* (< 1.3 and > 1.3), whilst Figure 6.25 shows box plots for the same data.

From Figure 6.24 and Figure 6.25 it can be seen that logs with a taper value above 1.3 tend not to contain any battens of above average stiffness, but that within the below 1.3 group there are still many battens which are below average stiffness.

Table 6.13 shows values of mean E_{cb}, standard deviation and standard error for grouped *Log taper* values (> 1.3 and < 1.3).

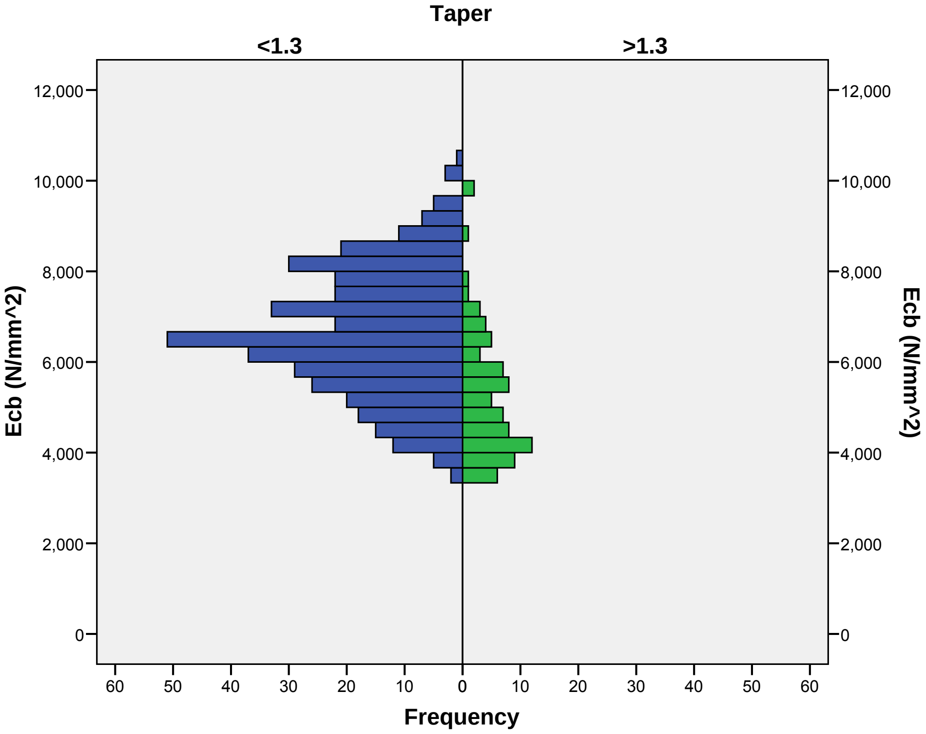

Figure 6.24: Histograms of E_{cb} for grouped values of *Log taper* (FR1- 4).

(original in colour)

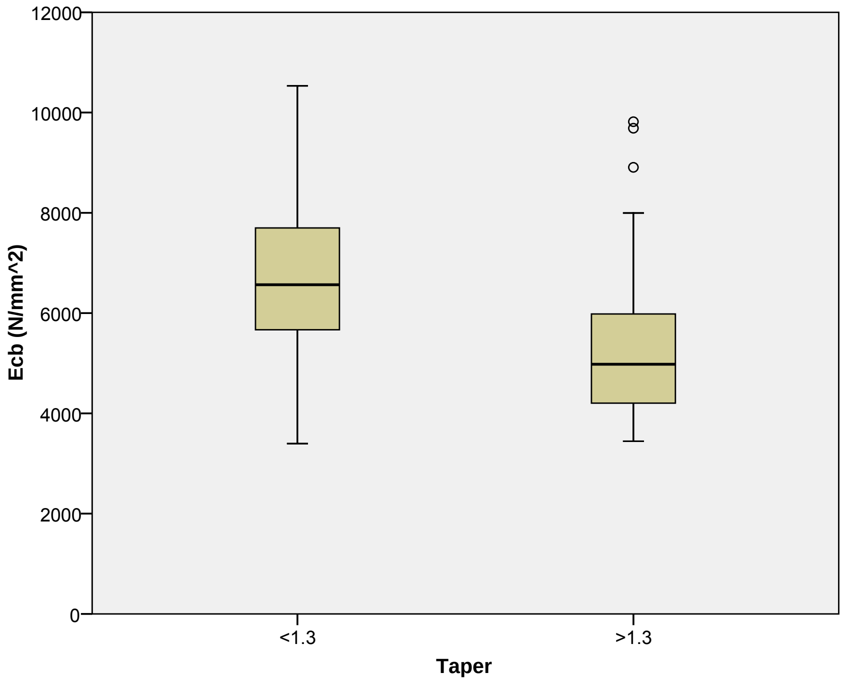

Figure 6.25: Box plots of E_{cb} for grouped values of *Log taper* (FR1- 4).

Table 6.13: Mean values, standard deviation and standard error for E_{cb} grouped by *Log taper* (FR1- 4, all battens)

E_{cb}	N	Mean	Std. Deviation	Std. Error
Log taper < 1.3	404	6640	1440	72
Log taper > 1.3	82	5250	1380	153
Total	486	6400	1520	69

Using ANOVA the differences in the population means for the two groups was determined to be significant at the $p<0.001$ level.

6.12 Log diameter and tree diameter at breast height (*DBH*)

No consistent pattern was evident in the individual relationships between E_{cb} and *Log diameter* or *DBH* for the sub-groups of upper log and butt log material.

6.13 Log curvature (*Log arc* and *Log max deviation*)

No consistent pattern was evident in the individual relationships between E_{cb} and *Log arc* or *Log max deviation* for sub-groups of upper log and butt log material. A weak relationship between stiffness and log curvature was observed for a combined group of FR1-4 upper and butt log material (R^2 = 0.17) which was determined to due to the tendency for butt logs to exhibit higher levels of curvature (*e.g.* butt sweep) compared to upper logs.

6.14 Tree height

Overall, when considering groups of combined upper and butt log material from FR1/2 and FR3/4 no significant relationship was evident between E_{cb} and *Tree height* for these individual localities. For the FR4 100 x 47 mm batten data group it was noted that there was a tendency for there to be a difference between the stiffness of butt log and upper log material for the shorter trees (Figure 6.26). The line of best fit for the butt log data has been determined on the basis of a very small number of observations and should be considered to be of limited reliability.

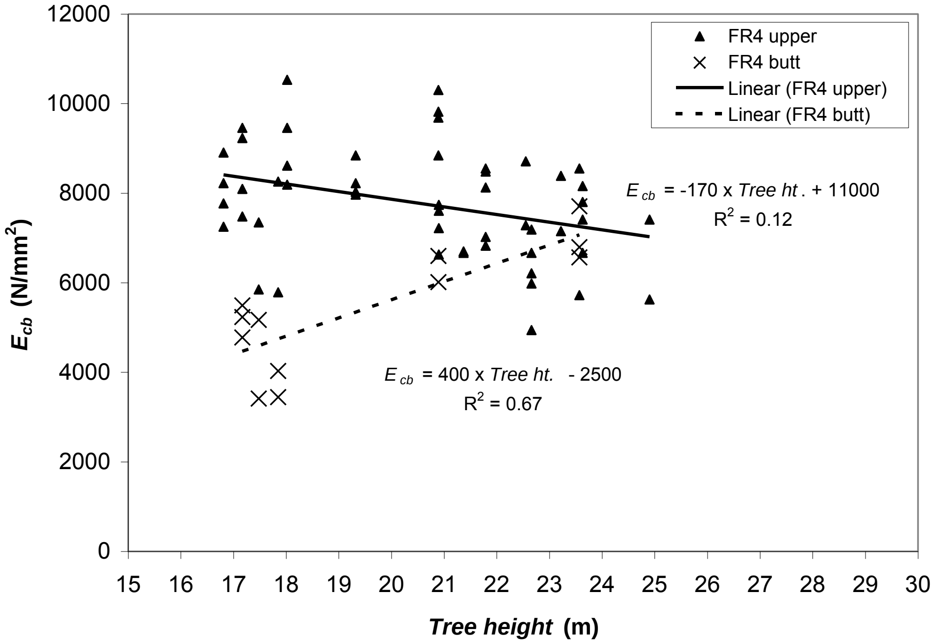

Figure 6.26: E_{cb} plotted against *Tree height* (FR4 100 x 47 mm).

By inspection of the data (Table 6.14), it can be deduced that the battens originating from the shorter trees have, in common, been felled relatively low to the ground; consequently the butt logs have relatively high levels of *Log taper*. It appears likely that this was a deliberate action by the tree feller in order to maximise the timber available from these shorter trees. Such an action might not necessarily translate to industrial practice (*e.g.* using mechanical harvester), nevertheless the effect on this data is real. It can also be seen that the batten with the lowest stiffness (1GA) has the highest knot content and is from a butt log with the highest Log taper and lowest *Cut ht*.

Table 6.14: Batten data (FR4 100 x 47 mm butt logs).

Tree No.	Code	*E_{cb}*	*Cut ht.*	*JW*	*Sect*	*DBH* (cm)	*Tree ht* (m)	*Knot area %*	*Log taper (butt/ top)*
346	1GA	3410	0.37	0.79	1	21.5	17.48	3.12	1.45
346	1GB	5170	0.37	0.84	1	21.5	17.48	2.31	1.45
369	1OA	5230	0.44	0.98	0	24.5	17.17	1.88	1.37
369	1OB	4780	0.44	0.76	2	24.5	17.17	0.87	1.37
369	1OC	5490	0.44	0.18	2	24.5	17.17	1.28	1.37
317	1RA	3450	0.45	0.97	1	21.5	17.85	2.24	1.30
317	1RB	4030	0.45	0.9	1	21.5	17.85	2.19	1.30
382	3OA	6010	0.66	0.91	1	23	20.89	1.85	1.17
382	3OB	6600	0.66	0.96	1	23	20.89	1.64	1.17
481	OWA	6570	0.64	0.99	0	23.5	23.57	1.75	1.21
481	OWB	6790	0.64	0.87	2	23.5	23.57	0.78	1.21
481	OWC	7700	0.64	0.15	2	23.5	23.57	0.79	1.21

Figure 6.27 shows $E_{m,g}$ (*i.e.* stiffness derived from EN 408:2003 bending tests) plotted against *Tree height* for the FR4 100 upper log battens, confirming the relationship observed for grader derived stiffness (E_{cb}) for these data. Table 6.15 shows the correlations between $E_{m,g}$ for this dataset.

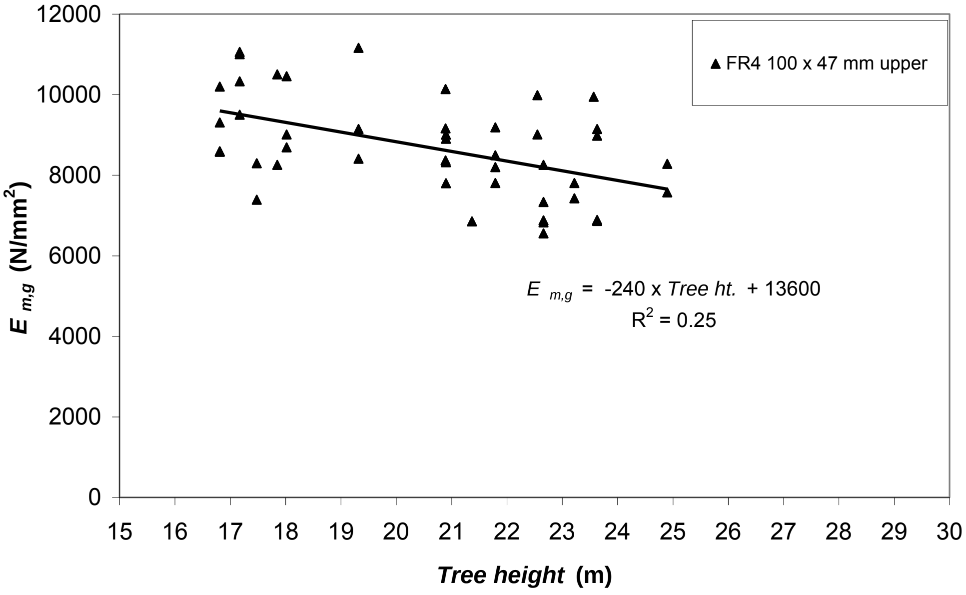

Figure 6.27: $E_{m,g}$ plotted against *Tree height* (FR4 100 x 47 mm upper log).

Table 6.15: Correlation table for $E_{m,g}$ (FR4 100 x 47 mm upper log battens).

R	$E_{m,g}$	*Tree ht*	*Dens*
Tree ht (m)	-0.50**		
Dens	0.39**	-0.40**	
Cut ht.	0.13	0.27	0.18
Log taper (butt/mid)	0.33*	-0.52**	0.30*
Log taper (butt/top)	0.39**	-0.62**	0.47**
Log taper (mid/top)	0.33*	-0.51**	0.49**
Tree ht/Cut ht	-0.33*	0.10	-0.35*
Log diameter, Top	-0.39**	0.49**	-0.59**
Log diameter, Mid	-0.37*	0.43**	-0.55**
Log diameter, Butt	-0.30*	0.29*	-0.51**
Ovality	-0.02	0.19	0.01
Pith X	0.24	0.20	0.01
Tree ht/DBH	-0.33*	0.81**	-0.26
DBH	-0.21	0.12	-0.20
Section	0.08	0.04	-0.10
Kn900%	-0.47**	0.14	-0.16
JW	-0.09	-0.01	-0.23
Ring width	-0.22	0.28*	-0.42**
Pith Dist	0.07	0.12	-0.05

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N = 46

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that $E_{m,g}$ correlates negatively to *Tree height* and knot content over the central 900 mm section (*Kn900%*). It can also be seen that batten stiffness is not related to the radial position variables (*Pith Dist* and *Section*), nor to *JW*. Notable is the strong correlation between *Tree ht*/*DBH* and *Tree ht.*, indicating that the taller trees on the site are more slender. Notable also is the negative relationship between log diameter and density, which is in agreement with Brazier (1991).

6.15 Discussion and summary of observations on variables affecting batten stiffness (E_{cb})

From Section 6.1 to 6.14 the following summary can be made:

A tendency for butt log battens to exhibit increasing stiffness (E_{cb}) with height was noted (Section 6.2). This observation of the so-called "weak butt effect", is in agreement with Brazier (1991). However this effect was noted to be variable between trees and sites, with some trees hardly exhibiting this feature at all. Axial position (*i.e. Cut ht.*) was, in certain groups of butt log battens, found strongly related to batten stiffness. Using ANOVA, differences in the population means for E_{cb} grouped by *Cut ht*., were confirmed as statistically significant.

It is evident that by avoiding the near-buttwood material, and by felling trees slightly higher in the stem, that comparatively large and worthwhile gains in batten stiffness are possible for certain stands. Certainly, a change in forestry practice that involved felling trees much closer to the ground would run the risk of a greater number of rejects occurring when grading using a Cook-Bolinder machine, and possibly also with other types of grading machine which operate on a similar principle of 3-point bending.

Variables relating to radial position (*Pith Dist* and *Section*) were not found to be significantly related to batten stiffness (Section 6.3). This finding is in agreement with recent work on Sitka spruce reported by Moore et al. (2007), on trees of a similar size. However, in other work on an uncommon 83-year-old stand of much larger trees (Moore and Lyon, 2008), strong trends for increasing stiffness and strength from pith to bark where established.

Although differences in the mean value of E_{cb} for battens grouped by *Section* (corresponding to radial position within the stem) were found statistically significant (Section 6.3), the small differences between these groups are not likely to be of any practical value. In contrast a much larger difference in mean stiffness was observed for battens grouped by axial position *i.e*. *Cut ht*. (Section 6.2).

It follows that a scanner operating on the principle of measurement of *Pith Dist* or identification of *Section* on sawn timber (should this be technically possible) will be ineffective for current harvest ages. Notable is that the variables *Pith Dist* and *Section* were strongly related to distortion in the form of twist (Section 5.1). The measurements on battens useful for predicting distortion may be of little value, overall, in predicting stiffness.

Overall, for combined groups of upper and butt log material no relation was evident between E_{cb} and juvenile wood content (Section 6.4). This may be due to the fact that the juvenile wood content of battens tends to increase with height in the stem, whereas the E_{cb} trends indicate that stiffness is generally lower at the butt end. Thus it is probable that these factors counteract each other. For certain groups of 100 x 47 mm butt log battens, radial variation in batten stiffness was observed within individual trees. For these groups the variation in stiffness was determined to be a function of juvenile wood content (*JW*) and knot content (*Knotarea%*). For these battens, the marked variation in stiffness was probably a function of the cutting pattern in that 3 no. 100 x 47 mm battens had been cut from each log, which had resulted in one central batten comprised largely of juvenile wood, and two outliers (Figure 6.14).

Stiffness (E_{cb}) was found to be negatively related to knot content (*Knotarea%)* for groups of butt log material, whilst no relation was observed between knot content and stiffness for upper log material (Section 6.6). This is in agreement with Brazier (1991). This implies that assessment of knot content for upper log material *e.g.* by scanner will be ineffective. This does not mean that sorting by knot content overall will be ineffective, *i.e.* on combined upper and butt log material. The most effective knot variable was noted to be one based on percentage cover on all faces and edges (*Knotarea%*), whilst *TKAR* was found to be ineffective.

Stiffness (E_{cb}) was found to be positively related to density for upper log material (in agreement with Glos and Denzler, 2007), but only very weakly (Section 6.7). For butt log material no relation was evident between stiffness and density. This indicates that measurement of density during sorting or strength grading will only be partly effective on mixed groups of upper and butt log material, and ineffective on groups of butt log material which may consist of larger section sizes that tend to be used for more critical applications.

No significant relation between stiffness (E_{cb}) and slope of grain (*SoG outer*) was observed (Section 6.8). This indicates that slope of grain measurement (*e.g.* by laser tracheid effect), although found useful for determination of propensity to develop twist on drying (as detailed in Chapter 5) will not be useful for sorting on the basis of stiffness and hence structural grade. This result is similar to that obtained for Sitka spruce by Moore *et al.* (2007) and Glos *et al.* (2007), but contrasts to the findings of Maun (1998). Brazier (1954) determined that for clear samples of Canadian Sitka spruce increases in slope of grain corresponded to reductions in both stiffness and strength; however the variance in slope of grain in his samples is much wider than that encountered in the FR1-4 battens. It is also probable that any effect of slope of grain on stiffness was overridden by the effect of knots or the weak butt effect.

No significant relation between stiffness (E_{cb}) and compression wood content (in terms of the variable *CW total adj*) was observed in full-scale battens (Section 6.9). This is probably due to the quite low incidence of compression wood in the sample, or the overriding influence of other factors such as knots or the weak butt effect. It is also possible that the CW variables derived are quite poor indicators of batten compression wood content. This result is similar to that reported by Glos *et al*. (2007), and Moore *et al.* (2007). However, Ni Dhubhain *et al.* (1988), obtained a negative relationship between stiffness and compression wood for Sitka spruce. In the work reported by Moore *et al.* (2007) the method of assessment of compression wood content of battens was based on surface appearance, essentially similar to the method used in this work (see Appendix A2.15), whereas the method of compression wood assessment used by Ni Dhubhain *et al.* (1988) was based on examination of the cross-section at the point of failure. Furthermore the battens were deliberately placed in the test rig with the compression wood on the tension face, rather than randomly placed. This is likely to have been a better method of determining the compression wood content of a batten, but is not representative of the random orientation of battens that occurs in service.

Overall, the log shape variables *Ovality* and *Pith X* were not found related to batten stiffness *i.e*. E_{cb}, (Section 6.10), indicating that these are not useful sorting parameters. The use of these variables in the analysis is quite simplistic. No account has been made of the relative position of individual battens within the log section. For example, timber on each side of an eccentric pith may exhibit different mechanical properties. It may be quite possible for one batten to be above average stiffness and for the other to be below average stiffness - in which case no correlation would be obtained. However, sorting timber on the basis of individual position within each log relative to the pith would be practically impossible.

The variable *Log taper* was found to be significantly related to the stiffness (E_{cb}) of butt log battens for one forest stand (Benmore), but not the other (Lochaline), (Section 6.11). It was demonstrated using ANOVA that for the combined group, the difference in stiffness for groups of battens from logs with *Log taper* > 1.3 and *Log taper* < 1.3, was significant at the $p < 0.001$ level.

No consistent pattern was evident in the individual relationships between E_{cb} and log diameter or *DBH* for the sub-groups of upper log and butt log material. No consistent pattern was evident in the individual relations between E_{cb} and *Log arc* or *Log max dev* for sub-groups of upper log and butt log material. A very weak relationship between stiffness and log curvature was observed for a combined group of FR1-4 upper and butt log material ($R^2 = 0.17$) which was determined to due to the tendency for butt logs to exhibit higher levels of curvature (*e.g.* butt sweep) compared to upper logs.

When considering combined groups of upper and butt log material from FR1/2 and FR3/4 no relationship was evident between E_{cb} and *Tree height* (Section 6.14). For the upper log battens of FR4 a negative relationship was evident between E_{cb} and *Tree ht*., which was confirmed in the measurements of $E_{m,g}$ (EN 408:2003 derived stiffness). A strong correlation between *Tree taper* (*i.e. Tree ht*./*DBH*) and *Tree ht.* was also observed, indicating that the taller trees on the site are more slender. For the Benmore material an inverse relationship between *Tree ht*. and *Density* was observed (this group had a much wider variance in *Tree ht.* compared to the Lochaline material). It is possible that the lower stiffness of the upper log material of the taller trees of this stand is related to wind exposure (such effects are reported by Brüchert, 2000), rather than a simple aspect of growth rate.

Overall, relationships between stiffness and variables which could potentially be used as sorting criteria were found to be weak. These relationships were also observed to be group specific – both by batten size, stand and axial position (in terms of upper logs and butt logs).

7 Correlations and models for E_{cb} based on a combined data group

7.1 Correlations of E_{cb} with log and tree variables

Table 7.1 details the correlations apparent between E_{cb} and *Cut ht.*, *Log taper*, *Density*, *Ring width*, *Knotarea%*, and *Whorl minimum spacing* when treating all the material from FR1-4 as one data group (with the exception of the 200 x 47 mm battens from FR2, for which limited knot data was recorded). An assumption that such a data group represents the material likely to enter any sawmill may not be valid, and the results dependent on the relative proportions from the two localities. Relationships between certain variables may be stand-specific, and may not necessarily transfer to mixed material from a number of sources grown over different timescales.

Table 7.1: Correlation table for E_{cb} (FR1- 4, all battens).

R	E_{cb}	*Cut ht.*	*Log Taper*	*Dens*	*Ring width*	*Knot Area%*
Cut ht.	0.40**					
Log taper	-0.36**	-0.59**				
Dens	0.21**	-0.12*	0.24**			
Ring width	-0.35**	0.15**	-0.04	-0.21**		
Knot area%	-0.36**	-0.19**	0.32**	0.20**	0.21**	
Whorl min spacing	0.47**	0.29**	-0.32**	-0.01	-0.16**	-0.16**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N ~ 465

From the above table (note that correlations with R > 0.4 are shaded) it can be seen E_{cb} relates positively to increasing *Cut ht.* and *Whorl min* *spacing*, whilst relating negatively to increasing *Log taper*, *Knotarea%* and *Ring width*. As might be expected, *Log taper* and *Cut ht.*, relate strongly to each other. The relationship between E_{cb} and *Density* is notably weak. It can also be seen that *Whorl min spacing* relates positively to *Cut ht.* and negatively to *Log taper*. The most significant variables are therefore all related to axial position within the stem.

Variables relating to radial position, *i.e. Section* and *Pith Dist* were not found significantly related to E_{cb}, nor were any of the compression wood variables, nor juvenile wood content. The knot variables *Kn300%*, *TKAR* and *MKAR* were found less significantly related to stiffness than *Knotarea%*. Tree variables such as *Tree ht.*, *Tree taper* and *DBH* were also not found to be significantly related to E_{cb}. None of the slope of grain variables (either raw or absolute values) were found to be related significantly to E_{cb}. *Ovality* and *Pith X* were also found to be weakly related negatively to E_{cb}, but these also tend to correlate negatively with height and so these relationships are not likely to be causal.

7.2 Multiple regression and correlation

Table 7.2 and Table 7.3 detail the MRC model for E_{cb} based on the variables *Density, Ring width*, *Knotarea%*, *Cut ht.*, and *Log taper*, when treating all the battens from FR1 - 4 as one data group. The objective of including these variables in MRC models is to determine their relative usefulness as sorting parameters. Note that although these variables may correlate, they represent measurements which are independent of each other (*i.e*. the measurement of one variable does not influence the measurement of another, nor are these measurements intrinsically the same.)

Table 7.2: E_{cb} model summary (all data, using most significant variables).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.64(a)	0.42	0.40	1155.0

a Predictors: (Constant), *Density*, *Ring width*, *Knotarea%*, *Cut ht.*, *Log taper.*

Table 7.3: E_{cb} model coefficients (all data, using most significant variables).

Model		Unstandardised Coefficients		Standardised Coefficients		.
		B	Std. Error	Beta	T	Sig
1	(Constant)	6371.7	854.0		7.46	0.000
	Cut ht.	198.0	26.0	0.345	7.60	0.000
	Log taper	-1725.2	565.8	-0.143	-3.05	0.002
	Dens	10.4	1.52	0.266	6.87	0.000
	Ring width	-272.9	36.7	-0.288	-7.43	0.000
	Knotarea%	-689.3	118.8	-0.230	-5.80	0.000

a Dependent variable: E_{cb}

As with other MRC models, the un-standardised coefficients form the predictive equation , in this instance:

$$E_{cb} = 6371 + (198 \times Cut\ ht) + (-1725 \times Log\ taper) + (10.4 \times Dens) + (-272.9 \times Ring\ width) + (-689.3 \times Knotarea\%) \qquad \text{Eqn. 4.}$$

Note that units are defined in Chapter 3. The standard error of the estimate for the MRC model (Table 7.3) is the average error of the prediction, and gives an indication its accuracy when compared to the variance of the criterion (E_{cb}).

Figure 7.1 shows the model fit.

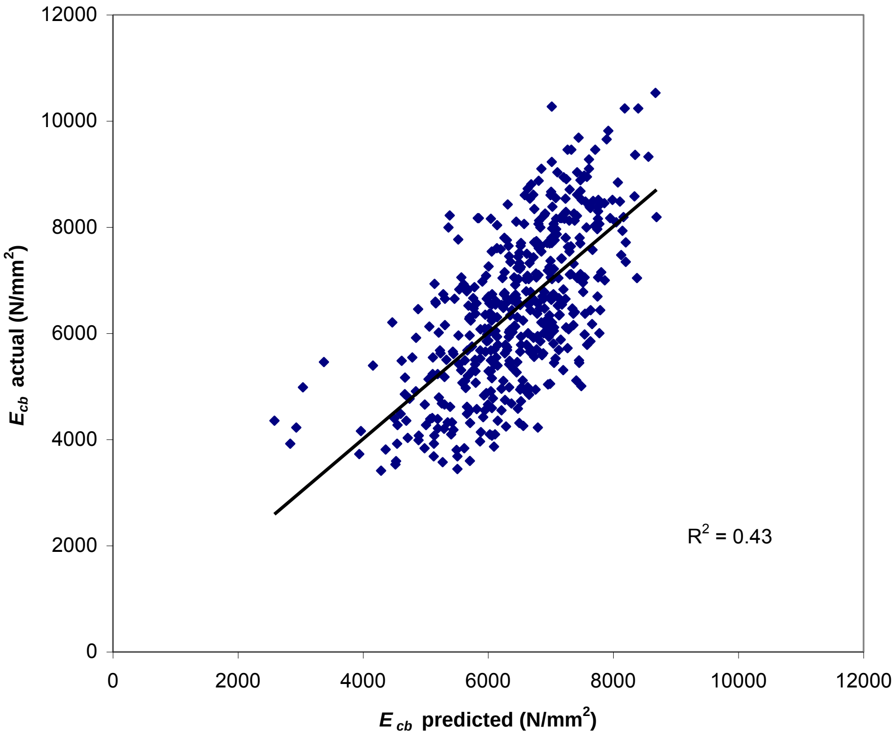

Figure 7.1: Model fit for E_{cb} (using *Density*, *Ring width*, *Knotarea%*, *Cut ht.* and *Log taper*).

Note that although the variable *Whorl min spacing* can be included in the above model (resulting in an R^2 of 0.5), its inclusion causes the t value of *Log taper* to drop markedly indicating that there is a possible problem with multicollinearity (*i.e.* the variables are highly dependent). Although from Table 7.1 it can be seen that both *Log taper* and *Cut ht.* correlate strongly, this problem did not appear to occur when both these variables were included in the model. This is probably due to the order of the inclusion of the variables, or the polarity of the relationship of the variables to E_{cb}. Where two or more of the variables are included in the MRC model are related, or are simple proxies for each other (*e.g*. log top diameter and log bottom diameter), then it is no longer possible to attach a weight to those variables. Note that the purpose of this work is to determine which variables and combinations of variables are useful predictors, and to identify where such problems might occur.

Figure 7.2 shows a population pyramid (histobar) with the E_{cb} predicted values split into groups of below and above mean E_{cb} actual (*i.e.* the corresponding distributions are the E_{cb} actual values sorted into two groups using the model).

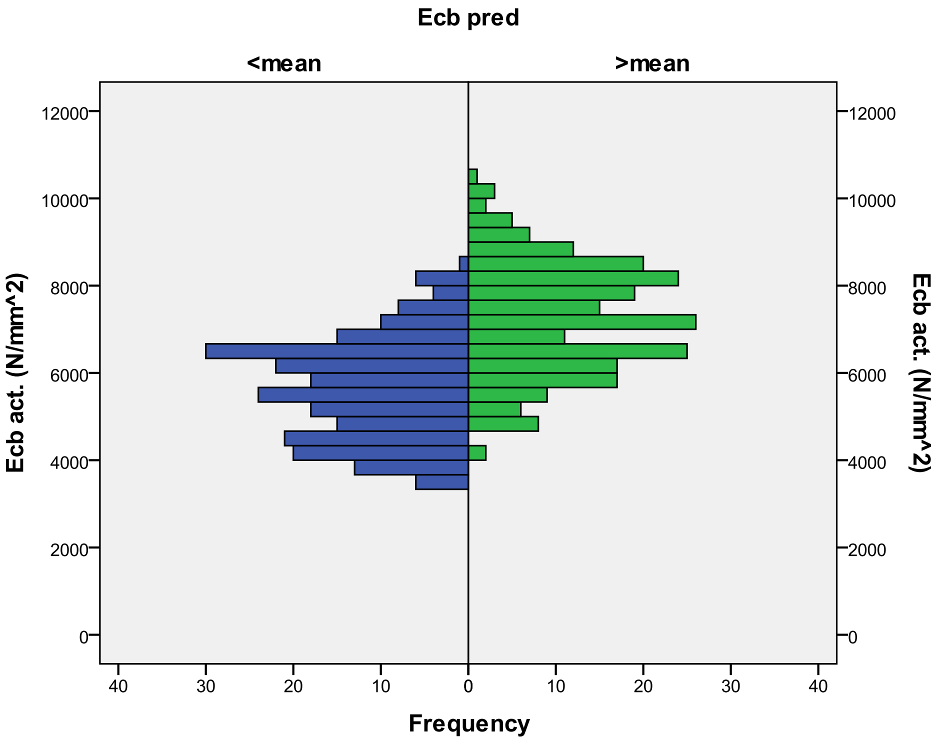

Figure 7.2: Population pyramid (histogram) for E_{cb} model, predicted and actual values.
(original in colour)

From Figure 7.2 it can be seen that the two distributions are offset, and that the lower stiffness battens (for example those with E_{cb} values lower than 4,000 N/mm^2) can readily be distinguished from the higher stiffness battens (for example those with E_{cb} values higher than 9,000 N/mm^2).

Although it is possible to include a greater number of knot variables in the above model, these do not add significantly to its effectiveness.

If the variable *Cut ht*. is unknown, the adjusted R squared for the model incorporating all of the remaining variables falls to 0.33. (Table 7.4). As fewer variables are included the effectiveness of the model can be seen to reduce (Table 7.5, and Table 7.6).

Table 7.4: E_{cb} model summary (with *Density, Ring width, Knotarea%, Log taper*).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.58(a)	0.34	0.33	1225.0

a Predictors: (Constant), *Dens*, *Ring width*, *Knotarea%*, *Log taper*

Table 7.5: E_{cb} model summary (with *Knotarea%*, *Ring width* and *Log taper*).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.51(a)	0.26	0.26	1289.9

a Predictors: (Constant), *Knotarea%*, *Ring width*, *Log taper*

Table 7.6: E_{cb} model summary (with *Ring width* and *Log taper* variables only).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.50(a)	0.25	0.24	1272.6

a Predictors: (Constant), *Ring width*, *Log taper*

Figure 7.3 shows the model fit using the variables *Ring width*, *Log taper* only, whilst Figure 7.4 shows corresponding population pyramid (histobar). Similarly with Figure 7.2 the E_{cb} predicted values have been split into two groups of below mean and above mean E_{cb} actual.

