Strength grading of sawn timber in Europe – an explanation for engineers and researchers

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Abstract

This paper is a concise explanation of the normative background to strength grading in Europe, addressing important aspects that are commonly misunderstood by structural engineers and timber researchers. It also highlights changes that are being made to the standards to: incorporate requirements of the Construction Products Regulations; add improvements to the system to accommodate the latest knowledge and technology; and widen the application of the standards.

Where designs need to be optimised, there is an opportunity to use the system more intelligently, in combination with the latest technology, to better fit design values to the true properties of the timber resource. This can bring a design enhancement equivalent to effort improving other aspects of the structure, such as connectors and reinforcement. Parallel to this, researchers working on other aspects of structural improvement need to understand what grades really mean in respect of the properties of the timber, in order to correctly analyse the results of testing. It is also useful to know how techniques used in grading can assist with material properties characterisation for research.

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. This paper provides an overview of what is required for this.

1 Introduction

Wood has a wide range of physical and mechanical properties. These properties, and the correlations between them, vary from species to species and depend on growth conditions. When structural timber is produced, the key properties need to be assessed in order to ensure structural safety, and economic use of the material.

The European system for grading structural timber is set out by the harmonised standard EN14081 and supporting standards. It sorts rectangular cross-section timber into categories based on strength, stiffness and density. In Europe the correct name for this is “strength grading” although the process is often called “stress grading”. Despite these names, the grading itself is not always about strength and the limiting property of a species (or species combination), source and grade may well be stiffness or density.

It is important for structural engineers and timber researchers to understand the core principles, and the limitations, of the strength grading system. It has a direct bearing on properties that are crucial to engineering design and therefore also structural safety and the efficient and economical use of the available material. Without knowing the theory and practice of grading, misunderstandings may arise that compromise safety, or mean that timber is over specified to compensate for lack of confidence of the designer.

The standards for timber grading in Europe are currently under revision to incorporate the requirements of the Construction Products Regulations; to add improvements to the system to accommodate the latest knowledge and technology; and also to widen the application of the standards. This brings about opportunities for better use of timber in construction.

Where designs need to be optimised, there is an opportunity to use the system more intelligently: taking advantage of the flexibility of strength classes to make better use of the true properties of the timber used, and thereby bring a design performance benefit equivalent to research and development effort improving other aspects of the structure, such as connectors and reinforcement. Parallel to this, researchers working on those other aspects of structural improvement need to understand what grades really mean, in respect of the properties of the timber, in order to correctly analyse the results of testing. This paper also provides information to researchers for development of grading assignments, and for undertaking timber properties research in a way that could contribute to a grading dataset at a later date.

1.1 The origin of variation in timber properties

The macroscopic factors that affect timber properties are familiar to anyone who has worked with wood although they do not tell the whole picture. These include the size and position of knots, the closeness of the grain, the slope and spirality of the grain in the piece, the density of the wood, the ratio of early wood and latewood, fissures, reaction wood, wane, rot and other damage. Alongside these are factors that are less readily assessable such as the relative amounts of the main component molecules that make up the cell wall (lignin, cellulose and hemicellulose), the degree of crystallinity of the cellulose, the orientation of those crystals within the cell wall (microfibril angle), and the quantity and nature of extractives.

These factors are affected by the genetics of the tree, the environment in which it grew, and the management of the forest. The processing of the timber, such as sawing and drying, adds additional factors. The degree of variability is such that two pieces of the same tree can be more different, in terms of the key mechanical and physical properties for construction, than two pieces of different species.

The degree of variability of timber properties has been the subject of much research in recent years both in respect of the impact on timber grading (e.g. Ranta-Maunus et al. 2011, "Gradewood Project") and on the opportunities to improve the timber resource through tree breeding, forest management and resource segregation (e.g. Moore et al. 2013, Baltrušaitis and Pranckevičienė 2012, Rais et al. 2014). It is known that there is considerable variation of wood properties within a tree (related to the biomechanics of tree growth), but also a crucial geographical variation that is caused, in part, by environmental and silvicultural factors and, therefore, varies with time. For grading, it is also important to recognise that the correlations between the parameters used for grading and strength, stiffness and density also varies, and is influenced by the factors just mentioned.

There are two important consequences of this variation. Firstly, large, carefully sampled, datasets are necessary to properly quantify key timber properties and secondly, the quantification of timber properties (and hence grading) has to be tied to a defined population, covering at least the species, the growth area, and the range in cross-section. Unfortunately, this means that timber cannot readily be graded for use in construction unless the testing work to support the grading has been carried out. This presents a hurdle 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.

1.2 Strength grades and strength classes

The terminology within the various European grading standards is slightly inconsistent but a "strength grade" is a category of timber describing its relative quality for construction. A "strength class" is a "strength grade" with specific mechanical and physical properties assigned to it that can be used in design calculations.

EN338 lists a set of bending strength classes for softwoods (C-grades) and a set for hardwoods (D-grades). The softwood and hardwood strength classes are defined in such a way that they fit reasonably well to the property profiles of most species commonly used in construction. The two types of strength class recognise the different property profiles between softwoods and hardwoods but, as a wider range of hardwoods is being used in construction the C-grades are being opened up to species such as poplar and chestnut (FprEN338:2015) that may fit better to the softwood profiles due to relatively low density (e.g. Brunetti et al. 2013). The new version of the standard also includes tension (T) classes, which are intended for use in glulam manufacture, and other situations where tension, rather than bending, is the dominating load.

It is important to realise that these are not the only strength classes that can be used. EN338 is merely a convenient set of widely known strength classes to facilitate easy trade. Other strength classes can and are being used. One example is the grade TR26 which is in long-standing common usage in the trussed rafter industry in the UK. There is nothing in principle to stop a strength class being defined that best matches a particular timber resource, or the requirements of a particular end use. This can be done in order to make optimum use of the timber resource, although doing so requires testing data to allow timber to be graded to that strength class (see 3 and 7). Within Europe, it is the Declaration of Performance for the timber, together with the CE mark, that specifies the properties that are important for design, and the strength class is one way of describing most of those properties.

