5th International Conference on Structural Health
Assessment of Timber Structures
SHATiS'19

25-27 September 2019, Guimarães, Portugal

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

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Keywords: Timber grading, In situ assessment, Norway spruce

Abstract

The estimation of the mechanical properties of in situ timber elements is an essential part of the structural appraisal of many existing buildings and structures. Currently, in the UK, this appraisal of load-bearing timber is generally carried out by a structural engineer based on a combination of engineering judgement and visual assessment; frequently making use of UK codes of practice for visual strength grading (CP112, BS4978 or BS5765). Despite their frequent use in this manner, these visual grading codes were not written for this purpose and were never intended to be used in this way. The intended use of the codes is the strength grading of consignments of timber elements prior to their use in the construction industry. It is therefore necessary to consider the validly of the methodology of using the visual grading codes for in situ strength assessment. As a case study, 143 structural sized specimens of Norway spruce (Picea abies), sourced from the UK, were visually graded (using CP112) and then tested to destruction to obtain their mechanical properties. The results, when analysed, illustrate the weakness in prediction by visual grading. The key implication of this is that structural engineers in the UK should be made aware of the basis and limitations of using visual grading codes in the assessment of individual in situ structural timber elements, so that they do not overestimate the power of visual grading methods and the importance of visual grading indicators, but also do not unnecessarily under-evaluate the performance of timber in situ.

1 INTRODUCTION

For structural timber, certain key properties need to be assessed in order to ensure building safety and economic use of the material. For new timber, the means by which this is achieved is known as ‘strength grading’, and sometimes by the old terminology ‘stress grading’. Timber is sorted into grades which are associated with certain property values for use in design calculations; usually by reference to a predefined set of properties. In the modern EN1995 [1] and EN14081 [2] European system these sets are called ‘strength classes’ but the word grade is commonly used synonymously. A strength class is a grade with property values for design calculations.

For building inspection, the same properties need to be assessed for the same structural design calculations. The means by which this is done is also commonly called ‘grading’, and while it may be done by similar means as strength grading, the context is not the same. This can lead to confusion about the basis and limitations of strength grading and assessment of in situ timber. Further confusion is added by mixed use of codes and standards for limit state (load and resistance factor) and permissible stress (working stress) philosophies.

1.1 Assessment of in situ timber

In the UK, the most common approach is for a structural engineer to make use of a visual grading code of practice in combination with the exercise of their engineering judgement. There is widespread agreement on this approach [3–10] and of the two UK visual grading codes for softwood, the older, withdrawn and superseded British Standard Code of Practice CP112:Part 2:1971 The Structural use of Timber, Part 2. Metric units amended by AMD1265 [11] (hereafter referred to simply as CP112) is generally preferred over the newer BS4978 [12] as its grading rules can be more readily applied to in situ timber.

For in situ timber, there is no UK code of practice and the current suite of Eurocode standards are written for new construction. Other countries have begun to address the need to be able to determine the mechanical properties of in situ timber [13,14], however, their methods are similar to that in the UK of adapting a visual grading approach.

1.2 Brief introduction to CP112

The first of four versions of CP112 was published in 1952 and provides just two basic stresses for two groups of timber species with limitations placed on knot sizes, slope of grain (SoG) and rate of growth (RoG) [15]. Of all versions of this permissible stress 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 apart from conversion to metric units). In 1973, Amendment 1265 to the metric version of the code was published, making it the most attractive to structural engineers practising now. This amended version of CP112 is the one discussed below.

2 BASIC STRESSES IN CP112

The approach of CP112 is to determine, for any of 14 given 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.'* [16]. In modern terminology this is basing full-size structural properties on small clear testing, an approach now only used under

EN14081 for tropical hardwood species. However, by having design values specific to species and growth areas the code does, at least in principle, offer the advantage over modern standards and their much more generic strength classes, which may significantly under-value some of the true properties of the timber (those not grade limiting).

In their 1967 commentary on the code, Booth and Reece 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 [17]. The basic stresses are used to determine four grade stresses (75 Grade, 65 Grade, 50 Grade and 40 Grade) which are intended to broadly relate to percentage reductions in permissible stresses; for instance, 75 Grade timber has approximately 75% of its basic strength (that of the basic stress) remaining after consideration of knots, SoG, etc. This sounds, in theory, a logical and attractive approach for in-situ assessment, especially as it offers the apparent precision of four different grades, compared to the modern BS4978 system of only two (SS and GS). Regarding the basic stresses, taking the first four of the five strength reducing factors in turn, we can better understand the methodology behind the code.

