WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

THINKING BEYOND THE USUAL STRENGTH GRADES – WITH EXAMPLES OF BRITISH SPRUCE AND LARCH

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ABSTRACT: This paper summarises the processes and normative requirements involved in grading of structural timber, and outlines a number of areas in which matters may be improved, so as to make better use of the true properties of the timber resource used. The activities of resource segregation and timber grading are well researched, but what is not commonly realised is that there are opportunities to do things more efficiently. This is especially true when the structural timber is produced with a specific customer, project, or end use in mind. The paper uses data from research projects, and development of machine grading settings, to illustrate how assignment of timber to a limited set of strength grades can, in exchange for convenience in trade, involve considerable compromise in design properties. In some cases, this trade convenience is not necessary or can still be obtained while also permitting less of a compromise in design properties. The paper also explains why, in research, knowledge of the timber grade is not all that useful and why it is necessary to take other steps to characterise the material. The focus of the paper is strength grading in Europe, but many of the aspects are also applicable elsewhere.

KEYWORDS: Strength grading, Strength classes, Sawn timber, Characterisation, Prediction

1 INTRODUCTION

The physical and mechanical properties of wood vary considerably, even within a single tree. This variation is influenced by both environmental factors and by silviculture. This means that when structural timber is produced, the key properties need to be assessed in order to ensure structural safety, while also maintaining economic use of the material. This is achieved by a process in which the timber is graded (by various means, visually and by machine) into categories, according to quality. For convenience and easy trade the categories are commonly assigned to a limited set of strength grades with defined design properties (also known as strength classes) that are published in standards such as EN 338 [1].

These general strength classes are defined in such a way that the commonly used ones fit reasonably well to the property profiles of the species (and growth areas) in long standing usage, but they do not fit any species exactly. When timber is assigned to a strength class it takes the design properties of that strength class, some (or even all) of which may be significantly lower than the true properties of that timber.

The convenience of easy specification and trade, afforded by the use of general strength classes, therefore comes at the expense of a compromise in timber properties. In some cases the compromise can be very large – resulting in design that is less material efficient or in unnecessary grading reject for the application. It therefore makes sense, in a given situation, to consider whether this compromise is really needed.

2 AN OUTLINE OF STRENGTH GRADING IN EUROPE

2.1 GRADE DETERMINING PROPERTIES

Timber strength grading in Europe (to EN 14081 [2]) is based on three key grade determining properties: strength, stiffness and density. Specifically, there are two sets of grade determining properties permitted by EN 384 [3]:

- "Bending grades"
  - Bending strength, bending stiffness, density
- "Tension grades"
  - Tension strength, tension stiffness, density

Bending grades (established based on bending tests) are most commonly in use for general construction timber, while the tension grades (established based on tension

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tests) are more useful for grading of lamellas for the manufacture of glued laminated products.
The three key properties are normally specified at a reference moisture content consistent with 65% relative humidity and 20°C (12% moisture content for most species). They are expressed as characteristic values:

- Strength as the lower 5th percentile
- Stiffness as the mean
- Density as the lower 5th percentile

Here density is for use as predictor of strength (e.g. for fasteners) and fire resistance (charring rate) which is why it is the lower 5% percentile. This measure of density is not good for situations where a higher value is problematic (e.g. self-weight) because grading only ensures that the timber does not have lower characteristic density than the strength class – there is no upper limit.

2.2 SECONDARY PROPERTIES

The three grade determining properties are not sufficient for design, so other properties must be conservatively estimated from the three primary properties. The secondary properties include: tension and compressive strength perpendicular to grain, shear strength and shear modulus.
It would be too expensive and impractical to undertake the large number of tests necessary to routinely treat secondary properties to the same level of confidence as the three grade determining properties. Furthermore, because these properties vary considerably between species (particularly for hardwoods) the conservative relationships are limited by the least good species in common usage, and often do not fit well to the real properties of timber graded to strength classes at the lower and upper ends of the range.
In the case of the T classes the tension strength is the primary property, established based on testing, and bending strength is a secondary property that must be conservatively estimated from it. For the C classes the bending strength is the primary property and tension strength is the secondary property that must be conservatively estimated from it. This is the reason why the softwood T classes (tension) in EN 338:2016 [1] are different from the softwood C classes (bending).
The calculation basis, in EN 384:2016 [3], for the secondary properties of softwood edgewise bending grades is:

- Based on bending strength
  - Tension strength parallel to grain
  - Compression strength parallel to grain
  - Shear strength (up to C24, thereafter fixed)
- Based on bending stiffness
  - 5th percentile stiffness parallel to grain (*)
  - Stiffness perpendicular to grain (*)
  - Shear modulus (*)
- Based on density
  - Compression strength perpendicular to grain
  - Mean density (*)
- Fixed value (applies to all strength classes)
  - Tension strength perpendicular to grain

In EN 384:2016 the calculation of secondary properties marked (*) is directly proportional to the primary property: a 10% increase in the primary property gives a 10% increase in the secondary property. Compression strength parallel to grain would be increased by a little under 5% by a 10% increase in bending strength. The corresponding increase in tension strength parallel to grain would be between about 11% and 14%, depending on the level of the bending strength. Shear strength would increase by between 0% and about 5%, also depending on the level of the bending strength.
Note that, as more research data is collected, the equations for secondary properties may be adjusted accordingly and the grade definition updated. It is important for designers to realise that the properties of the standard strength classes are not permanently fixed.

