WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

HARDWOOD STRENGTH GRADING – CONSIDERATIONS FOR DENSITY AND COMPRESSION STRENGTH

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ABSTRACT: It can be a challenge to achieve effective sorting of temperate hardwoods for density when using visual strength grading rules and some types of machine grading. Different solutions have been proposed, including using a single conservative density across hardwood strength classes, or declaring density based on direct measurements without reference to a strength class. These solutions would also affect secondary properties that are estimated from assigned density. In the European Standards, compression strength perpendicular to grain is one example. In this study, grading of a sample of UK-grown sycamore maple was simulated, using dynamic stiffness as the indicating property (IP). Characteristic (5th percentile) values of density and compression strength parallel and perpendicular to grain could not be effectively raised by rejecting pieces with low IP values. If density is used as an IP, higher compression strengths perpendicular to grain can be graded for. Compression strength parallel to grain is likely constant for a timber source across different strength classes but could be predicted from density using an inter-species relationship. Using established prediction equations in the European Standard EN 384, characteristic values for compression strength parallel and perpendicular to grain are very conservative.

KEYWORDS: secondary properties, *Acer pseudoplatanus*, strength classes

1 – INTRODUCTION

In Europe, increasing consideration is being given to use of temperate hardwoods in construction; not just for the well-known higher density woods, such as oak, beech and ash, on which the EN 338 [1] hardwood “D” strength classes are based, but also for lower density woods like poplar. Some new hardwoods were added to the 2024 version of EN 1912 [2], the European Standard that lists many of the assignments of visual grades, species and growth areas to the EN 338 strength classes. This presented a problem, with many hardwoods new to the market failing to grade well due to relatively high target density of D-classes. The problem is made worse by the difficulty of grading effectively for density based solely on visual grading rules, since ring width (if even visible) is only weakly correlated with density at best. Grading for density can also be difficult for some kinds of machine strength grading because, for hardwoods, there can be little correlation between density and the indicating properties based on stiffness or grain angle. Many types of machine strength grading can, of course, measure density directly, and a direct density measurement is also a possibility for visual strength grading. However, even when density can be directly measured, the grading is complicated by difficulty in the control and measurement of moisture content in production.

Research to date has mostly focused on the three primary grade determining properties (bending or tension strength, stiffness parallel to grain, and density), but there is growing awareness that the EN 384 [1] equations to calculate secondary properties might not always be conservative for hardwoods new to the grading system. On the other hand, in some cases they might underestimate the secondary properties to such large extent that it reduces the usefulness of the timber; especially in the kinds of applications where hardwoods are expected to have advantage over softwoods. While the European system already has flexibility beyond EN 338 strength classes [3] the use of these well-known commodity strength classes is very important to the timber market.

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https://doi.org/10.52202/080513-0267

2 – BACKGROUND

Several authors find that grading assignments for temperate hardwoods might be unnecessarily limited by density, as effective sorting for density in visual grading is not achieved. This is the case even for relatively mainstream hardwoods e.g. [4]. The relationship between density and dynamic modulus of elasticity is also often reported to be weak, e.g. [5], so that an effective sorting by density might also not be possible when a stiffness based indicating property is used for machine grading. The inclusion of direct density measurement is allowed in both visual and machine grading under the overarching harmonised standard EN 14081-1 [6] but is not always desirable in practice, and accounting for moisture content is often more challenging for hardwoods. Kovryga et. al [4] propose solutions for hardwood (tensile) strength classes: to set constant density across strength classes, or to declare density separately from the strength class. The latter might also help address the problem of actual timber handling weights sometimes being much higher than the strength class indicates. These considerations to density design values would also affect design values that are calculated from density, such as compression strength perpendicular to grain and fastener withdrawal strength. In practice, however, it is unclear how well these secondary properties are actually related to density, and how much they might differ between different grades and species. Secondary properties that are constant across grades could potentially be predicted from a constant density, utilising prediction equations established on a range of species of different densities.

3 – PROJECT DESCRIPTION

The testing described in this paper is part of several projects that aim to characterise the properties of lesser-used UK species that might become more relevant in future forestry and thus timber production. As more and more different broadleaf species are considered for structural building applications, these projects also aim at assessing the suitability of current grading options for temperate hardwoods, including the suitability of current, commonly used hardwood strength classes and the prediction of secondary properties.

Data on bending properties of various UK-grown wood species was gathered as part of the Strategic Integrated Research in Timber (SIRT) project. This included testing of sycamore (*Acer pseudoplatanus*). The Building from England's Woodlands (BfEW) project subsequently included the characterisation of various temperate hardwood species to assess their suitability for different building products. Mechanical properties, including compression strength parallel to grain, were collected, mostly on small specimens due to limited timber availability.

