Technical note on the use of visual grading codes for the appraisal of individual in situ structural timber elements

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Summary

It is common practice in the UK, the continent of Europe and in the USA for structural engineers to use visual grading codes when carrying out an appraisal of individual structural timber elements in an existing structure. The purpose of this technical note is to present the findings of a limited study into the background and efficacy of this process. Following a literature review of visual grading, three codes are used to visually grade a sample of new timber joists (n=527) of four lesser used species and the results are compared with the results of the laboratory testing of the same joists.

It is concluded that the three visual grading codes reviewed are poor predictors of the mechanical and physical properties of individual timber joists. This outcome was expected and reflects the inappropriate use of the codes in this context rather than a fault in their use as intended (grading large numbers of timber elements from known sources for commercial purposes). Some aspects of visual grading could be used in the creation of a more appropriate model to predict the key mechanical properties of in situ structural timber.

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1 Introduction

It is common practice in the UK, the continent of Europe and in the USA for structural engineers to use visual grading codes when carrying out an appraisal of individual structural timber elements in an existing structure. The purpose of this technical note is to present the findings of a limited study into the background and efficiency of this process. Following a literature review of visual grading, three codes are used to visually grade a sample of timber joists (n=527) of lesser used species and the results are compared with the results of the laboratory testing of the same joists.

In this technical note, visual grading codes are discussed and reviewed in relation to the appraisal of individual in situ timber elements. Visual grading codes make use of visual features to estimate the mechanical and physical properties of batches of timber. They are also used by structural engineers when appraising the properties of in situ structural timber. So, it is important to understand their efficacy, and their strengths and weaknesses.

In this technical note, there is a brief introduction to visual grading together with a short literature review, covering the purpose and development of visual grading together with a review of three of the national visual grading codes, currently used with the Eurocodes. The three codes are used to visually grade a sample of new minor species joists (n=527) and the results are compared with the results of the laboratory testing of the same joists. How well the visual grading codes categorise groups of joists and individual joists in relation to their mechanical and physical properties is considered. Finally, if visual grading codes are not appropriate for the appraisal of in situ timber elements, then are any parts of them potentially useful in building a predictive model for this job?

2 Literature review

2.1 The purpose of visual grading codes

The natural variability of timber is so great that producers have, over time, found it necessary to grade timber as best they can to give some measure of assurance to purchasers and users. Appearance grading is useful for architects and other users and specifiers of wood who require minimum requirements for surface appearance. Strength grading is useful for structural engineers who need to specify structural timber with minimum requirements for mechanical and physical properties. So for instance, for the highest appearance grades, no splay or bark ringed knots are permitted regardless of their size as these are considered unsightly. Whereas, for strength grades, knot sizes are limited according to their perceived effects on bending strength and stiffness and so knots of this nature could be acceptable, even for the highest of grades.

Strength grading can be done through visual or mechanical grading. The focus of this technical note is on strength grading carried out by visual grading followed by strength classification.

Of particular importance to structural engineers are the characteristic values of the key properties of bending strength, stiffness and density. The strength properties of an ungraded batch of timber can vary so much that the strongest piece may be up to ten times stronger than the weakest. Thus, for economic reasons, it is useful to adopt a small number of strength classes to divide up a batch of timber. Due to the limited correlation between visual grading parameters (and indeed machine grading indicating properties) and the mechanical and physical properties of individual pieces of graded timber, there is much overlapping of the strength classes.

In short, visual grading codes form a link in a chain of 'strength grading' which is a process enabling (i) timber suppliers to economically sell their structural timber to the construction industry and (ii) structural engineers to specify structural timber safely and straightforwardly.

Specifically, the Eurocodes (CEN, 2013, 2016b, 2019) define a two stage process of (i) visual grading which places packages of timber elements into visual grading categories (mechanical grading does the same thing) and (ii) strength classification which allots the visual grading categories into strength classes. Structural engineers can then make use of the strengths and stiffnesses in the allotted strength classes when designing buildings and structures (CEN, 2006). Modern strength grading allows a structural engineer to simply specify a strength class (e.g. C24) for structural timber fulfilling a particular purpose and to be sure that the minimum associated values of the mechanical and physical properties of the supplied timber will be provided with a specified level of reliability.

This deceptively simple explanation is reliant on extensive, controlled testing of carefully defined and sampled datasets, the results of which are statistically manipulated, again in a standardised way, to allow the quantification of the properties of timber elements of a particular size, for a particular species from a particular source (CEN, 2010, 2012, 2016a). It is important to note that the visual grading categories and the strength classes relate to sets of pieces of timber and not to individual pieces of timber. Each strength class is defined by lower bound limits of the key mechanical and physical properties and the strength class to which a batch of timber is allotted is determined by the lowest values of the batch's key mechanical and physical properties. Thus, a batch of timber of low density (but high bending strength and stiffness) joists could only achieve a low strength class (due to their low density).

Broadly, for the structural appraisal of in situ timber elements, structural engineers need to determine separately each of the mechanical and physical properties of each individual timber element. The timber elements' properties can then be used to prove their adequacy in their individual situations (span, loading, etc.). Additionally, structural appraisals of in situ timber are typically carried out for 'borderline' situations where the timber elements are expected to be marginally adequate to support their applied loads. In situations like this, finer gradations between estimates of properties are preferable to allow an engineer to use the least conservative (but safe) values in structural calculations. Unfortunately, it is seen that broad brush strength grading is unsuitable for these purposes.

2.2 The development of visual grading codes

Structural engineers and architects have always had to manage the structural quality of timber used in their building projects and, prior to ‘strength grading’ (as the above process is termed in the Eurocodes), other methods had to be used, some of which are more prescriptive and less flexible. None of which provide accurate estimates of the strength and stiffness of individual pieces of structural timber.

2.2.1 19th century

During the 19th century, from experience and trade books on the matter, those working in construction in the UK would have been aware of the relative merits of the various species of softwood available. This is shown in historical documents such as the ‘*Specification of the Works to be performed in the Erection of Schools at Brixton for the Worshipful the Freemen's Orphan School Committee - James B. Bunning, Architect, 1851-52’ Carpenter materials* (Donaldson, 1860):

> *“The fir to be new best yellow crown Memel, free from all defects.*
>
> *The deals to be the best thoroughly seasoned hearty yellow Christiana, free from all defects.*
>
> *The oak to be the best English growth…”*

This specification (typical of its time) limits the supply of timber on the project to particular species from particular sources. Memel and Christiana are old names for Baltic ports in Lithuania and Denmark respectively and ‘yellow’ Baltic timber typically (but not always consistently) refers to European spruce. The term ‘crown’ relates to a high quality timber to be supplied based on appearance grading (Vandenabeele, Bertels and Wouters, 2016).

Some of the pitfalls of this approach are illustrated in another specification from this century. In the Specification of the Works for a new stable and coach house at Castleton Grange in Rochdale (Peters, 1869), it was required that: “*The timber for the sashes and frames and outside door frames must be the best Red Deal or Baltic Timber. The timber for joists, spars and flooring boards must be the best White Deal. The remainder of the timber throughout the premises unless otherwise specified must be the best American Yellow Pine*.”

The European species *Pinus sylvestris* and *Picea abies* are specified for the external and structural timber and, as several species from North America are termed yellow pine, other cheaper American timber is loosely specified for the remainder of the works.

It is ironic that this careful specification, which presumably functioned perfectly well in the region of Rochdale makes use of such imprecise terms as ‘White Deal’ and ‘American Yellow Pine’. From a variety of contemporaneous records, from the US and the UK, the term American Yellow Pine could be applied to several different species of North American trees. Nevertheless, in the 19th century, structural timber can be seen to have been approximately specified on the basis of both species and growth area.

Additionally, some reference to quality (i.e. terms such as ‘best’, ‘free from defects’, and ‘crown’) is also commonly used.

It must be borne in mind that very few specifications have survived from the 19th century and these typically relate to institutional buildings and other structures where documentation firstly, had to be produced for the initial construction and secondly, has been safely stored following construction. The select group of structures to which the specifications belong are not therefore representative of all construction of that period (e.g. lower quality housing and speculatively built commercial properties). Far fewer specifications have survived from earlier centuries.

Wood has for a long time been sorted on the basis of its appearance, using commercial or appearance grades such as the Scandinavian system of Unsorted (I, II, III and IV), Fifths and Sixths (Tredwell, 1973), and although this can be an adequate system for joinery, none of the grades are direct indicators of strength or stiffness. Even so, the appearance grades are a useful indication of the likely strength of a piece of wood. Other European countries adopt similar but different approaches, for instance the Russian equivalent of the above grades would approximately be Unsorted (I, II and III), Fourths and Fifths (Coulson, 2012).

In the UK, early works on carpentry (Nicholson, 1826; Tredgold, 1875) presented the experimental studies of others: limited testing on very small samples of just a few species. As such, due to the variability of timber, these works were and are of very limited value (neither providing useful design information in the 19th century nor historical information on the properties of 19th century timber to structural engineers in this century).

2.2.2 Early 20th century

In the USA the first guidelines for strength grading rules appeared in 1927 as ASTM Standard D245 (Madsen, 1992). Grading rules in the Pacific Northwest of America (Export ‘R’ List Grading and Dressing Rules) were first published in 1929 as the N List and are the most widely used references for timber exported from this region (Pacific Lumber Inspection Bureau, 1971). These extensive rules use different nomenclature again but broadly follow the same approach of classifying timber according to the size and number of visible ‘defects’ apparent – without any particular regard to strength or stiffness.

Appearance grading (a.k.a. defect grading) does not account for matters such as: density, the positions of defects in relation to the cross section and in relation to the length of the piece of wood. Thus, pieces of wood with good appearance grades could and should be occasionally rejected in terms of strength, stiffness and density, should they be processed by a system of strength grading.

The standardisation of visual grading in the USA began at the start of the 20th century in relation to the needs of the railways (building large scale trestle bridges). Then, during the interwar years in the UK, a programme of testing of small clear specimens was begun in relation to the needs of the aircraft industry. This industry typically required greater confidence in strength and stiffness values than the construction industry and could afford to use clear wood as its structural members (despite increased costs). Hence the use of small clear specimens (Yeomans, 2020).

2.2.3 Later 20th century and CP112

In the UK, the first codified visual grading code was published in 1952 as the first of four editions of CP112. The first edition of the code provides just two basic stresses for two groups of timber species with limitations placed on knot sizes, slope of grain and rate of growth (BSI, 1952). This edition was based on the results of testing carried out between the wars and of all editions of the code, this one is based on the smallest volume of testing and its limited nature renders it the least attractive to structural engineers. Nevertheless, it forms the basis for the subsequent two revisions published in 1967 (imperial units) and 1971 (unrevised but converted to metric units). Finally, in 1973, Amendment 1265 to the metric version was published, making it the most attractive to structural engineers practising now. This most recent and amended version of CP112 is the one discussed below (unless noted otherwise).

The approach of the code is to determine, for each of 14 species, basic stresses which are *'governed by the general characteristics of the particular species, free from all visible defects'* and then to modify these basic stresses to create grade stresses which are *'governed by the effect of visible gross features such as knots, sloping grain, etc.'* (BSI, 1967). Booth and Reece (1967) specify the strength reducing factors used in the creation of the basic stresses as: (i) variability of strength; (ii) moisture content; (iii) long duration loading; (iv) factor of safety and (v) size and shape of members. The basic stresses are used to determine four stress grades (75 Grade, 65 Grade, 50 Grade and 40 Grade) which are intended to broadly relate to percentage reductions in permissible stresses; for instance, Grade 75 timber has approximately 75% of its strength remaining after consideration of knots, sloping grain, etc. Despite the availability of the stress grading of CP112, it was not widely used in the industry and the usual method of grading continued to be by appearance (Tredwell, 1973) for many years.

2.2.4 BS4978 and the Eurocodes

The first edition of the UK's current visual grading code was published in 1973 and this introduced the concept of knot area ratios. Until this point, the effect of knots had been quantified by the ratio of their diameter with the width of the face of the section on which they appear. This new code (BSI, 1973) established the principal of considering the ratio of the projected knot area with the cross sectional area of a piece of timber, in place of the surface knot area. This same method is still in use in the UK (BSI, 2017).