2.3 ASSIGNMENT TO A STRENGTH CLASS

Graded timber can be assigned to a strength class if the required characteristic values of the three grade determining properties (some listed in Table 1) are met (subject to some other adjustments [4]). When grading to the general strength classes, it is typical that only one of the three grade determining properties will be limiting, and indeed it may be that none of the properties are limiting.
This means that, if the grading is working correctly, the timber passing grading will have characteristic properties that exceed those stated for the strength class; especially in the case of secondary properties which may be considerably higher. It should also be understood that the characteristic properties are descriptions of the timber, collectively, in the grade and not of the individual pieces of timber. This means that knowledge of the strength class alone is not particularly useful for characterising timber used in research (See 5).

***Table 1**: Some strength class requirements*

Class [1] unless other ref	Bending strength $f_{m,k}$ N/mm²	Bending Stiffness $E_{m,0,mean}$ kN/mm²	Density ρ_k kg/m³
C14	14.0	7.0	290
C16	**16.0**	**8.0**	**310**
C18	**18.0**	**9.0**	**320**
C16+ [5]	18.5	8.0	330
C20	20.0	9.5	330
C22	22.0	10.0	340
C24	**24.0**	**11.0**	**350**
C27	27.0	11.5	360
TR26 [6]	28.3	11.0	370
C30	**30.0**	**12.0**	**380**

Note 1: $f_{m,k}$ and ρ_k are 5th percentiles, $E_{m,0,mean}$ is mean
Note 2: More common strength classes are shown bold

2.4 STRENGTH CLASSES CAN BE DEFINED

Within Europe, it is the Declaration of Performance (DOP) for the structural timber, together with the CE mark, that communicates the properties that are important for design. The common strength classes are a convenient way of describing most of those properties. They are, however, not the only way.

There is nothing to prevent new tailored strength classes being created to suit a particular timber resource, or a particular end use – although the work required to establish machine control settings, or visual grading assignments may be prohibitively expensive under the current system. Several strength classes exist outside of EN 338. One long standing example is TR26: a grade commonly used in the UK for trussed rafters. The origins of TR26 lie in industrial practice that predates the European standards, but the grade is retained in use because it is familiar to the industry, and is thought to suit the application and the raw material. In terms of its strength and density it sits between C27 and C30, but it has the relatively lower stiffness requirement of C24 (Table 1).

The bending grades in EN 338 are specifically for bending about the major axis ("edgewise") as this is the way the tests are carried out. It is presumed that these properties will be conservative when applied to bending about the minor axis due to the relative lesser impact of strength reducing defects (e.g. [7]). Strength classes could be created, based on bending about the minor axis, that would better suit timber products intended to be used that way in service, but in this case the characteristic bending strength could not be safely used to directly calculate resistance bending about the major axis (i.e. major axis bending strength would need to be a secondary property). For this reason, the timbers would have to be marked to clearly show they are for minor axis bending to ensure correct usage in practice.

2.5 DECLARING SECONDARY PROPERTIES

Rather than using the conservative equations for secondary properties (see 2.2), it is also permitted to create a strength class with values of those properties established by testing. Since this does not change the three primary properties, it does not change the calculation of grading settings, and this can be done retrospectively.

2.6 GRADING OF HARDWOODS TO "SOFTWOOD" STRENGTH CLASSES

EN 338 lists a set of bending strength classes for softwoods (the C grades) and a set for hardwoods (the D grades). They have different relative values for strength density and stiffness to fit reasonably well to the property profiles of commonly used softwoods and hardwoods. They also have different equations for secondary properties to reflect the different mechanical behaviour resulting from the differences in softwood and hardwood microstructure and nature of strength reducing defects.

However, as a wider range of hardwoods is being used in construction the C grades have now been opened up to species such as poplar and chestnut (EN 338:2016) that may fit better to the softwood profiles due to relatively low density (e.g. [8]).

The softwood equations for secondary properties in EN 384:2016 are regarded as conservative when applied to hardwoods, but the hardwood equations would not be safe to apply to softwoods. However, the secondary properties could be confirmed by testing (2.5).