In collaboration with Forest Research, twelve sycamore trees, grown in Central Scotland, were sampled for the SIRT project [7]. Battens of nominally 50 by 100 mm cross section and 3 m length were cut from logs taken at 1.3 m tree height. Cutting patterns were chosen to maximise the number of battens from each log, resulting in 105 battens. The battens were dried, conditioned to approximately 12% moisture content, and then tested at Edinburgh Napier University.

In this paper, grading of the sample is simulated, using longitudinal impact excitation resonance dynamic stiffness (MOEdyn) from measurement with a Brookhuis MTG960 timber grader and whole-piece-density as the indicating property (IP). The effect of setting certain IP thresholds on characteristic values for bending strength, stiffness (MOE), density and compression strength parallel and perpendicular to grain was investigated. From here onward compression strength parallel to grain will be referred to as "crushing strength" and compression strength perpendicular to grain as simply "compression strength".

Within the BfEW project, boards of eight hardwood species were procured from sawmills across England and Scotland. Boards were sawn into battens of nominally 50 by 100 mm cross section and one batten from each through-and-through cut board was randomly selected for sampling specimens for assessing secondary properties, including compression strength parallel to grain. In this paper it will be shown how these results might be used for predicting the characteristic crushing strength for different hardwoods.

4 – EXPERIMENTAL SETUP

After conditioning, and shortly before testing, the sycamore sample was non-destructively assessed with a Brookhuis MTG960 timber grader, recording longitudinal vibration frequency and whole piece density. These measurements and the specimen length were used to calculate MOEdyn.

The sample was then tested in four-point bending according to EN 384 [8] and EN 408 [9], which includes a density measurement on a small specimen taken from close to the break (density-sample-density) on which moisture content was also determined by the oven dry method (range 11-13.4%). Individual measurements (including MOEdyn) were, where appropriate, adjusted to a reference moisture content of 12% using equations

https://doi.org/10.52202/080513-0267

from EN 384. Characteristic values of the three primary properties, strength, stiffness and density, were calculated according to EN 14358 [10]. Characteristic values were further adjusted using appropriate factors listed in EN 384.

Some time later as an add-on study, specimens for measuring compression strength and crushing strength were taken from the unbroken section of the battens. This resulted in 74 compression specimens from 40 battens and 78 crushing strength specimens from 51 battens. Compression strength and crushing strength were determined according to EN 408 and individual crushing strength measurements were adjusted to 12% reference moisture content according to EN 384. Characteristic (5th percentile) values were determined according to EN 14358.

Specimens used for compression and crushing strength measurements were not free of defects. Macro defects were recorded and quantified. Growth ring width was measured on 49 of the crushing strength specimens that came from different battens. In the remaining three battens the growth rings were not discernible.

The BfEW sample added 105 specimens of eight hardwood species to the crushing strength dataset. They were tested in the same way as the sycamore specimens. The intra-species relationship between density, defect size and crushing strength is analysed in this paper.

5 – RESULTS

5.1 GRADING SIMULATION

The characteristic (5th percentile) bending strength of the whole sycamore sample was 26.6 N/mm^2, the characteristic (5th percentile) density 481 kg/m^3 and the characteristic (mean) stiffness 9.30 kN/mm^2 (see also Table 1). These properties would put the ungraded sycamore sample just above the requirements for EN 338 strength class D18 (Table 2).

The dynamic stiffness measurement obtained with the MTG timber grader could be used to establish IP thresholds so that a portion of the timber can be assigned to higher strength classes while a portion is rejected. Since the sample is small, this grading simulation is mostly useful to assess the likely effectiveness of dynamic stiffness as an IP for the different timber properties. A real grading assignment would require more data.

Table 1 Properties of the sycamore sample

Property	**Mean**	**5th percentile**
Bending strength	46.8 N/mm^2	26.6 N/mm^2
Bending stiffness (local MOE)	9.30 kN/mm^2	6.94 kN/mm^2
Density	481 kg/m^3	544 kg/m^3
Compression strength	7.8 N/mm^2	6.1 N/mm^2
Crushing strength	46.9 N/mm^2	36.1 N/mm^2

Table 2 EN 338 strength class requirements

Strength class	Characteristic bending strength in N/mm^2	Characteristic stiffness in kN/mm^2	Characteristic density in kg/m^3
D18	≥ 18	≥ 9.5	≥ 475
D24	≥ 24	≥ 10	≥ 485
D27	≥ 27	≥ 10.5	≥ 510

As can be seen in Figure 1, strength and the dynamic stiffness show a moderate correlation, and an IP threshold for achieving D27 strength in this simplified simulation can be readily set while still achieving a good yield (73%). Note that D24 strength is already met in the ungraded sample.