In the 1980s, the position in the UK, of (i) grading imported and home-grown timber using rules based on a defect system and (ii) grading a moderate and increasing proportion of the imported timber on a stress-grading basis, was considered '*somewhat unique*' (Desch and Dinwoodie, 1981). Strength grading (an alternative name to stress grading) is now the common form of grading throughout Europe, making use of either visual grading or machine grading.

Due to the wide variety of species, dimensions and uses of graded timber, the harmonization of visual grading rules in Europe led to a flexible standard that allows individual countries to develop and use their own grading rules as long as they account for certain minimum requirements in terms of the visible characteristics of wood that must be assessed (Glos, 1995; CEN, 2019).

Despite development over many years, the current standards only apply to rectangular timber, thus, there are no structural visual grading standards for differently shaped wood, such as round timber, nor for modified wood such as thermally modified or chemically modified wood.

It should be noted that each version of each visual grading code has been developed on the basis of testing carried out on specific growth areas and species at a certain time (reflecting the forestry practices of that time). Thus, as growth conditions and growth areas vary over time, then the applicability of older versions of visual grading codes reduces with age. Finally, despite advances in machine grading, much structural timber in Europe continues to be graded visually and based on national standards.

2.3 How visual grading is carried out in accordance with the Eurocodes

The simple two stage process (of visually grading and then allotting strength classes) described above is in reality rather more complex. Table 1 presents the key codes involved in the process of grading and strength classification. As is normal for the Eurocodes, a single process such as this requires the use of several different codes of practice which work together to reach the desired end point. The listing of the relevant codes of practice in Table 1 is a useful background exercise.

Table 1. Key Eurocodes involved in visual grading and strength classification

Eurocode reference and title	Comments
Framework within which the visual grading and strength classification takes place	
EN14081-1, Timber structures — Strength graded structural timber with rectangular cross section — Part 1: General requirements	Minimum requirements for visually grading timber
Choose sample number(s) and size(s)	
EN384, Structural timber — Determination of characteristic values of mechanical and physical properties and density	Choose source location/extent and species/species group and cross sectional size of timber elements Assessment methods, number of samples and compliance criteria Includes adjustment factors for characteristic values
Visually grade test pieces in sample(s)	
BS4978, Visual strength grading of softwood – Specification	Current visual grading code of practice for the UK DIN4074 and INSTA142 for instance for other countries
EN1309-3, Round and sawn timber. Methods of measurements. Features and biological degradations	Measurement of features in wood such as knots and slope of grain
EN844-9, Round and sawn timber — Terminology — Part 9: Terms relating to features of sawn timber	Terminology of sawn timber, with useful definitions
Laboratory testing of all test pieces in sample(s)	
EN408, Timber structures — Structural timber and glued laminated timber — Determination of some mechanical and physical properties	Test methods for determining the mechanical and physical properties (and dimensions, moisture content and density) of structural timber
EN13183-1, Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method	
Calculation of characteristic values of properties	
EN14358, Timber structures — Calculation and verification of characteristic values	Calculation method for characteristic values, mostly statistical methods
EN384, Structural timber — Determination of characteristic values of mechanical and physical properties and density	Assessment methods, number of samples and compliance criteria Includes adjustment factors for characteristic values
Allotting of strength classes	
EN1912, Structural Timber — Strength classes — Assignment of visual grades and species	Links visual grading classifications with strength classes for species and growth areas (but not an exhaustive list)
EN338, Structural timber — Strength classes	
Design structural timber	
EN1990, Eurocode - Basis of structural design	Reliability basis of the Eurocodes for materials and design
EN1995-1-1, Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings	Design of timber structures using strength classes and characteristic values
Recently superseded and withdrawn Eurocodes relating to structural timber and its grading	
EN1310:1997, Round and sawn timber — Method of measurement of features	Now superseded, withdrawn
EN518, Structural timber — Grading — Requirements for visual strength grading standards	Now superseded, withdrawn

The process defined by the Eurocodes has been outlined and described by others already (Ridley-Ellis, Stapel and Baño, 2016 , Porteous & Kermani, 2007) and this section merely comments on the most salient aspects of this process. Visual grading has developed over the course of the 20th century in different countries in different ways, to suit local species, growing conditions and timber quality and construction traditions. So much so, that the structural Eurocodes (which provide a harmonized set of European standards which give common rules for design and common technical specifications for building products) provide only a loose framework within which individual countries issue their own visual grading standards.

The framework document EN14081-1:2016 (CEN, 2019) lists requirements for the measurement of strength reducing characteristics such as knots and slope of grain and geometrical, biological and other characteristics. Knots must be measured in accordance with EN1310 (CEN, 1997a); slope of grain must be defined in accordance with EN844-9 (CEN, 1997b) and rate of growth limits are preferred to be given in increments 3mm, 4mm, 6mm, 8mm, 100mm and 15mm.

The framework document, EN14081-1 (CEN, 2019), also requires that either rate of growth (RoG) or density must be included in a visual grading standard (Clause A.1.3 Density and rate of growth) and typically, RoG is used.

Due to economic constraints, visual strength grading must be able to be carried out very quickly (just a few seconds for each piece of timber) and so the grading rules should be clear and simple and able to be applied quickly. Additionally, margins of safety must be included to allow for slight variances in quality and consistency of grading due to its speed. Overall, in the assessment of freshly sawn timber pieces, the balance favours economy over grading accuracy (Glos, 1995).

Due to the extent of testing required to create a new grading rule (for a particular species from a particular growth area), the grading standards impose significant expense on the timber industry. This cost is disproportionately high for minor species from limited growth areas. As graded structural timber can be sold for only slightly more than ungraded wood to be used for other purposes, the cost of testing serves to restrict the diversity in the supply of structural timber.

The process of strength grading in the UK is summarised below. This contrasts the relatively extensive initial testing process required when a new species or growth area is developed for the first time with the relatively simple strength grading process which can be followed from then on (involving cheap and quick visual grading) for timber elements from known species and growth areas.

INITIAL TESTING: (1) Define species and growth area, (2) Choose sample(s), (3) Visual grading of test pieces in sample, (4) Laboratory testing of test pieces in sample(s), (5) Using all test pieces in each visual grade, determine the characteristic values of their grade determining properties, (6) Assign strength classes to visual grades.

SUBSEQUENT STRENGTH GRADING: (1) Ensure that species and growth area of timber elements conform to initial testing, (2) Visually grade the timber elements, (3) Determine the strength class of each timber element based on: (i) visual grade, (ii) species and (iii) growth area.

The focus of these two processes on the defined species and growth areas includes an implicit assumption that forestry and sawmilling practices remain constant (along with climate and other growing conditions), which is a reasonable assumption over relatively short periods of time but becomes less reasonable as the period of time stretches from years to become decades (given the research also being done on silviculture and seed selection).

The application of current visual grading and strength classification processes to in situ timber would rely on assumptions about the in situ timber regarding: (i) growth areas, (ii) forestry and sawmilling practices at the time of felling trees for timber and (iii) climate and other growing conditions. Given that any one of these factors can significantly affect the mechanical and physical properties of timber (Høibø *et al.*, 2014; Zobel and van Buijtenen, 1989; Stapel and van de Kuilen, 2010), this is an important issue that appears to be currently overlooked.

It should be noted that the imprecision of visual grading means that the number of visual grading categories significantly affects the efficacy of the visual grading code. One of the chief criticisms of CP112 was the relatively high number of four categories plus reject (Tredwell, 1973) and this was one reason for its replacement by BS4978, with only two categories plus reject.

2.4 How well visual grading works in practice

2.4.1 New timber

There is little research on the effectiveness of visual grading rules and their application to new timber (Stapel and Van De Kuilen, 2014), and that which was found in this literature review typically focusses on one of three aspects: (i) the economics of grading and the grade boundaries and their effects on yield (and the characteristic values obtained in relation to strength classes) (Almazán *et al.*, 2008; Stapel and Van De Kuilen, 2014) and (ii) new methods of measurement to improve visual or machine grading (Roblot *et al.*, 2010; Lukacevic, Füssl and Eberhardsteiner, 2015; Viguier *et al.*, 2015) and (iii) new methods of combining measurements to improve visual or machine grading (Blass and Frese, 2004; Hanhijarvi, Ranta-Maunus and Turk, 2005; Hanhijarvi and Ranta-Maunus, 2008).

Although the aspects of grading discussed above are of interest, they do not directly address the predictive power of grading methods when applied to individual pieces of timber. It could be that a grading code functions adequately to sort timber into strength classes with a reasonable yield and with adequate characteristic values, but it has weak predictive powers. So, it is important at the outset to be clear that the purpose of visual grading and strength classification is not to estimate the mechanical and physical properties of individual timber elements but to reliably allocate timber elements into groups whose characteristic mechanical and physical properties accord with the strength classes of the Eurocodes. Accurate predictions of individual properties are not to be expected from visual grading and the results of this small study live up to these expectations.

It is worthwhile to report on three studies which focus on the efficacy of current visual grading codes in Europe. Stapel and Van De Kuilen (2014) drew several conclusions following the analysis of over 12 000 timber test pieces which validate the choice of DIN4074, INSTA142 and BS4978 for assessment in this study. These conclusions are summarised as follows:

1. The grading results for DIN4074, INSTA142 and BS4978 are similar and generally meet or nearly meet requirements for characteristic values
2. In most cases, attempting to grade C30 is problematic, leading to inadequate characteristic values
3. Visual grading codes with just two grading categories (plus Reject) such as BS4978 function better than those with more categories
4. The French national visual grading code (AFNOR, 1991) differentiated poorly between C18 and C24 (giving equal yields of each grade with similar characteristic values) and also produced low yields of C30
5. The Swiss national visual grading code (SIA, 2009) had such extreme reject rates that it was not practical to use

Almazan et al (2008) similarly compared the Spanish national visual grading code UNE56544 with DIN4074 and conclude that as the German code had lower reject rates and a simpler measure of knot measurement that the Spanish national code should be revised accordingly.

Stapel, Denzler and van de Kuilen (2017) reviewed one approach to extend growth areas used in visual grading. Based on Norway spruce from several growth areas of Europe (n=8487), calculated timber properties were found to vary considerably by region. So, pan-European grading areas are considered to be problematic if based solely on visual grading. This is not to say that visual assessment combined with NDT could not work adequately for combined growth areas.

2.4.2 In situ timber

There is little research on the effectiveness of visual grading rules and their application to individual in situ timber elements to determine their design strengths and stiffnesses. What has been found in this literature review is generally based on small sample sizes and rarely differentiates between the original purpose of the codes of practice used and the purpose to which they are being put in the research. It is concluded that the hoped for effectiveness is not investigated in any valid way.

There is a common misunderstanding that visual grading and strength classification codes use visual parameters to determine the strength or stiffness of the pieces of timber inspected, as opposed to the determination of the characteristic strength or stiffness of an entire batch of timber pieces being inspected. The absence of this distinction is generally illustrated in the text of journal articles (Piazza and Riggio, 2008, p. 269)

> *"The ability of a grading system to estimate strength (and other grade-determining properties) depends upon how reliably the measured characteristic(s) can predict the true strength of the timber, and how accurately the characteristics can be measured."*

This paragraph is ambiguous at best and suggests that visual grading codes predict the strength of individual pieces of timber.

Very few studies have been undertaken assessing the application of visual grading codes to individual timber elements. In one of the very few, Piazza and Riggio (2008) applied two Italian visual grading codes (UNI11035 and UNI11119) to spruce, larch and chestnut with disappointing results. UNI11035 and UNI11119 predicted values of MoR between -31% and +43% different to values obtained from testing; the predictions of this study are summarised in Table 2.

Table 2. Actual bending strength and stiffness compared with predictions from visual grading codes (Piazza and Riggio, 2008, p. 287)

	UNI11035			UNI11119		
	minimum	maximum	r	minimum	maximum	r
MoR	-66%	+74%	+0.6	-68%	+20%	+0.4
MoE	-31%	+43%	-0.3	-40%	+54%	+0.3
Density	-43%	-4%		-21%	+5%	

As density is considered to be a useful predictor of both MoE and MoR, its correlation coefficient for both was calculated and ranged from r = 0.21 (MoE) to r = 0.17 (MoR).