2.1 Variability of mechanical properties in timber

The large variability in the mechanical properties of timber is due to microscopic features such as chemical composition and microfibril angle and macroscopic features such as knots, SoG and density. These features in turn are significantly affected by genetics, geography, climate, silvicultural practice and processing [18]. Recent research into variability [19,20] shows its extent to be even greater than previously thought, and factors not apparent in visual grading have high influence (this is one reason why we still do not have a Europe-wide visual grading standard).

The variability of strength is dealt with using statistics. In this case, assuming a normal distribution, the basic stress is based on the lower 1st percentile which is determined using the mean and standard deviation of the results of testing a sample of timber specimens representative of a specific population. It should be noted that where this process is described in textbooks on CP112, the true nature of the 1% limit is not made clear and is typically stated that below the 1% limit value only 1 in 100 results would be expected to fall, thus framing it as a 99% confidence that the real strength is at least this value [9,17,21]. However it is necessary to more clearly understand the meaning of the 1% value and the assumptions and limitations of this statistical process.

2.1.1 Sampling and populations

Firstly and importantly, the basic stresses of CP112 are based on samples taken from enormous populations of timber (from around the world) which have enormous variations. For the statistical process to be valid, the samples must accurately reflect their populations. The basis of the sampling used in the preparation of CP112 is not clearly documented and this combined with the relatively small sample sizes means that, in the light of what we now know about the extent of variability, it is not possible to conclude with confidence that the basic stresses based on these samples are truly representative of any particular population of timber, let alone all timber in existing structures in the UK. Examples of the treatment of samples by CP112 show: (i) summing and averaging of groups of data from different species and countries [21] and (ii) very small sample sizes [17].

The 1952 version of CP112 is based on around 25 years of testing of 2” small clears and the later version (CP112:1971:AMD1265) builds on this knowledge with further testing, this time mainly 2cm small clears and as such is based on around 40 years of testing around the middle of the twentieth century. Therefore, when structural engineers believe that

CP112:1971:AMD1265 contains stresses of timbers representative of several decades (or even centuries) of construction, this is highly unlikely and the code more realistically represents timber from trees felled during a 40 year period spanning from 1927 to 1967 and as such is a product of that time: the conditions of forests then and the practices of silviculture; the economic conditions for the timber trade; methods of processing and transportation.

2.1.2 Confidence and prediction levels

Basic stresses are derived from the first percentile of the strength of all timber in a grade, as a concept of “minimum”. However, in the appraisal of in situ timber elements, a conservative estimate of the strength of an individual piece of timber is required and not an estimate of the lowest strength of a sample of pieces of timber that fall into the same grade. Since there are four grades in CP112 this is closer to being the same thing than with only one or two grades, but it is still not quite the same. Either way, the variance of the individual pieces of timber around the mean must be accounted for.

2.1.3 Calculation of basic stress from sample testing

The equation (1) for the basic stress of each species is given below [21] and comprises a safety factor as denominator and the 1% lower confidence limit as numerator:

$$f_b = \frac{f_m - k_p \times \sigma}{k_r} \tag{1}$$

where: f_b = basic stress, f_m = mean value of the failure stress, k_p = probability coefficient (taken as 2.33), σ = standard deviation, k_r = reduction factor / factor of safety (taken as 2.25 or 2.44 [9,17,21])

Where large sample sizes are used in deriving the basic stresses, it is appropriate to adopt the factors from a 'z' (standard normal) distribution and this is the origin of the 2.33 probability coefficient applied to the standard deviation. However, for smaller sample numbers, the increased uncertainty due to fewer data points should be accounted for by using a different distribution (a 't' distribution). This more appropriate distribution will increase k_p and so reduce the value of f_b (the basic stress) [22]. All three of the textbook commentaries on CP112 simply present the use of the 2.33 factor, despite sample numbers for some species being small. Reductions in the calculated value of basic stress for the sample sizes used in this study are in the order of 6% (n=69) and 2% (n=143).

Finally, these statistical calculations assume a normal distribution of strength and stiffness values for each species graded. Whereas now, it is generally assumed that strength values follow a lognormal distribution (as in EN14358 [23]). This slight difference in the statistical calculations is not large but tends to compound other irregularities.