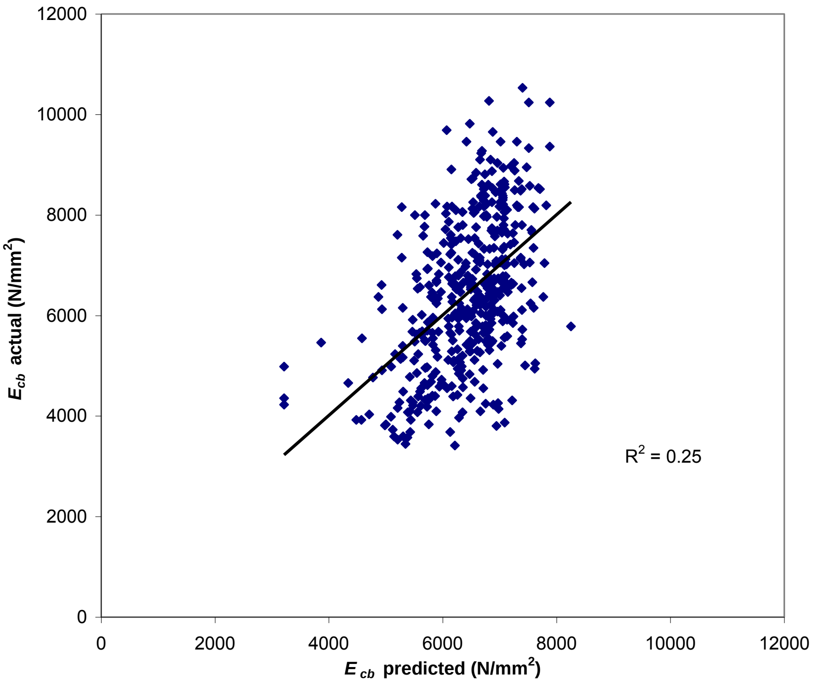

Figure 7.3: Model fit for E_{cb} (using *Ring width* and *Log taper* variables).

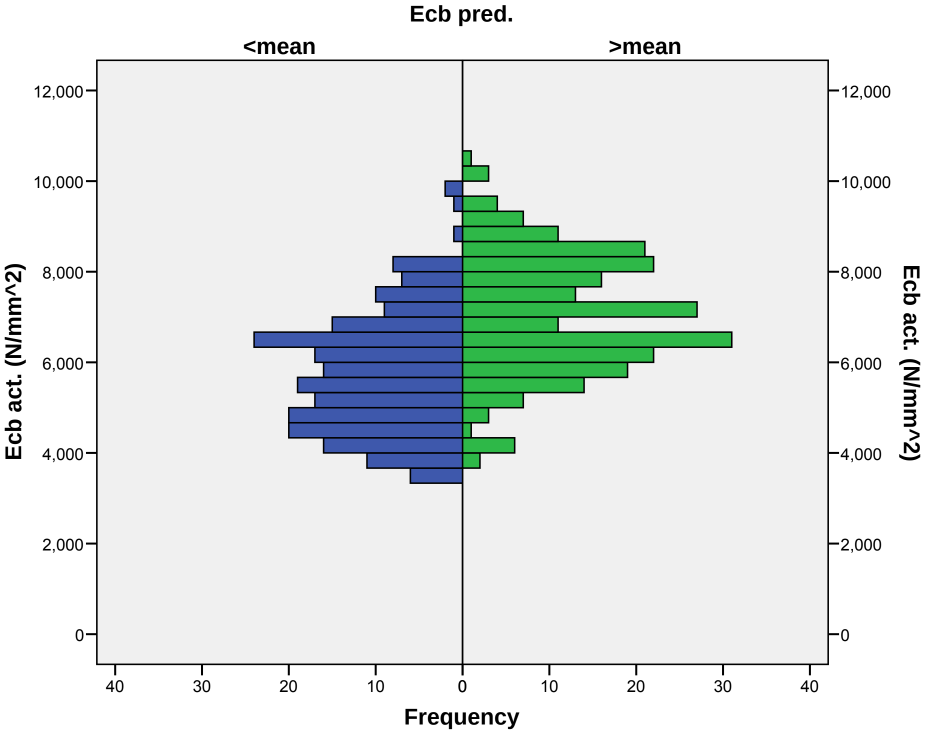

Figure 7.4: E_{cb} model predicted and actual values using *Log taper* and *Ring width* variables.

(original in colour)

From Figure 7.4 (with comparison to Figure 7.2) it can be seen that the model with fewer variables is less able to distinguish between above average and below average stiffness timber, *i.e.* the distributions are not as clearly offset.

These models illustrate the effect of simultaneous application of the sorting variables, and do not simulate the effect of sequential sorting into different quality classes at log and sawn timber stages (*e.g.* by *Log taper*, then at some later stage in the production process by *Ring width*).

7.3 **Principal components analysis**

Using the principal components analysis (PCA) method of Factor Reduction, a new set of variables can be determined based on those used above (*i.e. Whorl min spacing*, *Density*, *Ring width*, *Cut ht.*, *Tree ht.*, *Knotarea%*, and *Log taper*) with the aim of explaining as much as possible of the variance in the data with fewer factors. In simple terms, the operation can be thought of as revealing the “internal structure” of the data. Each component is a linear function of the original variables, referred to as an eigenvector. Table 7.7 details the relative and total variances explained by the components.

From this table it can be seen that components 1, 2 and 3 explain, cumulatively, nearly 73% of the total variance within the set of variables included in the analysis. It can also been seen that no single component explains more than 34% of the total variance in the data, and that components 4, 5 and 6 explain relatively small amounts of variance. Note that the number of components is not related to the number of variables. Figure 7.3 shows a graphical representation, termed a “scree plot”, of the contribution of each component.

Table 7.7: Variance explained by components.

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	2.052	34.2	34.2
2	1.273	21.2	55.4
3	1.032	17.2	72.6
4	0.730	12.2	84.8
5	0.551	9.2	94.0
6	0.361	6.0	100.0

Extraction Method: Principal Component Analysis.

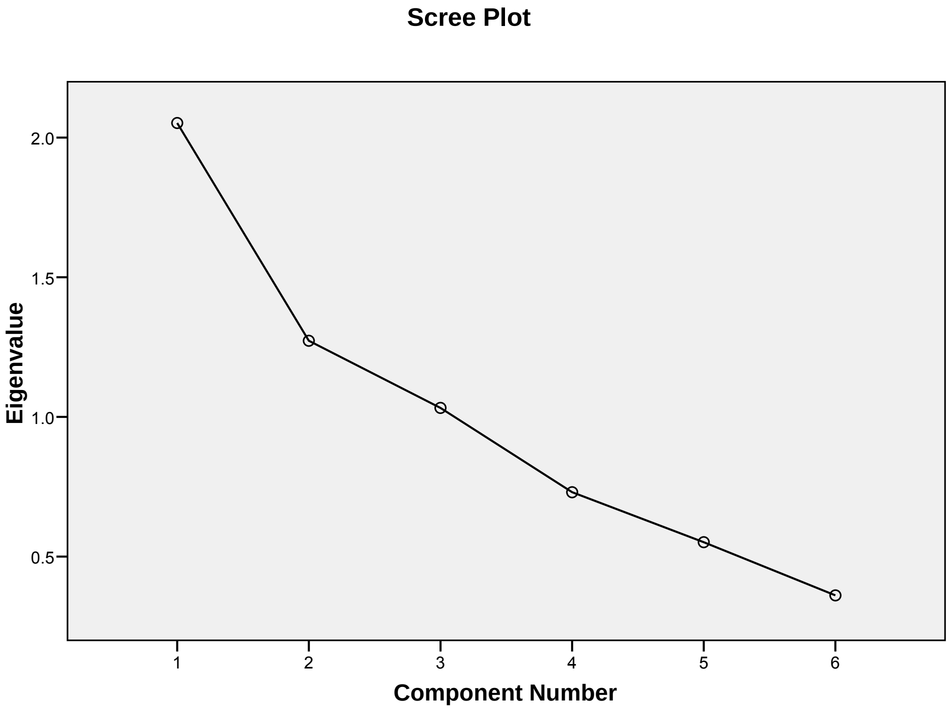

Figure 7.5: PCA Scree plot (FR1 - 4 variance).

From the above scree plot it can be seen that components 1 to 3 explain the largest proportion of variance, whilst components 4, 5 and 6 contribute relatively little. There is, however, no distinct “elbow” (*i.e.* abrupt change in curvature) to the graph indicating that there are no components which could be regarded as superfluous. To aid interpretation, the eigenvectors (which each represent a line passing through the data points in multidimensional space, where the number of variables is equal to the number of dimensions) can be rotated to achieve a simplified structure. One such process, termed varimax and commonly used in principal components analysis, is described in detail by Grimm and Yarnold (1995).

Table 7.8 shows the rotated component matrix for the above factor reduction, which details the relative proportion of the original variables in components 1, 2 and 3 (these being the largest components).

Table 7.8: Rotated component matrix.

	Component		
	1	2	3
Cut ht.	0.831	-0.099	0.237
Log taper	-0.787	0.335	0.003
Dens	-0.019	0.825	-0.256
Ring width	0.053	-0.093	0.896
Knotarea% (total)	-0.232	0.664	0.490
Whorl min spacing	0.678	0.155	-0.298

Extraction method: Principal component analysis.

Rotation method: Varimax with Kaiser normalisation.

a Rotation converged in 4 iterations.

From Table 7.8 it can be seen that Component 1 (which explained 34% of the variance within the set of variables) is predominantly a function of *Cut ht.*, *Log taper* and, to a lesser extent, *Whorl min spacing* (*i.e.* high values, positive or negative). It can also be seen that Component 2 is a largely a function of *Density* and, to a lesser extent, *Knotarea%*, and that Component 3 is largely a function of *Ring width*. Because Component 1 explains only 34% of the variation within the variables, and is a function of both *Cut ht.*, *Log taper* and *Whorl min spacing* there do not appear to be any variables which could be readily omitted from a predictive model without reducing its effectiveness.

7.4 Discussion and summary of findings

For the combined FR1-4 data group, stiffness (E_{cb}) was found to relate positively to increasing *Cut ht.* and *Minimum whorl spacing*, whilst relating negatively to increasing *Log taper*, *Knotarea%* and *Ring width* (Table 7.1). However, the relationships for this combined site, and both upper and butt log batten groups, are extremely weak - in contrast to the quite good relationships observed for certain sub-groups of battens shown in Sections 6.2 to 6.14. The variables *Log taper* and *Cut ht.*, as might be expected, were found to be related strongly to each other. *Density* was noted to be of relatively minor significance. The most significant variables (*Cut ht.* and *Log taper*) are related to axial position within the stem.

The MRC models constructed demonstrated the relative usefulness of combined groups of variables (Figure 7.1 and 7.3). As would be expected, the more variables included in the model the better the fit achieved. The MRC models, together with the PCA, indicate that only with combined knowledge of a wide range of variables can a reasonable fit be achieved. Part of the unexplained variance in the MRC models is likely to be due to error in the measurement of both the criterion and predictor variables (this aspect is further discussed in Section 13.3). Inclusion within the MRC models of variables which are strongly dependent was noted to cause problems of multicollinearity. Nevertheless this process was useful in further determining which variables are simple proxies for each other.

The results of the analysis indicate that provided *Log taper* is measured, the variable *Cut ht* makes a relatively small contribution to the effectiveness of the MRC model (this is as expected since they are quite strongly related). This means that it is not necessary to transfer felling height data to the sawmill for use as a sorting criterion (*e.g.* by log marking or electronic tagging).

It was demonstrated that in terms of sorting timber into above average and below average predicted stiffness groups (as might be attempted in a sawmill) that with a greater number of variables a clearer separation of the populations could be achieved (Figure 7.2 and Figure 7.4).

8 Correlations and models based on Lochaline dataset

8.1 Lochaline FR1

Table 8.1 shows the correlation table for E_{cb} with *Cut ht*, *Log taper*, *Density*, *Ring width*, *Knotarea%* and *Kn300%* for the Lochaline FR1 all battens data group (*i.e.* all sizes and combined groups of upper log and butt log material).

Table 8.1: E_{cb} correlation table (FR1 all batten sizes).

R	E_{cb}	*Cut ht.*	*Log taper*	*Dens*	*Ring width*	*Knot area%*
Cut ht.	0.20*					
Log taper	-0.27**	-0.70**				
Dens	0.12	-0.41**	0.31**			
Ring width	-0.21*	0.42**	-0.24**	-0.11		
Knot area%	-0.57**	-0.11	0.23**	0.06	0.13	
Kn300%	-0.43**	-0.04	0.16	0.07	0.07	0.61**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

N ~ 140

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that for the FR1 data group variables relating to knot content are relatively significant compared to those relating to proximity to the ground (*i.e. Cut ht.* and *Log taper*), whilst *Density* is not significant at all. As with the correlations detailed for the FR1-4 combined group detailed in Chapter 7, no correlation is observed between E_{cb} and slope of grain or the variables relating to compression wood content, nor *Pith Dist*, *Section*, *JW* or *DBH*.

Table 8.2 and Table 8.3 detail the MRC model using only the *Log taper* and knot content variables for the FR1 data group.

Table 8.2: E_{cb} model summary (FR1 all batten sizes).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.59(a)	0.35	0.33	1015.7

a Predictors: (Constant), *Log taper*, *Kn300%*, *Knotarea%.*

Table 8.3: E_{cb} model coefficients (FR1 all batten sizes).

Model		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	9212.1	765.1		12.040	0.000
	Knotarea%	-1175.0	297.3	-0.364	-3.953	0.000
	Kn300%	-213.6	85.3	-0.226	-2.505	0.014
	Log taper	-1389.7	669.8	-0.153	-2.075	0.040

a Dependent variable: E_{cb}

From the t-values shown in the above table it can be seen that *Knotarea%* is the most significant variable, whilst the *Log taper* variable contributes relatively little. It is recognised that the inclusion of knot variables which are related may cause problems of multicollinearity, however the model for FR1 has been constructed for the purposes of comparison to that for stand FR2 (detailed below).

8.2 Lochaline FR2

Table 8.4 shows the correlation for E_{cb} with *Cut ht*., *Log taper*, *Density, Ring width*, *Knotarea%* and *Kn300%* for FR2 (all battens sizes *i.e.* 100 x 47mm and 150 x 47 mm)

Table 8.4: E_{cb} correlation table (FR2 all batten sizes).

R	E_{cb}	*Cut ht.*	*Log taper*	*Dens*	*Ring width*	*Knot Area%*	*Kn300 %*
Cut ht.	0.41**						
Log taper	-0.38**	-0.68**					
Dens	-0.02	-0.29**	0.33**				
Ring width	-0.22*	0.39**	-0.25**	-0.34**			
Knot area%	-0.48**	-0.28**	0.23*	0.30**	0.09		
Kn300%	-0.32**	0.16	-0.11	0.11	0.32**	0.47**	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N ~ 115.

From the above table (note that correlations with R > 0.4 are shown shaded), and it can be seen that stiffness relates positively to *Cut ht.* and negatively to *Log taper* and *Knotarea%*. It can also be seen that there is no relation between *Knotarea%* and *Log taper*. No correlation is observed between stiffness and density for this group.

Table 8.5 and Table 8.6 detail the MRC model for FR2 based on the knot content variables *Knotarea%* and *Kn300%*, together with *Log taper*.

Table 8.5: E_{cb} model summary (FR2 all batten sizes).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.59(a)	0.34	0.32	1260.4

a Predictors: (Constant), *Log taper*, *Kn300%*, *Knotarea%*

Table 8.6: E_{cb} model coefficients (FR2 all batten sizes).

Model		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	13205.6	1220.7		10.8	0.000
	Knotarea%	-1025.8	321.2	-0.296	-3.19	0.002
	Kn300%	-274.4	107.7	-0.232	-2.54	0.012
	Log taper	-4137.4	1021.9	-0.335	-4.04	0.000

a Dependent variable: E_{cb}

From the t-values in the above table it can be seen that the variable which contributes the most to the model for FR2 is *Log taper*, in contrast to the above observations for FR1. Adding the variable *Cut ht.* to the above model did not significantly improve its effectiveness.

8.3 Discussion and summary of findings on correlations and models based on Lochaline dataset

From inspection of the individual MRC models for the individual stands from Lochaline (FR1 and FR2) comprising trees of differing spacings (as shown in Appendix 1), together with the bivariate correlations, it could be determined that these stands exhibited differing relationships between variables. For stand FR2 *Log taper* exhibited a better relation to stiffness than for FR1, consistent with observations of the trends in stiffness with height reported in Section 6.2. For the material from FR2 it was observed that there was a tendency for the trees to exhibit the so-called weak butt effect; consequently variables associated with proximity to the ground in terms of batten axial position (*i.e. Log taper* and *Cut ht.*) are found to be significant.

9 Correlations and models based on Benmore dataset

9.1 Butt logs

Table 9.1 shows the observed relationships between stiffness (E_{cb}) and the following variables (as defined in Chapter 3): *Tree ht.*, *Cut ht.*, *Log taper* (measured manually), *Knotarea%*, *Density*, *Ring width* and *JW* for FR3 and FR4 butt log material, for both 100 x 47 mm and 150 x 47 mm sized timber as a combined group.

Table 9.1: E_{cb} correlation table (FR3 and FR4 butt logs).

R	E_{cb}	*Tree ht.*	*Cut ht.*	*Log taper butt/top*	*Knot area%*	*Dens*	*Ring width*
Tree ht.	0.30**						
Cut ht.	0.33**	0.18					
Log taper butt/top	-0.54**	-0.63**	-0.57**				
Knot area%	-0.62**	-0.43**	-0.39**	0.61**			
Dens	-0.05	-0.44**	-0.06	0.12	0.20		
Ring Width	-0.47**	-0.24*	-0.02	0.35**	0.60**	0.10	
JW	-0.39**	-0.14	0.09	0.16	0.41**	0.19	0.69**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N=78

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that the stiffness of butt log material correlates negatively to *Log taper*, *Knotarea%*, *Ring width* and *JW*. As expected there is a strong correlation between *JW* and *Ring width*, since these variables are associated with battens cut from close to the pith. For butt log material as a whole, there is no correlation observed between E_{cb} and *Density*.

Table 9.2 shows the model summary based on MRC for FR3 and FR4 butt log material, using the variables as detailed, whilst Table 9.3 shows the model coefficients.

Table 9.2: E_{cb} model summary (FR3 and FR4 butt logs).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.68(a)	0.47	0.42	875.9

a Predictors: (Constant), *JW*, *Cut ht.*, *Tree ht*. , *Knotarea%*, *Ring width*, *Log taper (butt/top).*

b Dependent variable: E_{cb}

Table 9.3: E_{cb} model coefficients (FR3 and FR4 butt logs).

Model		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	T	Sig.
1	(Constant)	11143.3	2868.0		3.88	0.000
	Tree ht.	-28.1	43.4	-0.076	-0.649	0.518
	Cut ht.	603.6	729.7	0.094	0.827	0.411
	Log taper (butt/top)	-2798.5	1580.4	-0.274	-1.771	0.081
	Knotarea%	-709.1	263.3	-0.347	-2.693	0.009
	Ring width	-35.1	82.5	-0.059	-0.426	0.671
	JW	-807.0	555.3	-0.178	-1.453	0.151

a Dependent variable: E_{cb}

As with other MRC analysis reported, the un-standardised coefficients form the equation which predicts the dependent variable. From the respective t-values it can be seen that the variables Tree ht., Cut ht., and Ring width contribute relatively little to the model, whilst the predominant variables are Knotarea% and Log taper.

Figure 9.1 and Figure 9.2 show 3D representations of log FR4 360-0.55 which has the highest value of taper for that locality (yielding battens 70A, 70B, 70C). Notable are the undulations present close to the base, which are suggestive of branch swellings, but which may also influence log taper measurements.

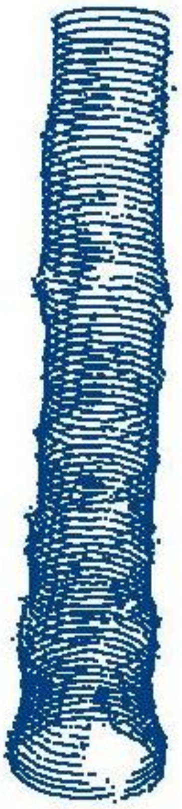

Figure 9.1: Three Dimensional representation of log FR4 360-0.55.

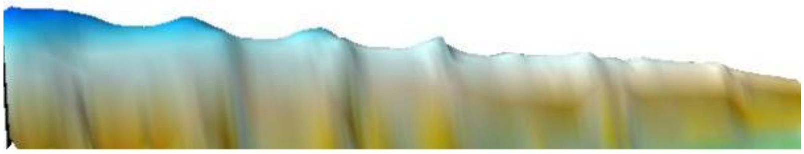

Figure 9.2: Three dimensional representation of log FR4 360-0.55 using surface interpolation.
(original in colour)

9.2 Upper logs

Table 9.4 shows the observed relations between E_{cb} and the variables *Tree ht.*, *Cut ht.*, *Log taper*, *Knotarea%*, *Density*, *Ring width* and *JW* for FR3 and FR4 upper log material, for both 100 x 47 mm and 150 x 47 mm battens.

Table 9.4: E_{cb} correlation table (FR3/4 upper logs).

R	E_{cb}	*Tree ht.*	*Cut ht.*	*log taper butt/top*	*Knot area%*	*Dens*	*Ring width*
Tree ht.	-0.30**						
Cut ht.	0.03	0.05					
Log taper (butt/top)	0.16	-0.68**	0.28**				
Knotarea %	-0.12	-0.36**	0.14	0.19*			
Dens	0.50**	-0.48**	0.09	0.38**	0.16*		
Ring width	-0.42**	0.15	0.12	-0.03	0.20*	-0.31**	
JW	-0.09	-0.27**	0.16	0.20*	0.43**	-0.02	0.44**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N = 143

From the above table (note that correlations with R > 0.4 are shown shaded) and comparison with Table 9.1, it can be seen that the variables which correlate to E_{cb} are markedly different between butt log material and upper log material, as expected from the graphical representations shown in Sections 6.7 and 6.11. Significantly, *Density* for upper log material correlates positively to E_{cb}, albeit very weakly. Notable also is that *Density* correlates negatively to *Tree ht.*, for both the upper log and butt log battens, indicating that the taller trees yield lower density battens throughout the stem.

Only a relatively poor fit can be achieved from use of these variables in an individual model for upper log material (Table 9.5 and Table 9.6).

Table 9.5: E_{cb} model summary (FR3/4 upper logs).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.61(a)	0.38	0.34	995.7

a Predictors: (Constant), *JW*, *Dens*, *Cut ht.*, *Knotarea%*, *Log taper* (butt/top), *Ring width*, *Tree ht.*

Table 9.6: E_{cb} model coefficients (FR3/4 upper logs).

Model 1	Unstandardised Coefficients		Standardised Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	10099.2	3244.1		3.113	0.002
Tree ht.	-102.1	50.3	-0.241	-2.026	0.045
Cut ht.	79.6	58.6	0.108	1.357	0.177
Log taper (butt/top)	-2846.8	1954.4	-0.154	-1.457	0.148
Knotarea%	-561.0	207.3	-0.224	-2.706	0.008
Dens	11.2	2.4	0.388	4.552	0.000
Ring width	-252.2	81.7	-0.261	-3.087	0.002
JW	345.1	511.0	0.059	0.675	0.501

a Dependent variable: E_{cb}

Note that the variables with low t-statistics are only included for purposes of comparison with the model for butt logs detailed above.

The poor fit for the model based on upper log material from FR3 and 4 is possibly a function of group’s narrower variation in stiffness. The taper, knot content and juvenile wood variables which were found useful for butt log material are not effective for upper log material. The low t value for *JW* indicates that this variable is superfluous for this model.

9.3 Butt logs and upper logs combined

Table 9.7 shows the correlation table for the combined group of FR3 and FR4 upper log and butt log material.

Table 9.7: E_{cb} correlation table (FR3/4 all battens).

R	E_{cb}	*Log taper butt/top*	*Knot area %*	*Tree ht*	*Dens*	*Cut ht.*	*Ring width*
Log taper butt/top	-0.52**						
Knot area%	-0.42**	0.49**					
Tree ht.	-0.02	-0.49**	-0.39**				
Dens	0.30**	0.14*	0.14*	-0.46**			
Cut ht.	0.55**	-0.54**	-0.22**	0.07	0.10		
Ring width	-0.45**	0.27**	0.43**	-0.04	-0.14*	-0.13	
Whorl mean spacing	0.54**	-0.68**	-0.35**	0.18**	-0.05	0.48**	-0.14*

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed). N = 221

Evident in the above table (note that correlations with R > 0.4 are shown shaded) is that the variable Tree ht. is no longer significant for the combined group, since it correlated positively with stiffness for butt log material, and negatively with stiffness for upper log material.

For the combined group of both upper log and butt log material, displaying greater variance in stiffness together with a greater range of log tapers and knot contents, a much better model can be derived (Table 9.8 and Table 9.9). Note that the variable Whorl mean spacing has been omitted from the model because of its strong correlation to Log taper (i.e. its inclusion was observed to markedly drop the t value), whilst not significantly improving the R2 value).

Table 9.8: E_{cb} model summary (FR3/4 all battens).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.77(a)	0.59	0.58	994.0

a Predictors: (Constant), *Dens*, *Ring width*, *Cut ht.*, *Tree ht.*, *Knotarea%*, *Log taper* (butt/top)
b Dependent variable: E_{cb}

Table 9.9: E_{cb} model coefficients (FR3/4 all battens).

Mod.		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	12387.4	1860.8		6.657	0.001
	Log taper (butt/top)	-4340.7	879.9	-0.333	-4.933	0.055
	Knotarea%	-589.2	158.7	-0.208	-3.712	0.001
	Tree ht.	-104.6	31.4	-0.202	-3.329	0.019
	Dens	8.39	1.96	0.221	4.270	0.000
	Cut ht.	174.9	32.3	0.299	5.408	0.000
	Ring width	-206.3	49.6	-0.211	-4.153	0.000

a Dependent variable: E_{cb}

Figure 9.3 shows the above model fit.

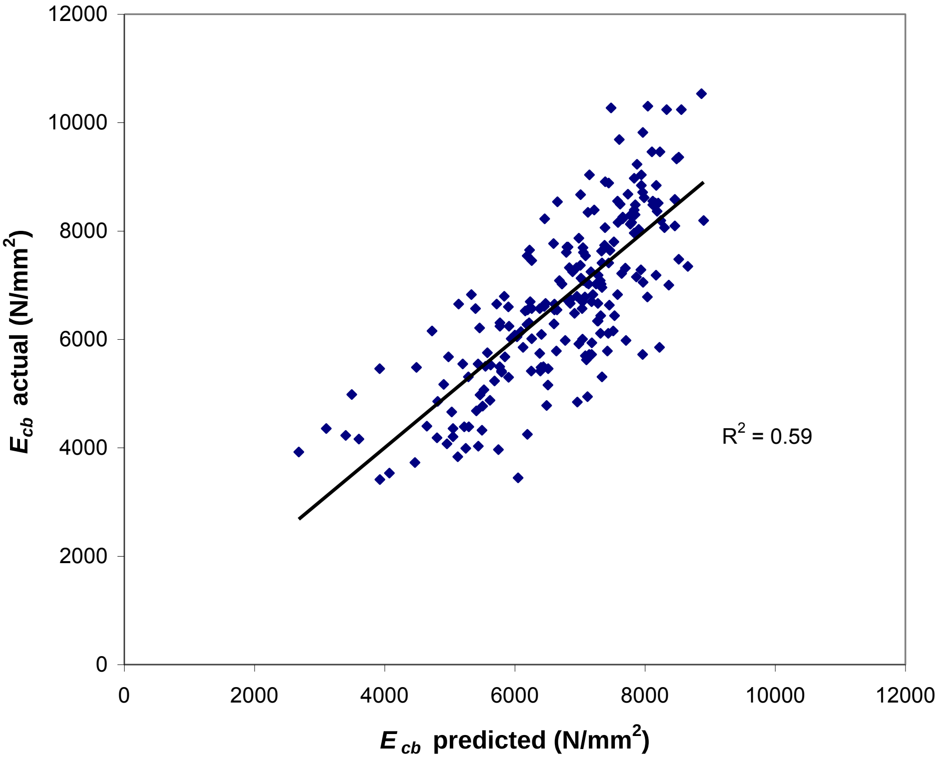

Figure 9.3: Model fit for FR3 and FR4 (all battens).

9.4 Summary of findings on correlations and models based on Benmore dataset

The stiffness of the Benmore butt log material was observed to correlate negatively to the variables *Log taper* and *Knotarea%*. For this group no correlation was observed between E_{cb} and *Density*. For the Benmore upper log material, in contrast, E_{cb} was observed to correlate positively to *Density*. For this group no correlation was observed between stiffness and the variables *Knotarea%* and *Log taper*. Thus the variables which correlate to E_{cb} are markedly different between butt log material and upper log material at this site.

For the combined group of upper log and butt log material, displaying greater variation in stiffness together with a greater range of log tapers and knot contents, an MRC model with a higher R^2 could be constructed than those for the individual sub-groups. The relationships observed between variables, and consequently the MRC models that might be constructed, therefore depend partly on the composition of the group.

The differing MRC models established, together with the difference in correlations between the variables observed, implies that sorting criteria applied to upper log material (*e.g*. measurement of density) may be ineffective on butt log material. Correlations that are determined from a set of timber which is composed principally of upper log battens (*e.g*. small section sizes such as 100 x 47 mm) may not be present, or may be be weaker, for mixed upper log and butt log material. Work which is aimed at establishing machine settings or threshold values for graders should, therefore, aim to be based on a sample which is as representative as possible. A silivicultural objective, such as increasing density, may also have lower benefit than anticipated if this has no relationship to stiffness for some proportion of the timber.

10 Correlations based on E_{cb}, $E_{m,g}$ and f_m

10.1 FR3/4 150 x 47 mm

Table 10.1 shows the correlation table for E_{cb}, $E_{m,g}$ and f_m, together with a series of log and batten variables, for the FR3/4 150 x 47 mm battens (*i.e.* both upper and butt logs combined). E_{cb} is the stiffness as measured by the Cook-Bolinder grader (as detailed in Chapter 3), whilst $E_{m,g}$ and f_m are stiffness and strength, respectively, as determined from EN 408:2003 tests. Note that f_m is based on the ultimate load. For this data group only battens where there are corresponding values for E_{cb}, $E_{m,g}$ and f_m are included to enable a direct comparison.

Table 10.1: Correlation table for E_{cb}, $E_{m,g}$ and f_m (FR3/4 150 x 47 mm).

R	E_{cb}	$E_{m,g}$	f_m
$E_{m,g}$	0.68**		
f_m	0.59**	0.69**	
Cut ht.	0.59**	0.30*	0.20
Log taper	-0.68**	-0.43**	-0.38**
Dens	0.31*	0.41**	0.27
Pith Dist	-0.03	0.12	-0.07
Ring width	-0.39**	-0.54**	-0.45**
JW	-0.22	-0.38**	-0.15
Knotarea%	-0.60**	-0.41**	-0.41**
kn900%	-0.57**	-0.44**	-0.40**
Kn300%	-0.39**	-0.40**	-0.33*
MKAR	-0.17	-0.35*	-0.25
TKAR	-0.27	-0.40**	-0.37**
Section	-0.07	0.06	-0.09

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
N = 51

From the above table (note that correlations with R > 0.4 are shown shaded) it can be seen that the batten stiffness and strength variables correlate quite strongly, and that E_{cb} is more strongly related to *Log taper* than $E_{m,g}$ and f_m. This is probably due to the nature of the test set-up (as detailed in Chapter 3), whereby E_{cb} is effectively the value of the lowest stiffness at one point on the board, and $E_{m,g}$ is a stiffness measure biased toward the middle of the test specimen. In the case of butt log battens E_{cb} very often is the stiffness at the lower end. From the above table it can also be seen that the variable that is the most strongly related to the both batten stiffness and strength is the knot variable based on total knot cover *i.e. Knotarea%*, whilst the KAR variables *MKAR* and *TKAR* are much less effective. Batten stiffness and strength also correlate negatively with *Ring width*, albeit less strongly. The variables *JW* and *Section* are ineffective.

Figure 10.1 shows box plots of E_{cb} and $E_{m,g}$ grouped by *Log taper* (*i.e.* < 1.3 and > 1.3), whilst Figure 10.2 shows strength (f_m) for the same groups. Note that E_{cb} was measured at 15 to 18% moisture content, and that $E_{m,g}$ and f_m was measured at around 12% moisture content following a prolonged period of storage. Note that for the grader derived stiffness, variation in moisture content is a potential source of error (according to EN 384:2004 a 1% variation in moisture content is commensurate with a 2% change in stiffness).