2.7 DIRECT DECLARATION OF PROPERTIES

As previously mentioned, within Europe, it is the Declaration of Performance (DOP) for the structural timber, together with the CE mark, that communicates the properties that are important for design. A strength class is a convenient way of describing most of those properties, but the properties could also be directly declared, without any reference to a strength class. Here it should be noted that the current system still requires the pre-selection of the strength class's primary property values before the calculation of machine grading settings and visual grading assignments, but the point is that it is not strictly necessary to stick to the standard combinations of formally defined strength classes: the relative levels of strength, stiffness and density could be more flexible to better suit the properties of the timber resource being graded.

The DOP accompanies the graded timber to the end user but, in normal practice, the building designer would have designed the building before the timber was purchased, using a common strength class that he or she knows can be obtained on the market from a number of different suppliers. Here, the benefit of using the strength class is clear: standard, commonly understood and widely available strength classes allow easy specification and trade of structural timber.

3 WHEN CONVENIENCE OF TRADE IS NOT REQUIRED

3.1 INTRODUCTION

The use of strength classes provides convenience of trade when timber is placed on the general market. However, there are some situations where the timber is not placed on the general market, but general strength classes are still commonly used.

3.2 GRADING OF IN-SITU TIMBER

When there is a need to evaluate the structural properties of timber in-situ, during building assessment, renovation or repair it is common practice to visually grade the timber and apply an assignment to a strength class. This is a reasonable approach to take when all the timber in a structure needs to be assessed, but only some of it can be visually graded, as this gives a measure of the general quality of the timber used in the building.

However, where specific members need to be assessed it would be better to think about estimating the properties of those specific pieces of timber individually, rather than apply a grading approach (which is concerned with the properties of all the timber assigned to a strength class – and not so much the properties of individual timbers.)

For visual grading, estimation of individual members would be complicated to achieve – requiring knowledge correlations of visual grading parameters to the structural properties. It is also not likely to be much more useful for accurate prediction since the correlations of the visual parameters are not strong – but it would be possible to consider the way the timbers are loaded and to grade certain sections of a single piece of timber as different grades. In this situation it is known how the structural timber is used in the building, unlike in general trade where it has to be assumed that the worst part of any timber member may possibly be used in a way that is critical to its performance.

It would also be legitimate to use any available knowledge of the actual characteristic properties of this species (and source) of timber when assigned to a visual grade (as calculated when the grading assignment was done) rather than apply the standard strength class value, which is likely an undervaluation of some properties (there is no benefit of using a standard strength class when the timber is not being placed on the market).

With the use of non-destructive testing technology (e.g. acoustic wave velocity) it becomes more practical to apply predictions (See e.g. [9]). Here it makes little sense to use the measurement to grade the timber as if in the sawmill as grading is not about the properties of individual pieces. Indeed, where there is a choice of machines and grade combinations a single piece of timber may legitimately be graded into one of several different strength classes. Grading individual pieces while picking the most favourable possible strength class for each would certainly violate the assumptions on which grading is based, but it is also likely that a process estimating properties of individual pieces would make better use of the true potential of the timber. This requires an understanding of the difference between grading, and predicting the properties of pieces (see 5.1).

3.3 GRADING OF TIMBER FOR A SPECIFIC BUILDING

When timber is being graded for a specific building with a one-off design it is never placed on the open market and there is no associated benefit to using a commonly used strength class. There is still some advantage to using existing visual grading assignments and machine settings, but they need not be so restricted. There is more freedom to use tailored strength classes and secondary properties as market familiarity is not necessary. Settings for a tailored strength class could be included, along with the standard ones, at the time the settings are calculated with relatively little additional work (see 4.1.3).

When visual grading (as in 3.2), it would also be legitimate to use any available knowledge of the actual characteristic properties of this species of timber when assigned to a visual grade. The same does not apply for machine grading as the current method of establishing the settings [10] means those settings can depend on the properties of the grade aimed for (primarily through the cost matrix).

It is particularly relevant to think differently when the building is making use of a predetermined timber resource (e.g. already felled and sawn timber from a local forest). In this case, it would be sensible to move to estimating the primary properties of the individual timbers and then calculating characteristic values of the whole (those timbers used, not the population from which they come as this is irrelevant to the building). Secondary properties can then be estimated from these calculated characteristic properties, and the building design can be carried out with the actual properties of the timber in mind. A sorting of the timbers into different qualities could also be done so that certain pieces can be selected for the most appropriate elements of the building. There are some important considerations to ensure safety (notably realising that correlations between grading indicators and wood properties can vary with species and growth area), but knowledge that was used to determine machine grading settings can certainly be reused to apply a more focussed approach on a particular set of timbers.

3.3.1 GRADING AT AN OFFSITE CONSTRUCTION FACILITY

Now that grading machines are getting smaller, more affordable, and easier to use, it opens up the possibility for the strength grading to be done by a pre-fabricator themselves (rather than by the sawmills supplying the raw materials). This is particularly true when the sawmill and the prefabricator are part of the same company. In this case the timber is never placed on the market and the market convenience of standard strength classes is irrelevant.