2.2 The effect of moisture content on timber

Much of the original testing for CP112 was carried out on 'green' timber, that is, unseasoned timber with a moisture content at or above its fibre saturation point (FSP). Up to a point, drier timber can support higher stresses than wetter timber and so the green basic stresses calculated for CP112 are converted to 'dry' basic stresses by multiplying them by a factor that links strengths at 18% moisture content to strengths at FSP. This is an imprecise conversion which depends on the knowledge of moisture content at the time of testing and the FSP, which is commonly rounded or approximated for a species or a group of species. This inevitably leads to less precision in the calculation of dry basic stresses (which apply to most timber elements in buildings). In any case, even when carefully applying this conversion process to the green stresses tabulated in CP112, it is not possible to obtain the dry stresses from the green ones in the code [21].

This is of concern as the green stresses from small clear specimens form the basis of the 1967 code, thus, many of the dry stress values useful for a practising engineer have passed through the conversion process described above.

2.3 Duration of load effects

Structural timber loses strength when under load over a long time. A modification factor of 0.6 (for duration of load) is typically cited (relating laboratory test results on small clear specimens to long term loading of structurally sized timber joists) and this figure is based on work by the Forest Products Laboratory in Madison, Wisconsin [24]. This work has subsequently been expanded upon with no significant change to the modification factor being proposed [25].

2.4 Factor of safety

Finally, a factor of safety (see Equation (1)) is applied to the 1% lower confidence limit value to give the basic stress. This is really a combined factor and different commentators consider that it accounts for different things and has different values [17,21], [9] and it is not possible to be sure which has been used or whether both have been used in different circumstances in the code.

Assuming that the factor of safety of 2.25 is used, then part of this factor is 'used up' due to the duration of load conversion factor of 0.6 hidden inside this value. From simple arithmetic, it is seen that on removal of the 0.6 conversion factor from the factor of safety, all that remains is a 1.35 factor (which is of the same value as that used currently in the Eurocodes for permanent actions alone).

3 GRADE STRESSES IN CP112

The basic stresses for each species are converted to the grade stresses used in structural design by considering the effects of the visual features of the timber. This is not a precise process and the correlation between visual grading parameters and mechanical properties, for instance, bending strength of timber, is poor. Typically, correlation coefficients are less than 0.5, even when combined [26].

3.1 Knots

Knots are considered to affect the strength of a section through two ways, firstly through the associated disturbance to the grain in the timber and secondly, through a simple reduction of the cross sectional area of a timber element (treating the knot as a void) and the subsequent reduction in its elastic section modulus. The first approach leads to proposed strength reductions based on empirical testing and the second approach can be carried out by calculation. By comparing the knot limits of CP112 with those calculated by elastic analysis, it is seen that there is good agreement for margin knots but no agreement for edge knots or face knots. An elastic analysis of edge knots (treating the knots as voids) suggests that the CP112 limits are not conservative, whereas the CP112 limits for face knots are particularly conservative. The real effect of knots is complex and the correlation of knot parameters with strength is perhaps not even direct. This explains why there are, still today, a variety of ways to treat knots in visual grading, depending on what works best in a country.

3.2 Slope of grain (SoG)

As the tensile strength of timber parallel to the grain can be as much as 40 times greater than its strength perpendicular to the grain, the greater the angle of the grain is to any tensile forces within the timber element, the weaker is the timber. The CP112 limits to SoG are based on research carried out by Wilson in the USA on three species (Douglas fir, Sitka spruce and commercial white ash) [17] and match most closely the results for Douglas fir, which suffers the greater strength reductions of the two softwoods [27]. Nevertheless, although the limits to SoG in CP112 are conservative for the highest three grades, the limit for the 40 Grade is not conservative. Taking Wilson's results for Douglas fir and interpolating for the CP112 limits relating to the four grades, the following remaining strength ratios would be expected: 75 Grade: 77.2%, 65 Grade: 67.7%, 50 Grade: 51.1% and 40 Grade: 30.8%. This, of course, assumes that the measurable SoG is equally influential for structural sized timber as it is for small clear specimens.

Bearing in mind the variability of the 14 different species from North America and Europe included in the code of practice, the CP112 limits to SoG have been derived from tests on just one species, potentially from just one geographic source; a further example of the limited basis on which the code is founded.

3.3 Rate of growth or growth ring width (RoG)

For most softwoods, growth rings comprise denser late wood bands of relatively constant thickness and lighter early wood bands which vary in thickness and so are the main cause of both changes in growth ring width and the density of the wood. Thus, RoG can be used as a weak predictor of density, which in turn can be used as a weak predictor of strength. Since rings also tend to get thinner as the tree grows (and the ring diameter increases) there is an association of ring width with wood properties due to radial trends from pith to bark. It must also be borne in mind that both these effects are very dependent on species, growth conditions, silvicultural practices, and other growth area effects [25] and so for timber from more than one source, growth ring width becomes an even weaker predictor of density and strength. This caveat certainly applies to the wide ranging sources of timber presented in CP112.