1.3 Grade determining properties

Timber strength grading in Europe is based on three key grade determining properties: strength, stiffness and density. These are determined through EN408 and EN384 for, normally, a reference moisture content consistent with 65% relative humidity and 20°C (12% moisture content for most species). Specifically, there are two sets of grade determining properties:

i. *Bending* strength, *bending* stiffness, and density (e.g. C and D classes in EN338)
ii. *Tension* strength, *tension* stiffness, and density (e.g. T classes in FprEN338:2015)

The first is most commonly in use for general construction timber, while the second is more useful for grading of lamellas for the manufacture of glued laminated products such as glulam beams. Tension grades have existed for a long time, but they are now being made more visible within the European standards. There is a risk of confusion if the basis of grading is not understood.

Bending grades are based on data from bending tests. Tension (and other) properties must therefore be conservatively estimated from bending properties and density.

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This means that bending grades and tension grades are not equivalent and should not be conflated. A bending grade will have more conservative tension properties, while a tension grade will have more conservative bending properties.

A number of other properties must also be conservatively estimated from the grade determining properties and they include: tension and compressive strength perpendicular to grain, shear strength and shear modulus. The equations for these secondary properties are based on a great deal of testing for softwoods, but there has been less testing of hardwoods, which are more diverse in properties. It would be prohibitively expensive to undertake the great many tests necessary to treat secondary properties to the same level of confidence as the three grade determining properties, but where testing has been done, it can be used to support changes to the standards. This partly explains why there are some difference in design properties within FprEN338:2015 compared to previous versions. It is possible to create a strength class with values of these properties established by testing and, if a design is very dependent on a secondary property, a testing programme may provide better values for design.

A close reading of the standards will reveal that the bending grades in EN338 are specifically for bending about the major axis, 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. Steffen et al. 2007). 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 safely be used to directly calculate resistance bending about the major axis. For this reason, the timbers would have to be marked accordingly.

The limits of the three grade determining properties are, as for other construction materials, defined by characteristic values that equate to the most useful description of the level and variation of a property for structural engineering. Strength and density are defined by a lower fifth percentile value while stiffness is defined by a mean. It is these characteristic values that must be met for the requirements of a strength class to be satisfied (although see 6.6). The use of characteristic values for properties is not peculiar to timber as uncertainty is inherent in all materials (see EN1990).

Typically, only one of the grade determining properties will be limiting, and indeed it may be that no properties are limiting. It may be, for example, that the grading threshold is purposefully raised to provide a better yield for another grade in combination, or that the strength class that is required for trade is lower than the strength class that best fits the resource. This means that timber will have characteristic properties that *exceed* those stated for the strength class; especially in the case of secondary properties which may be considerably higher. This must be appreciated when analysing the results of tests and, in research, it would be a mistake to treat two pieces of the same strength class as being equal. In fact, grading does not work on an individual piece level at all because strength classes are descriptions of populations not pieces. Strength classes data applies to the set of timber assigned to that strength class and so measurements made on individual pieces of timber may well be below the requirements of the strength class it is assigned. This is intrinsic in the definition of characteristic properties and is true for construction materials generally. This uncertainty is, thanks to the grading procedure, quantifiable and accounted for in the design rules (e.g. EN1995).

For research, the same non-destructive measurements used in grading can be used to estimate properties (with confidence intervals) of individual pieces, and to match pieces of similar properties for use in comparative testing of, for example, fasteners and reinforcements. Although for the same reasons as for grading, the relationships must be established on material of the same species and provenance.

2 Systems of grading

Under the current European system there are two parallel systems for grading: visual and machine. They both operate by relating measures, which can be made non-destructively, to the three grade determining properties based on relationships established by destructive testing. These non-destructive measures are used to assign pieces of timber to strength classes in such a way that the timber pieces that make up each class have more tightly defined, and predictable, values of those properties.

The two systems differ not only with regard to the parameters of the timber that may be used for grading but also to normative requirements. The system used, therefore, makes a difference to grading yield, but, from the point of view of the engineer, strength classes are equivalent irrespective of the system used for the grading. For purposes of traceability the grading system is identified within the CE marking.

No current system of grading can predict, with absolute certainty, what the grade determining properties of a piece of timber are. This means it is not possible to grade timber into strength classes that are close to each other. So while a wide spectrum of possible grades exists, visual grading assignments and machine grading settings typically sort to one, two or three grades (together with reject). The particular set of grades being graded to is known as a 'grade combination'.

2.1 Visual strength grading

Visual grading has a long basis in historical practice and is still widely used. It is not to be confused with appearance grading which is concerned with aesthetic aspects.

Visual grading is carried out according to grading rules that are usually (but do not have to be) national standards. The harmonised standard EN14081-1 outlines a number of basic principles that the visual grading rules must follow. A diversity of grading rules exists to allow for diversity of species, origins, quality, historic influences, requirements and uses. Example assignments for European redwood (Scots pine) visually graded to German, Spanish and British Standards are shown in Table 1. Assignment to a strength class is specific to a combination of grading standard and timber source, and some are listed in EN1912 (see 3). The visual grading rules, which have their origins in older standards, tend to be optimised for the needs of the publishing country. They have different yields, as well as different strength class assignments, so the assignments alone do not provide a simple indication of relative quality for different sources. It is also possible for grading rules to be created specifically for the needs of a single company.

Table 1: Selected strength class assignments for *Pinus sylvestris* (European redwood/Scots pine) from EN1912

Strength class	Strength grade				
EN338	Grading standard & timber source	DIN 4074-1 CNE*	UNE 56544 Spain	BS 4978 CNE*	BS 4978 UK
C30		S13, S13K			
C27			ME1		
C24		S10, S10K		SS	
C22			MEG		SS
C18		S7, S7K	ME2		
C16				GS	
C14					GS

* CNE = Central, Northern and Eastern Europe

For each piece of timber the features that affect strength, stiffness and density are assessed including knots, slope of grain, ring width and reaction wood. Grading rules specify limits for these features to assign pieces of timber into a grade. The grades are assigned to strength classes, together with species and growth area, based on the results of destructive testing.

Visual characteristics are not powerful predictors of grade determining properties and, together with a level of safety added to account for human fallibility, this means that visual grading does not make best advantage of the real properties of the timber resource. However, visual grading can, in principle, be checked at a later stage to ensure that the visual grading rules have been correctly followed. For reasons that are partly legacy of previous standards, the establishment of visual grading assignments to strength classes can be based on smaller testing programmes than machine grading, and existing assignments also cover much wider growth areas than machine grading. The lesser requirement on test data, and simplicity of the grading process, makes visual grading a good first route for getting more diverse species into construction, although a smaller testing programme usually results in lower grading assignments, due to the adjustments, applied by the standards, for statistical uncertainty according to sample size. However, in order to get the true potential from a species it is prudent to also collect data for machine grading for future use.