A prefabricator making many units of standard design might make commercial savings that offset the cost of the grading technology. Here, strength classes tailored to the timber resource can make much better use of its true properties. Strength classes could also be specified to suit particular elements of the construction.

If the grading is integrated into a modern manufacturing process the grading could also take account of the specific use of the timbers in the building, with x-ray or visual systems deciding the optimum place for cuts, and the positioning of defects that effect the manufacturing process (e.g. knots for nail fouling). In normal grading, the strength class is determined by the worst part of the piece, with no knowledge of whether that will be positioned critically in the structure (the required assumption) or removed when the timber is cut to length for fabrication of an element. Grading within the fabrication process also avoids the practical problems that would arise from handling multiple grades and lengths between the sawmill and the receiving yard of the fabricator.

3.4 GRADING BY A SAWMILL FOR A CERTAIN MARKET

When the end user, and general application of the timber, is known in advance through an arranged commercial relationship the general market familiarity of the strength classes used is not so important. As long as the end user is aware of the design properties, tailored strength classes and enhanced secondary properties could be used with no detriment to ease of trade.

When a specific type of end use is targeted (sale is to a certain sector, such as glulam manufacturers, trussed rafters or structural decking) it makes sense to consider whether the primary strength property of the strength class is the best one.

3.5 GRADING FOR THE GENERAL MARKET

When grading structural timber for the general market, where the end user and application of the timber is not known, it makes sense to use the convenience of the standard strength classes. It may not be necessary to make a total compromise on the properties though, as timber can be put on the market as a standard grade, but have enhanced properties in the DOP for use by those in the know (see, e.g. 4.1.3).

4 EXAMPLES

The following examples illustrate the range of strength, stiffness and density values within the grading of two species combinations grown in the British Isles: spruce and larch. It is shown how some properties are undervalued by grading to standard strength classes. These datasets are also used later in the paper to demonstrate how machine grading information can be used to estimate properties of individual pieces (5.1).
In the following, four letter codes for the species combinations are as per EN 14081-1 [2] and for species as per EN 13556 [11].

4.1 BRITISH SPRUCE

4.1.1 Dataset

In the UK it is standard practice to grade timber to the strength class C16 (as listed in EN338 [1]). This results in a near 100% pass rate when machine grading British spruce (WPCS) in a single grade/reject process.
British spruce is a mixture of Sitka spruce (*Picea sitchensis,* PCST) and Norway spruce (*Picea abies,* PCAB). The two species have very similar properties but the mix is, anyway, mostly Sitka spruce (~90%). This timber is commonly used in construction for elements such as stud walls, and less commonly used for beams, where engineered timber joists are preferred.
Machine grading settings have been developed for a number of different grading machines and strength class combinations. Among them is a group of settings for grading dry timber with Brookhuis machines [12,13,14]:

- MTG 920
  - Based on acoustic velocity
  - Portable (EN 384 k_v factor not applied)
- mtgBATCH 922/926
  - Based on acoustic velocity
  - Inline
- MTG 960
  - Based on acoustic velocity and density
  - Portable (EN 384 k_v factor not applied)
- mtgBATCH 962/966
  - Based on acoustic velocity and density
  - Inline

All of these machines operate on the basis of a measurement of longitudinal resonance. The dynamic MOE calculation (Equation 1) is based on the Newton-Laplace formula. In the case of the MTG 920 and mtgBATCH 922/926 machines the density is not measured – taking instead a fixed value for the species.

$$[\text{dynamic MOE}]=[\text{density}]\times[\text{speed of sound}]^2 \quad (1)$$
where
$$[\text{speed of sound}]= 2\times[\text{length}]\times[1^{\text{st}} \text{ frequency}]$$

Timber was sampled from the United Kingdom and the Republic of Ireland with the aim of representing the properties of the spruce resource in this area. Cross-section sizes ranged from 22×47 mm up to 75×150 mm (Table 2). The 22×47 mm section size is not at all typical of production but was included as a worst case example of 22 mm thickness timber. A total of 863 pieces were used in the analysis.

***Table 2**: Sizes in these samples of spruce and larch*

Nominal cross-section (mm)	Number of pieces Spruce WPCS	Larch WLAD
22×47	138	57
38×100	70	-
47×100	343	418
47×120	79	-
47×150	75	17
75×150	158	160
100×275	-	54
Total	**863**	**706**

4.1.2 The properties of the dataset

The grade limiting property for British spruce is usually bending stiffness. However for this dataset strength is also limiting for two reasons:

- The inclusion of the small dimension timber
- When grading with portable grading machines