3.4 Wane

Wane is the loss of section of a would-be rectangular timber element sawn too close to the circumferential outer edge of a log. Its presence chiefly affects bearing and the advice given to practising engineers to not apply visual grading rules in relation to wane when considering the strength and stiffness of in situ timber elements [28] appears reasonable.

3.5 Modulus of Elasticity (MoE)

Wilson's test results (discussed above) show that increased SoG reduces both MoR and MoE in Douglas fir and Sitka spruce [27]. Percentage reductions in MoR are only slightly greater than for MoE for unit changes in SoG. Thus, based on Douglas fir results again, for the CP112 limits relating to the four grades, the following remaining stiffness ratios would be expected: 75 Grade: 85%, 65 Grade: 78%, 50 Grade: 65% and 40 Grade: 50%. The current code of practice for strength classes of structural timber [29] gives fifth percentile and mean values of MoE which vary according to each strength class. From C14 to C30 strength classes, the 5th percentile values of MoE vary from 4.7 to 8 kN/mm^2 and the mean values vary from 7 to 12 kN/mm^2. It is surprising then that CP112 gives single mean (11.7 kN/mm^2) and “minimum” (actually first percentile) (6.6 kN/mm^2) values of MoE which remain constant for all the four stress grades.

This approximates to the current C24 strength class and may overestimate the stiffness of timber, particularly in the weaker stress grades.

4 ILLUSTRATIVE CASE STUDY METHODOLOGY

One hundred and forty three structural sized joists nominally sized 50 x 100mm x 3.1m were sawn from Norway spruce (*Picea abies*) trees in three sites in the UK. They were kiln dried and conditioned and graded in accordance with CP112; they were tested in four point bending, with worst defect in the middle of the span, in accordance with EN384; their density and moisture content were measured in accordance with EN408 and EN14385 by Moreno [30]

The MoE of the joists was calculated from their global bending stiffness and adjusted to be a 'shear free' value based on the relationship between measured local and global MoE. Density and MoE have been adjusted to a reference value of 12% moisture content. It should be borne in mind that the values of mechanical properties derived are largely in accordance with modern methods of testing and calculation and so, test results are only indirectly relatable to values in CP112. This is sufficient for the purposes of this study. Although knots were measured for all 143 joists, SoG and RoG were only measured for 69 joists. Hence results and statistics are presented for n=69 and n=143.

5 RESULTS AND DISCUSSION

5.1 Results and discussion of testing

A summary of results for density, MoR and MoE is presented in Table 1. All of the visual grading parameters measured (knots as total knot area ratio, SoG and RoG) have low correlation coefficients (see Table 2). The correlation between knots and density is likely an indirect effect relating to another factor, since density here is measured on clear wood taken from near the breakage. The correlation coefficients of knots for n=143 were even worse than for n=69.

Table 1: Summary of test results (two sided 50% confidence interval on mean and 5th percentile)

	Density (n=143) kg/m^3	**Density (n=69) kg/m^3**	**MoR (n=143) N/mm^2**	**MoR (n=69) N/mm^2**	**MoE (n=143) kN/mm^2**	**MoE (n=69) kN/mm^2**
Mean	404-408	391-397	34.1-35.2	32.3-34.0	8.6-8.8	7.9-8.2
CoV (%)	10	10	29	31	21	20
5th %ile	337-344	326-335	16.9-18.7	14.6-17.3	5.5-5.8	5.2-5.6

Table 2: Correlation coefficients (two sided 50% confidence interval from bootstrapping)

Correlation coefficients (r)	**Density**	**MoR**	**MoE**
SoG as slope percentage (n=69)	0.17-0.33	0.14-0.27	0.13-0.28
RoG as width of rings (n=69)	0.63-0.71	0.32-0.46	0.52-0.63
Knots as total knot area ratio (n=69)	0.39-0.51	0.49-0.59	0.50-0.60
Knots as total knot area ratio (n=143)	0.23-0.34	0.45-0.53	0.39-0.47

Joists were sorted into all four of the grades of CP112 plus Reject. For (n=69), 75 Grade had 1 joist; 65 Grade had 9; 50 Grade 31; 40 Grade 9 and Reject 19. For (n=143), based just on knots, 75 Grade had 3 joists; 65 Grade 20; 50 Grade 63; 40 Grade 22 and Reject 35. The most numerous grades were 50 Grade and Reject and only four joists in total were graded at 75 Grade.