It should be noted that the predicted MoR of UNI11035 is the characteristic MoR and so is expected to be significantly lower than the actual MoR. That at least one predicted value of MoR was 74% greater than the tested value of MoR of the same joist shows the weakness of this approach. Predicted values of MoE are mean values which would be expected to be more tightly grouped around the tested values of MoE (due to the lower CoV of MoE in general), however this is not apparent.

Finally, as discussed in the introduction, the superseded code of practice CP112 is commonly used in the UK in the appraisal of in situ structural timber by structural engineers. This old code does not accord with the Eurocodes and is therefore not considered as a potential basis for any possible future method of assessing in situ timber. However, due to its current widespread use in the UK, it is worthwhile considering its efficacy and this is done in a conference paper (Bather and Ridley-Ellis, 2019), the relevant points of which are briefly covered in this technical note.

2.5 Comparison of measures of visual grading codes in Europe

In this technical note three codes of practice from the UK, Germany and Denmark are considered (BS4978, DIN4074 and INSTA142) (Dansk Standard, 2009; Deutschen Institut für Normung, 2012; BSI, 2017). Each of these three codes of practice have been developed for timber from differing growth areas and hence, even for the same species, different approaches are to be expected. These differences are compounded by different saw milling and construction practices, such that, for instance, one region prefers large square shaped timber joists and another prefers small and thin joists (see Table 3 and the following paragraphs).

The visual grades from each code of practice have been linked to their relevant strength classes in EN338 using EN1912. All three visual grading codes specify limits on the sizes of the timber elements that they are to be used with. These are summarised in Table 3. DIN4074 has different grading limits for timber of different cross sectional proportions. From its Table 1, it is determined that '*Kantholz*' is the appropriate form of timber element for joists in general and for the nominal 50mm x 100mm timber test pieces used in this study. The grading limits for Kantholz are found in Table 2 of DIN4074.

Table 3. Section size limits for the three visual grading codes

	Narrow horizontal edge (b) (mm)	Wide vertical face (h) (mm)
INSTA142	≥ 45	≥ 75
DIN4074	≥ 40	$\geq 3b$
BS4978	$b \geq 20$ and $cross\ sectional\ area \geq 2000\ mm^2$	

The three most important visual features in visual grading codes are knots, slope of grain (SoG) and rate of growth (RoG) and so, the ways that these are dealt with are considered below.

BS4978 gives knot limits in terms of area ratios rather than dimension ratios. The limits given in the Table are therefore approximated from the area ratios given to allow comparison with the other two codes. In Table 4 it can be seen that knot limits vary significantly between visual grading codes in relation to the same strength classes. As the limiting ratios for DIN4074 are the same for both the narrow edge and wide face, in comparison with INSTA142, this code has tighter limits for the edge and looser limits for the face. As BS4978 limits both margin and total knot area ratios it is not necessary to limit the size of edge knots for both of the visual grading categories in the code.

Table 5 covers SoG and RoG. SoG is the three dimensional deviation of the grain from the longitudinal axis of the timber element, expressed as the deviation in mm over a 100mm length. RoG is given as ring width measured over as long a distance as possible, ideally more than 25mm away from the pith.

Table 4. Face and edge knot size limits as percentages in visual grading codes

	Horizontal narrow edge limits as a percentage of edge dimension (b)				Vertical wide face limits as a percentage of face dimension (h)			
	C14	C18	C24	C30	C14	C18	C24	C30
INSTA142	100	80	50	33	50	40	25	17
DIN4074		60	40	20		60	40	20
BS4978	100	100			50	33		

Table 5. SoG and RoG dimensional limits in visual grading codes

	Slope of grain (as deviation in mm over 100 mm length)				Rate of growth (as ring width measured in mm)			
	C14	C18	C24	C30	C14	C18	C24	C30
INSTA142	25	17	12	10	any	8	6	4
DIN4074		12	12	7		6	6	4
BS4978	17	10			10	6		

There is little agreement over limits for SoG, apart from Strength Class C24, for DIN4074 and INSTA142. Whereas, for RoG, there is agreement between the same two codes for both C24 and C30. Of interest is the lack of any limit for Strength Class C14 for INSTA142.

Table 6. Treatment of knots and minimum size of knots required to be considered in visual grading codes

	Knot clusters	Knot groups	mKAR/tKAR	Minimum knot size (mm)
INSTA142	Yes	No	No	≥ 7
DIN4074	No	No	No	≥ 5
BS4978	Yes	No	Yes	≥ 5

As is seen in Table 6, the three codes of practice treat knot clusters and knot groups differently and only BS4978 considers knot area ratios. Even the minimum size of knots to be considered in visual grading differs.

All in all, it can be seen in this small group of tables that all three visual grading codes are in agreement with a general pattern of reducing SoG and RoG and knot measures being linked with stronger strength classes, but the detailed limits used to differentiate between strength classes vary. The different ways of measuring knots vary from one code to another and the limits specified for knot measures, SoG and RoG also vary. It is hard to see any patterns in these differences and it is not possible to understand the logic behind them, leading to the conclusion that these differences relate to local forestry and saw milling practices or possibly are of an arbitrary nature.

3 Visual grading and strength classification

The sample of timber joists used in this study was created and tested as part of the work carried out by David Gil-Moreno in undertaking his thesis titled "*Potential of noble fir, Norway spruce, western red cedar and western hemlock grown for timber*" (2018). The thesis contains information on the manner in which the sample (n=527) of timber joists was created and the structural sized timber joists (nominally 50mm x 100mm x 3.1m long) were cut, seasoned, prepared, measured and tested in the laboratory. The four minor species are Noble fir (Abies procera), Western hemlock (Tsuga heterophylla), Norway spruce (Picea abies) and Western red cedar (Thuja plicata), and were grown in Scotland, England and Wales.

In addition to the laboratory testing, a four stage process was followed, beginning with the recording of the visual observations (knot measurements, SoG and RoG) of the joists. Secondly the rules of three visual grading codes (Dansk Standard, 2009; Deutschen Institut für Normung, 2012; BSI, 2017) were applied to each joist and visual grades established. Thirdly, EN1912 (CEN, 2013) was reviewed in order to choose the most appropriate strength classes to link with the visual grades determined. Finally, EN338 (CEN, 2016b) was used to determine the characteristic values of MoR, MoE and density for the joists graded.

Visual grades were determined and assessed for the three visual grading codes and additionally for CP112 (BSI, 1971). EN1912 links each visual grading category with a strength class only for a limited number of species and growth regions which it terms 'sources'. From Table 1 and Table 3 from EN1912 the links are estimated for the four minor species investigated and visually graded.

Regarding the four minor species of this study, EN1912 only directly relates the visual grades for a single species and growth area to strength classes (the BS4978 visual grades of Norway spruce, grown in the UK can be directly related to strength classes by EN1912). However, EN1912 does relate similar species of the same genii from northern European growth areas to strength classes. Thus, it is possible to link other visual grades for similar species from slightly different growth areas to strength classes in an approximate manner. Reference should be made to Table 1 of EN1912 which provides the reader with the background information used in creating the approximate links between the minor species, their growth areas in the UK, their visual grading categories and their strength classes.

For Europe, the growth area references used in EN1912 are given below:

NNE	Northern and North Eastern Europe
CNE	Central, Northern and Eastern Europe
G&A	Germany and Austria
D&N	Denmark and Norway
UK	United Kingdom
IRLD	Ireland

A literature review was unable to identify a map or any other document from the suite of Eurocodes that defines the combined growth areas (such as CNE and NNE) used in EN1912. However, the map in Figure 1 partitions Europe into several sectors including Northern (mid-blue), Western (turquoise), Central (yellow), Eastern (dark pink) and Southern (red and green) and is based on the CIA World Factbook (CIA, no date). This map was clearly never intended to be used for timber growth areas but adopts a sensible split of the continent, based roughly on climatic and cultural zones and following national boundaries.

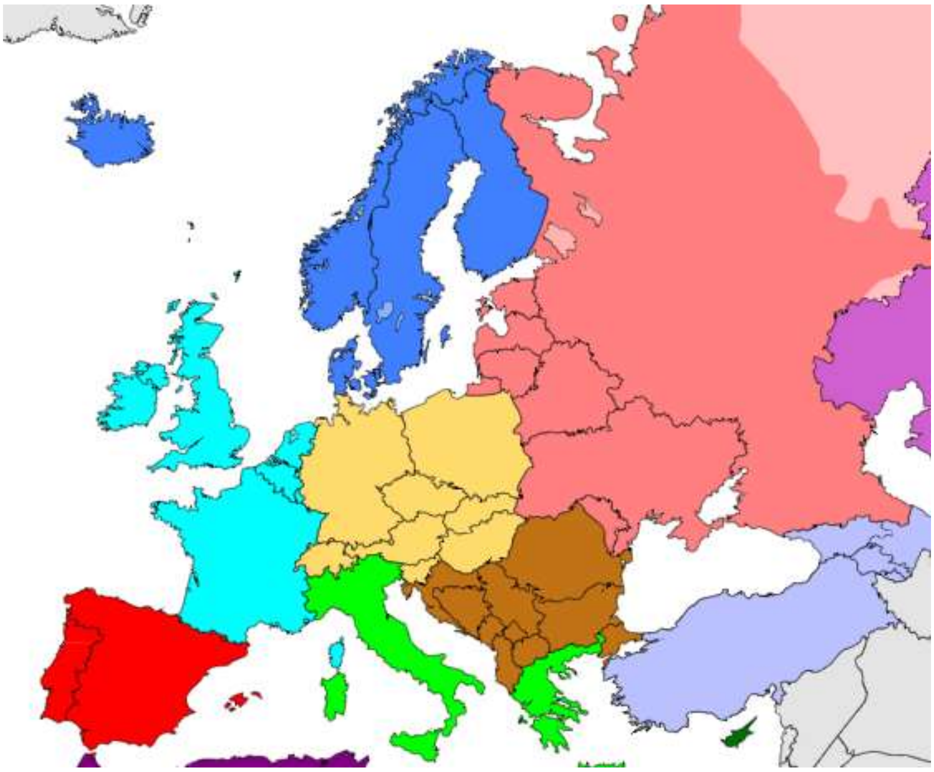

Figure 1. Map of Europe showing regions (Kolja21, no date)

If growth areas were to be included in any predictive models for the properties of in situ timber, it would be important to make clear their boundaries. The map in Figure 2 is extracted from the second Gradewood Project report (Ranta-Maunus, Denzler and Stapel, 2011); it was proposed to divide the growth areas of Europe based on a review of the results of testing over 30 000 timber test pieces. The approach of defining growth areas by climate and forestry and sawmilling practices appears to be theoretically superior to using national boundaries, which however are more convenient.