This dataset contains a number of unusually small dimension pieces which are, on average, less strong than the larger dimension sizes (due to the relatively large size of knots and other defects). The strength of these pieces are further reduced by the k_h factor of EN 384, which adjusts the measurement to a 150 mm reference depth (This has the effect of decreasing strength values, for depth of 47 mm, by 20%. This factor is then applied in reverse within EN 1995-1-1 [15] to increase the design strength based on the (previously reduced) characteristic strength. Whether there is a genuine size effect for timber is an open question (e.g. [16,17]).
EN 384 includes a further adjustment factor on strength. When grading bending strength classes (with characteristic bending strength less than or equal 30 N/mm^2) with an inline machine the target characteristic bending strength is reduced by a "k_v" factor of 1.12.
This k_v factor is there to account for lesser human involvement in machine grading in comparison to visual grading and the additional confidence that this is supposed to afford. The k_v factor is not applicable for portable grading machines as they entail more human involvement in setting up the equipment and undertaking

the grading, and cannot be subject to the same level of installation checking possible for in-line machines [4]. Without the 22×47 size included (725 pieces remain), the characteristic properties of the timber in this dataset exceed the requirements of C16 for grading with an inline grading machine (Figure 1). Without k_v, the strength still meets the C16 target).

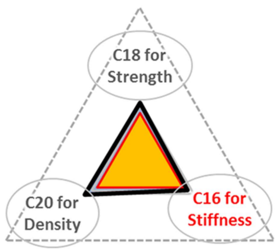

Figure 1: *The characteristic properties of this ungraded spruce dataset (without 22×47 dimension), and the strength classes met for each primary property separately (with the EN 384 k_v factor on strength)*

The number of different machines and grade combinations results in several different distributions of the primary properties when assigned to a strength class. Figure 2, Figure 3 and Figure 4 show the distributions of bending stiffness (E), bending strength (f_m) and density (ρ) for the timber assigned to C16 and C24 (the same 863 pieces graded by the machines under different grading combinations –alone or with another grade). The black circle denotes the characteristic value of the timber assigned to that strength class (mean for E, 5th percentile for f_m and ρ).

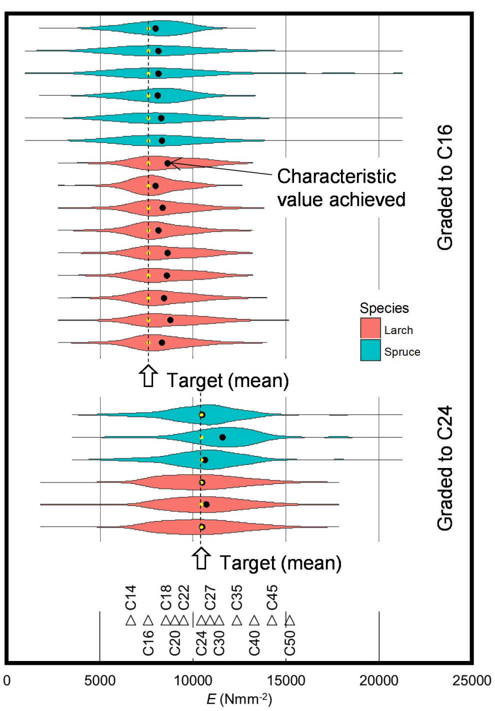

Figure 2: *Distributions of bending stiffness for timber assigned to C16 and C24 by various machine grading combinations*

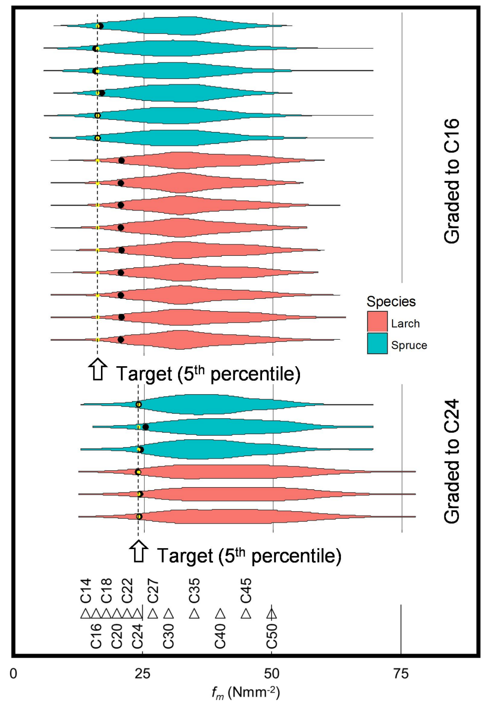

Figure 3: *Distributions of bending strength for timber assigned to C16 and C24 by various machine grading combinations*