Visual grading does not necessarily require a lot of manpower but can be carried out, or be assisted by, machine. New systems are being developed that automate more of the process (6.2).

2.2 Machine strength grading

Machine, or mechanical, strength grading has been used commercially for more than forty years. In Europe it can currently be carried out with predetermined machine settings (called "machine control") or by continuous testing of output (called "output control").

Like visual grading, machine strength grading requires the non-destructive assessment of every piece of timber. The difference is that it is a machine that senses one or more properties of the timber to predict the grade determining properties. These "indicating properties" (IP) are usually more powerful predictors of quality than can be measured by visual grading, and the grading can be done at a much faster rate with less risk of human error. The first grading machines worked by bending the timber about the minor axis to assess stiffness but there are now several technologies in use. They include longitudinal or flexural resonant frequency (with or without mass); x-ray measurement of density and knots; and ultrasonic wave speed.

The machine control and output control systems work differently, but timber graded by both is treated equally (as, simply, machine graded timber). In both cases an addition "visual override" step is required to inspect the timber for strength reducing defects that cannot be automatically identified by the machine.

Since even the most sophisticated grading machine cannot predict, with absolute certainty, what the grade determining properties of a piece of timber are, machine grading typically operates on the basis of a reject criterion in combination with IP thresholds for one, two or three strength classes. These IP thresholds (and the functions for IP) are known as settings and they are specific to the grade combinations (the set of strength classes being graded to). The threshold for a strength class in one grade combination may be different to the threshold for the same strength class in another combination.

2.2.1 Output control

Output control requires the producer to periodically proof test batches of graded timber and, if necessary (by statistical procedures), adjust the grading machine settings to ensure grading proceeds safely (in terms of building safety) and efficiently (from the point of view of the producer). This method is most appropriate for mills that grade a limited number of species and cross-sections so that the amount of testing required is not too onerous. The advantage is that settings are optimised for the incoming resource and that a large initial testing programme is not required. This system operates without the need for the settings approval described in Section 3. It is used by some mills in Europe, but is not common, so the procedures in EN14081 are not well developed (see 6.1).

2.2.2 Machine control

Machine control grading relies on settings developed in advance from the results of a destructive testing programme (see 3). It allows the producer to grade timber without any requirement for them to test timber to ensure grade properties are met (although some testing is required by EN14081 for grading of higher strength classes, see 3.4).

The relationship between the IP and the three grade determining properties varies from species to species and from region to region. This is the reason why grading settings are unique to a species (or similar species group) and grading region. Since grading machines measure IPs differently (sometimes using an algorithm known only to the manufacturer) settings are also unique to machines. Timber cannot be correctly graded with settings from another region, even if the species is the same.

3 Approval of settings and assignments

The procedure for output control machine grading is covered by EN14081-2 and EN14081-3. Machine control and visual grading assignments both require extensive mechanical testing data for which further rules are specified by EN384.

For machine control settings, and for visual grading assignments to be listed in EN1912, reports must be submitted for examination by European Committee for Standardization (CEN) committee TC124/WG2/TG1 (TG1), which consists of a panel of experts with knowledge of the correct standard procedures and sufficient experience to be able to query potential problems. This is a vital matter for construction safety and so settings are thoroughly examined before they are approved for use. This is done not to check that the standard procedures are followed correctly (although this is obviously a precondition), but to uncover issues that affect *correct grading* that were not anticipated when the standards were written. As part of this process TG1 compiles a set of additional rules (TG1 2014) that must be followed until those rules can be incorporated into the standards themselves. This process is an integral part of ensuring the safety of timber grading and of developing standards to adapt to new technology and trade practices.

Visual grading assignments need not be published in EN1912 and, if that is the case, the reports must be examined by a Notified Body with appropriate competence. These assignments must not conflict with any grading assignments that are published in EN1912 (EN14081-1 states that the current version of EN1912 assignment takes precedence).

3.1 Sampling

Grading settings and assignments rely heavily on the destructive testing work. It is not possible to write rules for sampling that cover all eventualities but TG1 has formulated guidelines (TG1 2012). Nevertheless, it is vital that researchers use their knowledge and experience, and that of others, when designing the sampling strategy.

The overriding requirement is that the timber tested is representative of the timber to be graded in production. The aim is for the sampling to resemble this timber population in terms of the mean and variance of grade determining properties, and the variation in the relationships between characteristics assessed during grading (visual grading criteria for visual grading and IP for machine grading) and the grade determining properties. This means that sampling strategy must not be designed in order to maximise yield beyond increasing the number of specimens to reduce statistical uncertainty.

The first thing to consider is the size of growth area, and the variation within it of factors that affect timber quality. If there is knowledge from previous research on the variability of the timber in the growth area this can be used to select the sources strategically. The availability of knowledge about the variability within the growth area should influence the number of sources needed. If weak areas are known, they should be taken into account accordingly. Where there is a lack of knowledge, more sources should be used and/or contain more specimens.

Sampling for a growth area that includes more than one country should contain at least one source of specimens from each country (unless test data exists that verifies that timber from one country can be safely graded using settings from another country without being included in the sampling). This is a relatively new addition to the rules to deal with regional variability of the resource (See 6.1).

Ideally the timber to be tested should be taken from normal sawmill production (planed or unplaned) provided the source is known. Pieces that have defects that would be rejected by visual override inspection (see 2.2) should not be included. Sampling based on selecting logs, as is commonly the case for timber properties research, is acceptable provided that normal sawing patterns are used and a sufficient number and diversity of logs are selected such that the sample is not biased.

If species are traded, and processed together without being differentiated (e.g. “European whitewood” *Picea abies* and *Abies alba*, WPCA), then the settings/assignments should be based on that species combination. EN14081-1 lists four letter codes for commercial species combinations, which are used in the labelling of graded timber.

It is important that the length of the specimens is sufficient to allow the tests to be carried out on the critical section (weakest point within the piece of timber). However, care should be taken to avoid biasing the sample through selection of unusually long lengths compared to industrial practice. This could bias the sampling towards larger trees which have different wood properties than smaller ones.

The range of sizes permitted to be graded by machine depends on the range of sizes included in the sampling, according to rules set by EN14081-2, so it is important to include a wide variation of sizes in the total sample. For visual grading there is no explicitly stated limit that depends on the testing but it is nevertheless prudent to include a range of sizes that is representative of industrial practice. Recent entries EN1912 were limited to the cross-sections that had been included in the sample.