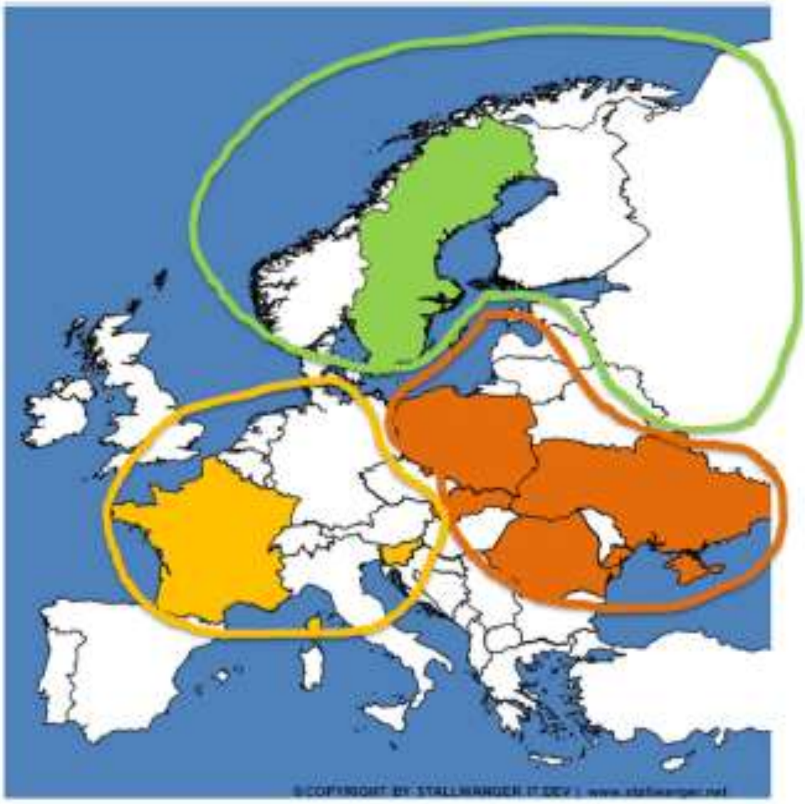

Figure 2. Proposed growth areas for Europe of Northern, Eastern and Central (Ranta-Maunus, Denzler and Stapel, 2011, p. 61)

DIN4074 relates solely to the CNE region (Central, Northern and Eastern Europe) and INSTA142 generally relates solely to the NNE region (Northern and North Eastern Europe) with just two references to Denmark and Norway. BS4978 relates to the UK, Ireland, USA and Canada (as well as a limited number of other sources with historical timber trading ties with the UK).

The minor species were grown in England, Wales and Scotland. Therefore, the references to the UK and Ireland are most directly relevant (Ireland has a similar climate to Great Britain and, in any case, there are only minor differences between Northern Ireland (included in the UK) and Ireland itself). EN1912 makes no mention of Western Europe as a growth area.

It would be expected that timber from the growing regions of CNE and NNE would be stronger and stiffer than that of the same species grown in the UK. Despite this and bearing in mind the approximate and apparently arbitrary nature of visual grading rules, it is not unreasonable to assume that the strength classes linked to DIN4074 and INSTA142 with their superior growth regions can also be used with timber from the UK. This is a working estimate and no more and this assumption must be borne in mind when comparing characteristic values of MoR, MoE and density calculated from the laboratory testing of the minor species with the characteristic values obtained from the strength classes in EN338.

The results of the Gradewood Project (Ranta-Maunus, 2009) bear out the expectation that timber properties from differing growth areas differ by differing degrees. The study found that for instance, different grading settings should be developed for Scots pine grown in Germany, France and the UK, whereas the same grading settings could be used for the for Nordic countries. Conversely, for Norway spruce, the same settings could be used throughout Central and Northern Europe (if these included the measurement of stiffness and knot sizes). Interestingly, this study's conclusions are based on the use of the predictors MoE and MoE_{dyn} which although acknowledged to be different were found to have relationships with MoR that are '*practically the same*'.

Table 7 is a much reduced version of Table 1 of EN1912, and only contains the species which have been visually graded and tested in this study. The visual grades in the green shaded cells are directly taken from EN1912. All other grades are estimates.

Table 7. Summary of the links assumed between visual grades and strength classes in relation to the minor species used in this thesis

Four test species Genus [EN1912 ID No]	C30		C24		C18			C14	
	DIN4074	INSTA142	DIN4074	INSTA142	BS4978	DIN4074	INSTA142	BS4978	INSTA142
Norway Spruce (NS) Spruce [22]	S13	T3	S10	T2	SS	S7	T1	GS	T0
Noble fir (AP) Fir [8]	S13	T3	S10	T2	SS	S7	T1	GS	T0
Western hemlock (WH) Hemlock [62]	S13	T3	S10	T2	SS	S7	T1	GS	T0
Red cedar (RC) Cedar [58]	S13	T3	S10	T2	SS	S7	T1	GS	T0

From Table 1 of EN338 (CEN, 2016b), the characteristic values of MoR, MoE and density can be found and these are presented in a simplified version: Table 8.

Table 8. Characteristic values, extracted from EN338, for MoR, MoE and density

	Class	C14	C18	C24	C30
Bending strength (N/mm^2)	$f_{m,k}$	14	18	24	30
Mean modulus of elasticity in parallel bending (kN/mm^2)	$E_{m,0,mean}$	7	9	11	12
Density (kg/m^3)	ρ_k	290	320	350	380

Following the above strength classification, the characteristic values for each visual grade of the sample were determined through laboratory testing and statistical analysis using EN14358, for comparison.

4 Results and discussion

In the first part of this section, an overview of the results of the visual grading is presented for the three visual grading codes BS4978, DIN4074 and INSTA142. In the second part, the determination of the characteristic values of the mechanical and physical properties of each visual grade is discussed.

The focus of this technical note is on visual grading and not on the methods of laboratory testing used in the strength classification processes. In short, preparation and testing were carried out in accordance with the Eurocodes EN384, EN408, EN14358, EN13183 and EN338.

4.1 Results of visual grading compared with measured properties

In practice, following visual grading, characteristic values are adjusted to become design values. In this stage several factors are applied, relating to (amongst other things):

- an estimation of load duration
- an estimate of service class or future moisture content of the timber
- depth factor to account for size effects
- material properties, model uncertainties and dimensional variations
- reduced uncertainty when the timber element can be relied on to act in concert with other timber elements

The result of the above is that the final design value of a property of a single timber element can vary significantly from one situation to another. It is considered that an attempt to model this part of the design process, in order to consider the efficacy of the visual grading codes, could lead to widely ranging results and would not be useful.

Initially, the results of the visual grading are compared with the measured mechanical and physical properties with no adjustments made (for example, for sample size, depth factors, calculation of characteristic values, logarithmic adjustments to the distribution, etc.).

4.1.1 BS4978

The visual grading of the 527 joists splits them into roughly three thirds: Reject, Grade GS and Grade SS, as shown in more detail in Table 9. It is seen that almost all of the western red cedar joists are graded as Reject while the other three species have proportionately fewer Reject gradings compared to either Grade GS or Grade SS.

Table 9. Summary of the BS4978 visual grading of the 527 joists by species

	Reject	Grade GS (C14)	Grade SS (C18)	All joists
All joists (%)	35	31	34	100
All joists	184	163	180	527
Norway spruce NS	32	49	62	143
Noble fir AP	25	55	47	127
Western hemlock WH	30	58	62	150
Western red cedar RC	97	1	9	107

From Table 10., it is seen that 290 of the 527 joists were graded due to just one visual grading characteristic (Sole) (i.e. only one visual grading characteristic fell within the limits of the lowest visual grade), most commonly, rate of growth (RoG), closely followed by knot cluster. The remaining 237 joists were graded due to more than one visual grading characteristic (Joint) (i.e. more than one visual grading characteristic fell within the limits of the lowest visual grade). Additionally, 41 joists had just two joint grade determining characteristics, while 183 had three or four joint grade determining characteristics. As over half of all joists are graded by just one characteristic, this shows the lack of agreement between the different characteristics.

Table 10. BS4978 sole or joint visual grade determining characteristics (n=527)

	Knot cluster	Single knot	SoG	RoG	Sub-total
Sole	128	0	14	148	290
Joint	235	196	137	221	237
Sub-total	363	196	151	369	

Of the 184 Reject joists, knot clusters were the sole grade determining feature for 70 joists, RoG for 106 joists and SoG for 1 joist; for the remaining 7 Reject joists, knot clusters and RoG were joint grade determining features.

From the above, knot clusters and RoG are seen to be the two key visual grading characteristics for the sample of joists. RoG is the sole determining visual grading characteristic for over one quarter of the sample of joists and as is discussed elsewhere in this thesis, the measurement of RoG is at best problematic and at worst impracticable for in situ timber. So the use of BS4978 to visually grade in situ timber would not be considered appropriate for this reason alone. A further compelling reason not to use BS4978 for in situ timber is the difficulty of measuring the knot area ratios of partially covered or inaccessible timber elements. Without access to one or both ends of a timber element and all four faces, the determination of knot area ratios is near impossible. Even when these circumstances prevail the process is convoluted, as is illustrated by Annex A of the code itself.

The importance of knot clusters (sole or joint grade determining characteristic for 363 joists) compared to single knots (sole or joint grade determining characteristic for 196 joists) is an indication that (at least for BS4978 and for this sample) knot clusters affect grading outcomes almost twice as strongly as single knots. SoG is the sole grade determining characteristic for only 14 joists and as such affects grading outcomes least of all.

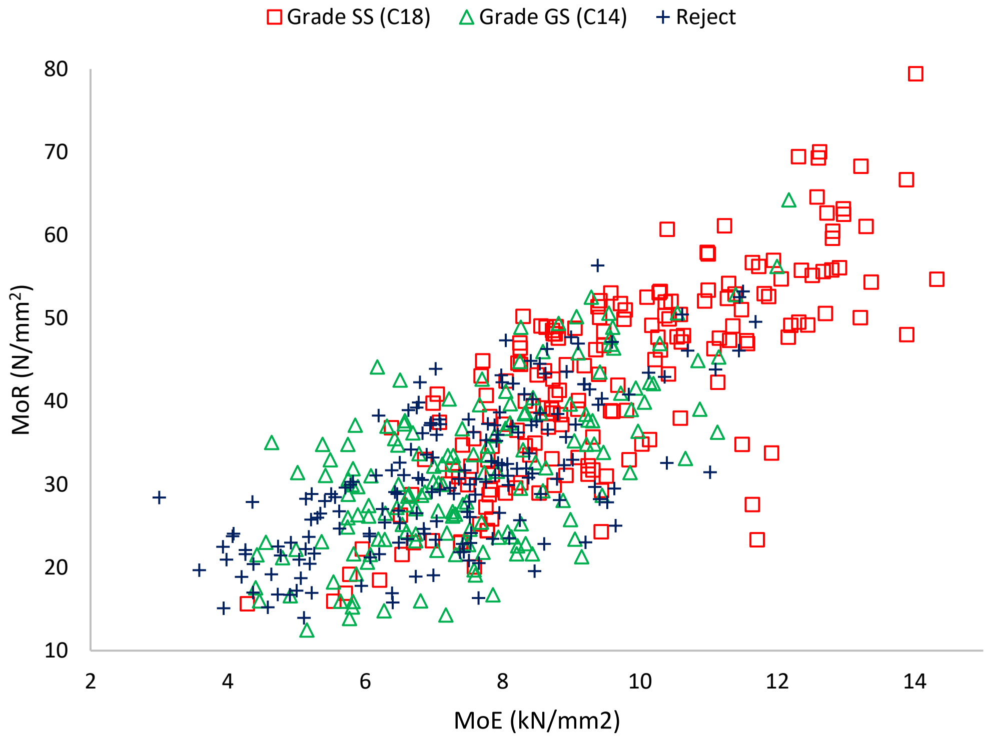

Figure 3. Graph comparing MoR and MoE for all joists visually graded using BS498

It is useful to understand how well the visual grading to BS4978 manages to differentiate between joists in relation to bending strength, stiffness and density. Broadly, it is seen from Figure 3. that there is significant overlap between the visual grades of BS4978 and that some of the weakest joists are graded as GS and SS. Nevertheless, the Grade SS data points are generally towards the top right quadrant of the graph leaving the Grade GS and Reject points intermingled towards the bottom left quadrant of the graph. This suggests some useful differentiation by visual grading for the stronger and stiffer joists but less so for the weaker ones. So, as knot clusters and RoG are the most common grade determining features, they appear to be effective to differentiate higher quality timber but not for lower quality timber.

A similar graph (Figure 4.) shows density and MoR and shows even less differentiation for density for all grades.