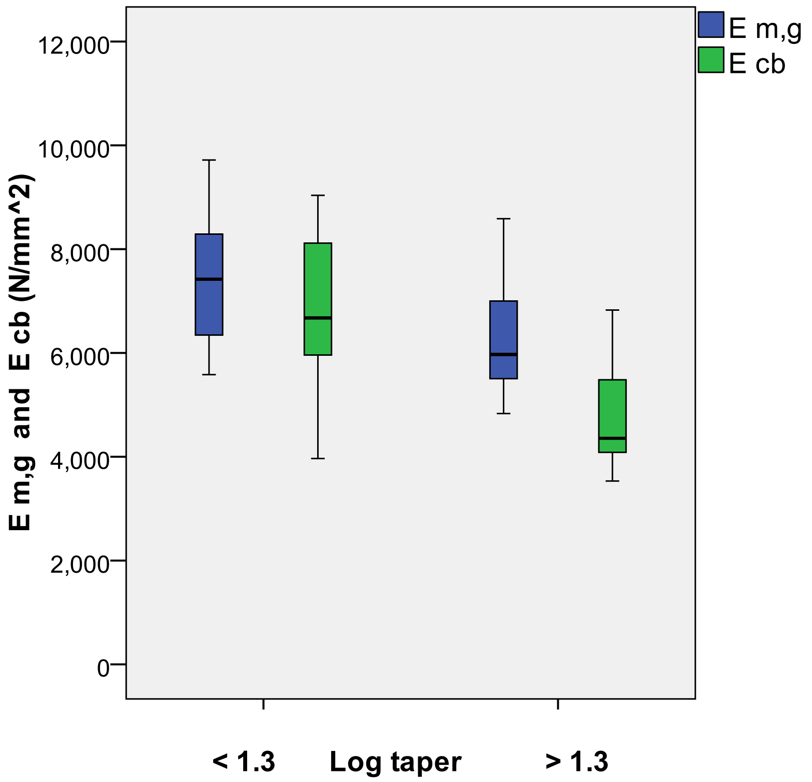

Figure 10.1: Box plots of E_{cb} and $E_{m,g}$ grouped by *Log taper* (FR3/4 150 x 47 mm).

(original in colour)

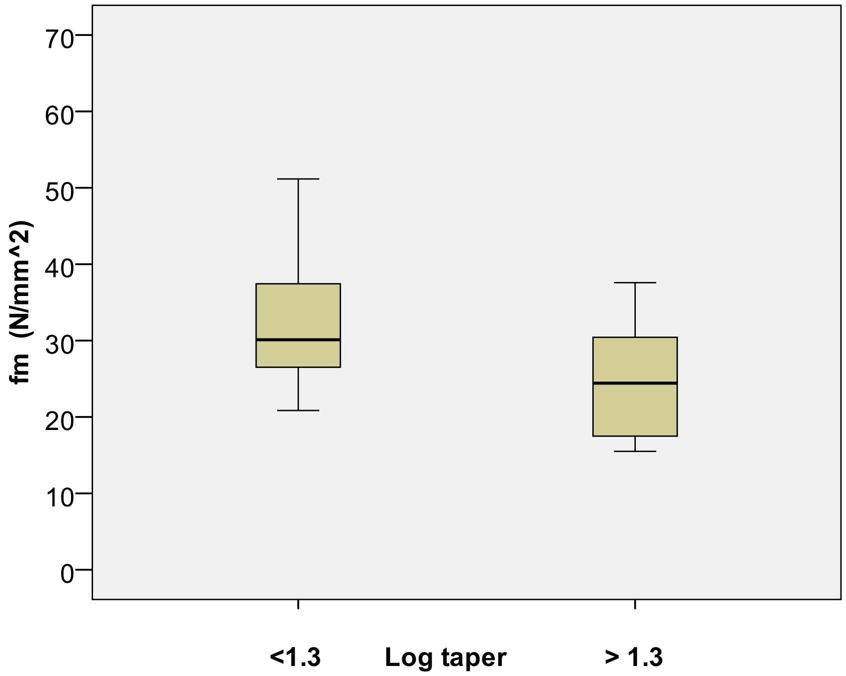

Figure 10.2: Box plots of strength (f_m) grouped by *Log taper* (FR3/4 150 x 47 mm battens).

Using 1-way ANOVA it was determined that in the case of E_{cb} the difference in the population means of battens grouped by *Log taper* (*i.e.* > 1.3 and < 1.3) is significant at the $p < 0.001$ level, whereas for the same groups the differences in $E_{m,g}$ and f_m are of lower statistical significance ($p = 0.04$, in both cases). Note that because the data have been grouped into 2 groups *post hoc* tests are unnecessary. The above result was also checked using the Brown and Welch-Forsythe tests for equality of means. Table 10.2 shows the descriptives for these groups.

Table 10.2: E_{cb}, $E_{m,g}$ and f_m descriptives for groups of *Log taper* (FR3/4 150 x 47 mm battens).

	Log taper	N	Mean	Std. Deviation	Std. Error
E_{cb}	<1.3	36	6880	1327	221
	>1.3	15	4760	937	242
	Total	51	6260	1559	218
$E_{m,g}$	<1.3	36	7400	1129	188
	>1.3	15	6330	1176	303
	Total	51	7090	1235	172
f_m	< 1.3	36	32.0	7.9	1.3
	> 1.3	15	24.8	7.5	1.95
	Total	51	29.9	8.4	1.17

10.2 FR3/4 150 x 47 mm and 100 x 47 mm combined

Figure 10.3, Figure 10.4 and Figure 10.5 show histograms of E_{cb}, $E_{m,g}$ and f_m respectively for the FR3/4 150 x 47 mm and 100 x 47 mm combined group. From these histograms it can be seen that in each case the distribution is approximately normal. The data presented are consistent with strength class C14 to C16 as defined by EN 338 (note that bending strength is based on the characteristic or lower 5th % value *i.e.* 16 N/mm^2), although the mean value for E_{cb} is markedly lower than $E_{m,g}$. Notable is that this difference is greater than can be accounted for by the relationship between stiffness and m/c given in EN 384:2004 (this aspect is further discussed in Section 10.7).

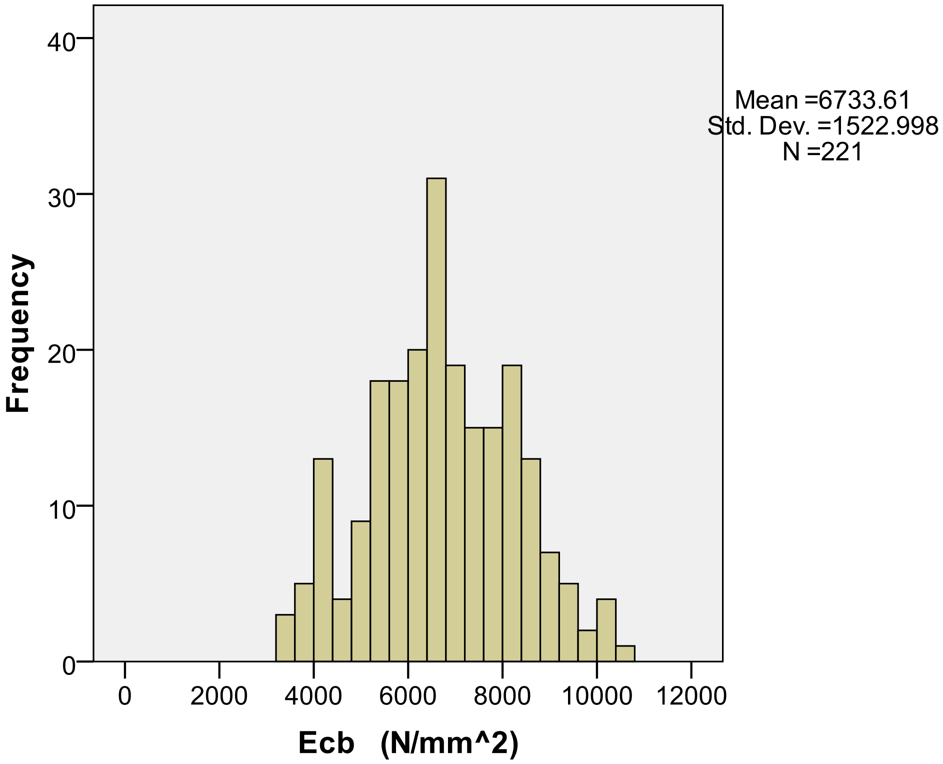

Figure 10.3: Histogram of E_{cb} for the FR3/4 150 x 47 mm and 100 x 47 mm combined group.

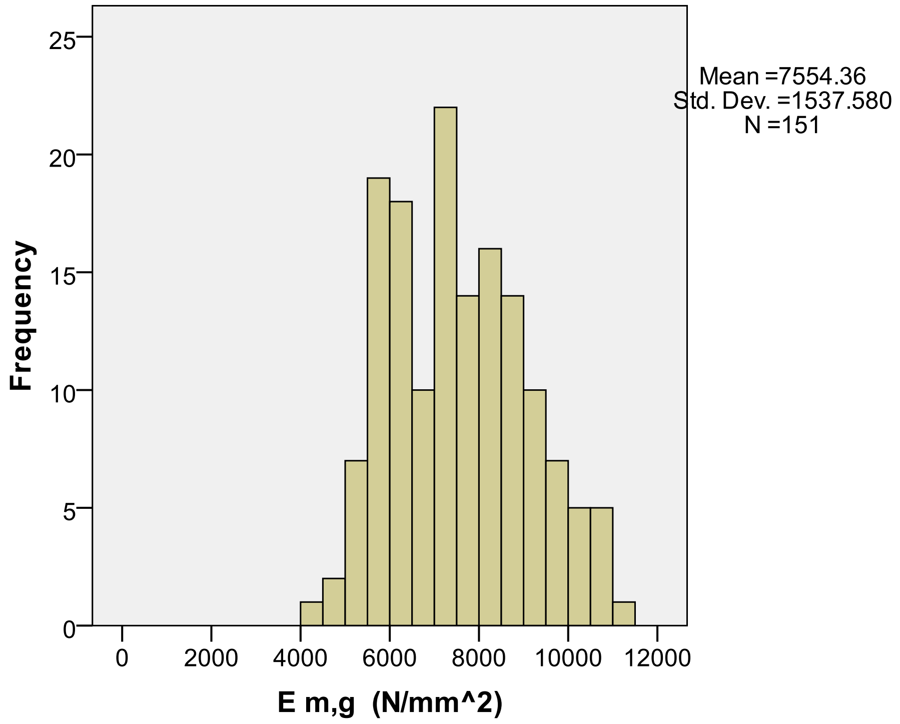

Figure 10.4: Histogram of $E_{m,g}$ for the FR3/4 150 x 47 mm and 100 x 47 mm combined group.

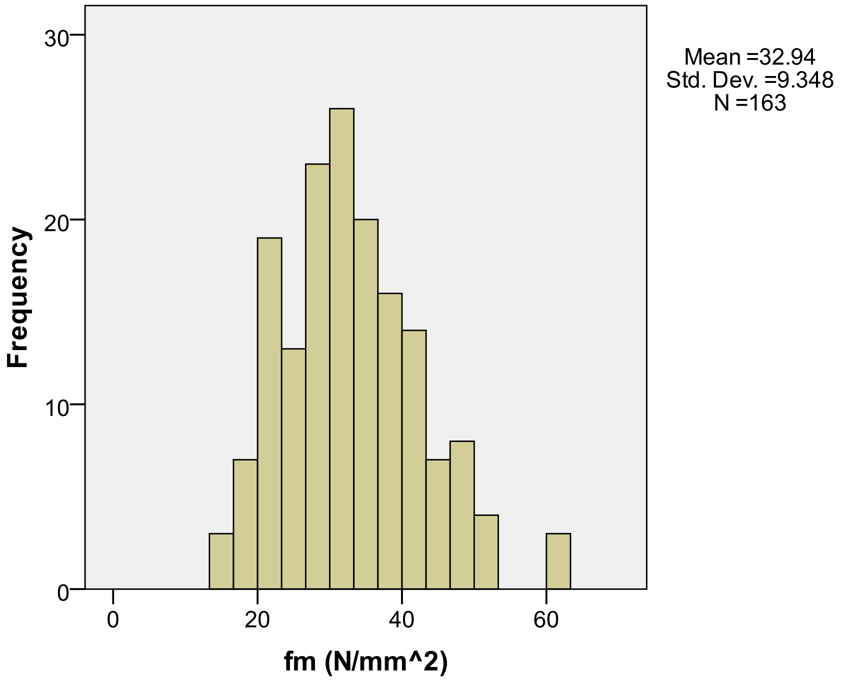

Figure 10.5: Histogram of f_m for the FR3/4 150 x 47 mm and 100 x 47 mm combined group.

Table 10.3 shows the correlation table for E_{cb}, $E_{m,g}$ and f_m, together with a series of log and batten variables, for the FR3/4 150 x 47 mm and 100 x 47 mm combined group.

Table 10.3: Correlation table for E_{cb}, $E_{m,g}$ and f_m
(FR3/4 100 x 47 mm and 150 x 47 mm).

R	E_{cb}	$E_{m,g}$	f_m
$E_{m,g}$	0.70**		
f_m	0.54**	0.65**	
Cut ht.	0.55**	0.34**	0.20**
Log taper	-0.45**	-0.12**	-0.05
Dens	0.30*	0.37**	0.32**
Pith Dist	-0.05	0.04	-0.10
Ring width	-0.45**	-0.41**	-0.31**
JW	-0.05	-0.15	-0.04
Knotarea%	-0.42**	-0.27**	-0.23**
Mid 900 knot area/face area kN900%	-0.53**	-0.40**	-0.37**
Kn300%	-0.20**	-0.17*	-0.11
MKAR	-0.10	-0.25*	-0.23*
TKAR	-0.20*	-0.30*	-0.33**
Section	-0.04	0.09	-0.07
DBH	0.05	-0.05	-0.08
Tree ht	-0.02	-0.25**	-0.26**

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
N ~ 220 for E_{cb} . N ~ 150 for $E_{m,g}$ and f_m .

From the above table it can be seen that E_{cb} correlates quite well to $E_{m,g}$ and $f_{m.}$ Notable, in particular, are absences of correlations between these mechanical properties and *Section*, *JW*, *DBH* and *Tree ht*., indicating that overall these are not useful measurements. The inclusion of the 100 x 47 mm battens results in significant differences in the relationships observed compared to those for the 150 x 47 mm battens alone (Table 10.1). The combined group exhibits a slightly better relationship between mechanical properties and *Density*, but a worse relation to *Log taper*. Notable, also, is the absence of any strong relationships between strength (f_m) and the variables listed indicating that none of the measurements are particularly useful predictors. This is probably because f_m is based on the ultimate load (*i.e.* an actual fracture), and subject to more unaccounted variation than in the case of stiffness.

Table 10.4 details the E_{cb}, $E_{m,g}$ and f_m mean, standard deviation and standard error of the mean values, for groups of *Log taper* (*i.e*. <1.3 and >1.3) for the FR3/4 150 x 47 mm and 100 x 47 mm battens.

Table 10.4: E_{cb}, $E_{m,g}$ and f_m descriptives for groups of *Log taper* (FR3/4 150 x 47 mm and 100 x 47 mm battens).

	Log taper	N	Mean	Std. Deviation	Std. Error
E_{cb}	<1.3	186	6990	1374	100
	>1.3	35	5360	1558	263
	Total	221	6730	1522	102
$E_{m,g}$	<1.3	125	7660	1463	130
	>1.3	26	7040	1798	350
	Total	151	7550	1537	125
f_m	< 1.3	137	33.5	8.84	0.76
	> 1.3	26	29.7	11.3	2.21
	Total	151	32.9	9.34	0.73

Table 10.5 details the ANOVA results for E_{cb}, $E_{m,g}$ and f_m grouped by *Log taper* (*i.e.* <1.3 and >1.3) for the combined FR3/4 150 x 47 mm and 100 x 47 mm battens.

Table 10.5: ANOVA results for E_{cb}, $E_{m,g}$ and f_m for groups of *Log taper* (FR3/4 150 x 47 mm and 100 x 47 mm battens).

ANOVA

	Log taper groups		Sum of Squares	df	Mean Square	F	Sig.
E_{cb}	*Log taper* >1.3 and <1.3	(Combined)	7.84×10^7	1	7.84×10^7	39.7	0.000
		Within Groups	4.31×10^8	219	1970000		
		Total	5.10×10^8	220			
$E_{m,g}$	*Log taper* >1.3 and <1.3	(Combined)	8260000	1	8250000	3.55	0.061
		Within Groups	3.46×10^8	149	2320000		
		Total	3.55×10^8	150			
f_m	*Log taper* >1.3 and <1.3	(Combined)	312	1	312.3	3.63	0.058
		Within Groups	13800	161	86.0		
		Total	14200	162			

From the above tables, it can be seen that the weak butt effect has a much lower influence on both $E_{m,g}$ and f_m, than it does on E_{cb}. In the case of E_{cb} the difference in the mean value of battens grouped by *Log taper* (*i.e.* > 1.3 and < 1.3) is significant at the $p < 0.001$ level, whereas for the same groups the differences in $E_{m,g}$ and f_m are of much lower statistical significance ($p > 0.05$).

By a similar one-way ANOVA process using grouped values of *Knotarea%* (*i.e*. ranges of 0 to 1%, 1 to 2%, and 2 to 3%), it was determined that there were statistically significant differences at the $p < 0.001$ level between the population means of the highest and lowest knot content groups for E_{cb}, $E_{m,g}$ *and* f_m (Table 10.6).

Table 10.6: ANOVA Multiple comparisons for E_{cb}, $E_{m,g}$ and f_m grouped by knot content (FR3/4 150 x 47 mm and 100 x 47 mm battens).

ANOVA

Method = Tamhane

Dependent variable	(I) *Knotarea%* group	(J) *Knotarea%* group	Mean Difference (I-J)	Std. Error	Sig.
E_{cb}	0 to 1%	1 to 2%	6.56×10^2	1.98×10^2	0.003
		2 to 3%	2.15×10^3	3.80×10^2	0.000
	1 to 2%	0 to 1%	-6.56×10^2	1.98×10^2	0.003
		2 to 3%	1.49×10^3	3.72×10^2	0.001
	2 to 3%	0 to 1%	-2.15×10^3	3.80×10^2	0.000
		1 to 2%	-1.49×10^3	3.72×10^2	0.001
$E_{m,g}$	0 to 1%	1 to 2%	4.23×10^2	2.70×10^2	0.321
		2 to 3%	1.58×10^3	4.02×10^2	0.002
	1 to 2%	0 to 1%	-4.23×10^2	2.70×10^2	0.321
		2 to 3%	1.16×10^3	3.73×10^2	0.017
	2 to 3%	0 to 1%	-1.59×10^3	4.02×10^2	0.002
		1 to 2%	-1.15×10^3	3.73×10^2	0.017
f_m	0 to 1%	1 to 2%	0.58	1.55	0.975
		2 to 3%	7.89	2.22	0.004
	1 to 2%	0 to 1%	-0.58	1.55	0.975
		2 to 3%	7.30	2.11	0.007
	2 to 3%	0 to 1%	-7.89	2.22	0.004
		1 to 2%	-7.30	2.11	0.007

Figure 10.6 shows box plots of f_m, for grouped *Knotarea%* for the FR3/4 150 x 47 mm and 100 x 47 mm battens.

Figure 10.6: Box plots of f_m , grouped by *Knotarea%* (FR3/4 150 x 47 mm and 100 x 47 mm).

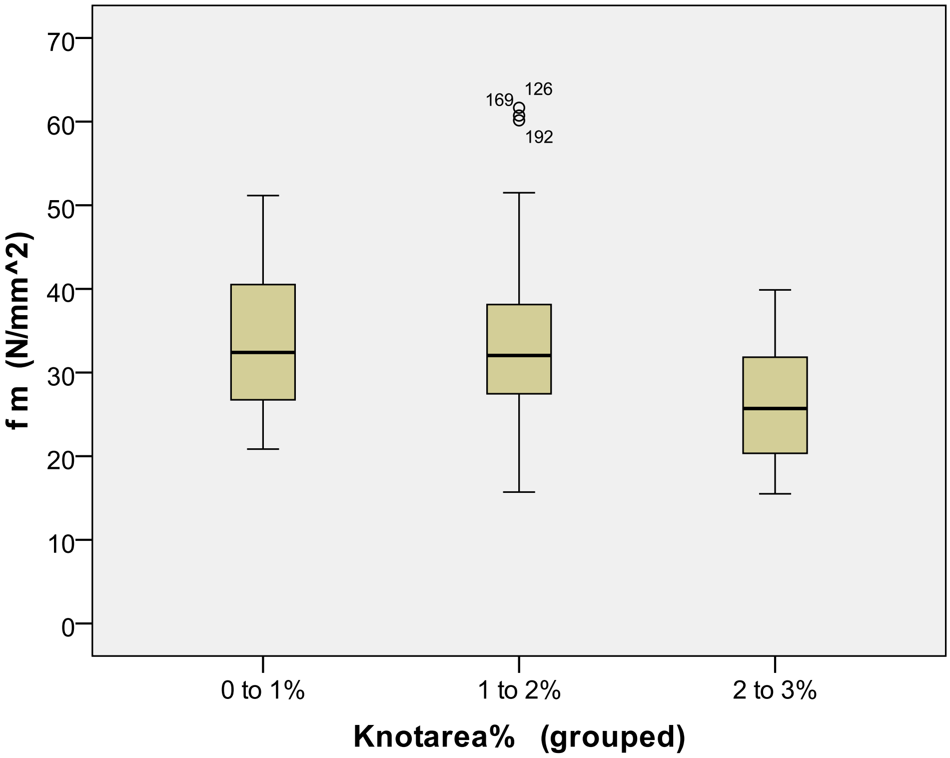

Figure 10.7: Box plots of f_m, grouped by *Knotarea%*

From inspection of the ANOVA descriptives (not shown) in could be determined that the mean of the group with the highest knot content is around 8 N/mm^2 lower in strength than the groups with lower knot content (*i.e*. a similar difference to that which exists between C16 and C24 strength classes as defined in EN 338). This indicates that sorting on the basis of knot cover could potentially be used to usefully separate timber into strength classes which differed significantly, but such a process would also need to consider the other required attributes of the strength class such as stiffness and density. Strength class is also based on characteristic values rather than mean values.

One–way ANOVA performed individually for E_{cb} and $E_{m,g}$, showed that the *Section* = 0 group (*i.e*. battens containing pith) had a lower population mean than those in more outward positions, and that this difference was statistically significant. However there was no trend for increasing stiffness from the pith outward. For f_m there was no statistically significant difference between groups of *Section*.

10.3 Univariate analysis of variance (FR3/4 100 x 47mm and 150 x 47mm)

Since *Knotarea%, Log taper* and *Section* represent variables which have been further defined into categorical variables representing possible sorting ranges or thresholds (as described above), Univariate analysis of variance can be used to test for interaction. Table 10.7 shows the results for the dependent variable E_{cb}.

From the above table it can be seen that for E_{cb} both *Knotarea%* and *Log taper* groupings are statistically significant at the $p < 0.05$ level, whilst *Section* is outside the statistically significant level at $p = 0.064$. None of the interaction terms are statistically significant. “Partial eta squared”, describes the proportion (expressed in this instance as a decimal) of variation explained in the dependent variable by the predictor, controlling for the influence of the other predictors included in the model.

Table 10.7: Tests of Between Subjects Effects for E_{cb} (FR3/4 150 x 47 mm and 100 x 47 mm battens).

Tests of Between-Subjects Effects

Dependent variable: E_{cb}

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1.53×10^{8} [a]	15	1.02×10^{7}	5.843	0.000	0.299
Intercept	1.98×10^{9}	1	1.98×10^{9}	1136.4	0.000	0.847
Log Taper	2.82×10^{7}	1	2.82×10^{7}	16.2	0.000	0.073
Knotarea%	2.04×10^{7}	2	1.02×10^{7}	5.86	0.003	0.054
Section	9730000	2	4865000	2.79	0.064	0.026
*Taper * Knotarea%*	805900	2	403000	0.231	0.794	0.002
*Taper * Section*	462700	2	231000	0.133	0.876	0.001
*Knotarea% * Section*	6790000	4	1700000	0.973	0.423	0.019
*Taper * Knotarea% * Section*	2795000	2	1400000	0.802	0.450	0.008
Error	3.58×10^{8}	205	1740000			
Total	1.05×10^{10}	221				
Corrected Total	5.10×10^{8}	220				

a. $R^2 = .299$
(Adjusted $R^2 = .248$)

Figure 10.8 shows the plot of estimated marginal means of E_{cb} grouped by *Log taper* and *Section* (note that these show the mean response for each factor, adjusted for any other variable in the model). The nearly parallel lines illustrate the lack of interaction between the variables, *i.e*. the graph shows that for all *Section* groups, *Log taper* has a similar effect. This means that the weak butt effect affects both the centre cut batten containing pith and the outlying battens to the same extent.

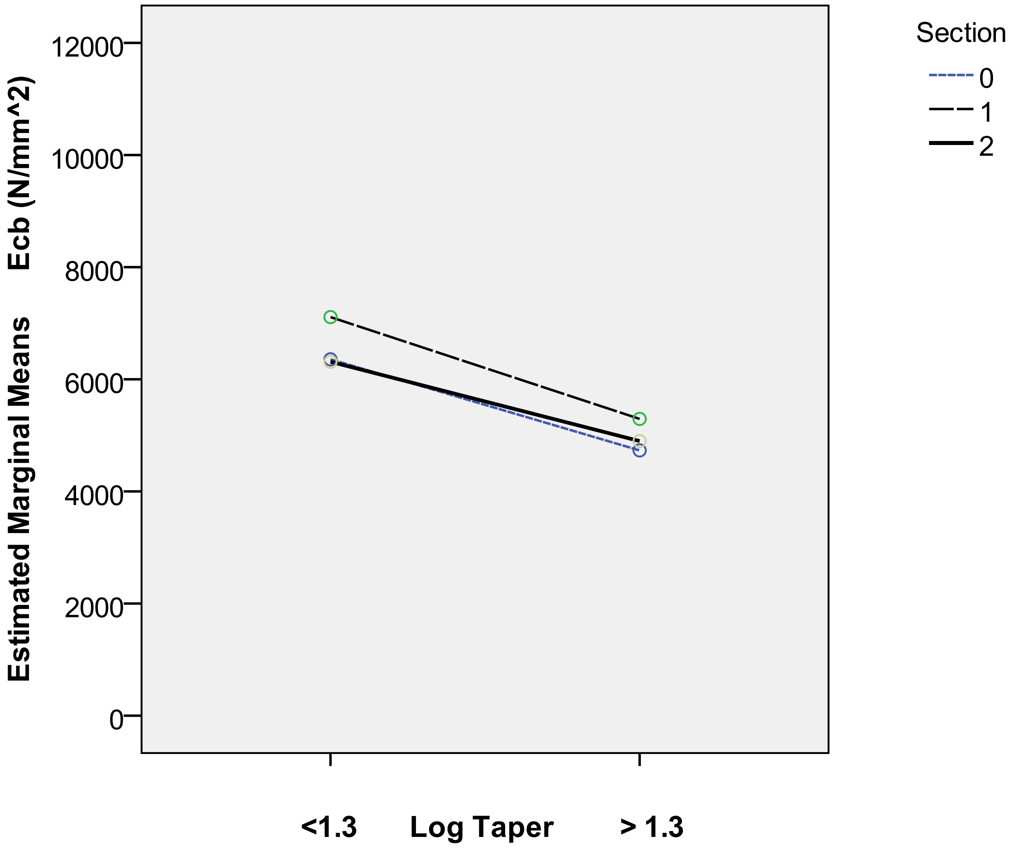

Figure 10.8: Estimated Marginal Means of E_{cb} grouped by *Log taper* and *Section*. (original in colour)

Since *Knotarea%* has been grouped into three categories and has been found significant in the E_{cb} model, *post hoc* tests can be performed. From inspection of the Multiple Comparisons (using the Scheffé test which is appropriate for groups of unequal size), it was confirmed that for E_{cb} all groups are significantly different at the $p< 0.05$ level.

From Table 10.7 it can be seen that the *Section* variable is of relatively low significance compared to *Log taper* and *Knotarea%*.

Note that it was not possible to reliably or usefully use Univariate analysis of variance on either $E_{m,g}$ or f_m for this data group because of the low number of battens in certain corresponding sub-categories of *Knotarea%*, *Section* and *Log Taper*. This is partly due to missing data, but moreover due to the generally higher knot content of butt log battens – *i.e.* the data groups are unbalanced, and consequently many of the marginal means are inestimable.

10.4 FR2,3,4 150 x 47 mm

Table 10.8 shows sorted data for the FR2,3,4 150 x 47 mm battens, with the eight lowest values of $E_{m,g}$ (shaded grey) and the eight highest (unshaded). By inspection of the data it can be seen that the battens with comparatively low values of both stiffness and strength are all from butt logs with high values of *Log taper*, and that these battens also have comparatively high knot contents. The converse is true of the eight stiffest battens.

Table 10.8: Sorted batten data for FR2,3,4 150 x 47 mm battens.

Site – tree no.	Cant ID	$E_{m,g}$	E_{cb}	f_m	*Cut ht.*	*Log taper*	*JW*	*Section*	*Knotarea%*
FR2 – 48	2YB	4200	3580	25.6	0.51	1.42	0.68	1	1.70
FR2 – 48	2YA	4770	3600	18.8	0.51	1.42	0.71	1	1.20
FR4 - 360	7OC	4830	4230	19.0	0.55	1.65	0.56	2	2.27
FR3 - 360	5YB	4890	3920	17.4	0.35	1.34	0.93	0	2.99
FR2-127	NNA	5410	3810	21.9	0.5	1.32	0.89	2	1.62
FR4-453	OGB	5450	4360	15.5	0.83	1.32	0.71	2	2.07
FR4-453	OGA	5470	3730	17.5	0.83	1.32	0.89	0	2.31
FR4-554	8RA	5540	4200	15.8	0.55	1.35	0.93	1	1.72
FR3-28	XYB	9360	9040	33.3	3.8	1.04	0.94	0	1.03
FR2-210	5BB	9500	6910	48.3	0.45	1.25	0	2	0.27
FR2-164	OBA	9530	6000	50.7	6.79	1.09	0.87	1	0.81
FR2-210	8BB	9660	8600	49.0	6.91	1.10	0.57	2	0.92
FR3-28	5BD	9720	7720	32.6	6.63	1.14	0	2	0.81
FR2-210	8BA	9950	9280	38.9	6.91	1.10	0.81	2	0.76
FR2-104	3BA	10170	8170	38.4	3.93	1.15	0.9	1	0.86
FR2-44	3PD	10220	7650	36.0	3.87	1.07	0.27	2	1.33

10.5 FR2,3,4 100 x 47 mm

Table 10.9 shows the correlation table for E_{cb}, $E_{m,g}$ and f_m, together with a series of log and batten variables, for the FR2,3,4 100 x 47 mm battens. Note that during the EN 408:2003 tests these battens were placed randomly with respect to the major axis and positioned centrally with regard to the lengthwise axis.

Table 10.9: Correlation table for E_{cb}, $E_{m,g}$ and f_m
(FR2,3,4 100 x 47 mm).

R	E_{cb}	$E_{m,g}$	f_m
$E_{m,g}$	0.78**		
f_m	0.59**	0.62**	
Cut ht.	0.46**	0.24*	0.25
Log taper	-0.31*	-0.14	-0.09
Dens	0.21*	0.18	0.10
Pith Dist	0.09	0.21**	0.19
Ring width	-0.45**	-0.41**	-0.32**
JW	-0.26**	-0.33**	-0.28**
Kn300%	-0.34**	-0.39**	-0.18
Knotarea%	-0.48**	-0.51**	-0.40**
Kn900%	-0.50*	-0.51**	-0.41**
MKAR	-0.12	-0.15	-0.15
TKAR	-0.13	-0.16	-0.18
Section	0.12	0.23*	0.07

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N =99.

From Table 10.9 (note that correlations with R > 0.4 are shown shaded) it can be seen that there are relatively strong correlations between grader derived stiffness (E_{cb}) and stiffness obtained by EN 408:2003 test ($E_{m,g}$), and that these stiffness variables also correlate well to strength (f_m). As with the 150 x 47 mm battens (Table 10.1) it can be seen that the variables of common significance to the mechanical properties are those that relate to knot content (*e.g. Knotarea%*), and that notably *Density* is not significant at all.

10.6 FR2 100 x 47 and 150 x 47mm

Table 10.10 shows the correlation table for E_{cb}, $E_{m,g}$ and f_m, together with a series of log and batten variables, for the FR2 100 x 47 mm and 150 x 47 mm group of battens.

From this table (note that correlations with R > 0.4 are shown shaded), it can be seen that E_{cb}, $E_{m,g}$ and f_m all correlate negatively to the knot content variable *Knotarea%*, and that correlations to other variables are comparatively weak or not existent; notably for *Density*, *Ring width*, *JW*, *MKAR*, *TKAR*, *DBH*, *Tree ht*., and the log shape variables *Pith X* and *Ovality*. Meaningful correlations were also not observed to *SoG outer*, *CW total adj.*, or any of the whorl spacing variables.

Tables 10.11, 10.12 and 10.13 show the descriptives for E_{cb}, $E_{m,g}$ and f_m grouped by *Log taper*, *Knotarea%* and *Section* for the FR2 100 x 47 mm and 150 x 47 mm battens. The following groups of *Knotarea%* were constructed (0 to 1%, 1 to 1.5% and above 1.5%) due to the low numbers of battens with knot content above 2%, in contrast to the FR3/4 material.

Table 10.10: Correlation table for E_{cb}, $E_{m,g}$ and f_m (FR2 100 x 47 mm and 150 x 47 mm).