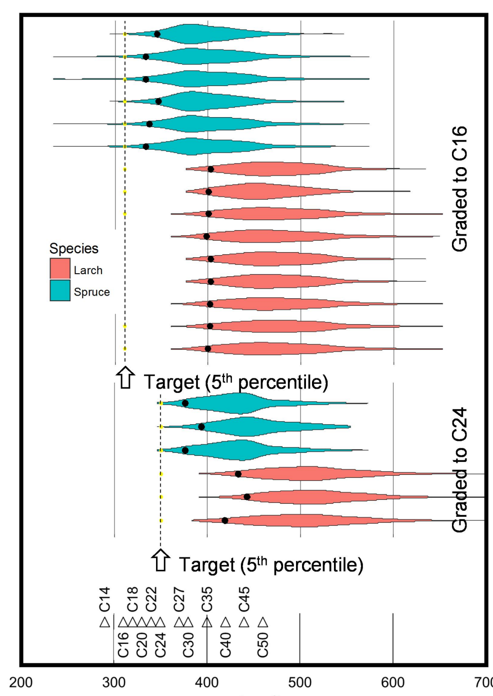

Figure 4: *Distributions of density for timber assigned to C16 and C24 by various machine grading combinations*

For inline machines, the k_v factor reduces the strength target by a factor of 1.12, which is why the achieved characteristic appears less than the requirement for some of the assignments.

These figures show the high degree of overlap between C16 and C24 in terms of the range of properties of pieces assigned to the strength classes, and how they can vary between machine and grade combination (even for machines operating on the same principle). This is quite normal for grading as the strength class definitions are actually quite close to each other and the machine grading parameter is not a strong predictor of strength (see 5.1).

The figures also show how, in this example, the characteristic density is commonly much higher than the strength class requirement (even for a species generally considered to have low density).

The range of the percentage of the target characteristic property achieved, for strength classes graded in various combinations with the different machines, is summarised in Table 3. For most cases, the assigned strength class properties are not far away from the true properties, but for C16, the usual grade produced in the UK, the strength and density properties are undervalued.

***Table 3**: Summary of target characteristic values achieved*

Class [1]	% of target bending strength	% of target bending stiffness	% of target Density
C14	110 to 126	112 to 116	114 to 115
C16	100 to 116	105 to 109	107 to 111
C18	100 to 104	100 to 105	105 to 110
C20	101 to 106	100 to 108	101 to 110
C22	101 to 124	102 to 113	100 to 110
C24	101 to 114	100 to 111	107 to 111

Note: this includes k_h and k_v factors

4.1.3 A way of using the properties better

When bending stiffness is not critical in the end usage, it makes little sense to limit the design values according to this property – with the associated unnecessary reduction in more relevant properties such as those governing compression and fastener capacity.

It is common in the UK to grade spruce to C16 and this is a recognised and familiar strength class. The sawmills are not really set up to handle grading in combination with any other grade, so although a higher grade can potentially be produced, it is desirable to focus on grading that produces a single grade with minimal rejects.

For this reason, a tailored strength class was created called C16+ (Table 1), which is compatible with C16 for the general market, but comes with potential for enhanced design when sold to customers who are familiar with the grade. The grading settings for C16+ can be identical to those of C16, meaning that this enhanced grade comes at no cost of increased rejects. The key secondary properties of C16+ could be further enhanced by establishing the values by testing (see 2.5), and specifying within the Declaration of Performance.

The strength class C16+ could also be sold and used as C16 as the properties are at least as good, so the use of a tailored strength class need not necessarily be incompatible with ease of trade provided there is no confusion.

4.2 UK-GROWN LARCH

4.2.1 Dataset

Structural timber has not been an important market for UK-grown larch, with timber typically going into fencing, packaging and cladding. However, sanitation felling in response to an outbreak of *Phytophthora ramorum* is resulting in larger volumes of larch timber being brought to market.

UK larch (WLAD) is a mixture of three species with similar properties: Hybrid larch (*Larix x eurolepis*, LAER), Japanese larch (*Larix kaempferi*, LAKM) and European larch (*Larix decidua*, LADC).

Until recently, UK-grown larch could only be graded visually (to C16 and C24), but now machine grading settings have been developed for a number of different grading machines and strength class combinations. Among them are settings for the same Brookhuis machines as in the spruce example (4.1.1).

Timber was sampled from the United Kingdom with the aim of representing the properties of the larch resource in this area. Cross-section sizes ranged from 22×47 mm up to 100×275 mm (Table 2). As with the spruce example, the 22×47 mm section size is not at all typical of production but was included as a worst case example of 22 mm thickness timber. A total of 706 pieces were used in the analysis.

4.2.2 The properties of the dataset

As with the spruce example, the presence of the small dimension timber in this dataset, and the lack of the k_v factor for the portable grading machines, makes strength more critical than it usually is for UK-grown larch.

Without the 22×47 size included (649 pieces remain), the characteristic properties of the timber in this dataset exceed the requirements of C22 for grading with an inline grading machine (Figure 5). Without k_v, the strength meets the C20 target and therefore becomes limiting).