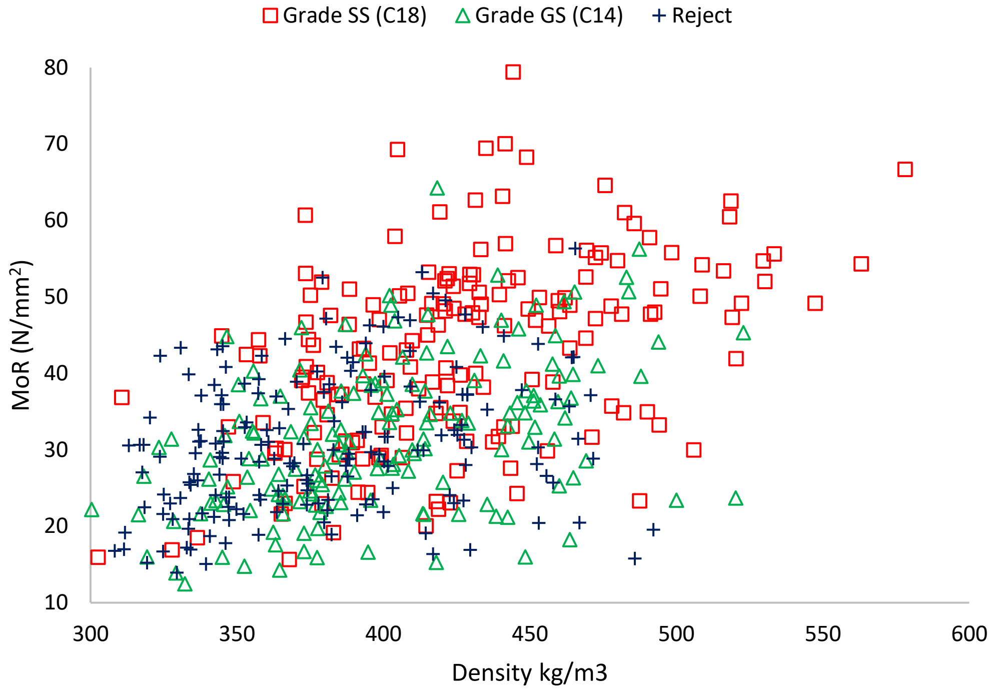

Figure 4. Graph comparing MoR and density MoE for all joists visually graded using BS498

ANOVA and T Tests were carried out to investigate the differences between the MoR values in each of the visual grades determined using BS4978. The F value (33.3) of the single factor ANOVA test is significantly higher than the F-crit value (2.38) which indicates that there are significant differences between the grades. Two sample T Tests (assuming unequal variances) were subsequently carried out to compare the MoR values between grades. Two tailed P-values are given in Table 11.1 which show that the means of the two different grades are significantly different, but that the means of the Reject category and Grade GS are not significantly different.

Table 11. Two tailed P-values for MoR values of groups based on BS4978 visual grades

Groups	P-value
Reject and GS Grade	0.350
GS Grade and SS Grade	1.58×10^{-18}
Reject and Graded	2.2×10^{-12}
All and Graded	0.005
Reject and All	1.99×10^{-7}

Table 11. indicates that although the visual grading rules of BS4978 appear to differentiate the bending strengths of the stronger joists to some degree, the rules do not do this for the weaker joists. This is also illustrated in Figure 5, which shows the adjusted mean MoR values for different visual grades, with 95% error bars based on standard error of the means. Joists allotted to a visual grading category are termed “Graded” (i.e. not Reject).

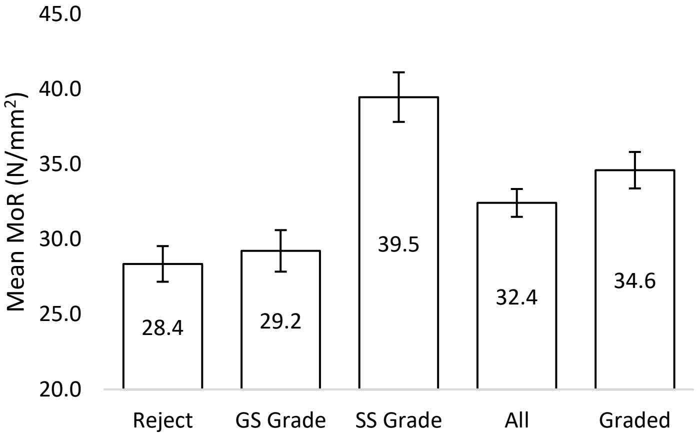

Figure 5. Mean adjusted MoR values and 95% error bars based on standard error of the means for the visual grades of BS4978

Similar exercises for MoE show a similar pattern with differentiation between Grade SS and both Grade GS and Reject but a lack of differentiation between Reject and Grade GS. For density, despite the intermingling of data points shown in Figure 4, differentiation between mean values is achieved between all grades.

Although the sample size is inadequate to carry out a grading of the minor species (n=527), the characteristic values of the mechanical and physical properties can be calculated for the groups of timber graded using BS4978. These values are presented in Table 12 and the grey shaded cells indicate characteristic values below those required in EN338.

Table 12. Characteristic values based on BS4978

	Reject	Grade GS C14	Grade SS C18	All	Graded
f_k (N/mm^2)	11.3	11.0	15.1	12.0	12.3
$E_{0,mean}$ (kN/mm^2)	6.65	6.95	8.83	7.52	7.96
Density (kg/m^3)	311	320	333	325	322

The performance of BS4978 is summarised below:

1. It sorts the stronger and stiffer joists into groups with similar mechanical and physical properties relatively well but fails to usefully sort the lower quality joists.
2. For density, each grade of the graded timber attains the characteristic values of the corresponding strength classes. For MoE, the characteristic values are borderline adequate. For MoR, the characteristic values are too low by around 3 N/mm^2.
3. The code of practice is impractical for use with in situ timber elements due to (i) the use of RoG and (ii) the use of knot area ratios; neither of which can be practicably measured in situ.
4. Knot clusters and RoG are the most important visual grading measures and SoG is the least.

4.1.2 DIN4074

The visual grading using DIN4074 sorted the majority of the joists (85%) into two just grades: Reject and Grade S10 (despite three grades being available), as shown in Table 13. This clumping of the joists mainly into two groups shows a poor relationship between the grading characteristics and the properties of the joists which vary in a more regular fashion.

Table 13. Summary of the DIN4074 visual grading of the 527 joists by species

	Reject	Grade S7 (C18)	Grade S10 (C24)	Grade S13 (C30)	All joists
All joists (%)	43	9	42	7	100
All joists	224	45	223	35	527
Norway spruce NS	20	22	90	11	143
Noble fir AP	61	10	47	9	127
Western hemlock WH	46	13	80	11	150
Red cedar RC	97	0	6	4	107

It should be noted that DIN4074 makes use of single knots but not groups or clusters of knots in its visual grading. From Table 14. it is seen that, in total, 372 of the 527 joists were graded due to just one visual grading characteristic (i.e. only one visual grading characteristic fell within the limits of the lowest visual grade), most commonly, rate of growth (226). Green shaded cells are sole grade determining characteristics. Of the remaining 155 joists, 121 had two joint grade determining characteristics and 34 had three joint grade determining characteristics.

Table 14. DIN4074 sole or joint visual grade determining characteristics (n=527)

	Single knot	SoG	RoG
Single knot	136	13	96
SoG		10	12
RoG			226

For 368 of the joists, RoG was the single or joint grade determining characteristic and for 279 of the joists, this was single knots. RoG was the sole grade determining characteristic of 205 of the 224 Reject joists, with the grade determining characteristics of the remaining 19 Reject joists split evenly between single knots (6), SoG (6) and joint causes (including RoG with SoG and RoG with single knots) (7).

So, it is seen that RoG is the dominant grade determining characteristic for this sample, particularly for the Reject grade. The approximate link between both the species and the growth areas of DIN4074 via EN1912 and the four minor species of this study (grown in the UK) could partially explain this and questions the validity of the link. However, the dominance of RoG for BS4978 (which directly links two species and growth areas) suggests that this would not be a complete explanation.

As is the case for BS4978, from Figure 6. it is seen that there is significant overlap between the visual grades of DIN4074 and that some of the weakest joists are graded as S7 and S10. Nevertheless, the Grade S13 data points are generally towards the top right quadrant of the graph leaving the Grade S7 and Reject points intermingled towards the bottom left quadrant of the graph.

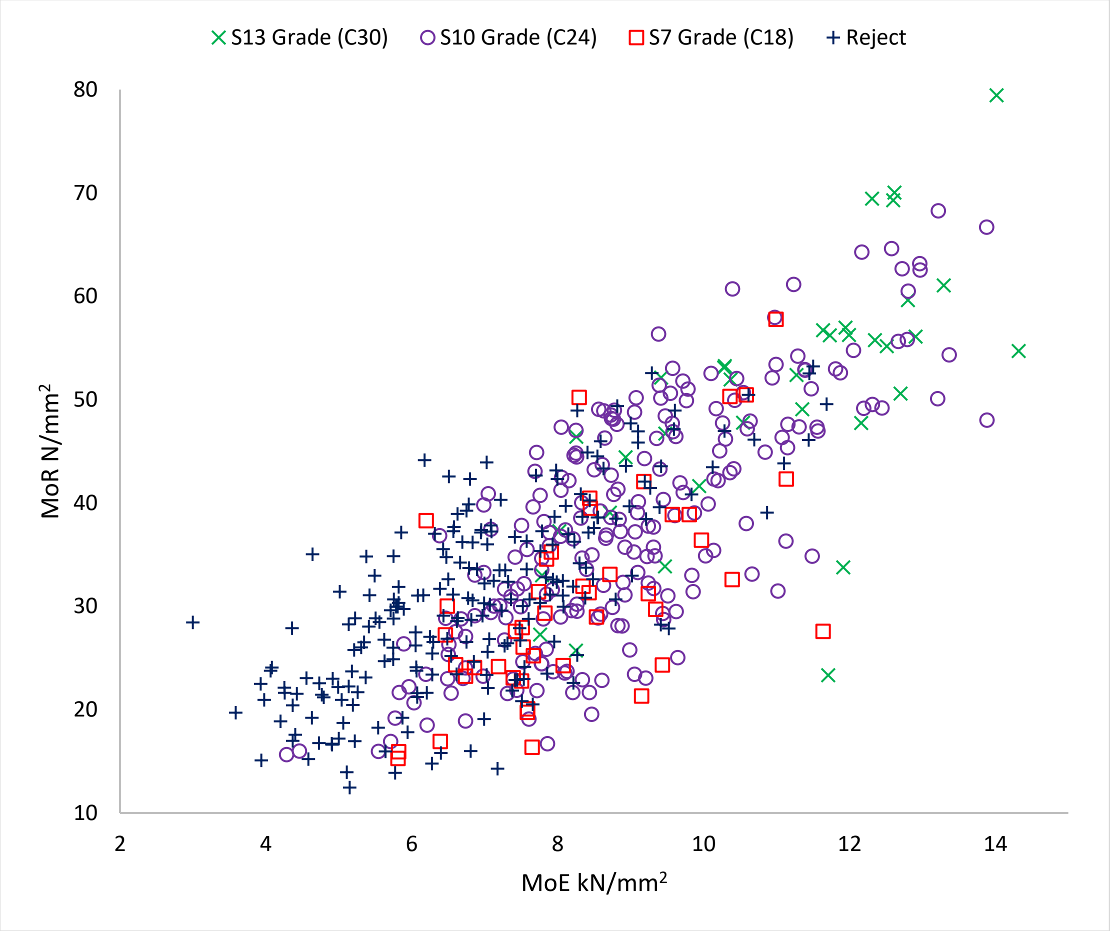

Figure 6. Graph comparing MoR and MoE for all joists visually graded using DIN4074

It is difficult to draw clear conclusions from Figure 6., due to the large degree of overlapping between the visual grades. For MoR, there is little difference to see between the Reject and S7 data points and again between the S10 and S13 data points (particularly for the stronger joists). These tentative conclusions are explored further using simple statistical analyses later in this technical note. For MoE, despite the intermingling of data points, there is a trend from less to more stiff that matches the visual grades.

ANOVA and T Tests were carried out to investigate the differences between the MoR values in each of the visual grades determined using DIN4074. The F value (26.4) of the single factor ANOVA test is significantly higher than the F-crit value (2.22) which indicates that there are significant differences between the grades. Two sample T Tests (assuming unequal variances) were subsequently carried out to compare the MoR values between grades. Two tailed P-values are given in Table 15. which show that the means of the different grades are significantly different, but that the means of the Reject category and Grade S7 are not significantly different.