The same sample of timber can be used to establish grading settings for a number of different grading machines and/or assignments for visual grades to different grading rules, but since the timber can only be destructively tested once the same sample cannot be used to establish both bending and tension strength classes.

3.2 Derivation of visual grading assignments

For visual grading, the first step is the selection, or the development, of the grading rules. Timber is acquired from sources (geographic places) within the growth area (the whole geographic area for which grading assignments will be applicable). The timber is assigned to grades according to the grading rules and then destructively tested. The purpose is to evaluate the characteristic values of strength, stiffness and density of the grades in order to determine which strength classes the grades satisfy the conditions of. Adjustments are made to compensate for statistical uncertainty resulting from the number of pieces tested and the number of sources evaluated for the grades.

For each source of timber there should be at least 40 specimens (pieces of timber) in each grade, but, depending on the size of the growth area and the variation within it a much larger dataset may be required (See 3.1). Larger datasets also reduce the statistical corrections resulting in grading assignments that make more efficient use of the resource. Efficient use of the resource also depends, to a large degree, on the ability of the grading rules to separate the timber by quality.

Previously, the strength of timbers was frequently assessed by evaluating the results of testing of small, clear specimens (pieces without defects). This removed the need for expensive testing; particularly helpful in the case of expensive tropical hardwoods. However, the effect of defects such as knots and grain deviation, is not always known so this route is now only possible for those tropical hardwoods for which there is existing data, from similar species, that can be used to adjust small clear test data to full size equivalent.

3.3 Derivation of machine control settings

For machine control grading, a large mechanical testing dataset is required (at least 450, but typically over 1,000). This is roughly ten times the dataset required to establish initial settings for machine output control, but is applicable to all machines of that type grading that species combination from that growth area. The whole sample consists of timber drawn from at least four sources (geographic places) within the growth area, each of which must consist of at least 100 specimens.

The overall procedure is as follows:

1. Determine the sampling strategy to represent the population to be graded (See 3.1)
2. Pass the timber through the grading machine for which settings are required
3. Test the timber to EN384 and EN408 to obtain strength, stiffness and density
4. Formulate a useful IP function with and relate the IP to the strength, stiffness and density (as EN384 and EN14081)
5. Follow the standard procedures to determine thresholds for IP that satisfy the requirements of strength classes for each grade combination, along with other conditions designed to ensure robust grading
6. Present the derived settings and calculations in a report to TG1 for examination

As with visual grading, there are adjustments to compensate for statistical uncertainty based on the number of specimens and sources. Larger testing programmes result in grading settings that make efficient use of the resource. This also depends, to a large degree, on the power of the IP to predict the grade limiting properties. Grade determining properties that are not critical, need not be well correlated to IP. This aspect of the performance of the grading machine depends, therefore, on the properties of the timber being graded.

One of the important findings of the Gradewood project (Ranta-Maunus et al. 2011) is that the degree of geographical variation of wood properties is larger than previously thought. As the industrial practice of grading develops, and the timber trade opens out to new and wider areas, it has become necessary to formulate new rules to ensure new settings and grade assignments are correct. These rules are known as the “country check”. This amounts to confirmation that the characteristic values of the strength classes, within countries that make up the whole sample, satisfy at least 90% of the requirements of the strength class (the tolerance is there to reflect statistical uncertainty because the number of specimens within grades within countries can be very low as the whole sample has been divided many times). This is the reason why sampling must include timber from all countries within the growth area.

It is recognised that political borders are an imperfect way of defining growth areas and variation within them, not least because countries range greatly in size and bear little relation to forested areas. This is one area for future development (see 6).

3.4 Proof testing for higher grades of softwoods

It is a requirement in machine strength grading for higher strength classes of softwoods to periodically select timber from production for proof testing to confirm that required characteristic strength values are being met. The rule applies for bending strength classes with a characteristic bending strength above 30 N/mm^2 and tension strength classes with a characteristic tension strength above 21 N/mm^2. It is recommended by TC124 WG2 that the same rule be applied for visual grading (Rouger, 2014). The requirement for testing was introduced at a time when there was limited experience with these higher grades and it is retained to provide an additional degree of safety for grades likely to be used for more critical members. The standards do not currently specify what to do if the testing is not satisfactory, but the action would necessarily have to correspond to the overall requirement on the producer to ensure that the declared values of the characteristics properties are maintained. A sensible first reaction would be to undertake more testing to confirm the results.

4 Wet and dry grading

Both machine and visual grading can be carried out with the timber at any moisture condition, and while yields can vary between wet (green) and dry grading, the graded timber may be treated as equivalent with one important exception. Dry-graded timber is timber that has been checked for fissures and distortion (bow, spring and twist) in the dry condition (although this could be as high as 20% moisture content). It could be that the rest of the grading process was carried out at a higher moisture content. For example, there are machine control settings for grading above fibre saturation point, which allow reject timber to be removed prior to kiln or air drying. However, providing that the fissures and distortion are checked after drying, the timber can be declared dry-graded. There is no formal designation of wet (or green) graded timber, rather there is simply dry-graded timber and timber that is not dry-graded. What dry-graded timber does not indicate is moisture condition of the timber when it is received, and this needs to be specified separately in the contractual arrangement. A specification for dry-graded timber is not, *per se*, a specification for graded timber that is dry, although it does mean that the timber *should* be kept dry between grading and use. Timber that is not dry-graded could be traded in the dry condition, *but would need to be checked for fissures and distortion before use*.

In short, graded timber that is dry is not necessarily dry-graded timber. This is something that has shifted in meaning and many older explanations of timber grading relate the term dry-graded to moisture condition *as traded* or to service classes in EN1995. This confusion is increased by the use of terms like dry and kiln dried (or KD) being used synonymously with dry-graded.

It is also important to realise that, in both wet and dry grading, the reference environment for the design properties normally equates to 12% moisture content (see 1.3 and EN384). Design values for timber that is used in another moisture conditions need to be subsequently adjusted in the design procedure.

5 Re-grading and re-sizing of timber

It is important to bear in mind, with strength graded timber, that the grading relates to characteristic properties and not the properties of individual pieces of timber. This is true of both visual and machine graded timber. Grading settings and assignments are based on the statistical properties of a defined population of the raw material. If the statistical properties of the pre-graded population change, then settings and assignments may no longer work correctly.