So, around one quarter of all joists are 'Reject' and yet, their performance differs only slightly from the timber successfully assigned Grades.

The CP112 visual grade for one quarter of the joists (18 of 69 specimens) was determined by the RoG parameter alone and for another quarter of the joists (17 of 69 specimens) RoG was the joint grade determining feature, along with knots. These are high proportions for a visual grading parameter (RoG) that is not generally possible to determine in situ.

The important question yet unanswered is whether the specimens graded to higher grades actually have better properties. Table 3 shows the measured mechanical properties of the visually graded joists (n=69). Values are quoted as two sided 50% confidence intervals using the parametric approach and assumed normal distribution, since this example dataset is also small. Nevertheless, it can be seen that strength and stiffness are barely improved by the grading, with the sole exception of MoR for Grade 65 (which still might be a random effect). These raw observations need adjusting for variation, duration of load, etc. before they can be usefully compared to the bending stresses in CP112 Table 4, but the expected increase in “minimum” (as 1st percentile) MoR with grading is not really apparent for Grade 40 and Grade 50, although mean MoR does improve from Grade 40 to Grade 50 to Grade 65, and broadly in agreement with what CP112 implies about mean MoR if back calculating from grade stress using equation (1) and assumed CoV of 30%: 25, 36 and 44 N/mm^2 respectively.

Table 3: MoR & MoE by CP112 Grades (“min” is 1st %ile, & observations are 50% confidence intervals)

MoR (N/mm^2)				**MoE (kN/mm^2)**			
CP112 (Table 4)		**Observations**		**CP112 (Table 4)**		**Observations**	
Grade	**Stress**	**“Min”**	**Mean**	**Mean**	**Min**	**“Min”**	**Mean**
Basic	11.0			6.9	3.8		
Grade 75	7.2	NA	NA	6.9	3.8	NA	NA
Grade 65	5.9	20-27	40-53	6.9	3.8	6.0-7.0	8.9-9.4
Grade 50	4.8	4.2-9.4	31-34	6.9	3.8	3.9-4.6	7.8-8.2
Grade 40	3.4	7.4-13.5	24-27	6.9	3.8	4.3-5.2	6.9-7.4
Reject	0	9.0-14.5	31-34	6.9	3.8	3.2-4.3	7.7-8.6
All specimens		7.2-10.5	32-34			4.1-4.6	7.9-8.2

For MoE, it is seen that both the mean and minimum MoE values of CP112 are broadly in agreement, but contrary to both MoR and the CP112 values there is some sign that stiffness is slightly increased by grading. The mean value of density is slightly greater than the mean value of 380 kg/m^3 given in CP112 Table 1.

5.2 General discussion

Arising from the literature review are three important issues pertaining to the use of CP112 for in situ timber. Firstly, the statistical basis of the code, using the 1% confidence limit, relates to all timber graded into a grade and not as a prediction of individual pieces.

Secondly, as with all statistics, the validity of CP112 (for both strength grading new timber and assessing in situ timber) is highly dependent on the extent and appropriateness of the sampling used in its creation. In the light of recent research, for new timber, the methods of sampling and extent of sampling are considered to be inadequate, which is one reason why CP112 has been replaced. When considering the enormous extent of the populations from which in situ timber in the UK has been drawn, it is hard to even contemplate the scale of a sufficient sampling programme.

Thirdly, it is not possible to clearly understand the derivation of many of the values given in CP112. An accumulation of conversions from small clear to structural size; from green to dry; from one species to another; from imperial to metric, combine with an obscure 'factor of safety' to render the code opaque. Finally, despite its grading rules and approaches seeming logical and powerful, they are in fact much poorer grading predictors than commonly assumed.

6 CONCLUSIONS

The two key issues with using CP112 for in situ timber relate to statistics: (i) the inadequacy of the sampling carried out for the code and (ii) the inappropriate use of the code's procedures to predict the mechanical properties of individual timber elements, with no consideration of confidence levels. These two issues are compounded by (i) the opacity of CP112 and its many hidden conversion factors, (ii) the poor real-word predictive power of the visual characteristics of timber (such as knots, SoG and RoG)

Currently, there is no better alternative, in the UK, to using CP112 (or a similar visual grading code) in conjunction with engineering judgement. This research allows practising structural engineers, using CP112, to be aware of its basis and its limitations, thus improving their judgement. Future areas of research could usefully focus on the documentation of sources of timber used in the UK during the 20th century and the development of non-destructive testing for in situ timber elements.

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