Table 15. Two tailed P-values for MoR values of groups based on DIN4074 visual grades

Groups	P-value
Reject and S7 Grade	0.983
S7 Grade and S10 Grade	2.65×10^{-5}
S10 Grade and S13 Grade	7.42×10^{-6}
Reject and Graded	2.27×10^{-15}
All and Graded	0.0002
Reject and All	4.83×10^{-8}

Table 15 indicates that although the visual grading rules of DIN4074 appear to differentiate the bending strengths of the stronger joists to some degree, the rules do not do this for the weaker joists. This is also illustrated in Figure 7, which shows the adjusted mean MoR values for different visual grades, with 95% error bars based on standard error of the means. This confirms the lack of differentiation of MoR between Reject and Grade S7.

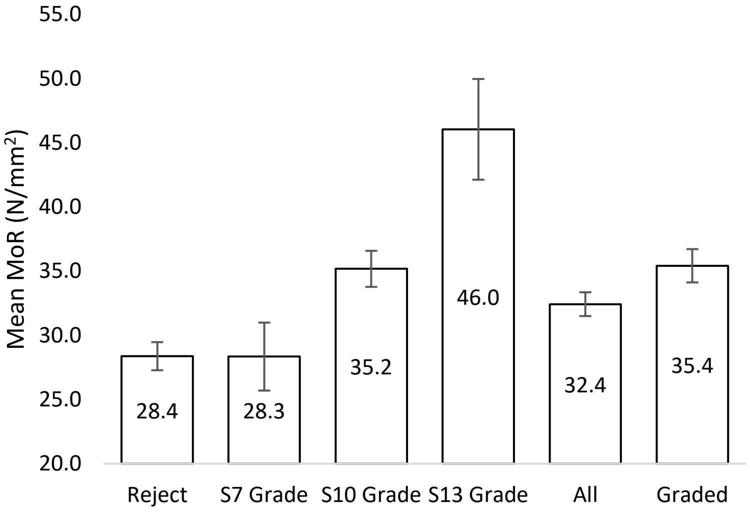

Figure 7. Mean adjusted MoR values and 95% error bars based on standard error of the means for the visual grades of DIN4074

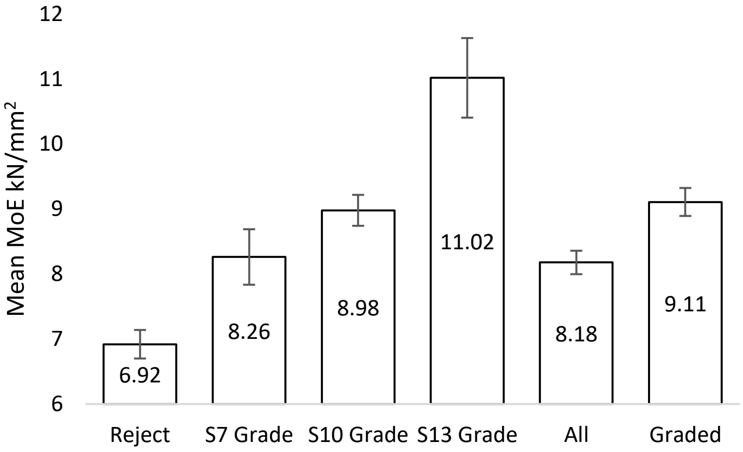

Figure 8. Mean MoE values and 95% error bars based on standard error of the means for the visual grades of DIN4074

Figure 8 shows that there are significant differences between the means of MoE of each grade and Reject apart from Grades S7 and S10 whose error bars just overlap. The differentiation of the Reject Grade for MoE is much clearer than for MoR.

Mean density is also considered and this increases with each increase in visual grading category, however, the error bars of all three grades overlap and very nearly overlap with the means of adjacent visual grades, showing only weak differentiation.

The characteristic values of the mechanical and physical properties are presented in Table 16 and the grey shaded cells show the characteristic values below those required in EN338.

Table 16. Characteristic values based on DIN4074

	Reject	Grade S7 C18	Grade S1 C24	Grade S13 C30	All	Graded
f_k (N/mm²)	11.0	10.6	13.2	18.4	12.0	12.8
$E_{0,mean}$ (kN/mm²)	6.34	7.51	8.24	10.00	7.52	8.37
Density (kg/m³)	267	307	294	312	280	298

The performance of DIN4074 is summarised below:

1. It sorts the stronger and stiffer joists into groups with similar mechanical and physical properties relatively well but fails to usefully sort the lower quality joists for MoR.
2. As expected, for a code of practice intended for growth areas quite different to the UK, not one of the grades of the graded timber attains the characteristic value of the corresponding strength class.
3. The code of practice is impractical for use with in situ timber elements due to the use of RoG. However, this is a particularly simple visual grading code to apply to new timber.
4. RoG is the most important visual grading measure and SoG is the least. Single knots are used with simple knot measures (without knot groups or knot clusters).

4.1.3 INSTA142

The visual grading using INSTA142 sorted the joists fairly evenly into four grades and Reject. Grade T1 (C18) takes the lion's share of 189 joists (36%), whereas, only 45 joists in total are allocated to Reject and only 46 joists to Grade T3, as shown in Table 17.

Table 17. Summary of the INSTA142 visual grading of the 527 joists by species

	Reject	T0 Grade (C14)	T1 Grade (C18)	T2 Grade (C24)	T3 Grade (C30)	All joists
All joists (%)	9	22	36	24	9	100
All joists	45	118	189	129	46	527
Norway spruce NS	20	27	59	32	5	143
Noble fir AP	11	45	46	21	4	127
Western hemlock WH	14	39	55	34	8	150
Red cedar RC	0	7	29	42	29	107

From Table 18 it is seen that 307 of the 527 joists were graded due to just one visual grading characteristic (Sole), most commonly, one of the two knot measures (257 joists). The remaining 220 joists were graded due to more than one visual grading characteristic (Joint). Additionally, 175 joists had just two joint grade determining characteristics, while 45 had three or four joint grade determining characteristics.

Table 18. INSTA142 sole or joint visual grade determining characteristics (n=527)

	Knot cluster		Single knot	SoG	RoG	Sub-total
Sole	152		105	2	48	307
Joint	189		194	19	97	220
Sub-total	341		299	21	145	

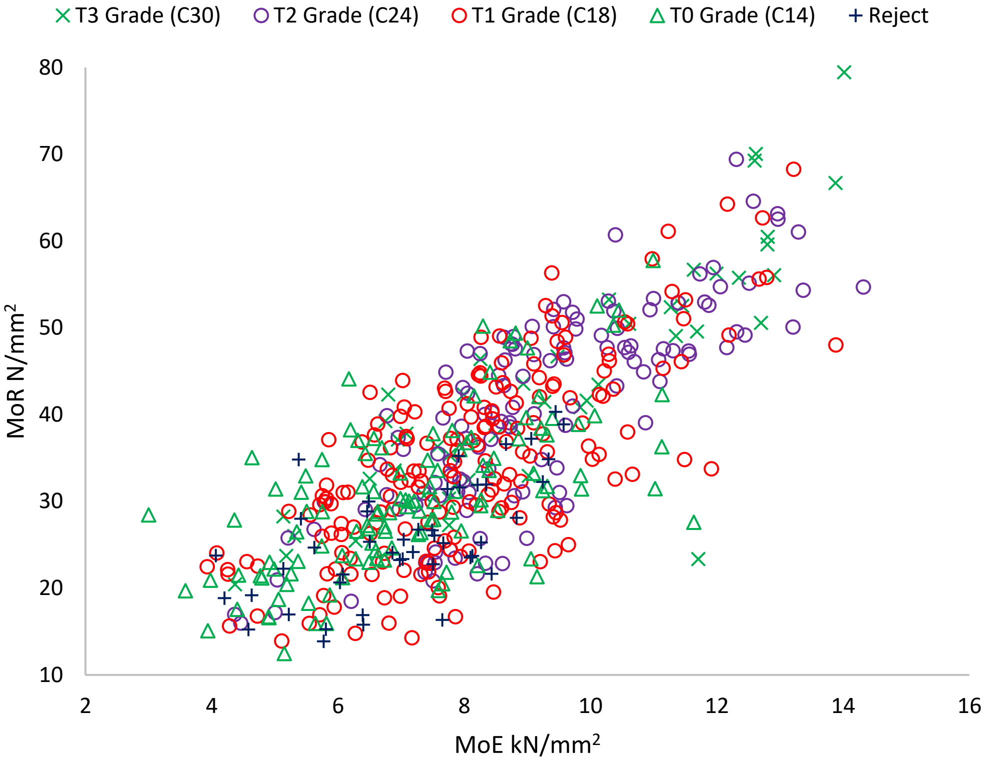

Figure 9. Graph comparing MoR and MoE for all joists visually graded using INSTA142

In Figure 9 broadly, it is seen the data points of the Reject and T0 grades are towards the bottom left quadrant of the graph and the data points of T2 and T3 are towards the top right quadrant. The data points of T1 are to be spread throughout the scatter plot.

ANOVA and T Tests were carried out to investigate the differences between the MoR values in each of the visual grades determined using INSTA142. The F value (18.1) of the single factor ANOVA test is significantly higher than the F-crit value (2.10) which indicates that there are significant differences between the grades. Two sample T Tests (assuming unequal variances) were subsequently carried out to compare the MoR values between grades. Two tailed P-values are given in Table 19 which show that the means of the different grades are significantly different, but that neither the means of the T2 and T3 Grades, nor All and Graded, are significantly different. Bearing in mind the small number of Reject and T3 joists, these two outcomes really require further investigation. These two outcomes are also illustrated in Figure 10, which shows the adjusted mean MoR values for different visual grades, with 95% error bars based on standard error of the means.

Table 19. Two tailed P-values for MoR values of groups based on INSTA142 visual grades

Groups	P-value
Reject and T0 Grade	4.69×10^{-4}
T0 Grade and T1 Grade	4.28×10^{-4}
T1 Grade and T2 Grade	5.22×10^{-6}
T2 Grade and T3 Grade	0.223
Reject and Graded	3.58×10^{-13}
All and Graded	0.234
Reject and All	7.93×10^{-12}

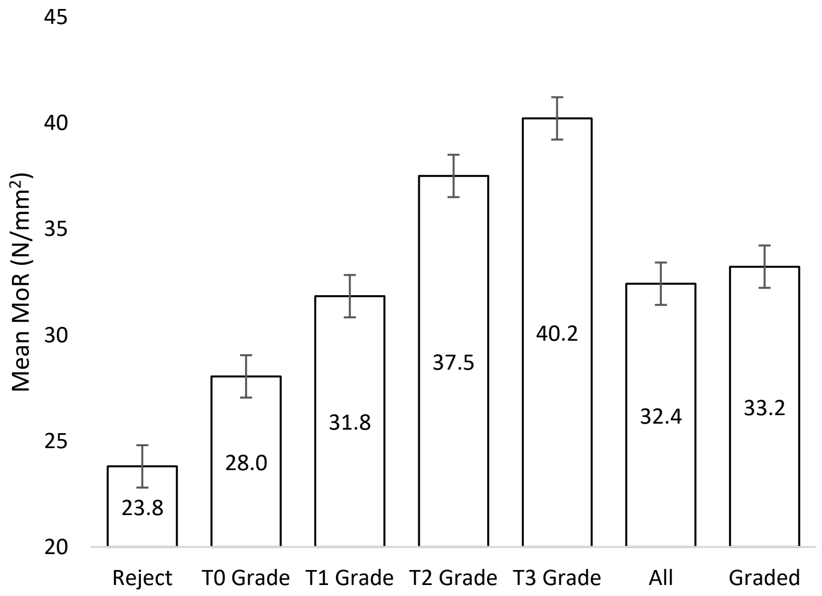

Figure 10. Mean MoR values and 95% error bars based on standard error of the means for the visual grades of INSTA142

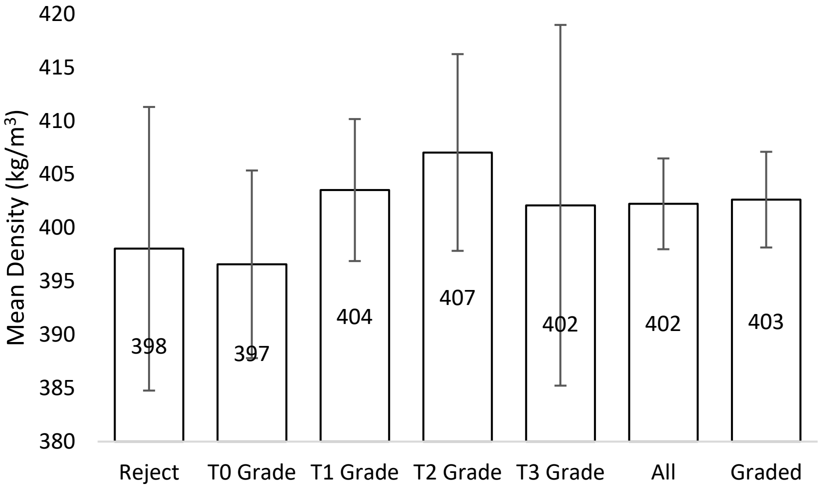

Figure 11. Mean density values and 95% error bars based on standard error of the means for the visual grades of INSTA142

Figure 11 shows broadly similar densities, regardless of grade, with relatively large error bands (made apparently even larger by to the truncated vertical scale of the graph). Based on this graph, it appears that there are no significant differences between mean density values of any of the grades, with the possible exception of T0 and T1 Grade.