For this reason, the re-grading of timber that has previously been graded (or rejected by a grading process) must not be carried out, unless the settings (for machine grading) or assignments (for visual grading) used for regrading have been determined with due allowances for the changes to the timber population caused by the previous grading. It is permissible to verify the visual grade of a piece by applying the same grading rules, but not to re-grade with different grading rules or visually grade timber rejected by machine grading.

In the early days of machine grading, it was always done by machines that physically bend the timber. An observer may mistake this type of machine for a proof loading test and erroneously conclude that re-grading is not allowed because the grading machine progressively damages the timber every time it operates. The real reason is better understood by the following reasoning:

1. The grading process works by sorting timber into grades and each grade must satisfy the characteristic values of the strength class to which it is assigned.
2. During grading, it is likely that at least one of the grade determining properties is close to the minimum required for the strength class. (i.e. there is a grade limiting property).
3. If pieces are subsequently removed from the set of timber that makes up that grade and they are removed in such a way that the pieces with higher values of the grade limiting property are removed preferentially, then the characteristic values of that grade must reduce as a result. This could mean that the requirements of the strength class are no longer met.
4. The same must be true of those pieces were removed *before* the grading took place.
5. Any previous grading process must have preferentially removed better pieces from the population because that is the purpose of grading. Previous grading must therefore affect the operation of subsequent re-grading.

There is one exception to this rule. If the cross-section of the timber is substantially changed by re-processing then the original grading will no longer be valid (not applying to x-ray grading machines that are permitted to run with a board-splitting mode). This is because the mechanical properties of timber are not uniform within a piece and removal of part of the cross-section will change the combined properties of what remains. For example, strength depends on the relative size of knots and where the knots are in the cross-section. Changing the cross-section therefore changes the impact of the knots. For this reason, EN14081 sets acceptable limits for cross-section change after grading (≤ 5 mm for dimensions between 22 mm and 100 mm and ≤ 10 mm for dimensions > 100 mm). Any reprocessing that is outside these limits requires the timber to be graded again, so reprocessing is a potential route to re-grading. However, it is still ought to be considered whether the re-grading will work and it is unlikely that reducing the cross-section of rejected timber will create a population similar to the original resource prior to grading.

The effect of changing the cross-section of graded timber ought also to be considered if this is done during the construction or fabrication process. Reducing the length of graded timber does not influence the strength class (although removing of defects and finger jointing does provide a route to improvement).

6 Current issues and the future of grading

A considerable research effort is being made to improve standards for production of graded timber in order to:

1. allow the industry to operate freely across borders;
2. work in new areas with new species;
3. make strength classes fit better to the resource and the requirements of particular construction products;
4. and permit the use of emerging technology.

The biggest influence on the development of grading settings in recent years is the Gradewood project and its follow on work. This international project was to enable the timber industries in Europe to take full advantage of the raw material properties through strength grading and to provide the research basis for greater standardisation on a pan-European level. A huge database was established by jointly analysing a large amount of confidential data (26,000 specimens) and by performing new experiments on another 6,000 specimens. One of the most significant outcomes is the awareness that the variability of timber properties, even within the production of a single sawmill, is significantly more pronounced than was previously thought. This has prompted modifications to the grading standards.

The following issues are ongoing or future research topics and are presented here as they will shape the development of grading standards over the next few years, and thereby affect industrial practice for structural timber production.

6.1 Coping with shifts in resource quality

The ability of output control to adjust rapidly enough to shifts in resource quality has been examined by research (e.g. Deublein et al. 2010) and, because it is not widely used in Europe, the current standard, EN14081-2, is not completely clear about how it should operate. This has been identified as an area that needs to be addressed in future, although it is likely the case that the method by which grading is done will change generally to merge the adaptive advantage of output control with the ease of use of machine control.

The quality of timber processed at a sawmill can change rapidly if new sources of raw material are used, but also can change gradually over time due to changes in forest management and climate. It is a requirement of the producers of graded timber to address this possibility within their factory production control, but it is not clear how this should be done within the current European standards. It is possible that the standards will be revised to incorporate a period of validity for visual grading assignments and machine control settings together with an approach for confirming that the assignments and settings can be renewed.

For machine grading with more modern machines, there are new possibilities for monitoring resource quality via records of the IP, and of using IP in different ways that are less dependent on a stable, predetermined, model of the timber resource quality (e.g. Sandomeer et al. 2008, Ranta-Maunus 2012, Ravenshorst and van de Kuilen 2014).

6.2 Parity between visual and machine

There is also a need to bring the two systems (visual and machine) onto a more common footing so that there are no artificial advantages to using one over the other and more equal treatment of graded timber producers (Stapel and van de Kuilen 2013). By bringing the two onto a common basis, the standards can be simplified. Additionally, it could be made possible for grading that makes use of visual grading principals combined with elements of machine grading such as measurement of resonance and density. Indeed these hybrid methods have been proposed by research already (e.g. Conde et al. 2007 and Vega et al. 2012) and are in use for glulam production and assessment of timber in situ.

Emerging surface scanning and image recognition technology also allows more of the visual grading process to be fully automated making the operation more like machine grading in its repeatability. The combination of “BoardMaster” and “EndSpy” manufactured by FinScan Oy is such an example that is available now, although it is not universally accepted by visual grading experts.

6.3 New developments in machine grading

The number of different types of grading machines has increased considerably in recent years.

6.3.1 Less costly and more portable machines

There are many portable devices that are capable of assessing timber quality via acoustic methods but it is only recently that these kinds of machines have been approved for timber grading. The first portable grading machine approved for use in Europe was the handheld Brookhuis MTG which, at the time, caused debate in the standardisation committees as to what constituted machine grading. The machine was approved on the basis that the settings did not use the k_v factor, which gives an advantage for machine grading on the basis of there being less human involvement (see 6.6). A portable version of MiCROTEC’s ViSCAN grading machine has also been approved. These sorts of machines, and their relatively inexpensive in-line equivalents, open up the possibility of timber grading being done outside the sawmill. Timber fabricators can grade their own timber and could do so to bespoke strength classes that maximise the use of the real properties of the timber resource, and fit to the requirements for specific elements of the building (both by member function and degree of loading within the structure).

6.3.2 New types of IP

Research is currently underway on grading machines that are capable of characterising more detail within the timber based on technologies such as laser tracheid (e.g. Olsson et al 2013), microwave (e.g. Denzler and Linsenmann 2014) and ultrasound (Yaitskova 2014) scanning. As computer processing speed increases, these techniques could potentially be combined with more deterministic models (e.g. Guaita and Baño 2012) to improve IP power further still.