R	E_{cb}	$E_{m,g}$	f_m
$E_{m,g}$	0.70**		
f_m	0.56**	0.67**	
Cut ht.	0.37**	0.21*	0.19
Log taper	-0.37**	-0.27**	-0.17
Dens	0.02	-0.05	0.08
Pith Dist	0.24**	0.31**	0.21
Ring width	-0.22*	-0.26**	-0.25*
JW	-0.15	-0.29**	-0.25*
Knotarea%	-0.48**	-0.56**	-0.43**
kN900%	-0.37**	-0.52**	-0.39**
Kn300%	-0.32**	-0.41**	-0.20*
MKAR	-0.12	-0.08	-0.25
TKAR	-0.18	-0.24*	-0.23*
Section	0.31**	0.30**	0.13
DBH	0.06	0.16	0.10
Tree ht.	0.03	0.23*	0.09
Ovality	-0.28**	-0.25*	-0.21
Pith X	-0.14	0.08	0.04

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
N = 115 for E_{cb}; N = 95 for $E_{m,g}$ and f_m.

Table 10.11: Descriptives, E_{cb}, $E_{m,g}$ and f_m for *Section* groups (FR2 100 x 47 mm and 150 x 47 mm).

	Section	N	Mean	Std. Deviation	Std. Error
E_{cb}	0	22	5670	1030	219
	1	40	6340	1498	236
	2	52	6940	1591	220
	Total	114	6480	1532	143
$E_{m,g}$	0	17	6660	817	198
	1	32	7190	1685	297
	2	45	7820	1370	204
	Total	94	7400	1466	151
f_m	0	17	30.7	5.04	1.22
	1	32	32.0	11.1	1.96
	2	45	33.8	8.52	1.27
	Total	94	32.6	9.03	0.93

Table 10.12: Descriptives, E_{cb}, $E_{m,g}$ and f_m for *Log taper* groups (FR2 100 x 47 mm and 150 x 47 mm).

	Log taper	N	Mean	Std. Deviation	Std. Error
E_{cb}	<1.3	96	6760	1459	148
	>1.3	19	5100	1052	241
	Total	115	6490	1526	142
$E_{m,g}$	<1.3	78	7620	1439	163
	>1.3	17	6400	1117	271
	Total	95	7400	1460	149
f_m	<1.3	78	33.8	9.0	1.0
	>1.3	17	27.5	7.0	1.7
	Total	95	32.6	8.9	0.92

Table 10.13: Descriptives, E_{cb}, $E_{m,g}$ and f_m for *Knotarea%* groups (FR2 100 x 47 mm and 150 x 47 mm).

	Knotarea%	N	Mean	Std. Deviation	Std. Error
E_{cb}	0 to 1%	59	7070	1437	187
	1.5 to 2%	39	6340	1225	196
	> 2%	16	4700	1057	264
	Total	114	6490	1533	143
$E_{m,g}$	0 to 1%	48	8130	1247	180
	1.5 to 2%	33	7030	1190	207
	> 2%	13	5660	997	276
	Total	94	7400	1467	151
f_m	0 to 1%	48	35.9	8.37	1.2
	1.5 to 2%	33	31.0	8.75	1.5
	> 2%	13	24.9	6.26	1.7
	Total	94	32.7	9.03	0.93

By inspection of the ANOVA multiple comparisons (not shown), it could be deduced that the difference in the population means for all the mechanical properties (E_{cb}, $E_{m,g}$ and f_m,) grouped by both *Log Taper* and *Knotarea%* are statistically siginificant at the $p < 0.05$ level.

For both E_{cb}, $E_{m,g}$ there are statistically significant differences between the means of *Section* = 0 and 2, but not between *Section* = 0 and 1, nor between *Section* = 1 and 2. For strength (f_m,) there was no statistically significant difference between the groups of *Section*.

Figure 10.9, Figure 10.10 and Figure 10.11 show box plots of $E_{m,g}$ for the above groups.

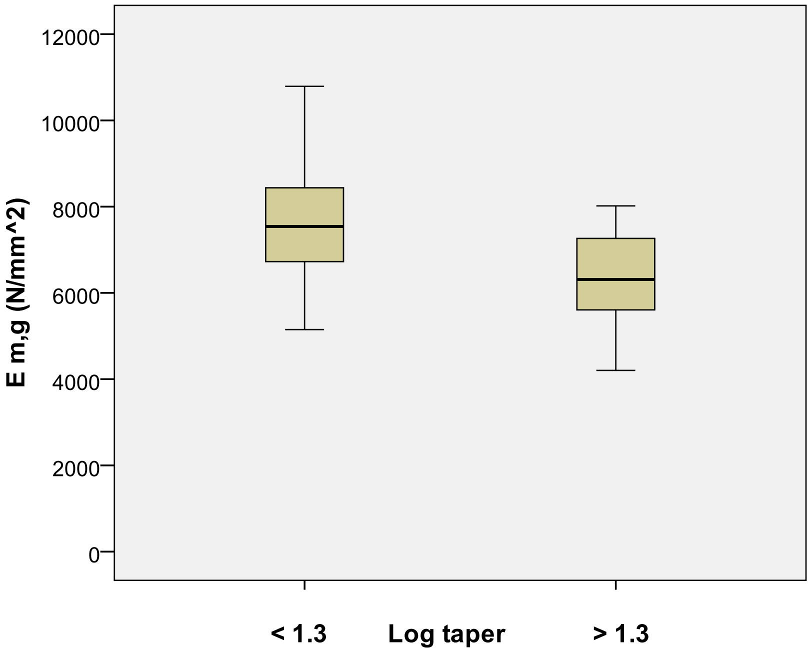

Figure 10.9: Box plot of $E_{m,g}$ grouped by *Log taper* (FR2 100 x 47 mm and 150 x 47 mm).

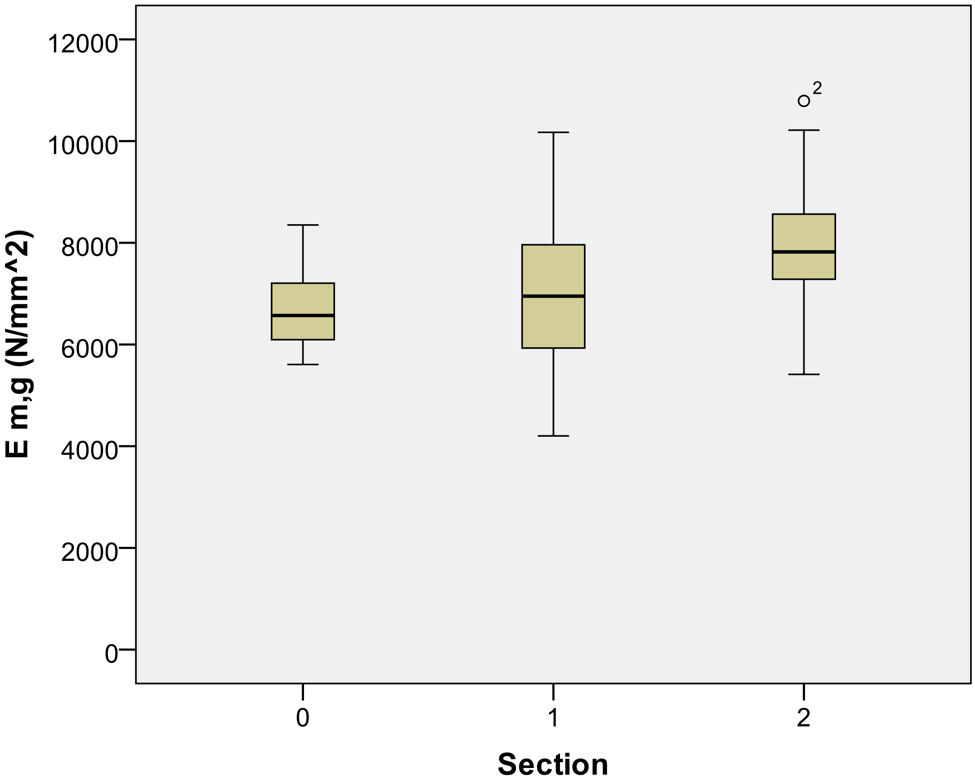

Figure 10.10: Box plot of $E_{m,g}$ grouped by *Section* (FR2 100 x 47 mm and 150 x 47 mm).

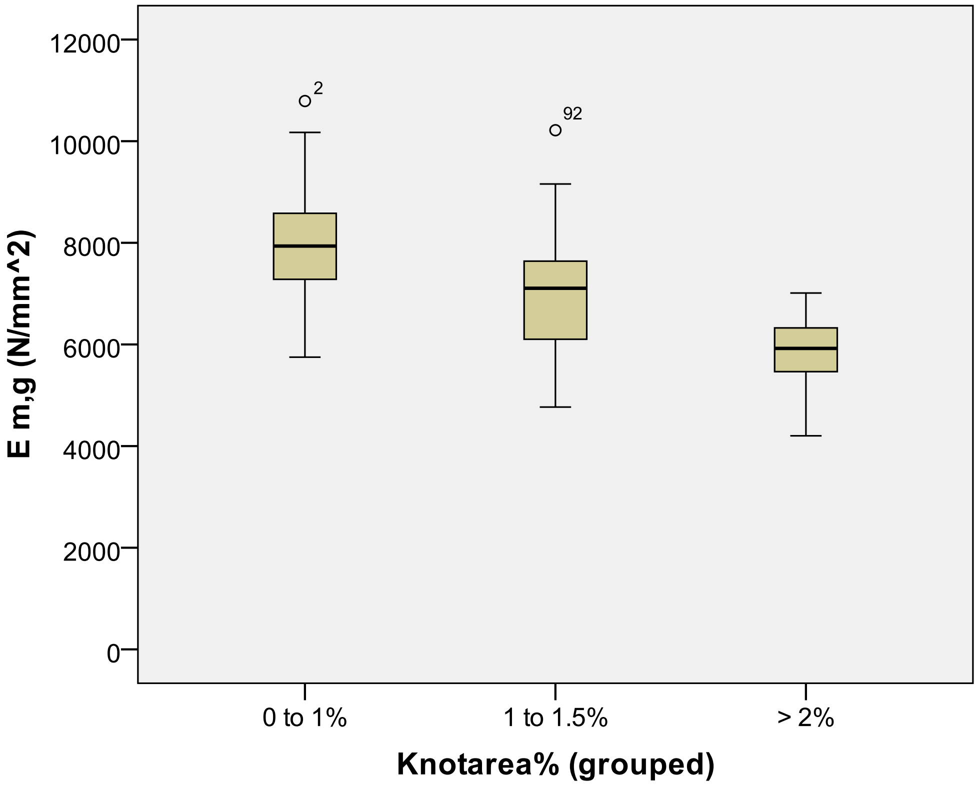

Figure 10.11: Box plot of $E_{m,g}$ grouped by *Knotarea%* (FR2 100 x 47 mm and 150 x 47 mm).

From Figure 10.11 it can be seen that there is a quite marked trend for a decrease in stiffness with increasing knot content, whereas from Figure 10.9 and Figure 10.10 it can be seen that there are only small differences in stiffness between the groups, which are unlikely to be of practical value. A distinction should be made between the trends identified within grouped values, to the coefficient of determination that might be obtained for a population (*i.e.* line of best fit through a scatter plot).

Univariate analysis of variance could not be used with any useful degree of reliability on this dataset due to the low number of battens in certain corresponding sub-groups of *Section*, *Knotarea%* and *Log Taper.*

10.7 Discussion and summary of findings on E_{cb}, $E_{m,g}$ and f_m

From the observations detailed above the following summary can be made.

For the various sets of data examined corresponding to different stand and batten size combinations, only modest correlations between grader derived stiffness (E_{cb}) and stiffness obtained by EN 408:2003 test ($E_{m,g}$), were obtained. For all the datasets examined stiffness was correlated to strength.

For the FR3/4 battens E_{cb} was noted to be more strongly related to *Log taper* than $E_{m,g}$ and f_m (Section 10.1 and 10.2). This is probably a facet of the nature of the test set-up (Chapter 3), whereby E_{cb} is effectively the value of the lowest stiffness at one point on the board, and $E_{m,g}$ is a stiffness measure biased toward the middle of the length. In the case of butt log battens E_{cb} very often is the stiffness at the lower end. Some of the variation between the Cook-Bolinder derived stiffness, and the stiffness derived from EN 408 bending tests, is also probably due to effects such as batten distortion and machine error.

The differences in mean stiffness derived by grader (E_{cb}) and stiffness obtained by EN 408:2003 test ($E_{m,g}$), as shown in Figures 10.3 and 10.4, are greater than can be accounted for by the relationship between stiffness and moisture content given in EN 384:2004 (*i.e.* a 1% change in moisture content relates to a 2% change in stiffness). Note that the EN 408:2003 tests were carried out at around 12% moisture content, whilst the timber was machine strength graded at around 15 to 18% moisture content. Although this would be consistent with the greater sensitivity of the Cook-Bolinder to the so called weak butt effect (as discussed above), it is also possible that this difference is a result of innaccuracy such the use of nominal rather than precise batten dimensions.

For the FR3/4 150 x 47mm and 100 x 47mm battens, it was determined using ANOVA that for E_{cb} the difference in the population means of battens grouped by *Log taper* (i.e. > 1.3 and < 1.3) is significant at the $p < 0.001$ level (Table 10.5), whereas for the same groups the differences in $E_{m,g}$ and f_m are of much lower statistical significance ($p < 0.05$).

It was also determined that there were statistically significant differences at the $p < 0.001$ level between the population means of the highest and lowest knot content groups (in terms of *Knotarea%)* for E_{cb}, $E_{m,g}$ *and* f_m.

The variable observed to be most strongly related to the both batten stiffness and strength is the knot variable based on total knot cover *i.e. Knotarea%*, whilst the KAR variables are much less effective.

For the FR3/4 150 x 47 mm and 100 x 47 mm battens, one–way ANOVA, performed individually for E_{cb} and $E_{m,g}$, showed that the *Section* = 0 group (*i.e*. battens containing pith) had a lower population mean than those in more outward positions, and that this difference was statistically significant. However there was no marked trend for increasing stiffness from the pith outward. For f_m there was no statistically significant difference between groups of *Section*. Kliger *et al.* (1995) found that the centre battens of fast grown Norway spruce were lower in both stiffness and strength.

The *Section* variable is a clearly a relatively crude measure of radial position which lacks the resolution of the variable *Pith Dist* (these being defined in A2.14 and A2.11, respectively). The limited number of *Section* categories conveniently lends it to ANOVA, although the variable remains ordinal rather than nominal (*i.e*. the numbers represent rank or quantity but only in a limited sense, rather than being simple labels). Notable is the quite strong correlation between *Section* and *Pith Dist* evident in Table 5.1. The usefulness of the *Section* variable lies in its representation of radial position in terms of what might readilly be achieved during mechanical sorting during sawing, *i.e.* segregation of centrally cut battens from those further away from the pith. In contrast, the measurement of *Pith Dist* in an industrial setting would require some form of complex optical scanner .

Univariate analysis of variance established that for E_{cb} there was no significant interaction between groupings of the variables *Log taper*, *Knotarea%* and *Section*. This means that differences observed in the means of stiffness grouped by *Log taper*, for example, aren't due differences in knot content or radial position. The lack of interaction observed between *Log taper* and *Section* groups means that the weak butt effect affects both the centre cut batten containing pith and the outlying battens.

The lack of strong trends for an increase in both radial stiffness ($E_{m,g}$) and strength (f_m) was confirmed in the FR2 150 x 47 mm and 100 x 47 mm group (Section 10.6). This is very likely to be due to the similar composition of battens from the same square cant cutting pattern. For this group E_{cb}, $E_{m,g}$ and f_m correlated negatively to the knot content variable *Knotarea%*, whilst correlations to *Density*, *Ring width*, *JW*, *MKAR*, *TKAR*, *DBH*, *Tree ht*., *Pith X*, *Ovality, SoG outer*, and *CW total adj.* were either weak or non-existent. This implies that for this group, only knot content is a useful sorting parameter, and that other measurements are of little or no practical value. This contrasts with the findings of Maun (1998) with respect to the influence (and hence usefulness) of slope of grain measurements to determine either stiffness or strength. It is possible, however, that the absence of certain relationships is due to limited variance within the dataset, or that the effect of slope of grain is over-ridden by other factors such as knot content. Brazier (1954) determined that for clear samples of Canadian Sitka spruce increases in slope of grain corresponded to reductions in both stiffness and strength. This suggests that a similar relationship exists for clear samples of British grown Sitka spruce.

The absence of a relationship between slope of grain and either stiffness or strength is in agreement with Zhou and Smith (1991) for Canadian grown White spruce (*Picea glauca*). Notably these authors used a more rigorous method of slope of grain measurement based on values obtained on two adjacent faces, but nevertheless concluded that other factors masked its influence on mechanical performance. It appears probable that this is also the case for this work.

Notable (in Table 10.3) is the absence of any strong relationships between strength (f_m) and any of the variables listed for this group of battens (*e.g*. *Cut ht.*, *Log taper*, *Density*, *JW*, *Knotarea%*, *TKAR*) indicating that none of the measurements are particularly useful predictors, or sorting parameters. This is probably because f_m is based on the ultimate load (*i.e.* an actual fracture), and subject to more unaccounted variation than in the case of stiffness. Knot variables such as *Knotarea%* and *TKAR* may not be good indicators for strength reducing features such as localised cross grain. The lack of strong correlations between strength and the above variables also suggests that these measurements would add little to the effectiveness of a grader (such as the Cook-Bolinder), which operates on the measurement of stiffness only. As discussed in Section 2.5.1, although the grade stresses tabulated in BS 5268-2 and EN 338 are suggestive of a relationship between density and the mechanical properties of stiffness and strength across a range of strength classes, within a limited sample of battens from a single species and site such relationships might not be evident.

11 Comparison with BRE Sitka spruce grading dataset

11.1 Correlations between measures of strength, stiffness and knot content

Fortunately, it is possible to make reference to an earlier “BRE Sitka spruce grading dataset” consisting of test results from a number of projects (c. 1990 to 2000), collated by Mr Clive Benham and Mr Chris Holland, which were used to establish the BS 5268 and EN 338 strength classifications, as well as the machine settings for the Cook-Bolinder grader. For these data E_{plank} is equivalent to E_{cb} (the original nomenclature has been retained for clarity), whilst E_{cen} is based on local shear free measurement similar to that defined (as local *MOE*) in EN 408:2003 (a proportion of the work predates the standard). These battens were tested with the worst defect (*i.e.* lowest *IP* position) as far as possible within the central portion of the span. *Density* (*i.e*. basic density as defined in Chapter 3) was recorded at the point of failure. *TKAR* and *MKAR* (as defined in BS 4978) are the only other variables available for these data. It is not possible to delineate these data into groups of butt logs and upper logs.

Figure 11.1 shows E_{plank} plotted against *Density* for all the available BRE British-grown Sitka spruce dataset.

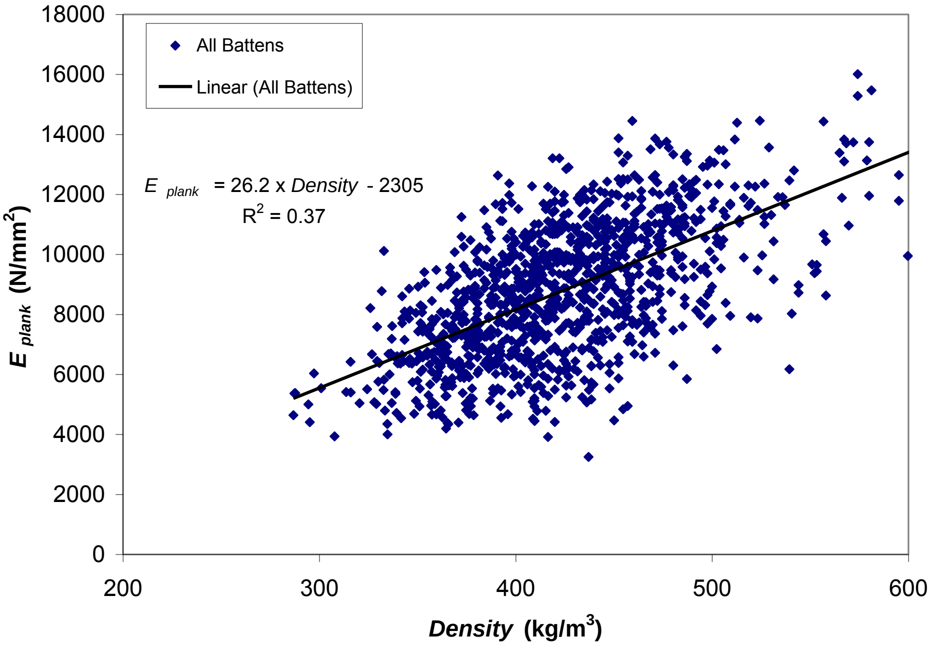

Figure 11.1: E_{plank} plotted against *Density* for all battens (BRE Sitka spruce grading dataset).

Figure 11.1 shows a similar positive relationship between Density and stiffness to the FR1-4 upper log data (as detailed in Section 6.7). The quite good correlation is possibly a function of the wide variance in density, which ranges from 300 to 600 kg/m3. Reasonable relationships between stiffness and density were also evident, by inspection, for individual subsets of batten sizes (ranging from 97 x 47 mm to 228 x 47 mm).

Only very poor relationships were evident between Eplank and either TKAR and MKAR for the BRE dataset. This indicates that use of these variables alone would be an ineffective sorting criteria, even if they could reliably be determined by a scanner (this would require determination of pith position). The data also suggests that knot area ratios are an ineffective measurement for predicting stiffness during visual grading. Note that an important consideration for this set of data is that the orientation of the batten during test is random with respect to the measurement of MKAR, which is defined as the knot area ratio in the worst margin. By inspection, it was also clear that there are large numbers of battens with low TKAR or MKAR but also low stiffness. It is possible that any relationship between knot content, is occluded by the presence of material which is of low stiffness but also relatively knot free.

TKAR is parameter measured about the major axis of the board whilst Eplank is measured about the minor axis. However, the relationship between TKAR or MKAR and Ecen was found to be no better.

A quite strong relationship between E_{plank} and E_{cen} for the BRE dataset was noted (Figure 11.2). This suggests that batten orientation has little influence, overall, on stiffness. There are, however, many instances where there are very large differences between E_{plank} and E_{cen} stiffness values for individual battens.

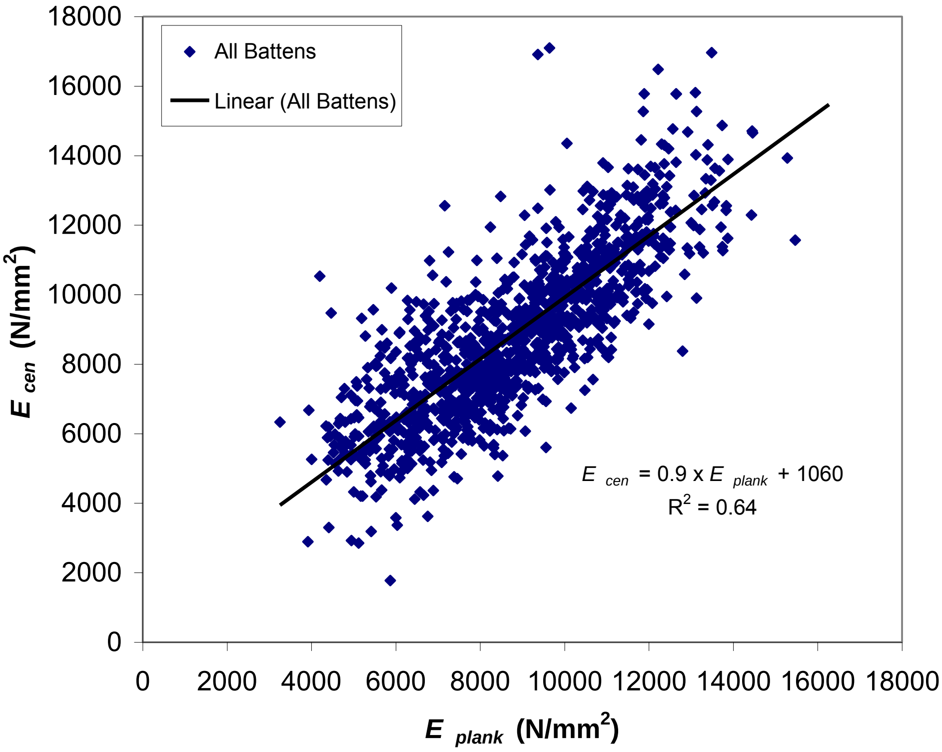

Figure 11.2: E_{cen} plotted against E_{plank} for BRE Sitka spruce grading dataset.

Table 11.1: Correlation table for BRE Sitka spruce grading dataset.

R	E_{cen}	E_{plank}	f_m	*MKAR*	*TKAR*
E_{plank}	0.80**				
f_m	0.77**	0.76**			
MKAR	-0.24**	-0.16**	-0.38**		
TKAR	-0.27**	-0.26**	-0.31**	0.54**	
Dens	0.54**	0.61**	0.55**	-0.08**	-0.06*

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed). N = 1149

From Table 11.1 it is evident that there is a good positive correlation between E_{cen} and *Density*, and less strong negative correlations with both *TKAR* and *MKAR* (note that all correlations with R > 0.4 are shown shaded). It can also be seen that the stiffness variables correlate well to each other, as well as to strength (*i.e.* f_m). It can also be seen that f_m correlates to *Density*, but less well to *TKAR* and *MKAR*, and appears to be more strongly correlated than either E_{cen} or E_{plank} to the knot area ratio variables.

11.2 Multiple regression and correlation

Table 11.2 and Table 11.3 detail the MRC model summary for E_{cen} based on *Density* and *TKAR*.

Table 11.2: Model summary for E_{cen} based on *Density* and *TKAR*.

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.59(a)	0.35	0.34	1982.8

a Predictors: (Constant), *TKAR*, *Density*

Table 11.3: Model summary for E_{cen} based on *Density* and *TKAR*.

Model		Unstandardised Coefficients		Standardised Coefficients		
		B	Std. Error	Beta	T	Sig.
1	Constant	-519.7	510.3		-1.018	0.309
	Dens	25.0	1.13	0.526	22.011	0.000
	TKAR	-4640.8	469.5	-0.236	-9.883	0.000

a Dependent variable: E_{cen}

By inspection of the fit of models for sub-groups of batten size based on *Density*, and both *Density* and *TKAR*, it was evident that *TKAR* contributed little to the effectiveness of the models.

11.3 Summary of findings on the BRE British-grown Sitka spruce grading dataset

For the BRE Sitka spruce grading dataset stiffness was positively correlated to density, but only very weakly correlated (negatively) to knot content in terms of *TKAR* and *MKAR.* This suggests that measurement of knot area ratios during visual grading is largely ineffective for Sitka spruce. The good relation observed between stiffness and density was probably due in part to the wide range of density in the dataset (compared to that encountered with the FR1-4 Lochaline and Benmore dataset). The good relation between stiffness and density is in agreement with Glos and Denzler (2007), as part of work to determine the machine settings for the GoldenEye^{TM} X- ray grader for British grown Sitka spruce.

As expected from the above results, The *TKAR* variable contributed almost nothing to the effectiveness of MRC models for stiffness (this is agreement to findings on the FR1 - 4 dataset, reported in Section 6.6).

Although E_{cen} was, overall, found to be quite strongly related to E_{plank}, many instances were evident where the two forms of stiffness measurement differed greatly for individual battens.

No other variables, such as *Log taper* or those relating to axial and radial position in the stem, are available for the BRE Sitka spruce grading dataset. Better MRC models are likely to have been constructed with more descriptive knot variables together with log shape variables such as taper (as with the FR1 - 4 dataset, see Chapter 7). Better relationships between stiffness and density might have also have been established if the battens in the grading set could have been separated into groups of upper logs and butt logs, to avoid the influence of the weak butt effect as observed with the FR3/4 Benmore battens (Section 6.7).

12 Test work on small clear samples

12.1 Objectives and methodology

The objective of this work was to identify the nature and properties of normal wood and compression wood free from the effect of other features such as knots. By studying selected samples, material with a much higher compression wood content and severity could be assessed than is possible with full-scale battens, which are seldom composed entirely of this form of reaction wood. This work also allowed the effect on stiffness and strength of other variables such as distance from pith, *MFA* and density to be determined. In addition, the nature of butt wood material was also assessed to identify the cause of the low stiffness material evident from the axial trends in E_{cb} (detailed in Section 6.2).

The main group of 85 small clear samples (20 x 20 x 300 mm) was selected to include a broad range of compression wood content. Since the timber samples were deliberately selected in this manner (from FR2 200 x 47mm battens but also including other material of unknown origin selected at random from commercial supplies), the group cannot be considered to represent a typical selection. Note that to avoid any group specific effects, a range of compression wood contents were obtained from each source, and these sets of data also analysed separately.

The samples were visually scored on an ordinal scale of 0 to 3 (*i.e.* 0 = no compression wood, 3 = high compression wood). Although this measurement (denoted *CW Score*) is a subjective assessment, it was carried out by the same wood scientist under identical conditions, and at the same time, in order to avoid introducing variations based on differing personal judgements amongst operators and to facilitate consistency. It is recognised that this experiment is not repeatable. The subset of samples with zero compression wood score can reasonably be considered to be representative of so-called “normal” wood and for this reason are particularly useful.

Longitudinal, radial and tangential shrinkage were measured using a micrometer between conditions at 20 °C and 95% relative humidity and at 20 °C and 65% relative humidity (*i.e.* approx 18% and 12% moisture content), and is defined as change in dimension divided by the original dimension and expressed as a percentage, as below:

$$\varepsilon_L = \frac{L_1 - L_2}{L_1} \times 100\% \qquad \text{Eqn. 5.}$$

where:

ε_L = Longitudinal shrinkage strain

L_1 = Sample original length

L_2 = Sample final length

Radial shrinkage strain (ε_R), and tangential shrinkage strain (ε_T) are similarly calculated.

Although shrinkage may be further quantified in terms of a coefficient (*i.e.* ε / Δ moisture content), since actual moisture contents were not recorded at the end of the work by the oven drying method this is not considered valid (note that the samples were used in other project work). The moisture content of compression wood may differ from normal wood in any given conditions of temperature and relative humidity.

The above shrinkage measurements are shown in A2.18.

Longitudinal shrinkage strain, in particular, may be regarded as a more reliable measure of compression wood severity rather than compression wood score.

MOE and *MOR* were obtained after conditioning at 20 °C and 65% relative humidity, according to BS 373: 1957 *i.e.* in a simple three point bending arrangement.

Other groups of small clear samples were also tested in order to determine the cause of the low stiffness encountered in butt wood material. In addition to *MFA* estimation based on microscope observations of pit angle (carried out at BRE), sections taken from the lower and upper ends of butt log battens were analysed using the SilviScan™ instrument at STFI-Packforsk, Sweden.

12.2 Analysis of variables affecting the *MOE* and *MOR* of clear wood

Figure 12.1 and Figure 12.2 show box plots of *MOE* and *MOR*, respectively, for the 85 small clear samples grouped into four categories of compression wood content (0 = none, to 3 = high).

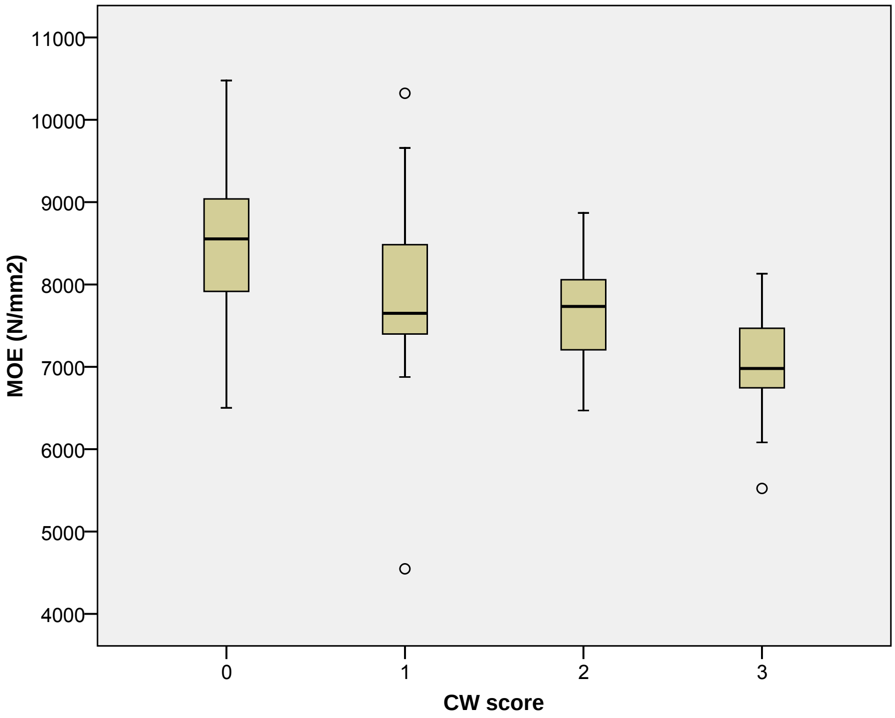

Figure 12.1: Box plots of *MOE* grouped by compression wood content.