For MoE, the error bars overlap means for Reject with T0 and for T2 with T3. Thus, for MoE and density, the visual grading does a poor job of differentiating between grades.

The characteristic values of the mechanical and physical properties are presented in Table 20 (grey shaded cells indicate characteristic values below those required in EN338) and are seen to be below the limits given in EN338 for all grades and properties.

Table 20. Characteristic values based on INSTA142

	Reject	Grade T0 C14	Grade T1 C18	Grade T2 C24	Grade T3 C30	All	Graded
f_k (N/mm^2)	9.8	11.1	11.9	14.2	15.0	12.0	12.1
$E_{0,mean}$ (kN/mm^2)	6.40	6.56	7.41	8.38	8.46	7.52	7.61
Density (kg/m^3)	277	273	282	275	260	280	277

The performance of INSTA142 is summarised below:

1. Perhaps due to its four grades, it fails to sort well between grades for all properties.
2. As expected, for a code of practice intended for growth areas quite different to the UK, none of the graded timber attains its characteristic value.
3. The code of practice is impractical for use with in situ timber elements due to the use of RoG. However, this is a simple visual grading code to apply to new timber.
4. Knot clusters and single knots are the most important visual grading measures, perhaps due to the slightly relaxed limits for RoG.

4.1.4 CP112

A conference paper presented at the Shatis'19 conference provides details of this assessment of CP112 (Bather and Ridley-Ellis, 2019). What follows is just one figure from the conference presentation which serves to illustrate the key outcomes in relation to the grading and testing to destruction of the 143 Norway spruce test pieces.

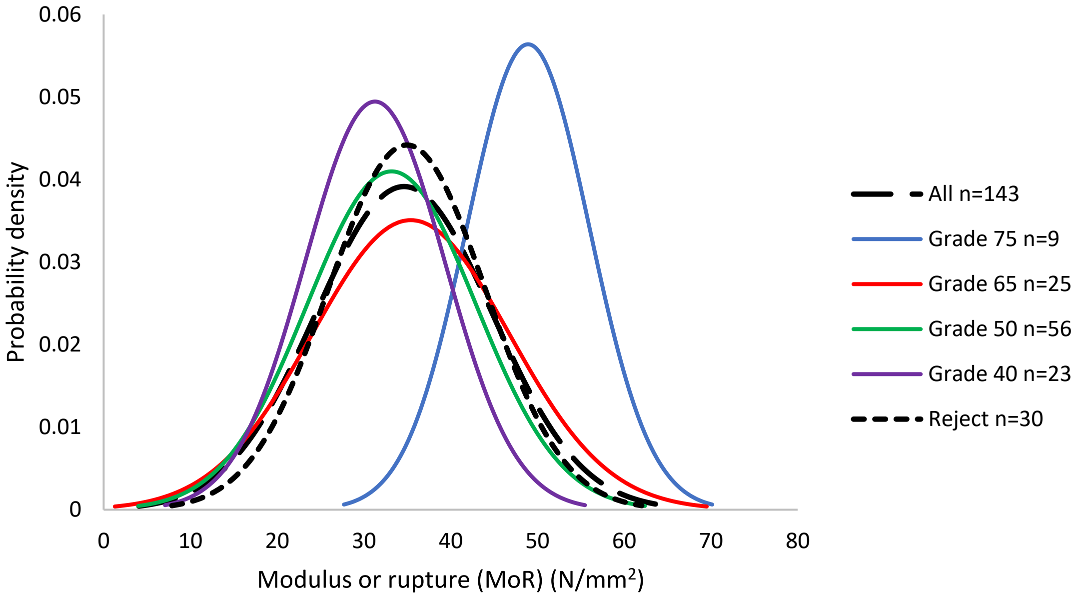

Figure 12. Probability density function for Norway spruce, showing the four different visual grading categories of CP112 (plus Reject)

Figure 12 shows the probability density functions of the test pieces, broken down into the four grades of CP112 plus Reject. It is seen that the mean bending strength of the 30 'rejected' joists is slightly higher than that of two of the four grading categories and broadly the same as for a third category and for all joists together. Thus, CP112 appears to be able to differentiate the higher grade only.

The rationale for CP112 is the same as for the other current national visual grading codes of practice and so its lack of precision comes as no surprise. Figure 12 illustrates the inability of the visual grading method to separate out timber joists clearly and consistently into tightly defined groups of similar properties. However, as for all of the grading codes, CP112 has some success in separating out the strongest group of joists into the highest grading category.

4.2 Discussion of the determination of characteristic values

The calculation of the characteristic values of the sample of minor species is carried out in accordance with EN14358 (CEN, 2016a). The code itself should be referred to for a fuller understanding. The code leaves room for judgement to be exercised, for instance, (i) where a sample is borderline normally distributed or logarithmically normally distributed or (ii) whether to use the parametric or non-parametric approach or (iii) whether to use the simplified expression for $k_s(n)$ or the Tables in the code (additionally, an approach based on statistical first principles could be adopted).

Further judgement needs to be exercised on the treatment of samples. For instance, in this study, the samples could be treated in a number of ways:

(i) All data together in a single sample of 'minor species'
(ii) Split the samples by species
(iii) Split the samples by growth areas
(iv) Split the samples by both species and growth areas

Different characteristic values are calculated depending on the choice of approaches. So the characteristic values using three approaches are compared and discussed. Despite being borderline normally distributed, a lognormal distribution of MoR data is assumed. Normal distributions of MoE and density and a lognormal distribution of MoR were found to be reasonable and thus did not require the use of a non-parametric approach.

With regard to the final adjustment of characteristic values in accordance with EN384, three approaches are considered. Approach 1 considers all species together as a single visually graded sample. Approach 2 considers each of the four species as a sub-sample of a larger sample (n=527). Approach 3 considers each species in turn as a single sample. Adopting these three different approaches for MoR, density and MoE and using the Formulae 11, 12 and 13 of EN384 leads to different characteristic values.

In industry, Approaches 1 and 2 would allow timber from all of the sites and all of the species to be combined and processed and sold as a single entity. This could be useful commercially to simplify processes and limit the need for close management of batches of timber. However, Approach 3, would require each species to be treated separately during processing and selling of the structural timber.

For each of the three approaches, the characteristic values of the joists are determined for the relevant properties, in each of the visual grading categories (and hence, the associated strength classes of EN338).

Approach 2 typically delivers the highest characteristic values but requires each species to be treated as a sub-sample of a larger sample. This inevitably leads to smaller sample sizes which significantly affect calculated values. For instance, with DIN4074, the characteristic value of the 224 Reject joists is 15.1 N/mm^2 and is higher than that of the Grade S7 joists (11.8 N/mm^2). This is despite their adjusted average values being almost identical. This is because the sample size of the Reject joists is 224 and that of Grade S7 only 45 and this significantly affects 5-percentile values, standard deviation values and confidence levels. This effect occurs to an even greater degree with Approach 3.

For this reason, in this study, it is considered most appropriate to use Approach 1, which treats all four species as if they are from a single population and subsequently allows sample sizes for grading categories to be larger than for Approach 2. Thus, the characteristic values given are based on Approach 1.

From using Approach 3 it is seen that western hemlock typically has the highest characteristic values of bending strength, stiffness and density and noble fir the lowest. To reinforce the point made in the paragraph above, it was not possible to determine characteristic values of red cedar in several instances due to reduced sample size.

Characteristic values of MoE and MoR rise with increasing visual grading category for all three visual grading codes but for density, this only occurs with BS4978. Characteristic densities fluctuate with no pattern between visual grades for DIN4074 and INSTA142.

For each visual grading category of each code, the characteristic values determined are below those required by the strength classes of EN338. Bending strength and stiffness are over-estimated by all visual grading codes. For density, the success rate is also poor, with only BS4978 correctly grading joists with densities high enough to satisfy the strength classes of EN338.

5 Discussion

5.1 Gap in the literature on visual grading

The literature review found research considering the efficacy of visual grading codes focussing on: (i) yields and (ii) characteristic values. Quite reasonably, almost no research considers the issue of key importance in the appraisal of individual in situ structural timber elements; namely, the accurate sorting of individual elements into narrowly defined groups with similar properties.

5.2 Similarities of and differences between visual grading codes

The Eurocodes have successfully created a harmonised inter-continental process for visually grading (including the creation of samples, laboratory testing, visual grading, strength classification and marking, etc.) and structural design. This encompasses and relies on the use of several national visual grading codes of practice which have been developed in diverse ways to accord with local conditions, leading to a series of divergent documents which in outline, agree with each other but in detail, differ significantly.

5.3 Visual grading is broad brush and imprecise

Even when carried out for timber from a designated growth area and for a single species, visually graded groups of timber have widely ranging mechanical and physical properties. This is due to a number of reasons including:

(i) visual grading features are only weakly correlated with mechanical and physical properties
(ii) each of the grade determining properties does not vary perfectly in step with the others and so stiff joists may have low bending strength, etc.
(iii) the relatively closely grouped categories of a visual grading code (compared with the overall variation of properties of timber) will necessarily contain joists with a wide range of properties

Visual grading followed by strength classification is therefore a broad brush method, which, even if it were to work perfectly, would lead to conservative outcomes. So much so, that it would be of limited use to a structural engineer appraising in situ structural timber in a borderline situation. Additionally, its ongoing use for new timber should be questioned due its relatively wasteful and conservative outcomes, particularly in relation to climate change.

The inability of the visual grading codes to sort joists into groups with different mechanical and physical properties is illustrated by the graph presented for CP112 and by the outcomes of the T Tests which found that several visual grading categories are not significantly different to other categories.

Nevertheless, the visual grading codes did manage to indistinctly sort timber into groups whose mechanical and physical properties had a general tendency to increase in line with visual grading categories. This shows some success for visual grading and suggests that the visual grading features have some predictive power.

5.4 Growth areas important but difficult to know for in situ timber

The current system of structural grading requires visual grading codes and their grading categories to be tied to specific growth areas and species (typically limited to the commercially important ones). This prevents the visual grading of outlying minor species/growth areas and so in this study, reasonable estimates were made to link the three visual grading codes with the four minor species grown in the UK. The analysis of the results of the grading show that these estimates do not work (i.e. did not sort timber into groups whose characteristic values reliably accorded with Table 1 of EN338) and need adjusting.

The inappropriateness of the estimated links serves to illustrate one of the dangers of applying visual grading codes to in situ structural timber of unknown growth area or species. From the literature review, it is known that growth areas significantly affect the mechanical and physical properties of timber and in practice, even though it is possible to determine the species of in situ structural timber, it is unlikely that its growth area can be known. Thus a predictive model that accounts for this variance but functions without the need to know growth areas (or species) would be useful.