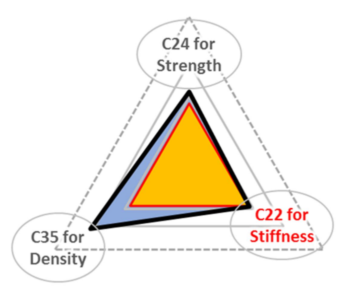

***Figure 5:** The characteristic properties of this ungraded larch dataset (without 22×47 dimension), and the strength classes met for each primary property separately (with the EN 384 k_v factor on strength)*

Figure 2, Figure 3 and Figure 4 show the distributions of bending stiffness (E), bending strength (f_m) and density (ρ) for the timber assigned to C16 and C24 (the same 706 pieces graded by the machines with different grading combinations). As with the spruce, there is a large overlap between C16 and C24 in terms of the range of properties of pieces assigned to the strength classes, which varies between machine and grade combination (even for machines operating on the same principle). Here density is much higher than the strength class requirement.

The range of the percentage of the target characteristic property achieved, for strength classes graded in various combinations with the different machines, is summarised in Table 4.

***Table 4**: Summary of target characteristic values achieved*

Class [1]	% of target bending strength	% of target bending stiffness	% of target density
C14	127 to 164	107 to 124	136 to 138
C16	128 to 144	105 to 119	128 to 130
C18	-	-	-
C20	107 to 107	106 to 106	123 to 123
C22	100 to 109	101 to 104	119 to 123
C24	100 to 111	100 to 103	119 to 126
C27	100 to 110	102 to 110	118 to 129
C30	101 to 110	103 to 114	115 to 129

Note: this includes k_h and k_v factors

4.2.3 A way of using the properties better

For larch, tailored strength classes could be created based on the most commonly traded, and familiar, strength classes, C16 and C24.

A tailored strength class for use in strength class/reject grading, with near 100% yield, could have the properties of C22 for stiffness, C24 for strength and C35 for density.

It should also be realised that sometimes there is an advantage to downgrading the timber to a lower strength class. For example, the settings table for the MTG 960 (hand-held grading machine with balance) includes C27 graded in combination with C16, but no settings for C24 in combination with C16. Those two strength classes, most demanded in the UK, cannot be graded together because the cost matrix in EN 14081-2 did not pass. However, it would be acceptable (and likely most commercially viable) to grade the combination of C27 with C16 and then mark down the C27 as C24. This 'C24' could still have enhanced properties on the DOP for those that want to use them.

5 SOME OTHER IMPORTANT THINGS FOR RESEARCHERS

Grading is aimed at construction – and its purpose is in ensuring that the properties of any individual piece are unlikely to be less than a certain value. The properties of individual pieces may be considerably higher, since it is likely only one property is limiting the timber to the grade. It may also be the case that the grading threshold has been purposefully lowered to improve yields – and all properties are higher than the strength class implies. Within timber graded to strength classes, there is also a wide range within the primary properties – a randomly selected piece of C16 may be stronger than a randomly selected piece of C24. Knowledge of the grade of a piece of timber *per se* is therefore not especially useful for research testing work and it is necessary to take additional steps to characterise the timber properties.

5.1 ESTIMATING PROPERTIES

In machine strength grading, one or more indicating properties are measured, non-destructively, on every piece of timber. These indicating properties allow estimation of the grade determining properties, but during grading they are estimating the characteristic properties of the timber passing the grading threshold, and not of the individual pieces of timber. Those indicating properties, can, of course, also estimate properties of individual pieces if used correctly.

The following is based on an ANOVA analysis of the spruce and larch datasets presented in sections 4.1and 4.2, but with the 22×47 cross section size removed from both datasets (since they are unusually small). Here strength properties of pieces are directly estimated, without application of the k_h factor adjusting to 150 mm nominal depth.

It was found that the dynamic modulus of elasticity from longitudinal resonance (E_{dyn} equation 1) was the best estimator of both strength and stiffness. For both these datasets, the density of the pieces (from weight of the whole piece) and dimensions did not add any additional predictive power. The equations for estimating strength and stiffness for pieces in these spruce and larch datasets are listed in Table 5, including 95% prediction interval (either upper or lower). These are also shown in Figure 6 and Figure 7.

***Table 5**: Equations for predicting the properties of individual pieces within these datasets of spruce and larch with a one tailed 95% prediction interval*

Property				PI
Bending strength (N/mm^2)				
The spruce	2.96	$\times E_{dyn}$	+5.1	±15.7
The larch	3.31	$\times E_{dyn}$	+6.2	±18.6
Bending stiffness (kN/mm^2)				
The spruce	0.905	$\times E_{dyn}$	-0.28	±2.85
The larch	0.805	$\times E_{dyn}$	+1.15	±2.53
Density (kg/m^3)				
Both	0.999	$\times \rho_{piece}$	-22	±38

Note 1: E_{dyn} is in units of kN/mm^2, ρ_{piece} is in kg/m^3

Note 2: this model is without the effects of k_h (it is for estimating directly the properties of individual pieces).

Note 3: Does not include the 22×47 mm cross section.