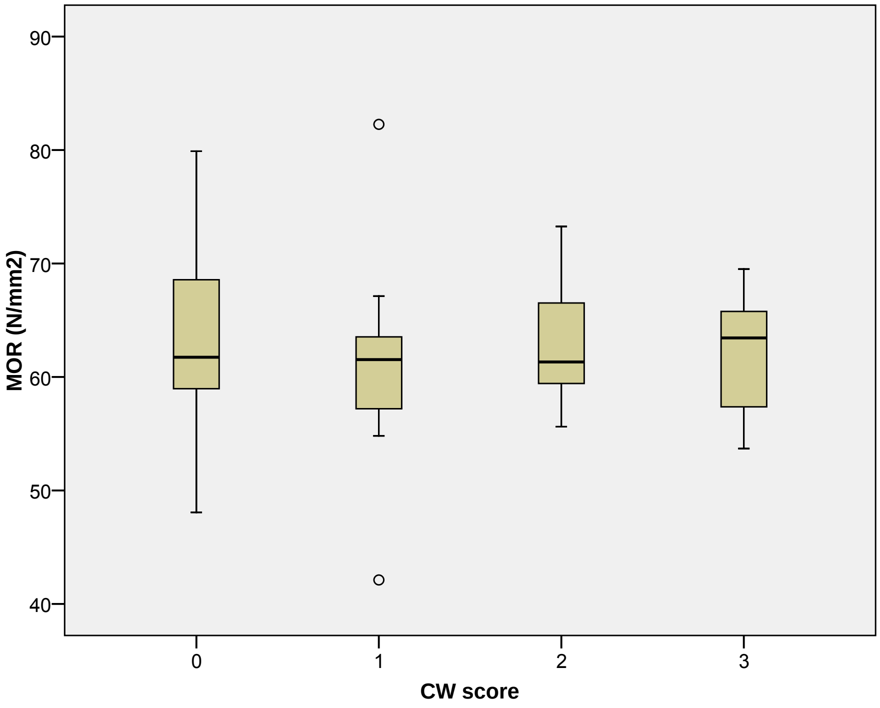

Figure 12.2: Box plots of *MOR* grouped by compression wood content.

From Figure 12.1 and Figure 12.2 it can be seen that stiffness tends to decrease with increasing levels of compression wood, whilst strength is unaffected (see below). This result is similar to that obtained by with Ni Dhubhain *et al.* (1988) who tested full-scale (114 x 44 mm) Irish-grown Sitka spruce. No relation between compression wood content and either stiffness or strength was noted for tests carried out on the full-scale battens from Lochaline and Benmore (Chapter 10), and it appears likely that this was a result of the lower incidence of compression wood in those samples. The presence of other stiffness reducing factors such as knots might also have occluded any affect from compression wood.

Figure 12.3 shows the box plot of density (*i.e.* bulk density after conditioning at 20 °C and 65% relative humidity) for grouped compression wood scores. The graph indicates that the samples classed as having the highest level of compression wood are denser than those classed as having lower compression wood contents.

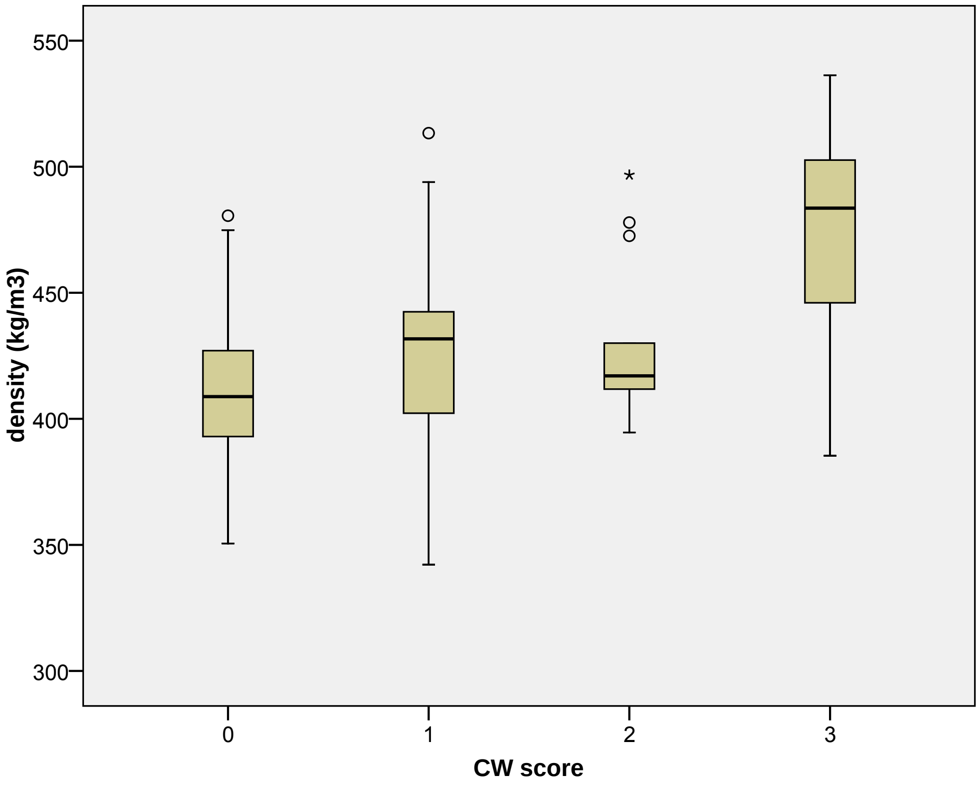

Figure 12.3: Box plots of density for grouped compression wood content.

Using ANOVA it was determined that the difference in the population means for *MOE* between samples grouped with *CW score* = 1 and *CW score* = 3 is significant at the $p < 0.001$ level, whilst the difference in *MOR* for all groups is not significant ($p \approx 1.0$). The difference in density between samples with *CW score* 1 and 3 is significant at the $p < 0.001$ level.

Figure 12.4 shows the relationship observed between *MOE* and density for subsets of the clear samples sorted into varying levels of compression wood content (note that the equations for the lines of best fit are in the same order as the key).

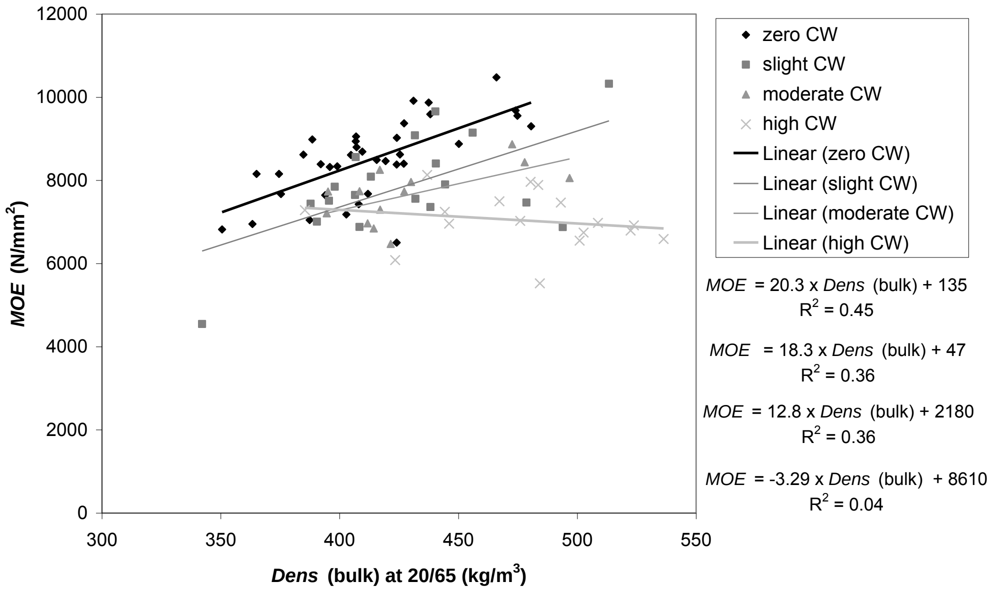

Figure 12.4: *MOE* v. *Dens*$_{(bulk)}$ for sorted compression wood content.
(original in colour)

From Figure 12.4 it can be seen that for the samples classed as zero compression wood there is a quite good relationship between stiffness and density, whilst for the samples classed as high compression wood the stiffness and density are not correlated at all. On the basis of its greater density a batten containing compression wood (but considered to behave like normal wood) might be assumed to have significantly better mechanical properties than it actually has. For example, a batten with a density of 525 kg/m^3 would be expected, when using the calibration line for normal wood, to have a stiffness of around 10,000 N/mm^2. If the batten's density was due to the presence of compression wood then the actual stiffness would only be around 6,000 N/mm^2. These effects are similarly present when considering the effect of compression wood on *MOR* (Figure 12.5). Similar results were reported in Norway spruce by Johansson and Warensjö (2004) and by Sonderegger *et al.* (2008).

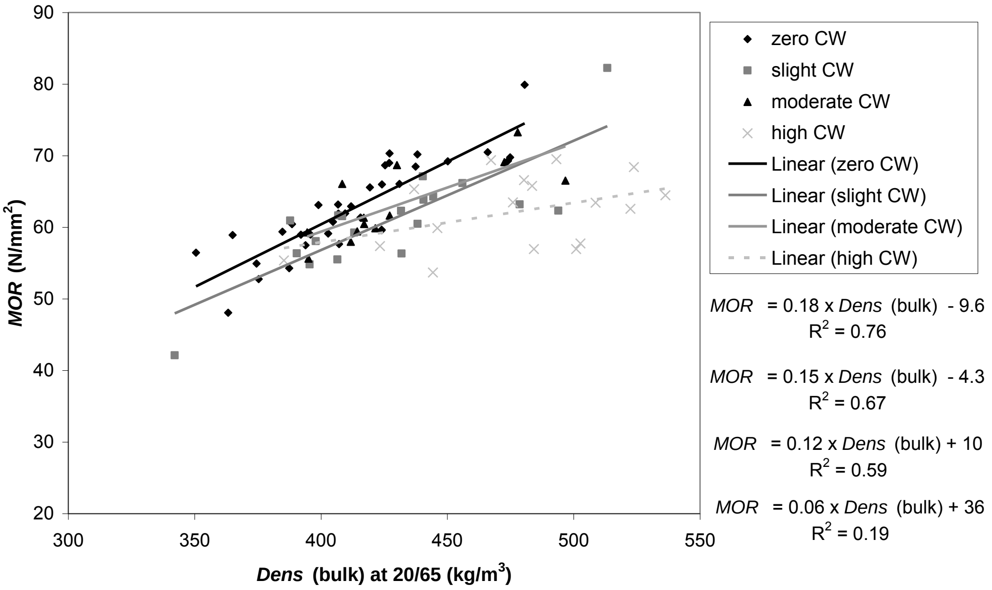

**Figure 12.5: *MOR* v. *Dens$_{(bulk)}$* for sorted compression wood content.
(original in colour).**

From Figure 12.4 and Figure 12.5 it can be seen that, as compression wood score increases, the correlation between density and stiffness, and between strength and stiffness becomes poorer.

Figure 12.6 shows longitudinal shrinkage strain plotted against *MOE* and shows that stiffness decreases with increasing longitudinal shrinkage (*i.e.* severity of compression wood content). No relationship between strength and longitudinal shrinkage strain was observed, indicating that strength is unaffected by compression wood content.

Microscopic examination of the cross-field pits of the latewood (note that this technique is detailed fully in Section 12.3), indicated relatively high microfibril angle in the samples with high *CW Score* (20° to 25°) compared to the normal wood sample (10° to 15°). Meylan and Probine (1969) illustrated similar marked increases in longitudinal shrinkage with increasing *MFA*, together with a reduction in tangential shrinkage.

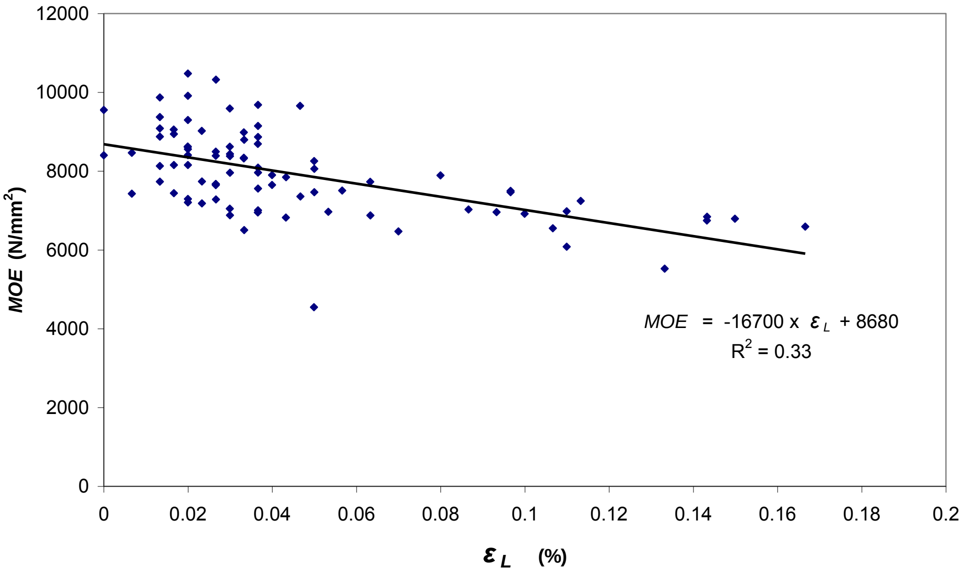

Figure 12.6: *MOE* v longitudinal shrinkage strain.

Figure 12.8 shows box plots for tangential shrinkage grouped by compression wood content.

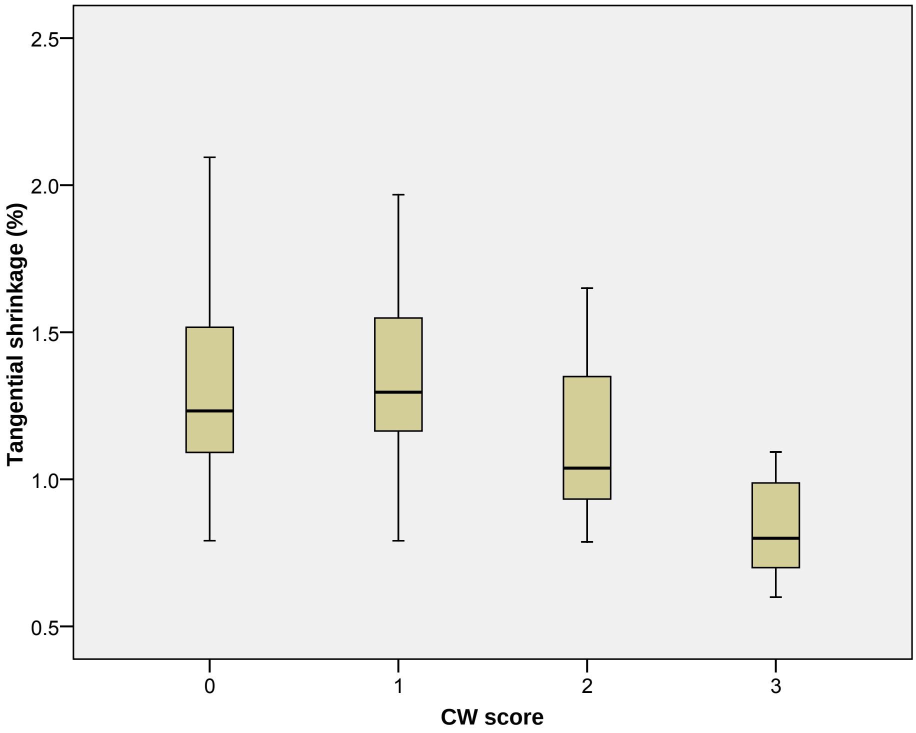

Figure 12.7: Box plots of tangential shrinkage grouped by compression wood content.

Figure 12.7 indicates that tangential shrinkage decreases with increasing compression wood content. Since tangential shrinkage is a factor in the twist of full-scale battens (according to Stevens, 1961), this suggests that battens containing compression wood will twist less than those without compression wood. However no relationship was observed between twist and compression wood for full-scale battens, as detailed in Chapter 5.

Table 12.1: shows the correlation table for the small clear samples

Table 12.1: Correlation table for small clear samples.

R	*CW score*	ε_L	ε_T	ε_R	*MOE*	*MOR*	*Dens (bulk)*
ε_L	0.71**						
ε_T	-0.51**	-0.55**					
ε_R	-0.39**	-0.48**	0.61**				
MOE	-0.50**	-0.57**	0.55**	0.56**			
MOR	-0.01	-0.16	0.37**	0.38**	0.64**		
Dens (bulk)	0.53**	0.52**	-0.09	0.04	0.06	0.60**	
Pith Dist	N/A	-0.19	0.16	-0.08	0.63**	0.54**	0.39*

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

N = 85 except for correlation with *Pith Dist* where N = 37 (note that these coincide with normal wood only). Correlations with R > 0.4 are shown shaded.

Note that since there is only a limited sense in which the ordinal scale or rank of *CW score* represents quantity, correlations to this variable are not valid. These are included for completeness and as a simple aid to interpretation. However, it can be seen that there is a strong correlation between longitudinal shrinkage (ε_L) and *CW score*. Because the samples where deliberately selected to include a range of compression wood contents the population should not be considered to represent a natural or typical distribution of timber. The values of pith distance were obtained in normal wood only.

For the small clear samples of normal wood a reasonably good relationship was observed between distance away from pith (*Pith Dist*) and stiffness (*MOE*), see Figure 12.8 (in agreement with Cockaday, 1992).

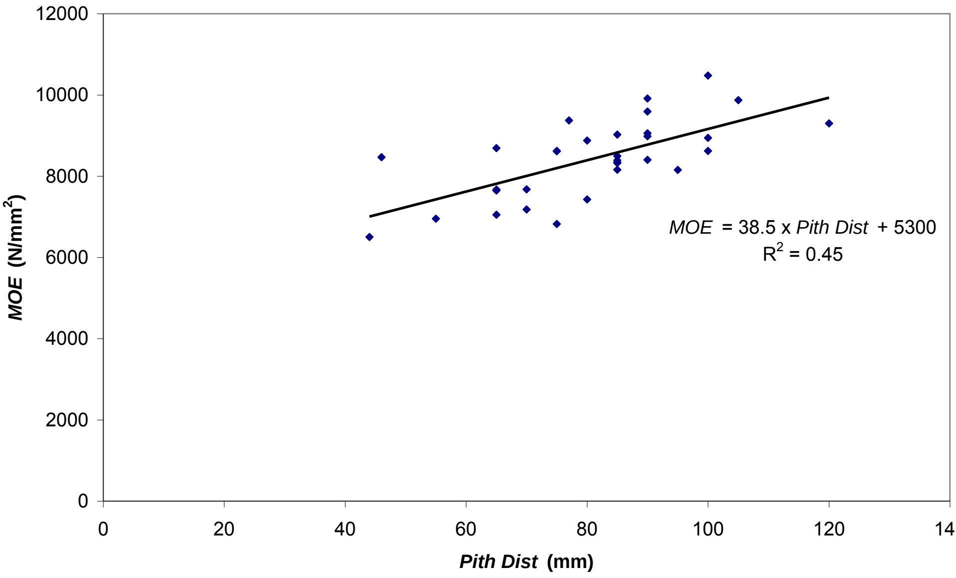

Figure 12.8: *MOE* v. *Pith Dist* (normal clear wood).

A similarly good relationship was found between *Pith Dist* and *MOR* (Figure 12.9).

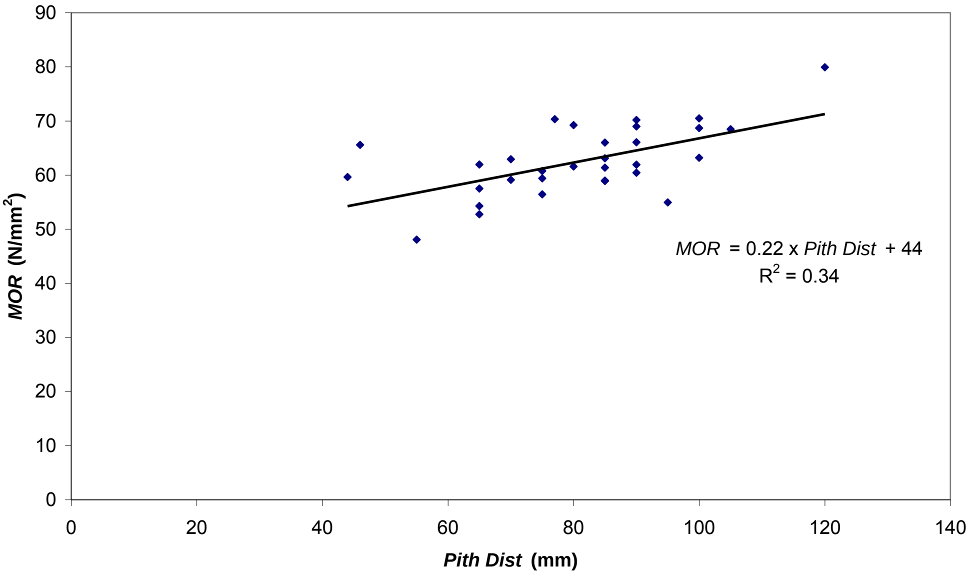

Figure 12.9: *MOR* v. *Pith Dist* (normal clear wood).

12.3 Microfibril angle of butt log material

To investigate the low stiffness of butt wood material, a number of battens that exhibited particularly pronounced trends for increasing stiffness with height were selected. Small clear samples 300 x 20 x 20 mm were obtained from the upper and lower (*i.e.* butt end) portions, nominally 3.5 m and 0.5 m, respectively, above ground level. These were tested in bending to BS 373: 1957. Radial sections around 20 to 30 µm thickness from the small clear samples were then examined under a microscope to determine an estimate of the microfibril angle through measurement of cross-field pit angle relative to axis of the cell wall. Difficulties and possible inaccuracy of this technique (which is described by Phillips, 1941) are discussed in Section 12.4.

In addition to the above work carried out at BRE, microfibril angle was also determined on batten sections using the SilviScan™ instrument at STFI-Packforsk, Sweden. This device measures *MFA* based on X-ray diffractometry. A full description of the operating principle of this device is given by Evans (1997).

Figure 12.10 and Figure 12.11 show examples of photomicrographs of samples from the upper and lower (*i.e.* butt end) ends of a batten.

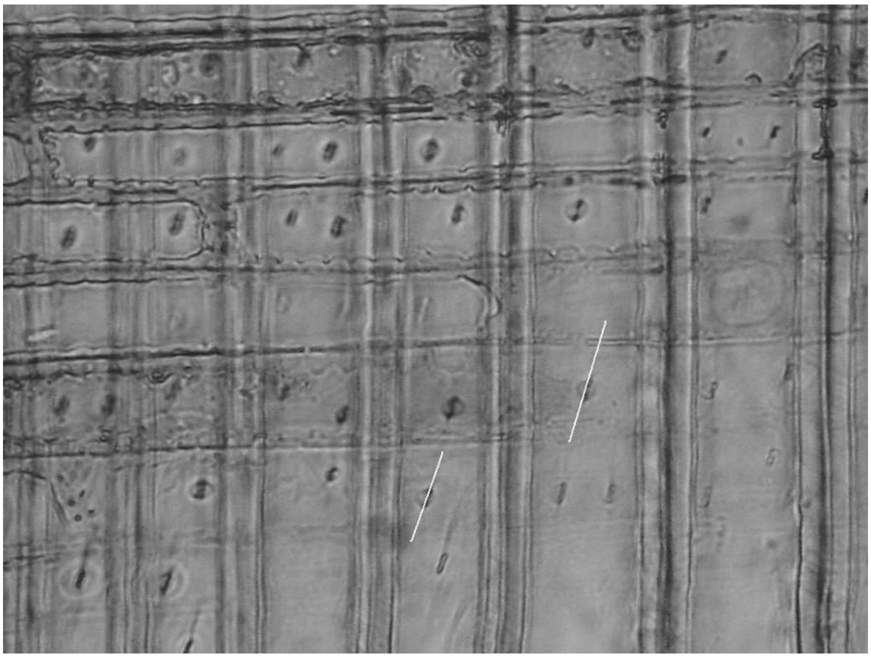

Figure 12.10: Photomicrograph showing pit angle as indication of *MFA*, from upper section of batten (x 500).

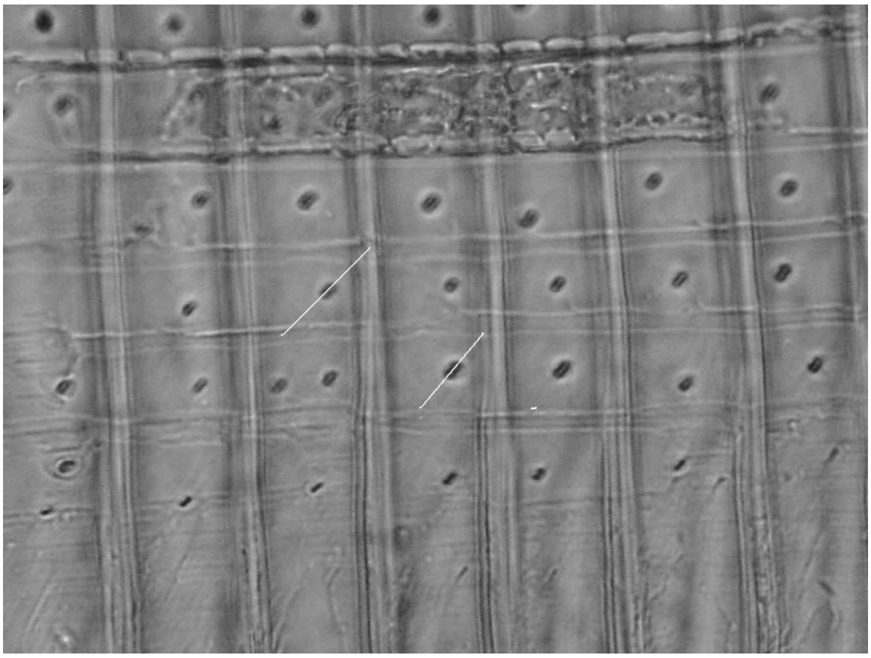

Figure 12.11: Photomicrograph showing pit angle as indication of *MFA*, from lower section of batten (x 500).

Figure 12.2 shows *MOE* plotted against latewood *MFA* estimated from pit angle measurement for upper and butt end samples from batten FR4 TWB.

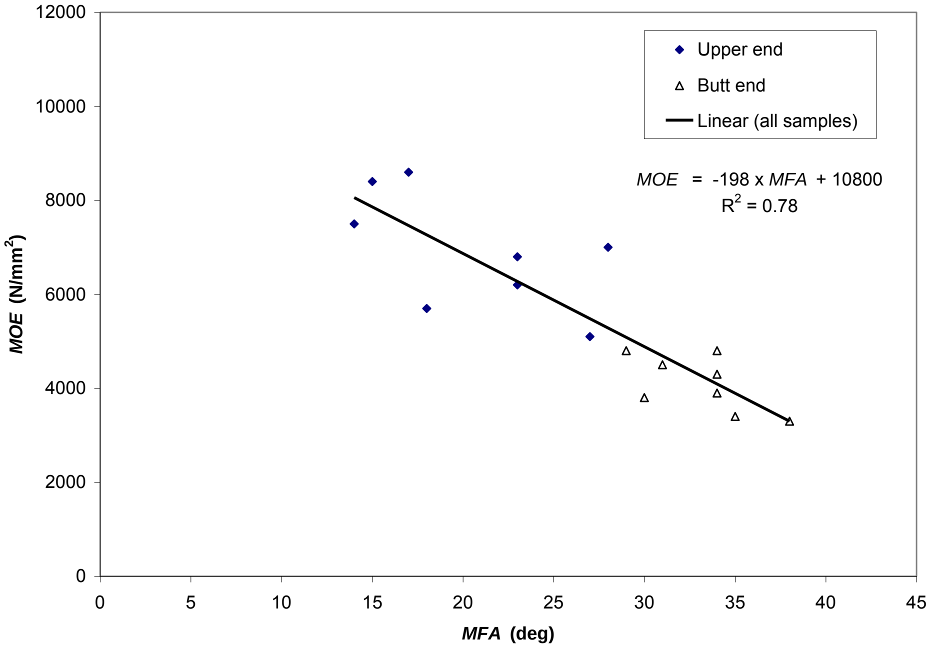

Figure 12.12: *MOE* plotted against *MFA* (latewood), estimated from pit angle measurement.

From Figure 12.12 it can be seen that the samples from the butt end of the batten are of relatively low stiffness and high *MFA*, compared with those of the upper end. A good correlation between *MFA* and *MOE* is evident. No correlation between density and stiffness was observed for these samples.

Figure 12.3 shows the SilviScan™ indicated *MFA* trends radially from the pith outward, for a pair of disc samples from the upper and butt end (FR3 Tree no. 148 batten XPA). Figure 12.14 shows the approximate position of the samples relative to the Cook-Bolinder derived stiffness profiles.

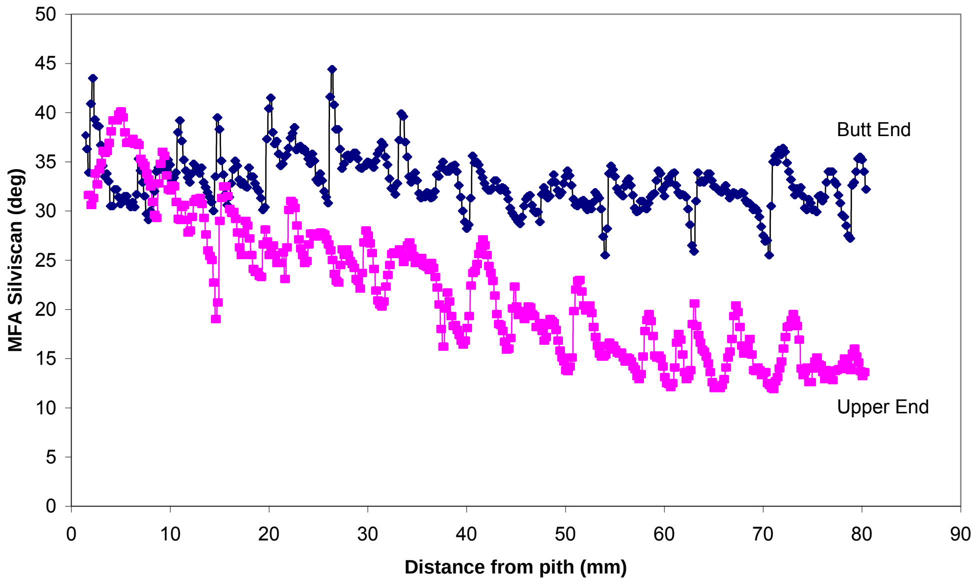

Figure 12.13: SilviScan™ indicated *MFA* trends, pith towards bark for a matched pair of samples from the upper and lower end of a butt log batten (FR3 Tree no. 148 batten XPA).

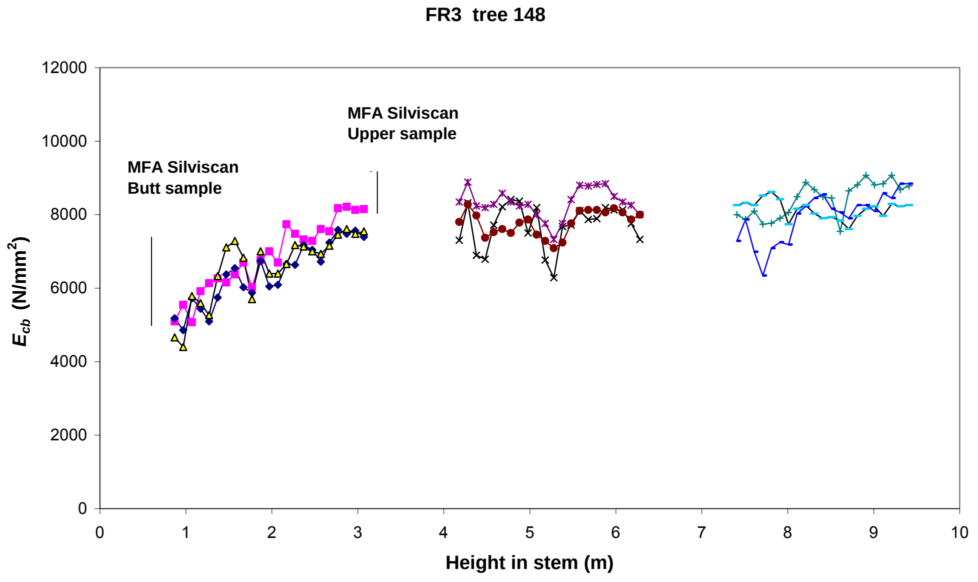

Figure 12.14: E_{cb} trends with height in stem (FR3 Tree no. 148) with position of SilviScan™ *MFA* measurements.

Note that the coloured lines represent E_{cb} values for individual battens.