Some of these kinds of grading machine can, potentially, operate on logs prior to sawing allowing the cutting pattern to be optimised for value. Indeed, such a machine already exists, based on computer tomography scanning to measure density and knots (MiCROTEC CT.LOG) although it could not, currently, be used for grading.

6.3.3 Pre-grading and resource segregation

Measurements made on logs and standing trees in the forest are able to segregate the timber resource (e.g. Moore et al. 2013, Baltrušaitis and Pranckevičienė 2012, Rais et al. 2014), diverting the better quality material to construction timber and the poorer material to other markets and reducing wastage. As methods of resource segregation become more effective this would allow decisions to be made about what strength classes to grade to for optimum value yield, but this raises the question as to whether the practice of resource segregation compromises existing grading settings and assignments for the reasons outlined in 5.

6.4 European visual grading standard

There is currently a diversity of standards for visual grading of timber that fit under the harmonised standard EN14081, and which vary in grading results (Stapel and van de Kuilen 2014). A common visual grading standard would be useful, from the perspective of ease of trade throughout Europe. The Gradewood project collected data on European redwood, but the extent of geographical variation in properties, and their correlation with visual grading parameters, is such that a pan-European standard would necessarily need to compromise yield and/or strength class assignments in return for ease of trade.

A common European standard for the specific case of visual grading of tropical hardwood species is, however, soon to be published (FprEN16737:2015)

6.5 Increasing the scope of grading

Currently, the scope of timber strength grading in Europe includes timber that is preservative treated against biological attack, but does not extend to wood that is treated with fire retardant products. This is because the effect of the chemical treatment on the mechanical properties has not yet been sufficiently quantified by research. The same is true for modified wood (e.g. acetylated and thermally modified wood) where research is needed to understand the how the process parameters can influence grade properties (especially the secondary ones), before this kind of timber construction product could be incorporated into a harmonised strength grading system.

The current harmonised standards also do not cover timber with non-rectangular cross-section (beyond the permitted limits for wane), including products like profiled structural decking, and roundwood.

6.6 Peculiarities

The present system of strength grading is built on the foundation of previous national grading and structural design standards (including also a change from permissible stress design to limit states design) and a long tradition of the use of timber in construction. This has resulted in a number of peculiarities which include the following.

The requirement for the characteristic value of bending or tension stiffness (the mean) is to equal or exceed 95% of the value for the strength class. This is in order to adapt the standard to previously existing practice and can be explained by the testing at the critical section (3.1) compared to random positioning.

For in-line machine strength grading of bending strength classes with characteristic bending strength less than or equal 30 N/mm^2 the target characteristic bending strength is reduced by a "k_v" factor of 1.12 (EN384). 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.

For both machine and visual grading, the bending and tension strength test results are also adjusted by a size factor, k_h, to a reference depth/width of 150 mm (EN384). This has the effect of decreasing characteristic values for depth/width of 100 mm by 8% and for depth/width of 40 mm by 30%. This factor is then applied in reverse within EN 1995-1-1 (clause 3.2) 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. Piter 2012, Denzler and Glos 2008). In a material such as steel, the size of possible defects increases with member size. For timber, the defects are more numerous in larger members, but their nature (e.g. diameter of knots) depends on the original log, and not the size of the timbers sawn from it.

The 95% factor on stiffness, and the k_v and k_h factors on strength mean that is not simply the case that the timber graded to a strength class must have characteristic values of strength and stiffness that exceed those of the strength class.

7 Illustration with real data –properties of timber assigned to a strength class

The following examples are greatly simplified, but they illustrate how the true properties of a timber grade are not necessarily well represented by a generic strength class.

7.1 Example 1: machine grading of UK larch

Research was conducted to establish settings for UK larch (a mix of *Larix decidua*, *Larix x eurolepsis* and *Larix kaempferi* grown in the United Kingdom, WLAD) to establish machine control settings for the Brookhuis mtgBATCH 962 in-line grading machine (Ridley-Ellis, 2014). Histograms for bending strength, bending stiffness and density of the timber assigned to the strength classes are shown in Figure 1 for the grading combinations C16/C27/reject (upright histograms) and C16/C30/reject (inverted histograms). There is considerable overlap between the histograms for the assigned strength classes because the definitions of the strength classes themselves overlap and because the indicating property used here (based on dynamic modulus of elasticity from longitudinal resonance) is an imperfect predictor, especially of strength and density. There is, in this case, an approximately 1 in 3 chance of a randomly chosen piece of timber assigned to C16 actually having higher strength than a randomly chosen piece of timber assigned to C27 from the same combination. Nevertheless, the characteristic values meet the requirements for both of the strength classes.

Figure 2 shows plots of IP against the measured values of each of the three grade determining properties (left-hand y-axis) for the C16/C27/reject combination. The calculated thresholds for the grades are shown together with lines tracing the degree to which the characteristic value of the timber above the IP meets the requirements of the grade (right hand y-axis). The variation in these lines on the right-hand side is due to the number of included specimens reducing, and the corresponding greater influence of random effects. In the case of C16 the calculation is after the C27 above the determined threshold is removed. Specimens are highlighted for which the actual grading has assigned a higher strength class than ‘optimum grading’ (a theoretical grading based on the best-case scenario of a grading machine with perfect knowledge of the specimen properties and maximum yield for the highest grade). These ‘upgraded’ specimens mean lower yield than the optimum grading (‘downgraded’ specimens are also highlighted) in order to maintain the required characteristic properties, and EN14081-2 imposes limits on the proportion of them through a cost matrix procedure. In this case, the IP is not particularly well correlated (especially for strength) but the correlation coefficient *per se* is less important than the IP being successful as a threshold for separating the better timber from the poorer timber. Here, a much better IP for density is available since the machine measures mass with a balance. However, this is not necessary to be used in this case since density is not a limiting property.

Error! Reference source not found. shows the characteristic values of bending strength, bending stiffness and density obtained from this research (adjusted for k_h), together with the requirements of the EN338 strength classes adjusted by the 0.95 factor on stiffness and k_v of 1.12 (for in-line machine grading of strength classes C30 and below, see 6.6). This timber is generally limited by its stiffness, although strength is critical for the C27 assignment. For both grading combinations, the timber assigned to the C16 strength class exceeds the strength requirement by more than 40% and the density requirement by nearly 30%. The C16 in combination with the C30 is stiffer than the C16 in combination with C27 because the former has a lower yield of the higher grade leaving what remains to exceed the requirements of C16 with minimal reject.