Note 4: Subtract PI for lower 95% prediction interval, add for upper 95% prediction interval.

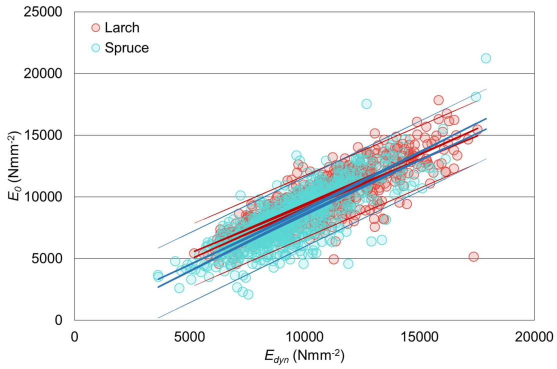

Figure 6: *Prediction models for bending stiffness of the larch and spruce from measured dynamic stiffness (inner lines are 95% confidence interval, outer lines are 95% prediction limits)*

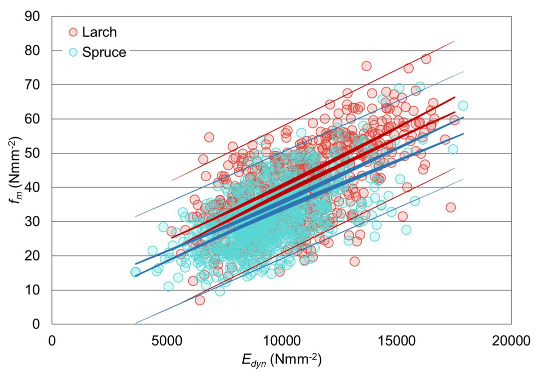

Figure 7: *Prediction models for bending strength of the larch and spruce from measured dynamic stiffness (inner lines are 95% confidence interval, outer lines are 95% prediction limits)*

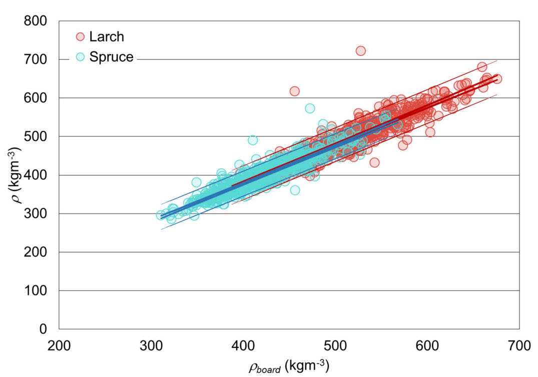

Figure 8: *Prediction model for density of the larch and spruce from measured full piece density (inner lines are 95% confidence interval, outer lines are 95% prediction limits)*

For density, the mass/volume of the whole piece at time of grading (adjusted to 12% moisture content) is a good estimator. Here both species can be estimated with the same model (Figure 8 and Table 5). The variation here is principally the variation of density within the individual pieces of wood (the density of a density sample taken after testing is being predicted).

6 SUMMARY

There is an opportunity to use grading more intelligently: taking advantage of the flexibility of strength classes to make better use of the true properties of the timber used. Tailored strength classes, and standard strength classes with enhanced secondary properties can be used when the graded timber is not placed on the open market, because it is graded within the same company that uses it, or is manufactured to order for a specific customer. Furthermore, if a company is grading timber for its own use manufacturing timber kits, or glued laminated members, then it makes sense to consider whether the general grades are the best option. With the availability of relatively inexpensive and simple portable grading machines, and the option of output control grading, it may also make better business sense to grade to strength classes tailored to the timber source, or the end use. Density is a particular case in point as it can be measured very well in the grading process.

Furthermore, it is necessary to realise that strength classes are not good descriptions of wood properties for research work and that the strength class of a single piece of timber gives little information about the properties of that particular piece, other than a statistically defined lower bound.

Finally, the amount of destructive testing involved in establishing machine grading settings and visual grading assignments presents a barrier to greater use of local timber, and diversification of commercial species, so it is important that any researcher assessing the properties of such species should consider, from the outset, doing the research in a way that can contribute to a grading dataset at a later date.

ACKNOWLEDGEMENT

The authors are grateful to the various funders and collaborators of the underlying research, including Forestry Commission Scotland, The European Regional Development Fund (ERDF), Scottish Enterprise, Wales Forest Business Partnership, Confor, BSW Timber, James Jones & Sons Ltd, Adam Wilson & Sons Ltd (Glennon Brothers), the Scottish Forestry Trust, Wood for Good, Adam Wilson & Sons, Euroforest, James Callander & Sons Ltd, John Gordon & Son Ltd; Scottish Woodlands Ltd, UPM-Tilhill, John Gordon & Son Ltd, Murray Timber Group Ltd, Brookhuis and MiCROTEC. Additional practical assistance was provided by Forest Research, Buccleuch, Living Solutions and NUI Galway.

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