From Figure 12.14 it can be seen that for this tree the low stiffness of butt wood (attributed to high *MFA*) is the defining feature, whilst there appears to be little effect due to radial position (*i.e.* the stiffness profiles of the three battens within each log practically overlap), and apparently only limited influence of knots (which can be seen in the variation in stiffness along the battens). The absence of any marked radial variation in Cook-Bolinder derived stiffness is anomalous to the radial variation in *MFA* derived by SilviScan™, certainly for the upper portion of the batten. From inspection of the wood density trends from the pith outward, which are also available from the SilviScan™ data (Lundqvist, 2008), the lack of radial variation in E_{cb} is explained in this instance by the comparatively higher density of material surrounding the pith which apparently compensates for the lower *MFA*. The estimated stiffness also reported by Lundqvist shows no trend from the pith outward, this estimation apparently being based on other work. However, the association of a marked axial trend for increasing stiffness with a general reduction in *MFA* from the butt upwards is quite clear.

From Figure 12.14 it can also be seen that for the butt log battens, the rate of change in stiffness from the butt upwards is quite constant with height, whilst from the log shape (Figure 12.15) it can seen that buttressing is limited to the lowest portion only. The increase in stiffness with height is therefore not an intrinsic function of taper.

Similar, marked differences in the trends in *MFA* from pith radially towards bark were also observed on five other pairs of samples taken from the upper and lower portions of FR4 butt log battens (3WA, TWA, 2GA, 2WB and 7OB). Figure 12.16 and Figure 12.17 show examples of the Siliviscan *MFA* measurements. In each case *MFA* is generally higher at the butt end of the batten, than higher in the stem.

Figure 12.15: Three-dimensional representation of butt log FR3-148-0.47, derived from sawmill scanner.

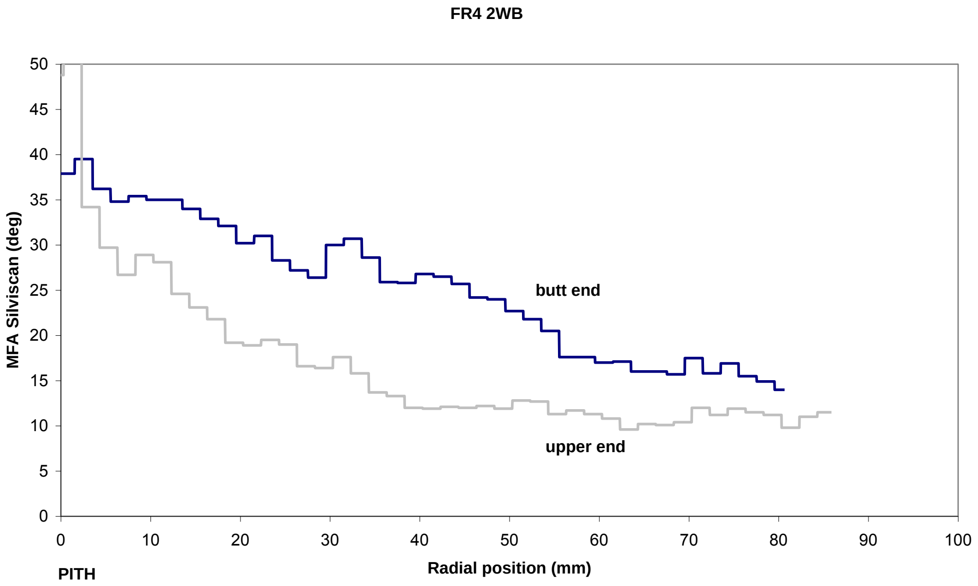

Figure 12.16: SilviScan™ indicated *MFA* trends batten FR4-TWA pith towards bark.

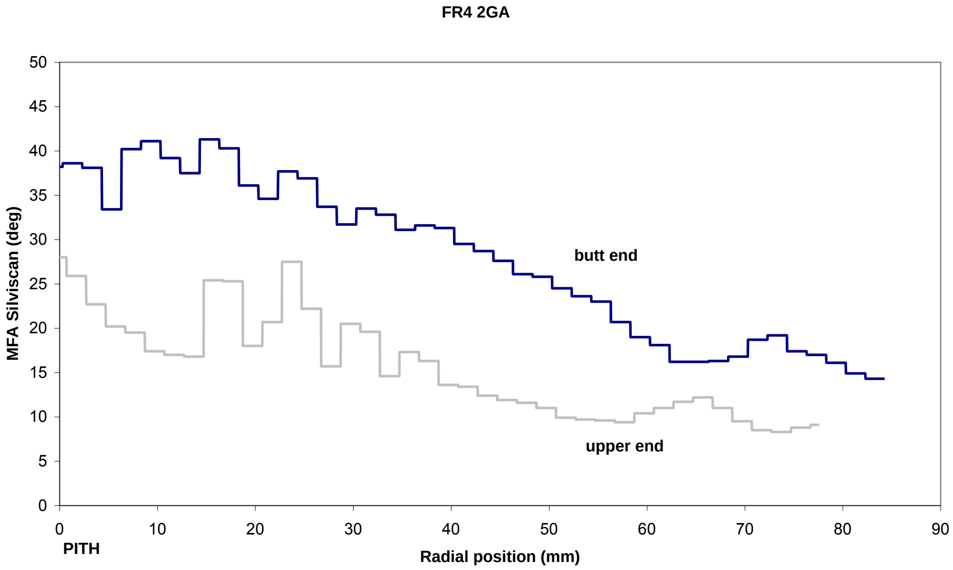

Figure 12.17: SilviScan™ indicated *MFA* trends batten FR4-2GA pith towards bark.

From inspection of the relative content of juvenile wood at the butt end of the batten compared with the top end of the batten, it could be seen that the change in stiffness from one end to the other for these battens was due a change in the nature of the juvenile wood, rather than a simple increase in its proportion. It was also determined that there was little difference (~5%) in density between samples taken from the butt and top of these battens (Table 12.2). It is clear that such small differences in density cannot account for the large change in stiffness observed in battens from the butt upwards.

Table 12.2: Density of samples from butt log battens.

Sample	*Density** (kg/m^3)	*Density* butt/ *Density* top
FR4 TWA top FR4 TWA butt	453 446	0.98
FR4 2GA top FR4 2GA butt	415 396	0.96
FR4 3WA top FR4 3WA butt	538 496	0.92
FR4 2WB top FR4 2WB butt	474 464	0.98
FR4 7OB top FR4 7OB butt	411 392	0.95

* bulk at 12% m/c

It is recognised that the above sample of battens is limited.

12.4 Summary of findings on small clear samples

For the small clear samples studied, stiffness (*MOE*) was observed to decrease with increasing compression wood content whilst strength (*MOR*) was unaffected (note that these samples were deliberately selected to include extremes of compression wood). Similar results were reported in Norway Spruce by Johansson and Warensjö (2004) and by Sonderegger *et al.* (2008). A reduction in *MOE* with increasing compression wood content for European larch (*L. decidua*) and Japanese larch (*L. kaempferi*) is also reported by Gardiner and

MacDonald, 2005. In contrast, no relation between stiffness and compression wood content was noted for full-scale battens (as detailed in Section 6.9).

The microfibril angle in compression wood was observed to be higher than normal wood, as was density. In contrast, Johansson and Warensjö (2004) reported that the density of Norway spruce compression wood was no higher than that of normal wood.

Compression wood was observed to have higher longitudinal shrinkage than normal wood, but lower tangential and radial shrinkage. Since tangential shrinkage is a factor in the development of twist on drying, this suggests that battens containing compression wood should twist less. However, no relation between twist and compression wood content was noted for full-scale battens (as detailed in Section 5.1)

For the small clear samples of normal wood (*i.e*. those classed as zero compression wood content) a quite good linear relation was observed between stiffness and density (R^2 = 0.45), as shown in Figure 12.4. A general proportionality between strength properties and specific gravity for timber is described by Desch (1947). However, for the full-scale battens relations between stiffness and density were observed to be generally poor. This is probably due to the influence of features such as knots, and the weak butt effect.

For the small clear samples of normal wood both stiffness and strength were positively correlated to distance from the pith. This is in contrast to the poor correlation observed between stiffness and radial position in terms of the variables *Pith Dist* and *Section* for full-scale battens, as detailed in Section 6.3 and Chapter 10. This is probably due to the fact that the small clear samples represent discrete elements from pith towards bark, whereas in the case of full-scale battens these tend to contain a mixture of juvenile and more adult wood**.** In particular for 150 x 47 mm size battens, the square cant conversion pattern tends to result in battens comprised of similar material. It is also probable that the Cook-Bolinder derived stiffness profiles are not sufficiency accurate to differentiate slight radial variations in stiffness, given experimental inaccuracy such as batten distortion, together with the effect of knots. Cockaday (1992) positively correlated stiffness to distance from the pith for small clear samples of Sitka spruce.

From Figure 12.8 it can be seen that there is only a relatively small increase in stiffness from pith to bark for discrete small-scale clear samples, compared to the large increase in stiffness of the full-scale battens from the butt upwards (Figure 12.14).

From the E_{cb} trends presented (Figure 12.14) both centre and outer battens from butt logs exhibit marked increases in stiffness from the butt upwards (in agreement with Brazier, 1991). It is not the case that only the centre batten is affected. Although Xu and Walker (2004) demonstrated that there was both a radial variation in stiffness and an axial variation in stiffness in the butt logs of radiata pine, the results shown by them are for relatively large logs which have been cut into relatively small size battens, and in a cutting pattern quite dissimilar to this work, aside from the obvious difference in species.

From inspection of the relative content of juvenile wood at the butt end of the batten compared with the top end of the batten, it could be seen that the change in stiffness from one end to the other for these battens was due a change in the nature of the juvenile wood, rather than a simple increase in its proportion.

An association was observed between a change in microfibril angle and the relatively low stiffness of butt wood material as indicated by Cook-Bolinder derived E_{cb} trends, which was in agreement with recent work by McLean (2007) on small-scale samples. This feature was, however, also noted in some of the earliest FPRL studies on British-grown Sitka spruce (as detailed in Section 2.6). The determination of constant or unchanging *MFA* in battens which did not exhibit an axial trend in Cook-Bolinder derived stiffness would be necessary to comprehensively establish a relation between *MFA* and E_{cb}. The estimation of *MFA* by measurement of pit angle is subject to errors such as distortion and tearing of the cell wall during sample preparation, and to the observer's judgement. Furthermore, the results have not been corrected for any difference between the axis of the cell wall and that of the sample (*e.g*. spiral grain). The number of samples examined is small.

Microfibril angle was found to be strongly related negatively to stiffness in the small clear samples, in agreement with Treacy *et al.* (2001) and Cockaday (1992). Notable is that range of *MFA* presented by Treacy *et al.* is from 12 to 22 degrees, whereas the inclusion of butt wood samples (Figure 12.12) enables the relation to be determined up to around 35°.

The cause of the relatively low stiffness of butt wood has not been established, nor has any relationship between its severity (which perhaps could be expressed in terms of the ratio of batten stiffness from the upper to the lower end) and any other tree or forest variable that has been examined in this work. However, it appears probable that this is a biomechanical response by the tree, possibly to avoid stress concentrations under wind loading (a tree is a cantilever and that the butt end is subject to the highest bending moment). Similarly with compression wood, it can be assumed that the impetus to produce cells with high *MFA* is not simply consequential with changes in cell dimensions or wall thickness that might occur, but be a 'deliberate' reaction.

13 Conclusions

13.1 Research questions answered

As a result of this work the following answers to the original research questions (as listed in Chapter 1) can be summarised, with reference to the following:

- Section 4.4 - Discussion and summary of findings on compression wood and distortion.
- Section 5.7 - Discussion and summary of findings on twist
- Section 6.15 – Discussion and summary of observations on variables affecting batten stiffness (E_{cb}) See also Sections 7.4, 8.3 and 9.4 detailing the summary of results and discussion on MRC models and other statistical analysis.
- Section 10.7 - Discussion and summary of findings on E_{cb}, $E_{m,g}$ and f_m
- Section 11.3 - Summary of findings on the BRE British-grown Sitka spruce grading dataset
- Section 12.4 - Summary of findings on small clear samples

The discussions listed above detail comparisons between the results obtained in this work and those reported by other researchers.

Note that the following are overall findings not necessarily supported by individual correlations between variables in particular data sets. Indeed, the differing relationships observed in some instances (for example, between groups of upper log battens and butt log battens, and between small clear samples and full-scale battens) is a key finding of this work. Nor is the suggestion made that these variables are worth measuring in economic terms, or simple to measure, in an industrial setting. Where particularly pertinent, cross references to the relative sections of the thesis are made.

1. What are the variables that affect timber stiffness and distortion?

Batten stiffness was positively correlated to axial position within the stem *i.e. Cut ht*. (Section 6.2); positively correlated to *Density* (Section 6.7, and Section 11.1); and negatively correlated to knot content in terms of the variable *Knotarea%* (Sections 6.6, 10.2 and 10.6).

Notably poor or absent correlations between stiffness and density were observed in battens from butt logs, and in small clear samples with high levels of compression wood.

For the full-scale battens, stiffness was not found to markedly vary radially within the stem (Sections 6.3 and 10.6), although evidence of a clear trend for an increase from pith to bark was observed for small clear samples (Figure 12.8). The wide variation in stiffness between individual trees which is evident in the grader *IP* profiles, together with the differences in stiffness between butt and upper logs, appears to render the variables *Section* and *Pith Dist* ineffective sorting parameters overall.

No evidence of a relationship between stiffness and slope of grain for full-scale battens was established in this work.

Although for small clear samples a decrease in stiffness with increasing compression wood content was observed (Section 12.2), this was not found to be the case for full-scale battens. This is probably due to the low incidence of compression wood in the full-scale battens combined with the overriding influence of other factors such as knot content. The absence of any relationship between strength and compression wood content for small clear samples suggests that the strength of full-scale battens will be unaffected by compression wood content.

MFA was found to be strongly related to stiffness (Figure 12.12).

Batten twist was positively correlated to spiral grain angle, and negatively correlated to radial position in terms of distance from the pith (Section 5.1).

No evidence of any systematic relationship between twist and compression wood content, or between twist and knot content was observed.

No evidence of a relationship between spiral grain angle and tree size (*i.e*. *DBH*), or between spiral grain angle and axial position with the stem (*i.e. Cut ht*.) was observed for the individual stands.

It was clear from the inspection of individual battens that compression wood was the cause of distortion in the form of bow and spring; although no correlation was observed between the compression wood variables derived (as detailed in Chapter 3) and these forms of distortion (Section 4.3).

2. How do these variables interrelate?

Of note is the correlation between *Log taper* and *Knotarea%* observed for the Benmore dataset (Table 9.1). This suggests that the knot content of certain logs may be indicated by relatively simple log shape measurements.

3. What measurable features on trees, logs and boards can be used as criteria to sort timber?

Batten stiffness was noted to be quite strongly related to the variable *Log taper* (Section 6.11), at least for one forest stand, although this may have been as a proxy for something else.

Of the batten knot content variables, the most effective variable was based on total knot cover (*Knotarea%*), whilst the least useful were based on knot area ratio *i.e*. *TKAR* and *MKAR* (Table 10.3 and Table 10.9).

The lack of relationships observed between stiffness, strength and *DBH* is notable since this is likely to be an often used quantitative measure of timber volume for individual stands (Table 10.3 and Table 10.9). Clearly, this variable fails to take into account any variation in *Cut ht*.

No significant relationships were observed between log shape variables (*Log taper*, *Log arc*, *Ovality* and *Pith X*) to distortion in the form of bow and spring, or twist. This indicates that 3D log shape scanners could not be used to sort timber for dimensional stability on drying.

Although distortion in the form of twist was found to be related to the *Section* and *Pith Dist* variables these were not, overall, found to be useful sorting criteria for either stiffness or strength. This suggests that these variables describe a different aspect of the radial position of battens - which is most probably some function of growth ring curvature - rather than merely tending to identify core or juvenile wood (the higher *MFA* of which could be counteracted by higher density). It is likely that the usefulness of *Pith Dist* or *Section* as sorting criteria is undermined by axial and between tree variation in stiffness.

4. What are the practical difficulties in making the measurements?

Log shape variables such as taper are readily available from 3D scanners. Potentially, much more complicated log shaper descriptors could be determined for features such as branch swellings, or other irregularity, that might indicate knot or compression wood content. However, it appears unlikely that more complicated log shape variables would be capable indicators of spiral grain angle.

No consideration in this work has been given to the practical difficulties in measuring, automatically, variables such as knot content and ring width on the surface of battens - rather this work has concentrated on establishing the relation to stiffness.

Spiral grain angle (relating to twist) needs to be measured on tangential batten face away from knots. This greatly complicates the operation of spiral grain measurement and implies that an automatic scanner would have to distinguish between appropriate and inappropriate batten faces, and to identify, or otherwise contend with, the influence of knots (Section 5.4).

The particular difficulty of determining the content and distribution of compression wood within a batten, based on surface appearance was noted. It is highly probable that the poor correlations observed between distortion in the form of both bow and spring, and the simplistic compression wood variables based on differences in surface appearance (Table 4.2 and Table 4.3), are due to the inadequacies of these descriptors.

5. What threshold values should be applied?

Battens from logs with *Log taper* > 1.3 tend to be of low stiffness, as are battens with *Knotarea%* > 2% (Chapter 10). However, the effect of applying thresholds in timber sorting has not been further explored in this work.

No threshold values of slope of grain were established or explored for distortion in the form of twist, or for compression wood content and bow and spring.

Threshold values would need to be determined on end-user or strength grade requirements. This would require a much more in depth study, also involving an assessment of the economics of the potential application of any sorting regime. This work has only achieved an initial assessment of the use of a limited number of potential sorting variables.

6. What benefits can be gained by combining variables obtained at tree or log stage with those for sawn timber?

For the combined group of Lochaline and Benmore battens it was demonstrated that the variables *Cut ht.* and *Log taper* could be combined with the batten variables *Ring width* and *Knotarea%* to produce an MRC model with an r^2 of 0.4. Combinations of fewer variables resulted in less effective models, as would be expected (Chapter 7).

No consideration has been given in this work to the practicalities of sorting on the basis of determination of these variables in an industrial setting. This would require not only measurement, but the application of the data at gathered at different stages in the conversion process.

7. What parts of the trees are more prone to distort on drying?

Battens with low values of *Pith Dist* (*i.e*. those close to, or containing, the pith) were noted to be prone to twist (Section 5.1 and 5.6).

No axial or radial variation in batten bow or spring was observed.

8. Which trees, and which parts of trees, are better for higher grade structural timber?

The upper logs from shorter trees on one stand (FR4) were found to be stiffer (Section 6.14). However smaller trees will yield smaller section sizes. No consideration has been given in this work to the number of such trees available in the stand.

Battens close to the butt (both centre and outer battens) will tend to grade lower when using a Cook-Bolinder grader which operates on a three point bending system. The influence of this low stiffness timber on a four point bending test to EN 338, will likely depend on the test arrangement and batten dimensions.

The radial increase in stiffness observed for discrete small clear samples appeared to translate into only a small increase in stiffness for full-scale battens. Structural size timber tends to originate from the central portion of the log, and, overall, no striking difference was observed between the population means of central pieces (*i.e.* those containing pith) and the population means of battens in more outward positions (Section 6.3 and 10.6). It is probably unrealistic to expect that battens in such close proximity, or composed of similar material, be particularly different. This work did show that the central battens containing pith could be segregated from the outer pieces without a reduction in average stiffness of these battens.

13.2 Limitations of the research

It is clear in this work that a number of relationships between dependent and independent variables have been encountered which are sample specific, although in many cases similar effects have been observed between groups. Some caution is required, therefore, before these findings can be assumed to be directly applicable to industrial practice.

The main sample of timber under study was obtained from two distinct sources, in terms of locality and age of planting. Different behaviours in terms of stiffness profiles with height in the stem were observed between the two groups, with one locality exhibiting a more marked tendency to have low stiffness material close to the base of trees (the so-called “weak butt effect”). Hence the precise relations between stiffness and variables relating to axial position (*i.e. Cut ht.* and *Log taper*) differ. Batten size specific relations were also observed. This confounds the simple derivation of a single (highly effective) predictive model for criterion variables, and graphically illustrates the “mixed” nature of the material likely to enter any sawmill. Large logs may, after all, originate from young fast grown trees, or from old slower grown trees. Small size battens may originate from butt logs (and thus contain weak butt wood material with high *MFA*), or originate from higher in the stem.

Although the specific findings for individual stands will be of interest to foresters, application of this knowledge in the industrial setting of a sawmill will depend on the nature of whatever sorting strategy can actually be applied in practice. Some sawmills may be able to separate butt logs from upper logs during production, whilst others cannot. A sorting strategy (or mode of operation of a scanner) may involve the use of batten size variables, together with other measurements, or may be reasonably effective without such consideration. A variable such as whorl spacing may be used even if it tends to identify another characteristic of the timber (*e.g.* height in stem), so long as it is effective. In the same way, sorting on the basis of log size may tend to separate both butt log material and material which is faster grown from the remainder.

Many of the variables used in this work are limited, pertaining to density or rate of growth measurements made at one end of the batten only. The efficacy and validity of the variables such as *Pith Dist*, *Section* and *Ring width* is likely to have been undermined for highly curved logs. More complex knot and log shape variables could also be determined. In particular, the compression wood variables, because they fail to describe both the severity of compression wood and its distribution through the batten section, are inadequate. These variables do, however, represent sorting criteria that could conceivably be used in practice. In some cases the usage of such less-than-perfect variables in this research work ultimately led to other useful observations.

In terms of the scientific assessment of the material, certain highly significant features such as severe cross grain are difficult to quantify into simple numerical values. Log shape attributes associated with stem-form correction such as abrupt change in curvature are also difficult to quantify. Variables such as knot area ratio and simplistic scores of surface compression wood belie the great complexity of natural timber. These un-measured and immeasurable factors also place a limit on the worth of this exercise. However, it is reasonable to suggest that sorting on the basis of knot content or compression wood visible on the outside faces of a board could be the *modus operandi* of a simple board scanner. Likewise, readily available log shape variables such as ovality may be utilised by existing sawmill scanners, although ultimately more complex descriptors relating to out-of-roundness might be obtained.

It is possible that at higher levels of log ovality and pith eccentricity than studied in this work, severe compression wood may be more common, and that the timber would be of lower stiffness, albeit with no reduction in strength (as shown in the work on small clear samples in Chapter 12).

A distinction must be made between compression wood in relatively clear straight grained timber (as tested) and compression wood formed as a result of stem deviation or the presence of large branches and hence knots. It was noted from other observations on machine grader rejects that compression wood could also be associated with severe cross grain, and hence greatly weakened timber. A characteristic pattern of anomalous growth ring interception on the face of the boards was noted (Figure 13.1 and Figure 13.2). Sometimes these growth ring interception patterns of were of a circular nature; this being evidence of stem deviation. In other instances the cross grain was observed to be associated with large knot groups, or the loss of leader. For a Sitka spruce batten, itself often only comprising a few years worth of growth, the presence of the majority of the growth rings on the edges in such frequency indicates severe loss in strength. Such battens can actually fracture during machine grading.

Figure 13.1: Batten with severe cross grain and associated compression wood.

Figure 13.2: Machine grader rejects exhibiting severe cross grain with characteristic anomalous growth ring interception.

A further limited aspect of this work is the determination of simple linear relations between criterion and predictor variables. Certain relations such as those between stiffness and knot content are likely to be better described in non-linear terms, whilst the weak butt effect is clearly a non linear function of height in the stem (see Figure 12.14). Thus a linear fit of E_{cb} versus *Cut ht.,* and its subsequent inclusion in an MRC model is an approximation. More useful sorting parameters might have also been derived based on logical functions, for example:

IF *Log Taper* > 1.3 AND *Knotarea%* > 2 AND *Section* = 0
THEN E_{cb} < 5000.

Unfortunately, such a process might only indentify a very few battens with almost no effect on the average stiffness of the remainder. No matter how technically effective a scanner or sorting regime is, it cannot (of course) actually improve the qualities of any idividual batten. If there are only a few battens with high levels of stiffness within any batch of timber, then there will still be a few battens with high levels of stiffness after they have been selectively sorted, regardless of the effort required.

13.3 Problems encountered and accuracy

In this work data were combined from a number of sources and different projects. Certain variables were not recorded for all the sets of timber, whilst some groups of battens were destructively tested in order to meet certain project goals of the time and were not subsequently available for further assessment. It was not possible to condition or handle the various batches of timber in precisely the same manner for all groups. A full dataset, without such variation, would have been much simpler to analyse, as would one that did not represent the complexities of industrial practice. It would have been much easier to analyse the data if all the battens were the same size, and all the trees had been felled at precisely the same height.

A proportion of the unexplained variance in stiffness and distortion can probably be attributed to experimental inadequacy outside of that caused by an inability to determine suitably descriptive variables for features such as knots. The output of the Cook-Bolinder grader is likely to have been affected by batten distortion, although overall the results appear quite consistent. It would probably have been better to have carried out the study of distortion and stiffness on separate sets of timber, even though this would have doubled the amount of work. It is probable that the Cook-Bolinder derived stiffness profiles are not sufficiently accurate to differentiate slight radial variations in stiffness, together with the influence of other variables such as slope of grain, whilst the EN 408:2003 bending tests are likely to be overtly influenced by the random positioning of knots. It is also suspected that distortion and the development of drying stresses might have affected the accuracy of the EN 408:2003 stiffness measurements. It also appears likely that errors due to misidentification battens have occurred, particularly at the machine grading stage. On occasion, the output of the Cook-Bolinder appears highly erratic - which may also be due to malfunction of the measurement system. Where highly distorted battens were tested, it is likely that the device was operating outside of its normal limits. The grader derived stiffness data from Benmore (FR3 and FR4) appears to be more reliable and consistent than that from Lochaline (FR1 and FR2). Fortunately, the material from Benmore is considered to be more typical of that likely to be available in the future. The Cook-Bolinder results have, however, been particularly useful in highlighting the relative weakness of buttwood, and the wide variation in stiffness between individual trees.

At the outset of this work the Cook-Bolinder grader was in widespread use in the UK, with similar types of bending machine in operation around the world. Moreover, in the absence of the widespread use of visual grading, the Cook-Bolinder was for many years the principle means by which structural softwood was assessed in this country. This grader, together with machine settings linked to strength class, operates on the basis of nominal batten sizes. Utilisation of precise batten dimensions in conversion of grader IP output into E_{cb} values (Chapter 3, Eqn 1), or use of timber that had been precision regularised, would very probably have enabled more reliable results to have been obtained. It appears likely that the nature of the bending tests carried out has enabled only the most significant variables to be identified. From Eqn 1 it can be determined that a +/- 1mm difference in both batten thickness and depth from the nominal size causes the calculated E_{cb} value to be up to 8% in error (note that batten thickness is the more critical variable). Although, from inspection of the timber at the time of grading, variation in batten dimensions was considered a random error which was representative of an industrial setting, such effects could have occluded the more subtle relationships. Use of precise batten dimensions in conversion of grader IP output into E_{cb} values – as appears to have happened during the determination of machine settings – might achieve a higher correlation to strength than was actually achievable in a sawmill.

For the measurements of batten bow, spring and twist a particular problem was clearly evident in that it is impossible to isolate these measures of distortion from each other. Battens often exhibit combined bow, spring and twist, and may spring one way over part of the central portion and then bow in the other direction. Thus they form complicated shapes in three dimensions rather than conform to the two dimensional definitions given in BS 4978:1996. Better relationships between predictor and criterion variables are likely to have been achieved if the timber had been sorted into groups which excluded as far as possible forms of distortion which had an undue influence on the measurements under examination. For example, only battens which primarily exhibited twist *without* bow and spring might have been analysed for relationship between slope of grain or distance to pith. A more industrially relevant study might also have concentrated on a study of timber which had been top-loaded during kiln drying in which case it is possible that certain forms of distortion such as bow might have been largely eliminated. Variation in moisture content at the time distortion measurement is also a source of error.

Despite the problems encountered, and inspite (and perhaps because of) the often poor correlations observed between variables, a great deal has been learned from this work about the nature and complexity of sorting timber. Comparisons to the work of other researchers on Sitka spruce have proved particularly useful. These have provided a necessary reminder of the limitations of datasets in terms of numbers of specimens, and the group specificity of any correlations observed.

13.4 Recommendations for further work

Against the natural variation in the quality of the timber encountered, the numbers of trees and quantity of battens studied in this work can only be considered limited. This material (which was essentially chosen on the simple basis to include a variety of log shapes) may not necessarily be regarded as either particularly representative of the stands from which they were selected, nor typical of that likely to enter any sawmill. Further study into the natural variation of timber quality between trees and stands, and of randomised material from a number of sources, would therefore be worthwhile.

This work has focused on determining the variables affecting the stiffness and distortion of Sitka spruce. Use of this knowledge in industrial practice, through trials of actual equipment such as commercially available scanners, or the effect sequential sorting at various production stages has not been studied. Other variables of potential interest include those based on near infra-red or microwave measurements. There are a number of relationships, such as those between log ovality and stiffness, and between slope of grain and stiffness, that would be better explored at a fundamental level by small-scale testing. The effect of knots, for example, could be better determined by testing matched samples of clear and knotty wood.

Sorting timber either at tree, log or batten stages into better and lower quality classes prior to strength grading may have a detrimental effect on the existing grading system which is based on tests carried out on an unsorted “representative” sample. Whether or not you undermine the grading system depends on the sorting scenario concerned. A sawmill may, for example, use a scanner to send knottier battens to the un-graded, un-dried supply chain (*e.g.* for agricultural use). Although there is no defined structural requirement for these un-graded battens, it is conceivable that the end user will notice the higher knot content. The battens with lower knot content can go on to be used structurally, and an improvement in quality for this group may be achieved. However, where a sawmill removes all the best logs from that stock which would have normally gone on to be graded at C16 /R combination and starts grading these at C24 the remainder may still pass as C16 having the required minimum machine *IP* values but on average this material will be of lower quality and therefore not have the characteristic properties required for the grade. Similar problems may occur when selectively sorting battens for propensity to distort. The possible detrimental effects on such sorting for various processing scenarios should, therefore, be further investigated.

13.5 Recommendations for forestry and industrial practice

Given the limitations of the work carried out (as detailed in Section 13.2), in terms the amount of material studied, and in particular because of the differences in behaviour between the individual forest stands encountered, the following recommendations should be confirmed by further investigation, including comparison to other recent work (*e.g.* Moore *et al.*, 2007). The material from Benmore (FR3 and FR4) is, however, considered by Forest Research to be typical of that which is likely to be available now and into the near future, *i.e.* material that is harvested at relatively young age and small diameter, having been planted at relatively close spacings.

As detailed in Chapter 3, this work has focused of Cook-Bolinder grader derived values of stiffness (*i.e.* E_{cb}). Note that although it was demonstrated (in Chapter 10) that quite strong correlations exist between E_{cb} and EN 308 test method derived $E_{m,g}$ and f_m (upon which EN 338 strength classifications are based), it was also observed that the latter test method was less sensitive to the so-called weak butt effect due to the arrangement of the applied bending moments (see Chapter 3). Density is also an important characteristic for structural timber. The following recommendations should therefore be viewed in this context. Where the term “stiffness” is used below this should be taken as referring to E_{cb}.

The forest variables examined (*Tree ht*., *DBH*, *Tree taper*) were found to have either a minor or inconsistent relationship to stiffness within the sub-groups of timber examined. Battens from relatively large trees were notably similar in stiffness to those from much smaller trees. Although the shorter trees on one particular site were found to yield stiffer upper log material (see Chapter 8) these battens were of corresponding smaller section size. These forest variables added little to the MRC models constructed (as detailed in Chapter 10). It is therefore not recommended that these forest variables be utilised in industrial sorting.

Probably the most significant feature of the timber studied is the tendency for there to be a marked trend for an increase in stiffness, in terms of $E_{cb,}$ from the butt upwards: the so called “weak butt” effect (Section 6.2). Directing all butt logs away from structural timber production, or felling all trees at higher levels might appear to be the obvious solution. However the trend for an increase in stiffness was found to be highly variable both between individual trees and between stands. Based on the correlations obtained for Benmore stand FR3 a 30% increase in stiffness may be achieved by increasing the height at which trees are felled to a minimum of 1.0 m. This is worth verification by further work.

In this study, lower stiffness timber was found in the centre battens (*i.e.* containing pith) from butt logs with the higher values of taper (Section 6.4). Within this group the knottier battens were noted to be the least stiff. The sawmiller should therefore avoid, cross-cut or selectively sort out knotty, highly tapered butt logs. In particular, butt logs with high knot content in the lower portions (*i.e*. close to the butt) should be avoided since the low stiffness clear wood may coincide with the weakening effect of knots. Use of log scanners capable of internal knot or knot group detection in combination to measurement of taper from outward shape would therefore facilitate worthwhile sorting, although the cost of such a scanner is unlikely to be justified. Much could be achieved from taper measurements alone, or by avoiding cutting patterns resulting in the production of battens comprising material from this central zone. In this study, logs with taper values greater than 1.3 (as defined in Appendix A2.5), were found to yield comparatively low stiffness timber (see Section 6.11, also Figure 6.24 and Figure 6.25).