Table 2 also shows the results for the combination of the UK trussed rafter grade TR26 with C14. In this case, the C14 produced exceeds all requirements by a significant margin (strength by 64%, stiffness by 24% and density by 38%). Indeed, the C14 exceeds the requirement for C16, although, in this case it could not be graded as such because of the cost matrix limit in EN14081-2. In this example, the C14 produced in combination with the TR26 has the same properties as the C16 produced in combination with C27.

Table 2: Characteristic properties of UK larch for grade combinations C16/C27 and C16/C30 graded with Brookhuis mtgBATCH 962

	Achieved (Ridley-Ellis 2014)			Required			% of required		
	Bending strength	Bending stiffness	Density	Bending strength (/1.12)	Bending stiffness (×0.95)	Density	Bending strength	Bending stiffness	Density
Class	N/mm²	kN/mm²	kg/m³	N/mm²	kN/mm²	kg/m³	%	%	%
C16 ✓	20.4	8.0	399	16.0 (14.3)	8.0 (7.6)	310	143% ✓	105% ✓	129% ✓
C27 ✓	24.1	11.2	451	27.0 (24.1)	11.5 (10.9)	370	100% ✓	103% ✓	122% ✓
C16 ✓	20.5	8.6	402	16.0 (14.3)	8.0 (7.6)	310	144% ✓	113% ✓	130% ✓
C30 ✓	29.4	12.1	479	30.0 (26.8)	12.0 (11.4)	380	110% ✓	101% ✓	126% ✓
C14 ✓	20.4	8.2	399	14.0 (12.5)	7.0 (6.6)	290	164% ✓	124% ✓	138% ✓
TR26 ✓	26.0	11.5	462	28.3 (25.3)	11.0 (10.4)	370	103% ✓	110% ✓	125% ✓

Note: Values for C-classes are according to EN338:2009. TR26 is a UK grade for trussed rafters

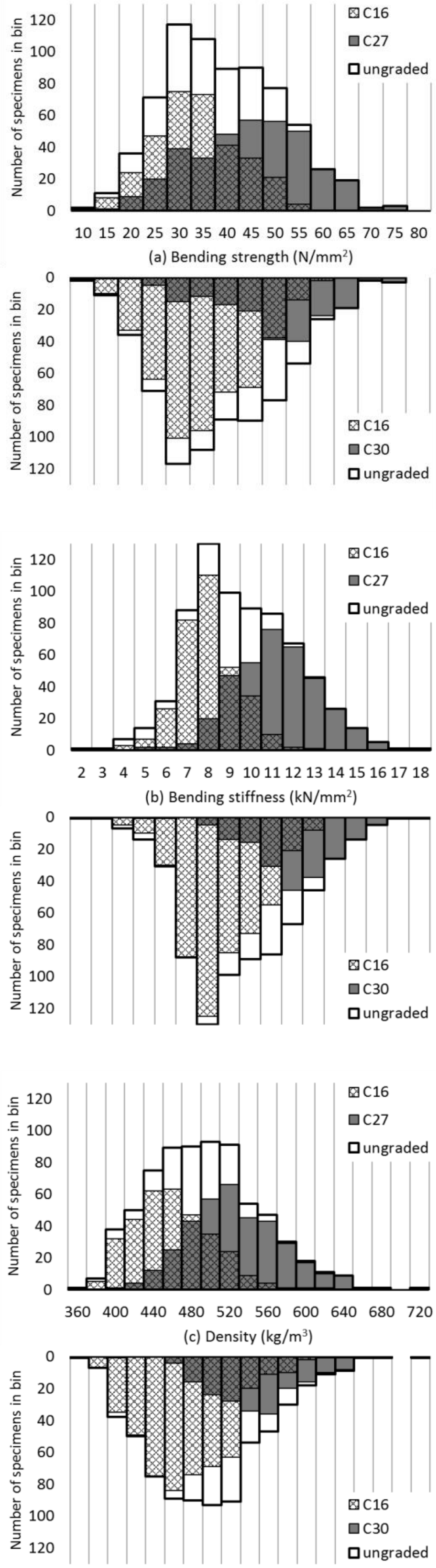

Figure 1: Distributions of (a) bending strength, (b) bending stiffness and (c) density for UK larch graded to C16/C27/reject and C16/C30/reject with a Brookhuis mtgBATCH 962 (total of 706 specimens)