5.5 Visual grading features

It is worthwhile considering the visual features used in the three visual grading codes. Firstly, the test pieces in this study, cut from relatively young trees, grown in the UK have wide growth rings which combine badly with the limits placed on RoG by the three visual grading codes. So, with the tight limits placed on RoG by DIN4074, almost half of the test pieces have their grade determined solely by RoG, and with the more relaxed limits of INSTA142 only around one tenth are rejected in this way.

Two of the three visual grading codes place over one third of the test pieces in the Reject category, thereby, giving no useful indication of these joists' mechanical and physical properties, other than that they have values lower than the weakest grades. This is a significant handicap exacerbated by the fact that many of the Reject grading is due to RoG which is typically impractical to measure in situ.

Secondly, due to the presence of so many factors in the visual grading codes reviewed, no clear conclusions can be drawn between the use of single knots, knot groups and knot clusters.

Thirdly, it may be that the sample of minor species in this study is of unusually straight grained timber, but SoG was found to be the sole grade determining factor only a handful of times, regardless of the visual grading code used. This, together with its weak correlation with the physical and mechanical properties of timber lead towards to the conclusion that it is unlikely to form a particularly useful part of a predictive model.

6 Conclusions

The three visual grading codes assessed are poor predictors of the mechanical and physical properties of individual timber joists. This outcome was expected and reflects the inappropriate use of the codes in this context rather than a fault in their use as intended (grading large numbers of timber elements from known sources for commercial purposes).

The three visual grading codes accomplish the same job, with similarly poor results, using a variety of ways of defining visual features, measuring them and comparing them to the dimensions of the original timber joist in order to grade them.

Strength classes are based on the worst performing parameter of the three key mechanical and physical properties of timber. As such, they may reflect well, one of these properties, and give very little indication of the other two properties. For instance, a joist classed as Reject due to its low MoR may have an MoE suitable for classification as C24. There were many joists with low MoR values in the sample used in this study and even though they may not be representative of the majority of the timber elements found in situ in the UK, this does not undermine the conclusions made.

References

AFNOR (1991) ‘AFNOR B 52-001-4 Regies d’utilisation du bois dans les constructions Partie 4: Classement visuel pour emploi en structure pour les principales essences resineuses et feuillues’. La Plaine Saint-Denis Cedex, France: Association Francaise de Normalisation.

Almazán, F. J. A. *et al.* (2008) ‘Comparison of the Spanish visual strength grading standard for structural sawn timber (UNE 56544) with the German one (DIN 4074) for Scots pine (Pinus sylvestris L.) from Germany’, *Holz Roh Werkst*, 66, pp. 253–258. doi: 10.1007/s00107-008-0241-9.

Bather, M. and Ridley-Ellis, D. (2019) ‘The use of a visual grading code of practice in the UK in the assessment of the mechanical properties of in situ structural timber elements’, in Branco, J. M., Poletti, E., and Sousa, H. S. (eds) *Proceedings of the International Conference on Structural Health Assessment of Timber Structures, SHATiS’2019*. Guimaraes Portugal: University of Minho.

Blass, H. and Frese, M. (2004) ‘Combined visual and machine strength grading’, *Holz als Roh und Werkstoff*. Available at: http://www.rz.uni-karlsruhe.de/~gc20/IHB/PUBLIC/38.pdf.

Booth, L. and Reece, P. (1967) *The Structural use of Timber*. First. London, UK: E and F N Spon.

BSI (1952) ‘CP 112 (1952) The structural use of timber in buildings’. London: British Standards Institution.

BSI (1967) ‘CP112:Part 2:1967 The Structural use of timber’. London, UK: British Standards Institution.

BSI (1971) ‘CP 112:Part 2:1971 The structural use of timber’. London: British Standards Institution.

BSI (1973) ‘BS 4978:1973 specification for Timber grades for structural use’. London: British Standards Institution.

BSI (2017) ‘BS 4978:2007+A2:2017 Visual strength grading of softwood – Specification’. London, UK: British Standards Institution.

CEN (1997a) ‘EN 1310:1997 Round and sawn timber – Method of measurement of features’. Brussels: European Committee for Standardization.

CEN (1997b) ‘EN 844-9:1997 Round and sawn timber - Terminology. Part 9. Terms relating to features of sawn timber’. Brussels: European Committee for Standardization.

CEN (2006) ‘EN 1995-1-1:2004+A2:2014 Incorporating corrigendum June 2006 Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings’. Brussels: European Committee for Standardization.

CEN (2010) ‘EN 384:2010. Structural timber — Determination of characteristic values of mechanical properties and density’. Brussels: European Committee for Standardization.

CEN (2012) ‘EN 408:2010+A1:2012 Timber structures — Structural timber and glued laminated timber — Determination of some physical and mechanical properties’. Brussels: European Committee for Standardization.

CEN (2013) ‘EN 1912:2012 Incorporating corrigendum August 2013 Structural Timber — Strength classes — Assignment of visual grades and species’. Brussels: European Committee for Standardization.

CEN (2016a) ‘EN 14358:2016 Timber structures — Calculation and verification of characteristic values’. Brussels: European Committee for Standardization.

CEN (2016b) ‘EN 338:2016 Structural timber — Strength classes’. Brussels: European Committee for Standardization.

CEN (2019) ‘EN 14081-1:2016+A1:2019 Timber structures — Strength graded structural timber with rectangular cross section Part 1: General requirements’. Brussels: European Committee for Standardization.

CIA (no date) *The World Factbook*, *Edition 21 January 2021*. Available at: https://www.cia.gov/the-world-factbook/ (Accessed: 22 January 2021).

Coulson, J. (James C. . (2012) *Wood in construction : how to avoid costly mistakes*. Chichester: Wiley-Blackwell.

Dansk Standard (2009) ‘DS/INSTA 142 Nordiske regler for visuel styrkesortering af konstruktionstrce (Nordic visual strength grading rules for timber)’. Charlottenlund: Dansk Standard.

Desch, H. E. and Dinwoodie, J. M. (1981) *Timber - Its structure, properties and utilisation*. Sixth. London: MacMillan Education.

Deutschen Institut für Normung (2012) ‘DIN 4074-1:2012’. Berlin: Deutschen Institut für Normung.

Donaldson, T. L. (1860) *Handbook of specifications: or, Practical guide to the architect, engineer, surveyor, and builder, in drawing up specifications and contracts for works and constructions*. London: Atchley and Co. Available at: http://hdl.handle.net/2027/nyp.33433066421409 (Accessed: 30 May 2018).

Gil-Moreno, D. (2018) *Potential of noble fir, Norway spruce, western red cedar and western hemlock grown for timber production in Great Britain*. Edinburgh Napier University. doi: 10.1080/20426445.2018.1546283.

Glos, P. (1995) ‘Strength grading’, in Blass, H. J. et al. (eds) *Timber Engineering STEP 1*. First. Almere, The Netherlands: Centrum Hout.

Hanhijarvi, A. and Ranta-Maunus, A. (2008) *Development of strength grading of timber using combined measurement techniques. Report of the Combigrade-project – phase 2*, *VTT*. Available at: http://www.vtt.fi/inf/pdf/publications/2008/P686.pdf.

Hanhijarvi, A., Ranta-Maunus, A. and Turk, G. (2005) *Potential of strength grading of timber with combined measurement techniques: Report of the Combigrade-project - Phase 1*, *VTT Publications*. Vuorimiehentie, Finland.

Høibø, O. *et al.* (2014) ‘Bending properties and strength grading of Norway spruce: variation within and between stands’, *Canadian Journal of Forest Research*, 44, pp. 128–135. doi: 10.1139/cjfr-2013-0187.

Kolja21 (no date) *Europe Regions Map (based on CIA World Factbook), own work, CC BY 3.0, Creativecommons.org.* Available at: https://commons.wikimedia.org/w/index.php?curid=6881466 (Accessed: 22 January 2021).

Lukacevic, M., Füssl, J. and Eberhardsteiner, J. (2015) ‘Discussion of common and new indicating properties for the strength grading of wooden boards’, *Wood Science and Technology*, 49(3), pp. 551–576. doi: 10.1007/s00226-015-0712-1.

Madsen, B. (1992) *Structural Behaviour of Timber*. North Vancouver: Timber Engineering Ltd.

Nicholson, P. (1826) *Practical Carpentry, Joinery and Cabinet Making: Being a New and Complete System of Lines for the Use of Workmen*. London, UK: Thomas Kelly.

Pacific Lumber Inspection Bureau (1971) *Export ‘R’ List. Grading and Dressing Rules*, *Pacific Lumber Inspection Bureau*. Bellevue, Washington, USA: Pacific Lumber Inspection Bureau. Available at: http://www.plib.org/resources/export-r-list/.

Peters, A. (1869) ‘Castleton Grange Specification of the works required to be done in the erection of a stable, coach house, loose box’. Held by Touchstones Rochdale, Rochdale Art Gallery and Museum.

Piazza, M. and Riggio, M. (2008) ‘Visual strength-grading and NDT of timber in traditional structures’, *Journal of Building Appraisal*, 3(4), pp. 267–296. doi: 10.1057/jba.2008.4.

Ranta-Maunus, A. (2009) *Strength of European timber. Part 1. Analysis of growth areas based on existing. VTT PUBLICATIONS 706*. Helsinki, Finland.

Ranta-Maunus, A., Denzler, J. K. and Stapel, P. (2011) *Strength of European timber. Part 2. Properties of spruce and pine tested in Gradewood project*. Helsinki, Finland.

Ridley-Ellis, D., Stapel, P. and Baño, V. (2016) ‘Strength grading of sawn timber in Europe: an explanation for engineers and researchers’, *European Journal of Wood and Wood Products*. Springer Berlin Heidelberg, 74(3), pp. 291–306. doi: 10.1007/s00107-016-1034-1.

Roblot, G. *et al.* (2010) ‘Automatic computation of the knot area ratio for machine strength grading of Douglas-fir and Spruce timber’, *European Journal of Environmental and Civil Engineering*, 14(10), pp. 1317–1332. doi: 10.1080/19648189.2010.9693296.

SIA (2009) ‘SIA 265/1:2009 Holzbau – Ergänzende Festlegunge’. Zürich: SIA Swiss Society of Engineers and Architects.

Stapel, P., Denzler, J. K. and van de Kuilen, J. W. G. (2017) ‘Analysis of determination methods for characteristic timber properties as related to growth area and grade yield’, *Wood Material Science and Engineering*. Taylor & Francis, 12(1), pp. 1–13. doi: 10.1080/17480272.2014.987317.

Stapel, P. and van de Kuilen, J. (2010) ‘Growth areas in Europe with regard to different wood species and grading principles’, in *WCTE 2010 - World Conference on Timber Engineering*. Riva del Garda, Italy.

Stapel, P. and Van De Kuilen, J. W. G. (2014) ‘Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: A critical evaluation of the common standards’, *Holzforschung*, 68(2), pp. 203–216. doi: 10.1515/hf-2013-0042.

Tredgold, T. (1875) *Elementary principles of carpentry*. 2nd edn. London: E and F N Spon. Available at: https://archive.org/details/elementaryprinci00treduoft.

Tredwell, T. (1973) ‘Visual stress grading of timber: Explanatory notes on BS4978:1973’. High Wycombe, Bucks.: TRADA.

Vandenabeele, L., Bertels, I. and Wouters, I. (2016) ‘Baltic shipping marks on nineteenth-century timber : their deciphering and a proposal for classifying old timber’, *Construction History*, 31(2), pp. 157–176.

Viguier, J. *et al.* (2015) ‘Improving strength grading of lumber by grain angle measurement and mechanical modeling’, *Wood Material Science and Engineeering*, 10(1), pp. 145–156. doi: 10.1080/17480272.2014.951071.

Yeomans, D. (2020) *The repair of historic timber structures*. London, UK: ICE Publishing.

Zobel, B. and van Buijtenen, J. (1989) *Wood variation — its causes and control*. First edit. Berlin: Springer-Verlag.