Although the cause of twist was identified as spiral grain, actual measurement of grain angle during industrial processing on battens (*e.g.* by laser tracheid effect) posses significant practical difficulties (Section 5.3). Spiral grain angle needs to be measured on a tangential face, clear of knots. Furthermore, slope of grain was not found to be a useful measurement to determine stiffness (Section 6.8), despite the observations of Maun (1992), but in agreement with the findings of Moore *et al.* (2007). In terms of timber quality, spiral grain is an undesirable feature in trees, which perhaps could be reduced by selective breeding. Although no relationship was observed between slope of grain and batten stiffness, some caution should be exercised before it is assumed that spiral grain does not provide some biomechanical advantage *e.g.* during early growth.

Twist would appear to be a systematic problem with Sitka spruce. Most battens are affected, albeit to varying degrees, and all twist in the same direction. Although a method of re-engineering boxed pith pieces by “back-to-back” glue lamination at green moisture content was developed by Cooper and Maun (2004), battens which are produced by standard conversion processes cannot be orientated within a structure such a floor, or during the lay up of standard glulam, so that distortion effects are counterbalanced. Unlike the situation with bow or spring, there is no element of control or mitigation through randomisation. Top loading during kiln drying has been found an effective and economic measure for reducing distortion in both Norway spruce and Sitka spruce (Tarvainen, 2005**).**

In this study, no systematic relationships between log shape variables and distortion were observed (Chapter 4). Some of the worst timber, in terms of development of bow and spring on drying, came from relatively straight trees without pronounced ovality or pith eccentricity. Inspection of the ends of logs would appear the only reliable indicator of likely compression wood content in battens and their subsequent quality. Sorting of battens on the basis of compression wood visible on the surface is problematic due to the complex internal structure of the growth rings. Overall, compression wood in straight grained timber, due to the relatively low incidence in its more severe form, appears to have little influence on stiffness and none at all on strength. However, logs with abrupt changes in curvature or exhibiting the characteristic of leader loss, should be avoided due to the likely presence of localised cross grain which may be accompanied by the formation of severe compression wood. Detection of irregularity in log shape by a 3D scanner would be worthwhile. Trees with wandering pith (*i.e.* poor stem-form in early tree life) were noted to yield battens which were prone to develop pronounced bow on drying. Such trees could be selectively thinned and used for fuel. Straight trees found to contain compression wood at maturity might usefully be used as economic foundation piling installed below the water table in log pole form (Reynolds and Bates, 2009), in an application where there was no prospect of distortion on drying.

13.6 Overall conclusions

In this work a detailed and extensive dataset was established of tree, log and board variables which could be related to timber properties of stiffness and distortion. The main bulk of the Sitka spruce timber assessed came from two localities in Scotland, with trees of different age and spacing. The battens were of three sizes commonly used in construction, obtained using industry standard cutting patterns. Small clear samples were also studied to determine the effect of variables such as compression wood content and density, free from the influence of defects such as knots. In addition, analysis was also performed on a large dataset of test work on Sitka spruce which was used by BRE to establish machine grade settings and BS 5268 strength classifications. The main objective of this work (as detailed in Section 1.1) was to identify the variables which affected the performance of Sitka spruce, and their usefulness in practical sorting.

Different behaviour in terms of the relationship between stiffness and variables such as density, knot content, log taper, tree height and axial position was noted between groups of upper log and butt log material, and between the individual stands studied. Relationships between stiffness and these variables were generally weak, in particular in the case of density. Variables based on radial position were not found to be useful sorting parameters. No relation between batten stiffness and compression wood content or slope of grain was observed. The comparatively low stiffness of butt wood material was observed to have an association with high microfibril angle, although this is based on a limited number of samples.

Within the small clear samples studied the influence of microfibril angle, compression wood content and longitudinal, radial and tangential shrinkage was also determined. For the small clear samples, compression wood was found to be less stiff than normal wood, although higher in density, whilst strength was unaffected. Longitudinal shrinkage was found to be higher in compression wood, whilst radial and tangential shrinkage was lower compared with normal wood.

Board twist was determined to be a function of spiral grain angle and distance from pith, however practical difficulties with the use of slope of grain measurements to determine batten twist were noted. The presence of frequent knot groups and a need to make the measurements on a tangential batten face greatly complicates assessment of spiral grain angle on boards. No other variables, such as those relating to log shape, knot content or axial position in the stem were found to affect this form of distortion, or to be useful sorting criteria. It was also noted from the grain angle measurements on boards that the majority had come from of trees (or portions of trees) which remained left-hand spiral grained. As a consequence, no boards were produced that had balanced spiral grain across their section.

Although severe forms of compression wood were observed to be associated with stem form correction, relatively straight logs and those which were round in section were also observed to contain compression wood and hence yield timber which distorted on drying. Systematic relations between bow or spring and variables based on compression wood distribution on board faces were not observed. Logs with wandering pith were noted to yield battens prone to develop bow. The particular effect on batten distortion of compression wood from relatively straight trees was noted. This form of compression wood occurred consistently along one side or face of the board, leading to distortion on drying. Despite the lower tangential shrinkage observed in small clear samples of compression wood, no relationship was observed between the compression wood content of full-scale battens and twist.

In particular, this work demonstrates the effect of sorting timber using combined variables (*e.g.* log shape and knot content). These findings may be of interest to (or utilised by) foresters, sawmillers and developers of timber scanning technologies.

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Publications related to this work

(See Appendix A4, A5 *etc*.)

Reynolds T. N. and Moore G. (2004) *The effect of compression wood on timber quality.* WCTE June 14-17 Lahti Finland.

Reynolds T (2007) *Aspects of timber quality in the UK* . COST E53 conference on Quality Control for Wood and Wood Products 15th – 16th March 2007 Warsaw, Poland.

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Project reports and websites.

EU Compression wood project - see Gardiner and MacDonald (2005) and

www.forestry.gov.uk/compressionwood

At the time of writing the following BRE project reports were available at www.bre.co.uk/timber/projects

- Innovative timber scanning techniques – Final Report. March 2008 Client report number 225 063.

- Linking batten performance to silvicultural models – Final Report. Sept 2008 Client report number 232 395

Appendix 1: Site and stand characteristics

Data supplied by Forest Research.

	Lochaline		Benmore	
	FR1	FR2	FR3	FR4
NGR Grid Reference	NM601472	NM602473	NN456261	NN455263
Latitude	56°33’19.69” N	56°33’23.10” N	56°24’7.08” N	56°24’13.42” N
Longitude	5°54’15.34” W	5°54’9.83” W	4°30’7.97” W	4°30’14.22” W
Species	Sitka spruce *(Picea sitchensis)*	Sitka spruce *(Picea sitchensis)*	Sitka spruce *(Picea sitchensis)*	Sitka spruce *(Picea sitchensis)*
Altitude (m)	70	100	330	280
Planting year	1954	1954	1961	1961
Age at felling	48	48	42	42
Estimated initial spacing (m)	2.19	1.92	1.73	1.91
Estimated initial stocking (stems/ha)	2080	2712	3358	2738
Number of live trees per hectare at felling	1360	1493	1442	1712
Thinning	N	N	N	N
Top height (m)	26.6	26.9	28.1	24.5
Mean *DBH* (cm)	28.4	26.1	24.6	22.3
Mean tree volume (m^3)	0.69	0.59	0.53	0.38
Average slope (degrees)	3	24	23	6
Mean hourly wind speed (m/s)	4.96		2.74	

NOTES:

1. Top height is the average height of the 100 trees of largest diameter per hectare
2. *DBH* = diameter at breast height, *i.e.* at 1.3 m above ground level
3. Estimated initial spacing is based on visible stumps on the ground.

Appendix 2: Measurement protocols and definitions.

Units and notation used in statistical analysis are given in Chapter 3 (Table 3.1, Table 3.2 and Table 3.3).

A2.1 Tree height (*Tree ht.*)

The vertical distance between ground level and the top of the tree.

A2.2 Tree diameter at breast height (*DBH*).

The average diameter overbark at 1.3 m above ground level.

A2.3 Tree taper

Tree taper = Tree ht./DBH

A2.4 Log diameter

Two sets of measurements are available: manual and those based on the sawmill 3D scanner. The former are overbark, the latter subject to debarking and butt reduction. In both cases the measurements were made at the ends of the logs.

A2.5 Log taper

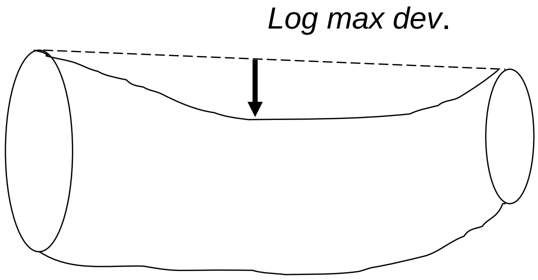
Log taper values are available based on sawmill scanner determined log diameters and from manual measurements made at the ends and middle of the log

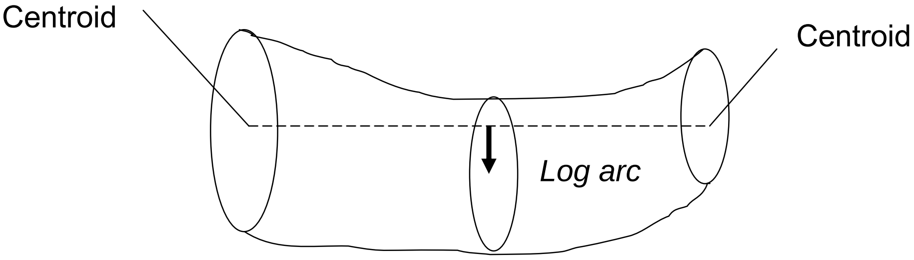
Log taper = bottom diameter/top diameter over 3 m, *i.e.* based on scanner measurements

Log taper (butt dia/mid dia) i.e. based on manual measurements
Log taper (butt dia/top dia) " "
Log taper (mid dia/top dia) " "

A2.6 Log arc and max deviation (curvature)

Maximum log deviation (*i.e. Log max dev*) is based on field measurements made by Forest Research, whilst *Log arc* is based on sawmill scanner data, as defined below:



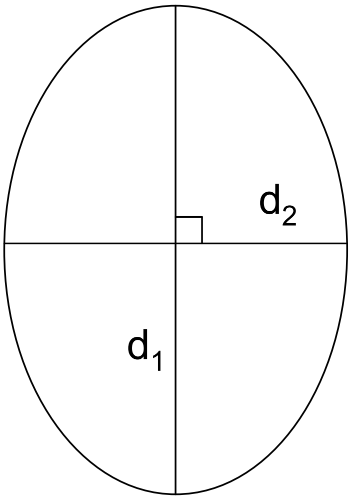


Log max dev is the maximum deviation from the surface of the log to a straight line joining the ends of the curved section (not necessarily over the over the length of the log), expressed as deviation/distance over which it is measured (cm/m). Where the log exhibits curvature in more than one direction, each section is measured separately and the maximum recorded. No allowance was made for log taper in the measurements.

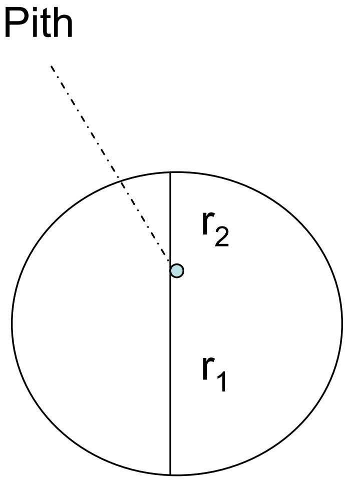
Log arc is based on the output of the sawmill 3D scanner and is based on the maximum deviation from a line passing through the centroid at each end of the log. Note that the log will have been subject to de-barking and butt reduction.

A2.7 Log ovality and pith eccentricity

Log ovality and pith eccentricity were measured manually based on disc images supplied by Forest Research. The measurements correspond to *Cut ht.* (*i.e.* the lower end of the log or batten) and are defined below:



Ovality = d_1 / d_2

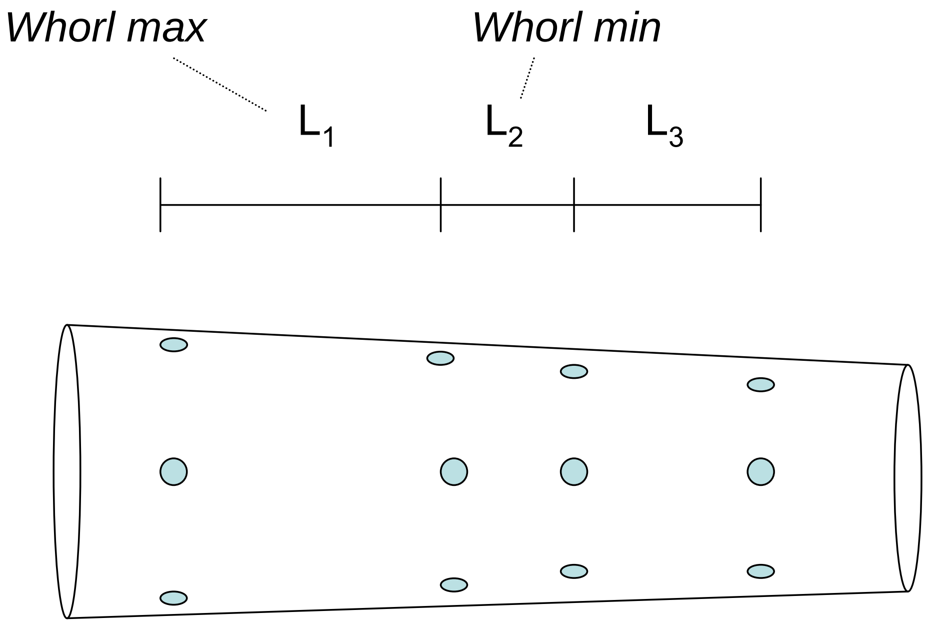


Pith X = r_1 / r_2

Note that for the variable *Ovality* d_1 is the major axis and does not necessarily have to pass through the pith, whilst d_2 is the largest axis at 90° to the major axis. For pith eccentricity r_1 and r_2 are radii of the major axis passing through the pith.

A2.8 Whorl spacings

Whorl spacing variables are based on manual field measurements and are defined below:



$$\textit{Whorl mean} = \frac{L_1 + L_2 + L_3}{\textit{Whorl no.}}$$

A2.9 Cut height

Cut height is defined as ground level to the lower end of batten or log.

A2.10 Density

Density = oven dry mass/sample volume.

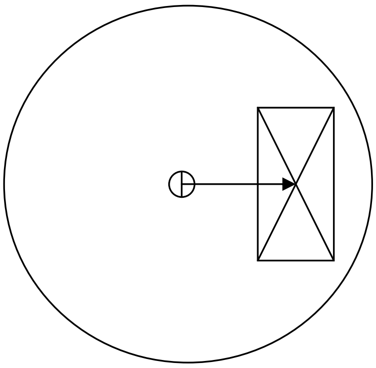
Note that the abbreviation *Dens* is used in tables for convenience.

The sample was taken at the lower end of the batten, with dimensions measured at around 12% moisture content.

A2.11 Pith distance

Pith Dist is the distance from the pith to the centre of the batten, measured at the lower end of the batten.

Pith Dist



A2.12 Ring width

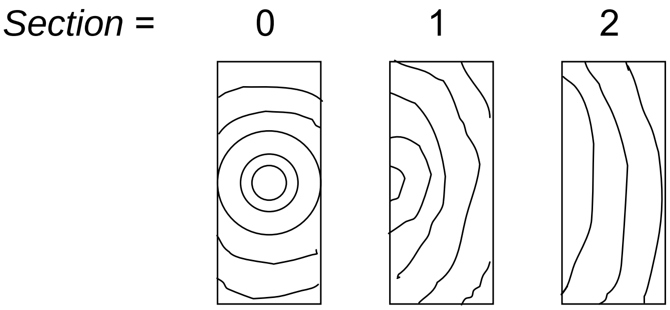
Ring width was based on the average value for the batten lower end.

A2.13 Juvenile wood content

Based on the percentage area within first 12 growth rings compared to the area outside the 12th growth ring, on the batten lower end, measured using an overlay grid of 5 mm squares.

A2.14 Section code

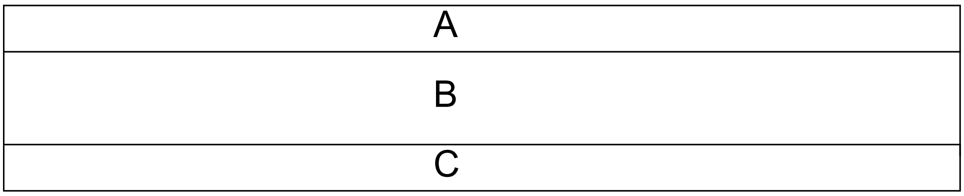
Section was defined as below:



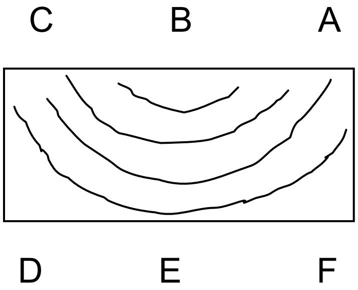
Section code (0 = pith central, 1 = pith on edge, 2 = pith outside). Note these are based on a section taken from the lower end of the batten.

A2.15 Compression wood score

On the batten inner face the outer quarters and inner half of the batten face were designated with zones A, B, and C, as below. Note that for battens with central pith, the inner and outer face designations are arbitrary.



The outer face was designated with zones D, E, and F. When viewed from the low end of the batten, the regions marked A to F look as below:



For each of the areas A to F the percentage of the area occupied by compression wood for the middle 2000 mm was recorded, with each area given a number according to the following:

1	Zero to 25% occupied by compression wood
2	25% to 50% occupied by compression wood
3	50% to 75% occupied by compression wood
4	75% to 100% occupied by compression wood

The figure below shows a typical example of compression wood marked out by the operator.

The following compression wood variables (related to the likely form of distortion) were also defined:

CW face diff (bow) = (C+2B+A)-(D+2E+F)
CW edge diff (spring) = (C+D)-(A+F)
CW total (adj) = (C+2B+A+D+2E+F)

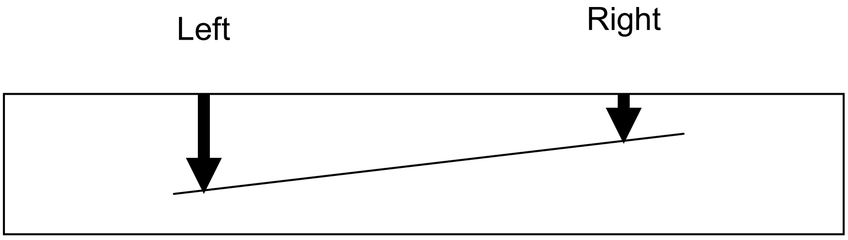
Where:

A = Inner face CW zone A
B = Inner face CW zone B
C = Inner face CW zone C
D = Outer face CW zone D
E = Outer face CW zone E
F = Outer face CW zone F

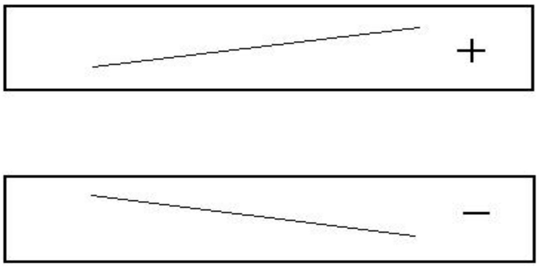
Note that the centre zones B and E represent twice the area of the edges zones A, C, D and F.

A2.16 Batten slope of grain.

Over the 2000 mm central region, a number of portions along this length slope of grain was marked using a scribe. The average slope was determined, taking into account variations between the scribed regions to obtain a representative value.



Positive and negative slope of grain is defined as below (*i.e.* positive = left hand, negative = right hand)



A2.17 Knots

Knot area ratios

KAR and TKAR were measured in accordance with to BS 4978:1996 Note that MKAR refers to the worst margin.

For the following variables knot area was based on the average diameter (*i.e.* average of the largest diameter and the smallest diameter). Knots smaller than 10 mm diameter were ignored. No distinction was made between live or dead knots.

Knot cover

Based on total knot area on batten faces and edges.

Knotarea% = (total knot area/total batten area) x 100%

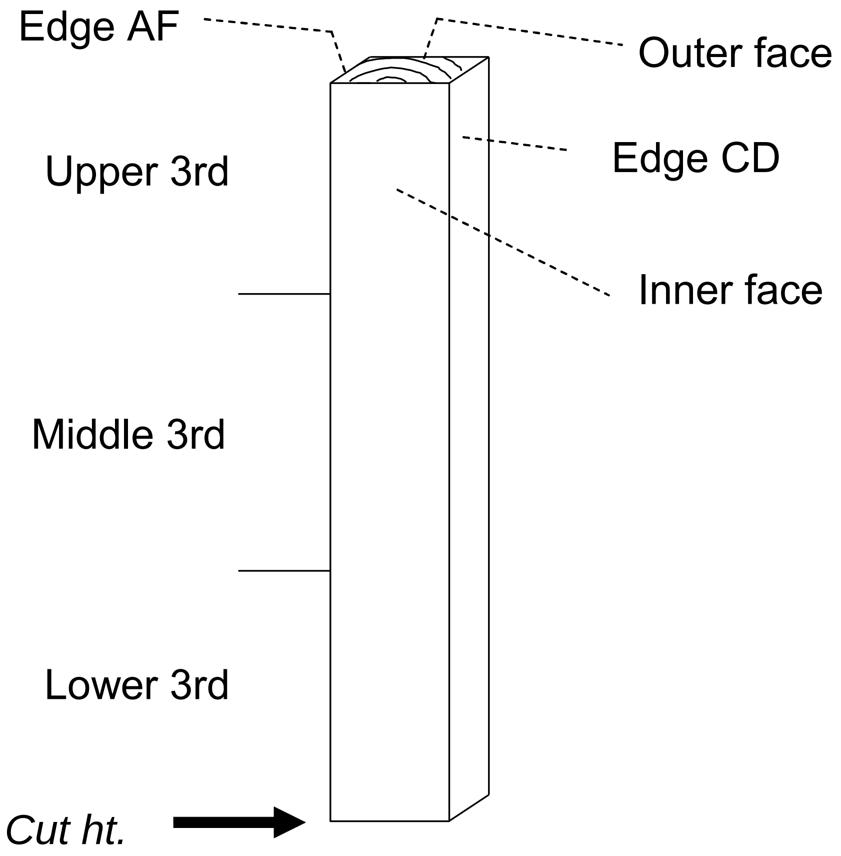
Kn900% = (total knot area over central 900mm zone/ area) x 100%

Knot concentration

Kn300% = (knot cover over worst 300 mm length on outer face/area) x 100%

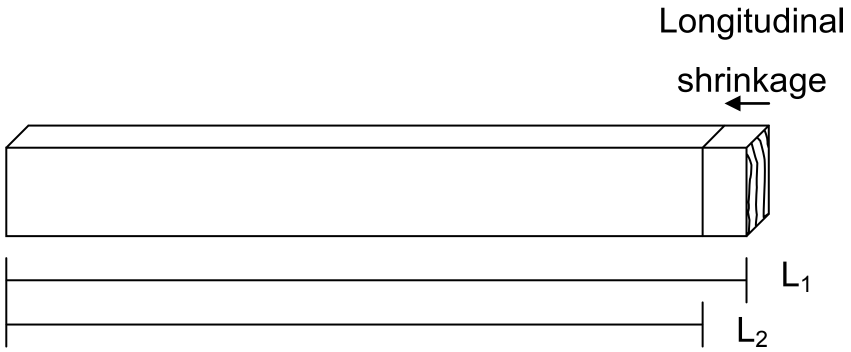
Knot distribution variables

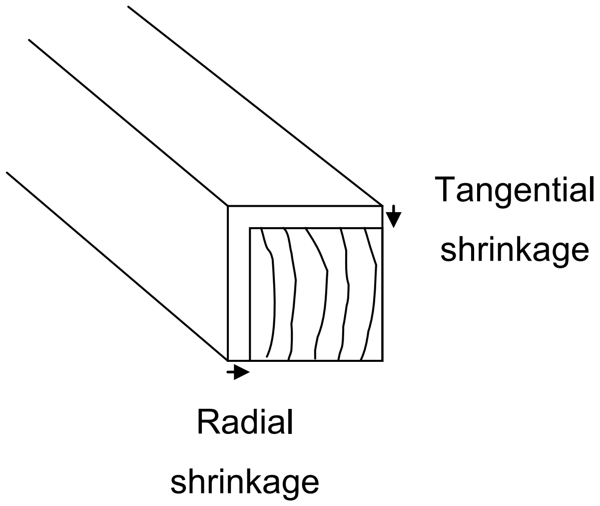
These are based on the above measurements of knot size, using the definitions of batten face and edge given in A2.15. Upper 3rd, Middle and Lower 3rd refer to the batten zones axially as shown below:



A2.18 Measurement of shrinkage

The shrinkage measurements made on small clear samples are defined below:





Appendix 3: Kiln schedules

Table A3.1 summarises the kiln schedule applied to the FR1 battens:

Table A3.1	Low temperature								
Phases	Heat up	Initial dry	Main dry	Main dry	Main dry	Main dry	Condition	Cooling	
	1	2	3	4	5	6	7	8	
T Dry bulb (°C)	20 - 57	60	61	62	62	62	58	58 - 20	
T Wet bulb (°C)	20 - 54	54	54	51	48	40	55	55 - 15	
M/C (%)	green	-	-	-	-	-	-	18	Total
Time (Hrs)	6	8	10	10	10	45	7	7	103

Note time controlled, with no m/c or RH logging.

Table A3.2 summarises the kiln schedule applied to the FR2, 3 and 4 battens:

Table A3.2	Low temperature								
Phases	Heat up	Initial dry	Main dry	Main dry	Main dry	Main dry	Condition	Cooling	
	1	2	3	4	5	6	7	8	
T Dry bulb (°C)	20 - 52	52 - 54	54 - 56	56 - 58	58 - 58	58 - 58	58	58 - 20	
T Wet bulb (°C)	20 - 48	48 - 48	48 - 48	48 - 46	46 - 42	42 - 42	56	56 - 20	
RH (%)	79	79 - 70	70 - 64	64 - 50	50 - 37	37 - 37	90	90	
EMC (%)	15	15 - 12.2	12 - 9	9 - 8.2	8.2 - 6.2	6.2	18	18	
M/C (%)	green	60	50	40	30	20	18	18	Total
Time (Hrs)	8	30	25	25	25	15	10	10	148

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COST E 53 Conference - Quality Control for Wood and Wood Products

Aspects of timber quality in the United Kingdom

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Keywords: Timber distortion, grade, knots, spiral grain, trussed rafters.

ABSTRACT

Developments in the use of structural timber particular to the UK are discussed together with end user quality requirements. Case histories of problems resulting from poor specification, selection and understanding of wood behaviour are given. Particular reference is made to the qualities of British-grown Sitka spruce.

INTRODUCTION

Timber is a highly capable and versatile construction material, used in applications as diverse as roof tiles (shingles) to foundation piles. Aside from being man’s only truly sustainable building material, timber is easy to work with being easy to cut and fix using a wide variety of connection types. Probably the biggest limiting factor in timber usage is its lack of dimensional stability on drying. Timber which distorts on drying can cause problems with fixings (eg joist hangers), result in cracks in plasterboard and creaking or uneven floors; whilst excessive differential movement of timber frame can lead to problems with windows, doors and services. These building defects can lead to extremely expensive remedial work, including re-housing of occupants.

For General Structural (ie C16) timber BS 4978 (2007) *Visual strength grading of softwood* which is often quoted in the UK by building designers, gives the following tolerances for distortion at 20% moisture content:

- bow not greater than 20mm over 2m,
- spring not greater than 12mm over 2m,
- twist not greater than 2mm per 25mm over 2m.

These are clearly considerable deviations from the ideal of timber which is straight, at least to the eye. In service moisture contents are typically around 12% for stud walls, but may be as low as 6% for intermediate floor joists exposed to effects of high levels of central heating or under floor heating. Distortion and shrinkage can therefore develop in service.

Timber is not the only material available for use in construction. Notable in the UK are recent developments in competing, alternative construction methods such large format thin joint masonry, light steel frame and Structural Insulated Panels. Off-site production methods using closed panel systems and modular units are now commonplace. Some system builders are known to have switched from timber frame to non-timber panelized systems specifically because of quality issues with timber. Good dimensional accuracy is needed to incorporate prefabricated bathroom and kitchen sub-assemblies. Even floor coverings are pre-cut in some instances to fit rooms. Although the proportion of timber frame construction has been increasing in recent years, particularly with the advent of multi-storey timber frame, on occasion there have been problems with differential movement caused by frame shrinkage. These problems can be caused in part by use of timber at high moisture content. For both timber frame and conventional construction there has been a significant move away from the use of solid floor joists to plyweb and metal web beams, specifically because of problems with timber distortion and shrinkage. These engineered wood products generally also require higher grades of timber such as TR26 or C24, as defined by BS 5268 (2002) *Structural use of timber.* Trussed rafters (which were invented in the 1950s by Shirley in Florida, and introduced into the UK in the late 1960's) also gravitate through design code requirements towards the usage of higher grade and better quality timber. BS 5268 Part 3 (2006) *Code of practice for trussed rafter roofs* stipulates much tighter limits for the distortion of timber used for trussed rafters:

- bow not greater than 10mm over 2m,
- spring not greater than 4mm over 2m,
- twist not greater than 1mm per 25mm over 2m.

The code also has other timber quality requirements for other defects such as fissures, wane and knots (with particular reference to their effect on connector plates).

QUALITY OF SITKA SPRUCE

The properties of British-grown Sitka spruce were the subject of extensive study by the Forest Products Research Laboratory (FPRL) during the 1930's, with the overall conclusion that, with suitable silvicultural management, it ought eventually to become more comparable with imported spruce for "utility" purposes. The end uses of timber at that time are in many respects quite different to that of today, with pit props and trench-lining being examples of uses which no longer exist. Domestic Sitka spruce and imported European (or Norway) spruce can be compared by reference to the Ministry of Technology Forest Products Research publication Bulletin 50 (Lavers, 1969). On the basis of the small clear samples studied, mean density at 12% mc for UK Sitka spruce is given as 384 kg/m^3, whilst the density of European spruce is given at 417 kg/m^3. For MOE the values are 8100 N/mm^2 and 10200 N/mm^2 respectively; and for MOR 67 N/mm^2 and 72 N/mm^2 respectively. It is perhaps unreasonable to compare the properties of timbers which have been produced over different timescales and conditions, yet an established grading and design system is bound to look less favourably on newer sources timber which are inferior. Nevertheless the possible use of domestic Sitka spruce for trussed rafters has been the subject of some experimentation (Harrod, 1975). BRE recently carried out number of structural tests on trussed rafters fabricated from Sitka spruce on behalf of a commercial client, which passed the requirements of BS 5268 Part 3. British-grown Sitka spruce generally readily meets the requirements for C16, but where the higher grades such as C24 or TR26 are sought, the necessary strictures of the grading system results in a much higher level of rejects (Figure 1).

With better tree selection processes and application of scanning technologies, high reject rates could be avoided when using higher grade combinations. Boards with spiral grain, and high proportions of juvenile wood or compression wood are fundamentally prone to distortion on drying (Figures 2 and 3). Scanning technologies can also be used to segregate the worst of this timber. Battens with central pith (termed "box pith") are prone to twisting even at low levels of spiral grain angle. A particular problem noted of British grown Sitka spruce is that the majority of boards twist in the same direction, regardless of their orientation. This can cause problems with glue-laminated timber. Compression wood can also cause problems with laminated timber particularly when fabricated at high moisture content (Figure 4). Board scanners can be used to sort timber on the basis of knot content, and can also be used to cross cut timber so that defects are avoided in critical areas such as at connections or nailing points.

FR1 100mm		
C16/R	C16	100%
	R	0%
C24/C16/R	C24	38%
	C16	32%
	R	30%

FR1 150mm		
C16/R	C16	97%
	R	3%
C24/C16/R	C24	40%
	C16	27%
	R	33%

FR1 200mm		
C16/R	C16	98%
	R	2%
C24/C16/R	C24	25%
	C16	25%
	R	50%

FR2 100mm		
C16/R	C16	92%
	R	8%
C24/C16/R	C24	60%
	C16	18%
	R	22%

FR2 150mm		
C16/R	C16	93%
	R	7%
C24/C16/R	C24	40%
	C16	25%
	R	35%

FR2 200mm		
C16/R	C16	78%
	R	22%
C24/C16/R	C24	0%
	C16	11%
	R	89%

FR3 100mm		
C16/R	C16	98%
	R	2%
C24/C16/R	C24	57%
	C16	28%
	R	15%

FR3 150mm		
C16/R	C16	100%
	R	0%
C24/C16/R	C24	73%
	C16	12%
	R	15%

FR4 100mm		
C16/R	C16	97%
	R	3%
C24/C16/R	C24	77%
	C16	10%
	R	13%

FR4 150mm		
C16/R	C16	89%
	R	11%
C24/C16/R	C24	50%
	C16	14%
	R	36%

Figure 1. Example of Cook Bolinder strength grader reject and pass rates for stands of Sitka spruce.

Figure 2. Bow of timber dried unrestrained, caused by juvenile wood and compression wood.

Figure 3. Twisted timber caused by spiral grain and high proximity to pith.