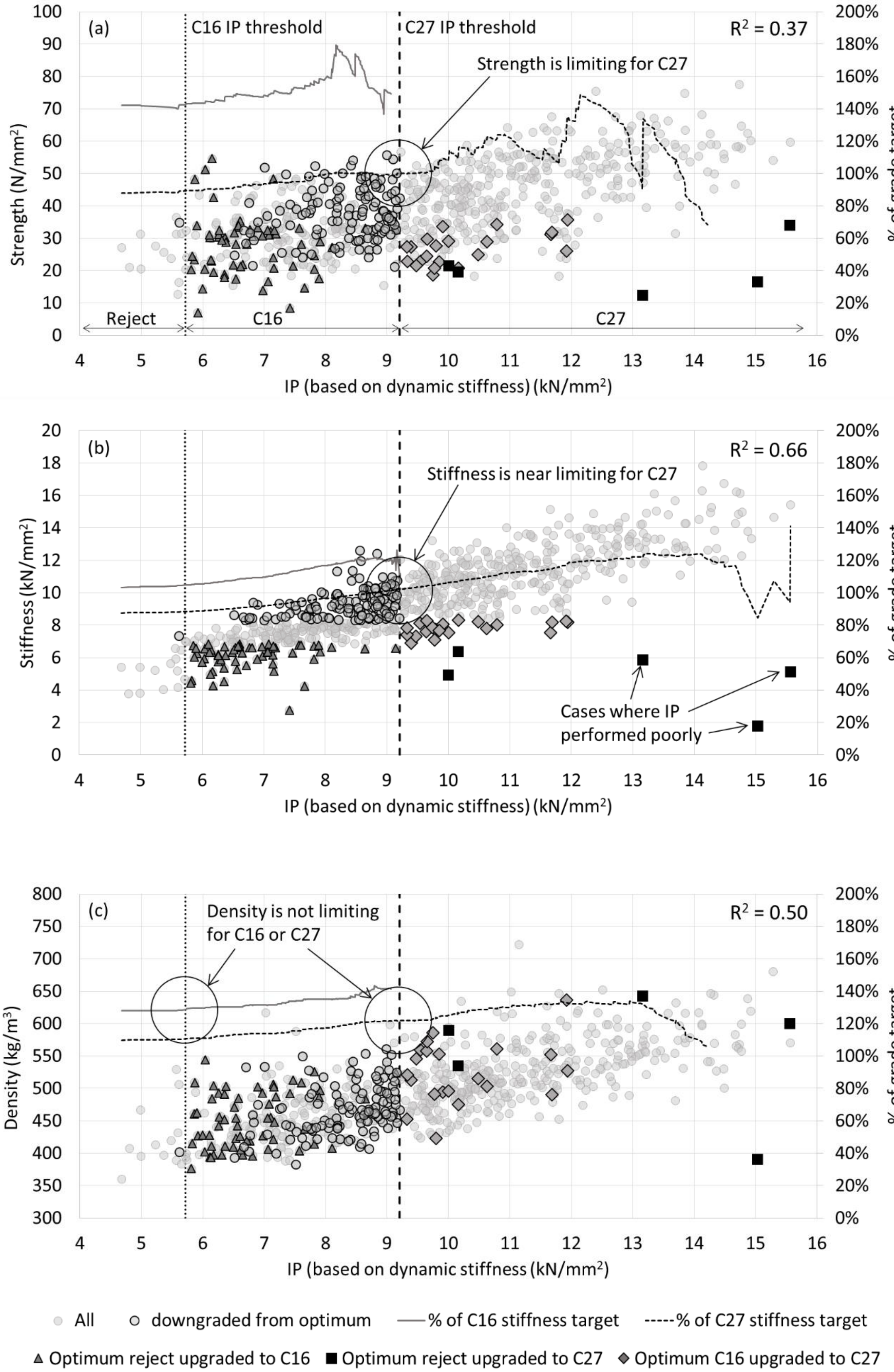

Figure 2: Plots of IP and (a) bending strength, (b) bending stiffness and (c) density for UK larch graded to C16/C27/reject with a Brookhuis mtgBATCH 962

7.2 Example 2: visual grading of Spanish sweet chestnut

Research has been conducted (Vega et al. 2013) towards obtaining strength class assignments for sweet chestnut (*Castanea sativa*) grown in Spain visually graded to the Spanish standard UNE 56546.

Table 3 shows the characteristic values of bending strength, bending stiffness and density obtained for the grade MEF (Structural hardwood timber with width ≤ 70mm), together with the requirements of the EN338 strength classes D24 and D30. With the 0.95 factor on stiffness and k_v of 1 (for visual grading, see 6.6) the timber would satisfy the requirement for D24 but fail for D30, being limited by its density and strength. The FprEN338:2015 offers a new strength class, D27, which fits much better, but a bespoke strength class would make fuller use of the timber's stiffness. By using a custom strength class, a 17% increase in strength, a 29% increase in stiffness, and a 5% increase in density can be achieved compared to the assignment to D24, which was otherwise the best strength class available in the contemporary version of EN338. UNE 56546 includes, in the Annex A, the characteristics values of the mechanical properties obtained by tests.

Table 3: Characteristic properties of Spanish sweet chestnut for grade MEF and possible strength class assignments

	Achieved (Vega et al. 2013)			Required			% of required		
	Bending strength	Bending stiffness	Density	Bending strength	Bending stiffness (×0.95)	Density	Bending strength	Bending stiffness	Density
Class	N/mm^2	kN/mm^2	kg/m^3	N/mm^2	kN/mm^2	kg/m^3	%	%	%
MEF	28.0	12.3	510						
D24 ✓				24.0	10.0 (9.5)	485	117% ✓	129% ✓	105% ✓
D30 ×				30.0	11.0 (10.5)	530	93% ×	118% ✓	96%×
D27 ✓				27.0	10.5 (10.0)	510	104% ✓	123% ✓	100% ✓
Bespoke✓				28.0	12.9 (12.3)	510	100% ✓	100% ✓	100% ✓

Note: Values for D-classes are according to EN338:2009, except (new class) D27 which is according to FprEN338:2015

8 Summary

Timber strength grading is undergoing a process of revision, driven by technology, the Construction Products Regulations, and the information gathered from research. The main changes relate to increased knowledge about the extent of variation within the timber resource, and the development of new technologies and approaches that are able to more accurately grade, or do so at less cost.

With advances in information technology it is less important for there to be commodity strength classes and it is possible for designers to use declared performances that make better use of the real properties of a grade. This is especially true where the timber is graded for a particular construction company, or indeed by that company for their own use. This can bring a design performance benefit equivalent to research and development effort improving other aspects of the structure, such as connectors and reinforcement. Parallel to this, researchers working on those other aspects of structural improvement need to understand what grades really mean in respect of the properties of the timber in order to correctly analyse the results of testing, and how the techniques used in grading can assist with material properties characterisation.

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. Visual grading is a good initial route for new species, but, as machine grading has more powerful indicating properties, it is prudent to consider machine grading too.

There are a number of commonly held misconceptions about timber grading, some of which are addressed in summary below:

- The strength classes in EN338 are not completely distinct from each other. There is a lot of overlap of the properties distributions they represent (e.g. Figure 1).
- The strength class does not indicate what the properties of a particular piece of timber are. It indicates a *lowest* distribution of properties that the timber belongs to. Knowledge of the grade of a piece of timber *per se* is therefore not especially useful for research testing work (see 1.3).
- Visual and machine grading do not have the capability to grade a timber resource into any of the strength classes that are listed in EN338. It is only possible to sort using a particular grade combination of, typically, one, two or three strength classes (see 2).
- Grading machines do not operate by proof testing the timber; although it is true that a grading system *could* work that way (Ziethén 2008). Not all grading machines apply any mechanical load at all to the timber, and those that do, do so in order to assess stiffness and not to check that the timber can withstand that load (see 5).
- Rejects can only be re-graded (visually or by machine) if the machine settings, or visual grading assignments used account for the impact of the first grading (i.e. they have been developed specifically for this re-grading situation). The reason timber cannot be re-graded is not because the grading machine progressively damages the timber (see 5).
- There is no direct correspondence between dry-graded timber and EN1995 service classes. The term dry-graded related specifically to the check for fissures and distortion having been carried out at a moisture content of 20% or less.
- The strength classes, defined by EN338, are not fixed forever; their properties can change when standards are revised.

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