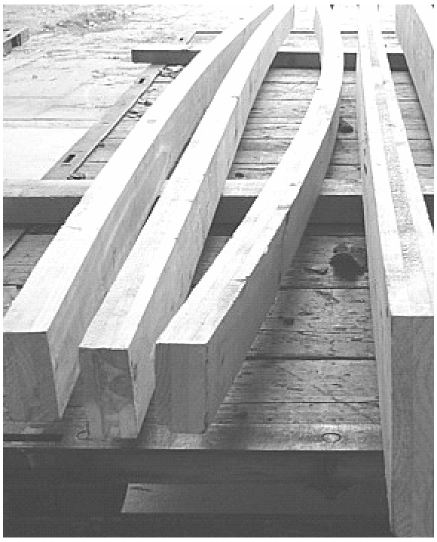

Figure 4. Bow of 3-ply glue-laminated elements caused by compression wood.

In comparative studies carried out by BRE, home grown Sitka spruce was found to be more prone to distortion that imported timber destined for the timber frame market, and to contain higher levels of knots (Figure 5 and 6).

		Average values (mm)				
		Twist	Bow	Spring	Cup	Moisture (%H_2O)
Imported	High m.c.	1.31	1.98	0.7	0.14	22
	Medium m.c.	5.49	2.37	1.03	0.32	16.9
	Low m.c.	6.24	2.53	1.12	0.35	14
Home grown	High m.c.	2.76	1.44	0.81	0.02	22.6
	Medium m.c.	4.97	2.78	1.61	0.32	16.8
	Low m.c.	7.44	2.99	1.75	0.3	14

Figure 5. Comparison of distortion measured in batches of timber studding during drying.

	Knot cover (%)	Average no. of knots per batten face	Average knot size (mm^2)
Imported	**0.52**	**6.1**	**185**
Home-grown	**0.82**	**8.4**	**206**

Figure 6. Comparison of knot content in batches of timber studding.

Figure 7. Battens used in timber frame panel manufacture. Imported timber (left), domestic (right).

PERFORMANCE PROBLEMS WITH TIMBER

Timber distortion can, on occasion, cause problems in service. In the examples given below, both imported and home-grown timber were involved.

The uneven gallery walls of a museum were investigated by BRE. The wall linings consisted of square edge butt jointed MDF panels fixed to timber studwork. In several places the boards were out of line with differences in the studwork alignment of up to around 8mm over 1m. The Architect's specification for un-graded softwood for framing out and non-structural use generally had referred to regularised timber; whilst the specification for cross section dimensions of structural softwood and hardwood timber referred to both BS EN 336 Tolerance Classes T1 (for sawn surfaces) and T2 (for further processed surfaces), but also to the use of timber generally at 20% moisture content. The lack of alignment horizontally along the length of the walls was determined to have been caused by a combination of shrinkage and distortion of the timber since installation together with poor carpentry. The builder had chosen to use rough sawn un-graded timber, probably at high moisture content initially.

Similar problems were reported at a timber frame office development in Ireland, where the 3.6m high wall panels and long corridor lengths extenuated the effects of timber distortion and movement. Wall panels were installed at high moisture content following attempts to prefabricate on the same site. The specification had not been clear on the quality of the timber used, with a non-standard size being quoted. The use of Canadian Lumber Size (CLS) timber which is machined at around 20% moisture content would have avoided many of the problems caused by the use of timber which was rough sawn at green.

Distortion in the form of twist and cup, together cross grain shrinkage, were noted to have caused problems of unevenness and creaking of timber floors in a catering development. The joists were determined to have been installed at high moisture content and were not well fixed in their hangers. Heat from the ovens had caused the timber to dry to 6% moisture content. Movement in the floor had caused a linoleum floor covering to leak cleaning water, resulting in a need to replace the decking and refit the kitchen.
Similar problems were caused for the extension of a hospital where solid timber joists had been used for an additional storey. The joists had been fixed without restraint from strutting. High levels of central heating caused cross grain shrinkage resulting in the floor becoming uneven.

DISCUSSION

Whilst British sawmills can and do provide high quality timber, large amounts of low grade timber are also sold in structural sizes. Non-discerning builders have been known to select and use low quality timber at inappropriate moisture contents, resulting in problems developing in service. Architects and developers, on occasion, have also been noted to specify in an illogical or unrealistic manner. Properly conditioned and regularized timber is available. Inadequate consideration for the movement and distortion of timber can cause serious problems in construction. These defects can result in expensive remedial work.

CONCLUSIONS

Items such as trussed rafters generally require high stiffness material with low knot content and low levels of distortion. Markets such as timber frame also prefer timber with low knot content. High reject rates have been noted when British grown Sitka spruce is graded for higher quality structural timber. In a comparative study, domestic timber was also noted to have a higher level of knots and distortion than imported. With better tree/log selection processes and application of scanning technologies, high reject rates could be avoided when using higher grade combinations to produce timber suitable for markets such as trussed rafters and other engineered wood products. Boards with spiral grain, and high proportions of juvenile wood or compression wood are fundamentally prone to distortion on drying. Scanning technologies can be used to segregate the worst of this timber, directing it to usage such as wood-fuel. Board scanners can be used to sort timber on the basis of knot content, and can also be used to cross cut timber so that defects are avoided in critical areas such as at connections or nailing points.

ACKNOWLEDGEMENTS

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For BS and EN standards see British Standards Institution, London.

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Variables affecting the performance of British grown Sitka spruce

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Keywords: Compression Wood, Distortion, Density, Knots, Slope of Grain, Stiffness.

ABSTRACT

This paper details the findings of a study into the relationships between tree, log and board variables to the mechanical properties and distortion of British grown Sitka spruce. The influence of knots, compression wood, slope of grain, log shape, density and other parameters is discussed, together with the effect of using these variables as sorting criteria or the basis of log or sawn timber scanning equipment. The database amassed by BRE in collaboration with Forest Research can also be used to develop predictive silvicultural models.

INTRODUCTION

Timber is an immensely useful but naturally variable material. Inherent in its structure, both in log and sawn form, are features which affect qualities of dimensional stability, stiffness and strength. These include knots, compression wood and spiral grain. Physical characteristics such as log shape, density, rate of growth, presence of juvenile wood and microfibril angle also affect these qualities and, in turn, utilisation. British-grown Sitka spruce trees reach maturity relatively quickly; as a consequence the timber differs significantly from slower grown softwoods imported from northern America and northern Europe. British-grown Sitka spruce tends to meet a lower structural grade than imported softwoods, which can exclude it from certain markets. For example, none at present is used for trussed rafters. Some UK timber frame manufacturers prefer imported timber because they consider the level of distortion and knots in British-grown material to be too high. Ply web beams and other glued laminated elements require timber which is not prone to distortion on drying, as does timber supplied to other markets such as the DIY trade where boards are often stacked unrestrained in heated buildings. Sorting of timber in the future is likely to be aided by automatic scanning equipment, but the effects of segregating the better quality from the lower, particularly on strength grading, need to be considered. With better information on the material being processed, optimised sorting can be performed. For example, material likely to distort excessively or be rejected at machine grader stage can be segregated prior to kiln drying. Relatively simple laser/camera setups can be used to measure grain angle and knot content on boards. Three dimensional log shape scanners are already used to optimise volumetric yield, and also have the potential to be used to determine timber quality. By investigating the relationships between timber variables the potential worth of these techniques can be indicated.

MATERIALS AND METHODS

The overall methodology used was to obtain sample batches of timber and relate the predictor variables of the logs and boards to the criterion variables of the end product. By additionally studying the behaviour of small scale samples, free of defects such a knots, the effect of variables such as density and compression wood content could be evaluated. Practical difficulties in the characterisation and measurement of timber variables, and their adequacy, were also investigated. The main bulk of the practical work comprised the testing and assessment of around 500 battens of Sitka spruce obtained from two localities in Scotland. Ninety logs of 3m length were manually assessed, then scanned by a 3D laser scanner. The timber was “curve sawn” into three nominal sizes 200 x 47mm, 150 x 47mm, 100 x 47mm which are commonly used in construction. Aside from the obviously required site, tree, log and batten number identification numbers and sawn timber dimensions, the following variables were determined: Tree height and diameter at breast height (dbh), tree taper (height/dbh), log diameter (top, middle, bottom),log taper (ratio of bottom diameter to top diameter), log maximum and overall curvature, number of whorls per log, whorl spacing (maximum, minimum and mean spacings), log spiral grain angle, log ovality, log pith eccentricity, log compression wood content, batten density, batten slope of grain on outer and inner faces and edges, compression wood content on outer and inner batten faces, knot content (number and area of knots on batten edges and sides, and maximum concentration of knots in any 300mm span), knot area ratios (MKAR, TKAR etc as defined by BS 4978), average ring width, percentage of juvenile wood, and distance from pith to centre of the batten.

The battens were machine strength graded using a Cook Bollinder grader to obtain detailed Indicating Parameter (IP) values along the board lengths. Since all of the battens were of the same nominal thickness a value of IP normalised for batten width could be determined. $E_{\text{(Cook Bollinder)}}$ was also calculated. Since the position of every batten was known, stiffness profiles both axially and radially within the trees could be established. MOE and MOR from bending tests to EN 408 were also obtained. Distortion measurements of bow, spring twist and cup where obtained following drying.

Other sets of timber were also used for purposes of validation, comparison and further study included sets of battens obtained from sawmills which were rejected at machine grading and because of excessive distortion. An extensive dataset of earlier test work on Sitka spruce was also analysed.

SPIRAL GRAIN AND TWIST

Spiral grain has long been known to influence distortion in the form of twist (Stevens 1961). Balodis (1972) noted that twist increased with increasing angle of spiral grain and decreased with increasing distance of the board from the pith. His analysis showed that twist was proportional to the ratio of grain angle: distance from pith; and that the constant of proportionality is a function of the tangential shrinkage component of the wood. Figure 1 shows the observed relation between twist and slope of grain recorded on the inner and outer faces of the boards for a subset of 100 x 47mm battens.

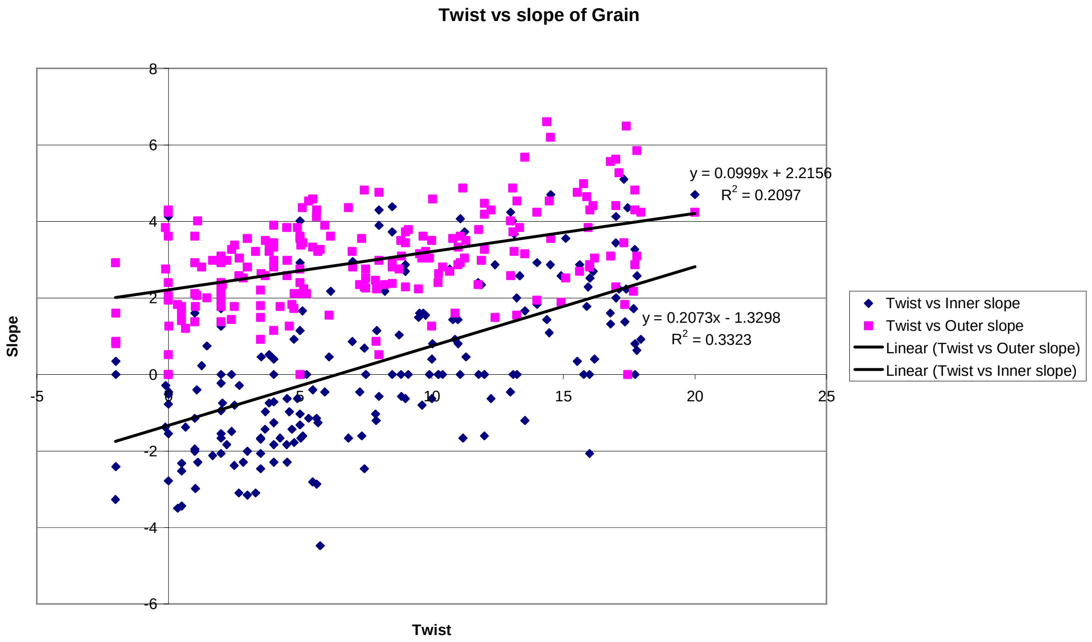

Figure 1. Twist (mm) plotted against slope of grain (deg)

A reasonable relationship between slope of grain measured on the faces and twist is evident. However the relationships between slope of grain on the outer face and inner face are different, most significantly on the intercept with the y axis. From the above graph (together with detailed inspection of the boards), the following could be deduced. Only a few boards with high values of slope of grain which are prone to twisting can be identified and possibly removed. There are very few boards which twist in the opposite direction to the bulk. Outer face slope of grain is almost always positive (relative to the observer, given the provisos of the measurement protocol). Twist appears to increase as inner face slope of grain ranges from negative values to positive. Large negative values of spiral grain are, apparently, associated with low twist. Battens with inner face spiral grain angles which are positive tend not to contain pith. A feature also observable in the dataset, since the orientation of the battens wrt height in the tree is known, is that the majority of battens have come from trees (or sections of trees) that have remained left hand spiral grained. It is also clear from the above graph that sorting on the basis of the magnitude of spiral grain angle alone will be ineffective. For predictions of twist, measurements of spiral grain angle must always be made on a tangential face. The influence of a variable relating to proximity to pith was also noted, with boards containing pith being particularly prone to twisting.

COMPRESSION WOOD

Compression wood is a type of reaction wood that tends to form in conifers that have been partially blown over, in trees on the windward side of exposed plantations, in the lower part of trees growing on a slope, and below heavy branches (Desch and Dinwoodie, 1996). The greater longitudinal shrinkage of compression wood causes bow and spring on drying. Compression wood in logs may be indicated by their shape and form, as shown in other work on Scots pine and Norway spruce (Warensjo, 2003). Industrial 3D laser scanners are used in many sawmills to optimise yield, and also have the potential to be used automatically for log sorting on the basis of propensity to distort.

In this study no clear systematic relations were observed between the log shape (ie ovality, pith eccentricity, arc), batten compression wood content, and distortion in the form of bow and spring. Although several logs with abrupt changes in curvature were noted to yield battens which bowed or sprung considerably (Figure 2), some relatively straight round logs contained high levels of compression wood, or yielded timber which distorted on drying. The high distortion of timber coming from these straight logs was attributed to the consistent imbalance of compression wood that could occur from one face or side of the board along its entire length (Figure 3).

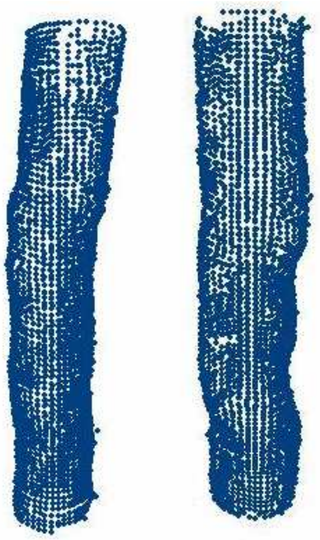

Figure 2. Scanned image of logs with abrupt changes in curvature which yielded distorted timber

As expected, severe compression wood was found to be associated with stem correction, particularly leader loss. Compression wood is denser than normal wood, and it was found that its presence undermined the quite good relation observed between stiffness and density for normal wood.

Figure 3. Distorted batten, originating from relatively straight log. (compression wood shown marked)

EFFECT OF KNOTS AND DENSITY ON STIFFNESS

A key feature of British grown Sitka spruce often noted is the presence low stiffness material near to the base of the tree. In this study, since the orientation of the battens was known, and kept constant during machine grading, stiffness profiles for each tree could be established (Figure 4). This feature was noted to be highly variable both between trees and stands. The effect is not attributed to any outwardly measurable feature on boards (such as knots, low density, slope of grain etc), but to high microfibrill angle. The feature is grade determining for many battens, and this has a profound effect on the efficacy of any potential sorting system.

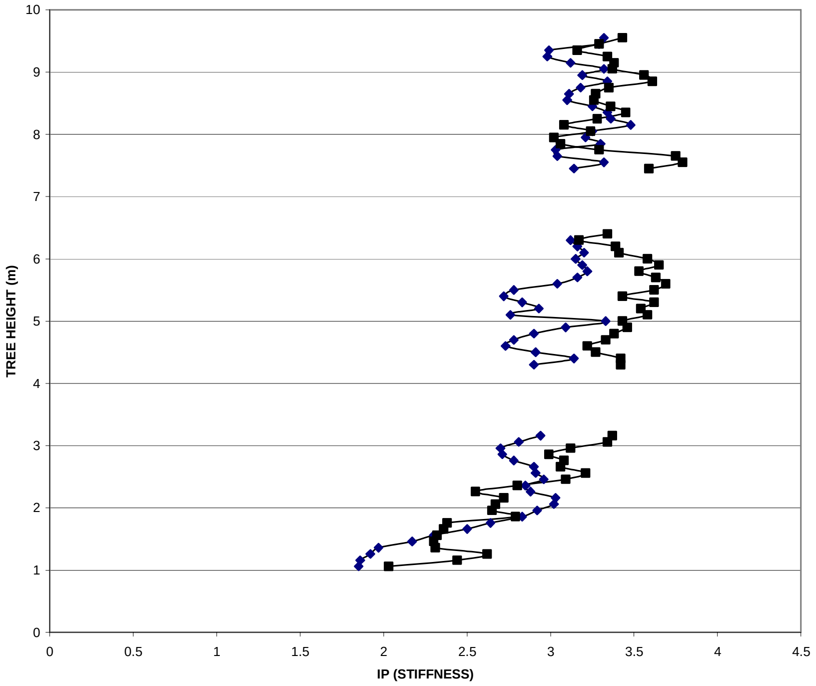

Figure 4. Batten stiffness profiles showing low stiffness at the base of trees.

As expected from the batten stiffness profiles, log variables associated with batten height (eg taper) were found significant. Figure 5 (below) shows that there is a reasonable relationship between density and stiffness for upper logs, but that this relation is apparently not present at all for the butt logs. For both small clear samples of normal wood and battens from upper logs, stiffness is was found to be directly proportional to density. Spiral grain angle was not found to be a significant variable.

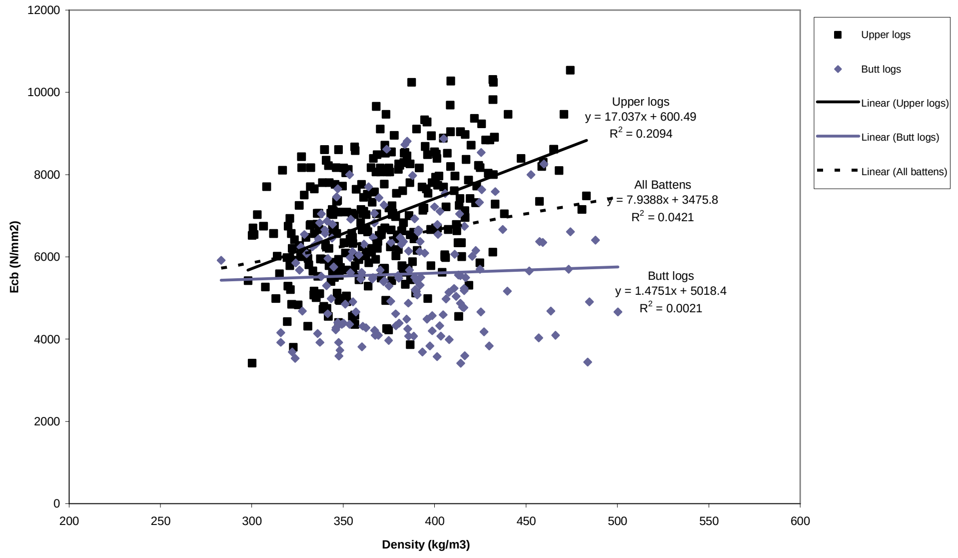

Figure 5. Stiffness plotted against density for subgroups of butt logs and upper logs.

Figure 6 below shows the observed non-linear relation between KAR and stiffness for a set of 97 x 45mm timber.

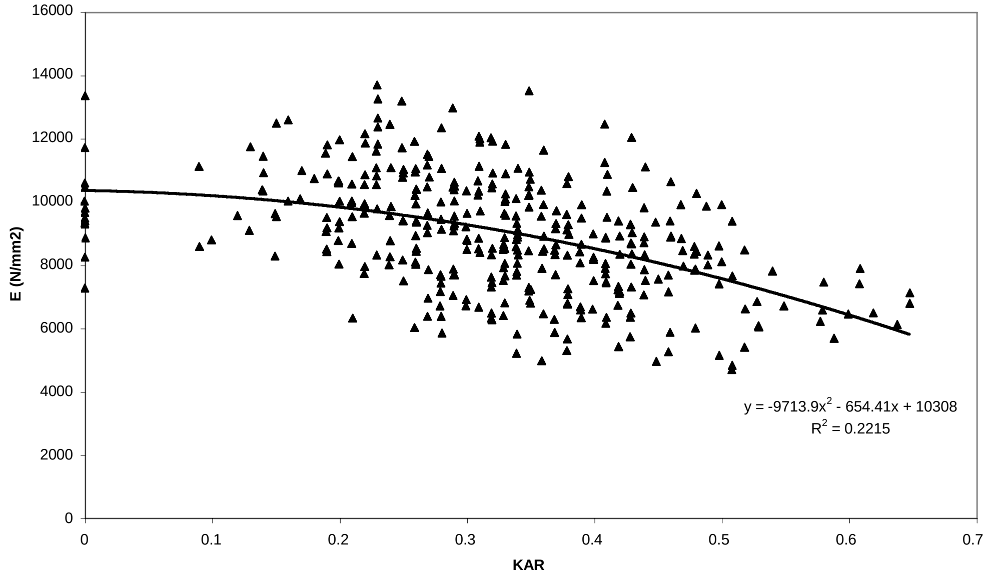

Figure 6. Relation observed between KAR and stiffness.

DISCUSSION

Good knowledge has been gained of the numerical relations between the variables affecting the performance of British grown Sitka spruce. The presence of low stiffness material near to the base of the trees was noted to be highly variable both between trees and stands, and the feature grade determining for many battens. This effect can occlude relations observed between other variables. Clearly extremes of knot content, slope of grain and log shape can be used as sorting criteria to improve quality. For segregation of timber into different quality groups, knowledge of the effect of combined variables is required. The necessary strictures of the grading system can also make certain forms of sorting un-worthwhile, or counter-productive. By selecting out better quality logs or battens the average quality of the remainder may fall. The database amassed by BRE in collaboration with Forest Research can also be used to develop predictive silvicultural models. From the study of machine grader rejects, severe cross grain associated with either large knot groups (Figure 7) or log curvature was noted to be highly significant. However determining descriptive variables for this feature is problematic.

Figure 7. Machine grader rejects with severe cross grain.

CONCLUSIONS

It was found that the presence of low stiffness clear wood at the base of the trees studied, together with the natural variability between individual trees and stands, has a profound effect on the ability to sort timber on the basis of industrially measurable variables such as density or knot content. Practical difficulties with the use of slope of grain measurements to determine batten twist were also noted. Relatively straight, round logs were observed to contain compression wood and hence yield timber which distorted on drying.

ACKNOWLEDGEMENTS

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The Effect of compression wood on timber quality

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Summary

As part of a large EU funded research project, the authors have carried out an assessment of the mechanical properties of compression wood in British grown Sitka spruce. Bending tests were performed on small scale samples of normal wood and compression wood, together with precise measurement of longitudinal shrinkage. The effect of compression wood on machine stress grading and full scale batten performance was assessed. It was found that compression wood tended to be less stiff than normal wood, although it had much higher density. Although specific strength tended to decrease with increasing compression wood, overall strength was unaffected. As expected from these results, compression wood was found to have little effect on machine stress grading. None of the full scale battens with high amounts of compression wood failed at levels below that expected from the machine grading results, although some of the fractures observed were quite brash

Key words: Compression wood, bending strength, machine stress grading.

1. Introduction

Compression wood is a type of reaction wood that tends to form in conifers that have been partially blown over, in trees on the windward side of exposed plantations, in the lower part of trees growing on a slope, and below heavy branches [1]. It is characterised by its relatively dark brown colour in contrast to normal wood, together with more highly developed late wood. The greater longitudinal shrinkage of compression wood causes bow and spring on drying, and the material is considered to have inferior bending strength, in particular being brittle. As part of a large EU funded research project, the authors have carried out an assessment of the mechanical properties of compression wood in British grown Sitka spruce. Bending tests were performed on small scale samples of normal wood and compression wood, together with precise measurement of longitudinal shrinkage. The effect of compression wood on machine stress grading and full scale batten performance was also assessed. This paper presents a summary of the work carried out.

2. Results

2.1 Test work on small samples

The objective of the work was to determine the physical properties (density, strength, stiffness and shrinkage) of British grown Sitka spruce (Picea sitchensis) containing normal wood and compression wood. Eighty-five small scale samples (20mm x 20mm x 300mm) were obtained from selected battens and small curved logs. These were visually scored for compression wood content on the following scale: 0 = no compression wood; to 3 = high compression wood. Precise measurements for longitudinal shrinkage were made at 20 deg C/ 90%RH and 20 deg C / 65%RH, with bending tests to BS 373 (MOE and MOR).

Figures 1 and 2 (below) show results of the bending tests:

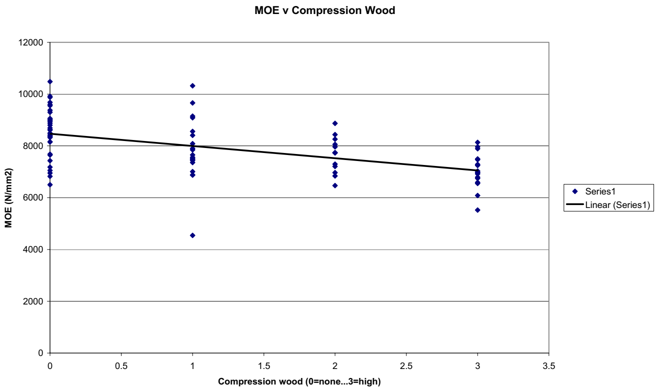


Figure 1: MOE v compression wood

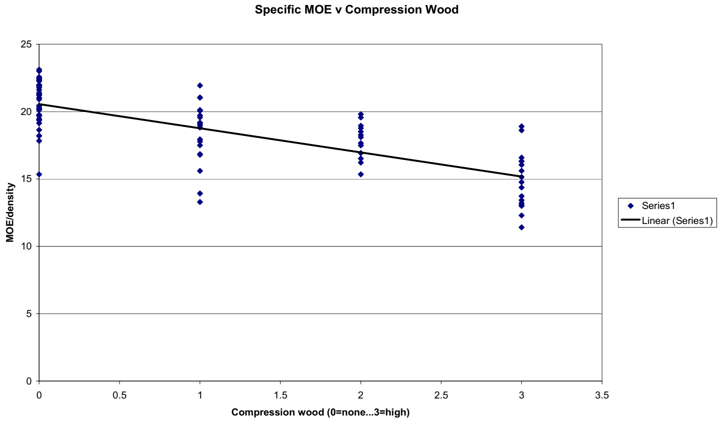


Figure 2: Specific MOE v compression wood

Table 1 (below) shows a comparison of the mean densities of the samples:

Compression Wood Content	Mean density at 20/90 (kg/m^3)
0 = none	422
1= slight	439
2= moderate	442
3= high	492

In the study in was found that stiffness tended to decrease with increasing compression wood content (probably due to the higher microfibril angle in the S_2 layer), and that this trend was even more marked for specific MOE. The implication of the slightly lower stiffness of the compression wood, is that compression wood should have little effect on machine grader output for full scale battens which rarely have very high levels of compression wood throughout. This also suggests that compression wood will not be a significant variable in a model which might aim to predict machine grader output or Indicating Parameter (IP). In any case, the grade determining low mean IP is very often at some knot position for UK grown Sitka spruce. However, whilst compression wood may have little effect on IP, this causes other problems for modelling, significant variables for which are density and rate of growth. Because compression wood is associated with eccentric growth about the pith - by definition the rate of growth can appear higher; whilst at the same time density increases markedly - yet there is no corresponding increase in stiffness. The problem with trying to assess the compression wood content in a batten is that what is seen on the surface very often poorly reflects the true content. Figure 3 (below) shows strength (MOR) v compression wood, indicating no trend for increased strength with increasing compression wood content, and therefore no trend for increasing strength with increasing density.

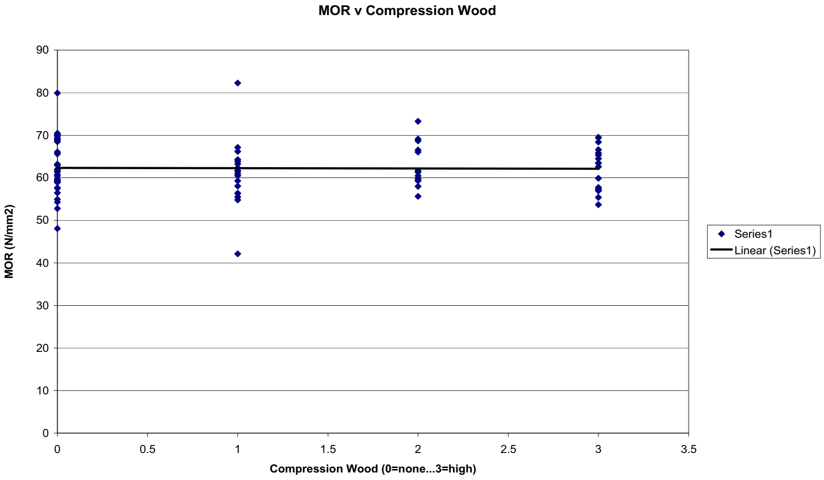


Figure 3: MOR v compression wood

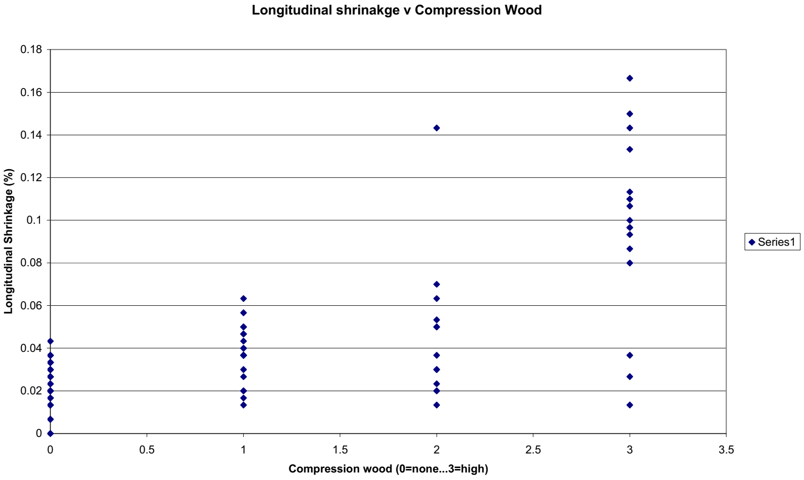
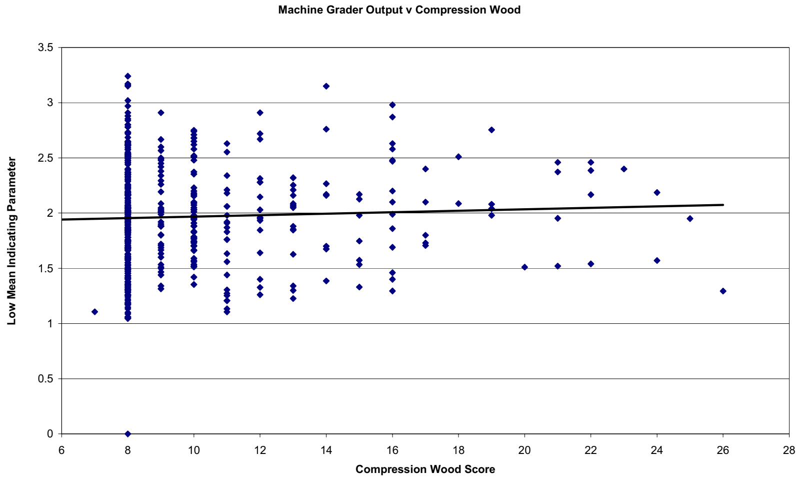


Figure 4: Longitudinal shrinkage v compression wood

Figure 4 (above) shows longitudinal shrinkage v compression wood, confirming that the majority of the samples were correctly assessed for compression wood content. It is interesting that significant shrinkage was only observed for samples with high compression wood.

2.1 Test work on machine stress grading and full scale bending

The objective of the work was to determine the effect of compression wood on machine stress grading (using a Cook Bollinder grader) and the subsequent performance of the battens in bending tests to EN 408, with analysis to EN 384. During the bending tests the batten was placed so that the compression wood was in the tension zone. The level of compression wood was assigned using a similar but more detailed visual scoring method to the small samples (on a scale of 0 to 32).



During bending tests to destruction, none of the full scale battens with high amounts of compression wood failed at levels below that expected from the machine grading results, although some of the fractures observed were quite brash.

Conclusions

It was found that compression wood tended to be less stiff than normal wood, although it had much higher density. Although specific strength tended to decrease with increasing compression wood, overall strength was unaffected on a volume by volume basis. As expected from these results, compression wood was found to have little effect on machine stress grading. None of the full scale battens with high amounts of compression wood when tested to destruction failed at levels below that expected from the machine grading results, although some of the fractures observed were quite brash. Further work involves measuring microfibril angle, relating compression wood to 3D log shape and correlating compression wood to distortion on drying.

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