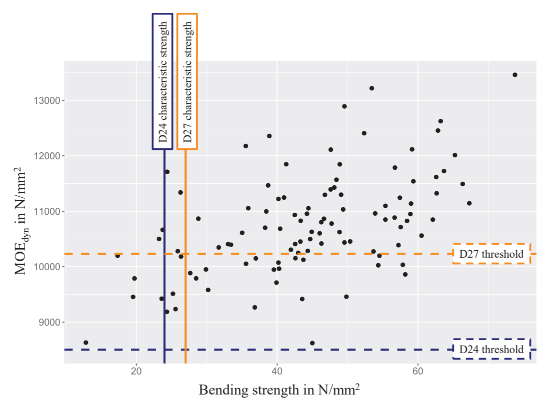

Figure 1 MOEdyn and bending strength with strength and IP thresholds for D24 (blue lines) and D27 (orange lines)

Bending stiffness from EN 408 four-point bending testing is moderately well correlated with MOEdyn (Figure 2 showing local MOE and MOEdyn), but the stiffness itself looks to be limiting the options for strength class assignments as it is comparatively low. In this simplified example, it can be raised above the D24 threshold with a yield of 90%, but D27 cannot be achieved with realistic yields (>40 pieces).

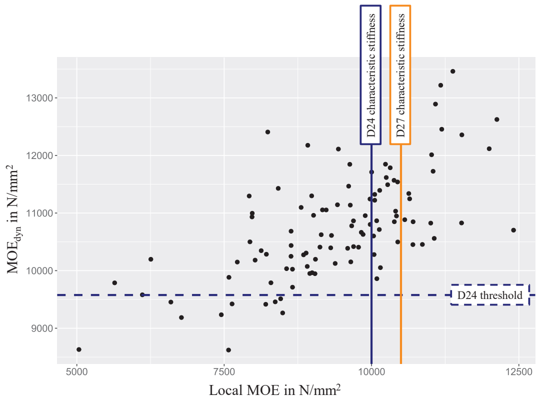

Figure 2 MOEdyn and static local MOE with MOE and IP thresholds – where applicable – for D24 (blue line) and D27 (orange line)

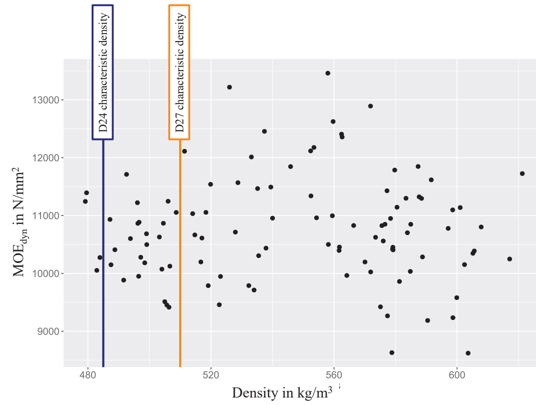

Figure 3 MOEdyn and density with density requirements for D24 (blue line) and D27 (orange line) – no IP thresholds are shown as density cannot be raised by rejecting low dynamic stiffness pieces

Here density is seen to have virtually no correlation with dynamic stiffness. No higher strength class assignment could be achieved using only dynamic stiffness as the IP (Figure 3), suggesting that density might become a limiting factor for assigning UK-grown sycamore to higher strength classes. The problem likely extends to other medium-dense hardwoods in which no sorting effect for density is achieved by using dynamic stiffness alone as an IP. This is shown, for example, by Lemke [11] for birch and by Kovryga et al. in maple [12].

Similar problems might arise in visual grading, where growth ring width is commonly assumed to have an effect on density of the graded timber. Whether or not this assumption holds true for ring-porous hardwoods can be discussed elsewhere, but it is commonly accepted that no direct relationship exists in diffuse-porous hardwoods like sycamore; although cambial age might affect both density and ring width so that a relationship is present in some diffuse-porous hardwoods, e.g. [13]. This could not be observed in the sample of the present study as shown by a coefficient of determination (R^2) of 0.01 between ring width and adjusted density-sample-density.

Seeing that commonly used IPs fail to achieve a sorting effect on density, one could use better predictors for density in grading, such as weight and dimensions. Since density sample density (from which the characteristic density is determined) and whole piece density have a very strong correlation (R^2=0.83 in this dataset), this would allow to reject low-density pieces reliably to raise characteristic density above strength class requirements. Using both whole piece density and dynamic stiffness as separate IPs, this sample could be graded to indicative strength class D24 with 62% yield. The characteristic density of the sample would, again, be very close to strength class requirements (493 kg/m³ with 485 kg/m³ required). This method might, however, not be desirable in practice either because it impacts the speed of grading decisions or because of difficulties in controlling and measuring moisture content in production. Only where density is the limiting criterion for a strength class assignment might this be considered as a commercially viable approach.

It has also been considered, by different authors, to rethink the hardwood strength classes of EN 338 to reflect the fact that hardwood density is not related to commonly used IPs in strength grading. Kovryga et al. propose that hardwood (tensile) strength classes could use a constant characteristic density for most strength classes, or characteristic density could be directly declared for different timber sources [4], [14]. The latter approach seems to be preferrable in that it does not exclude lower-density hardwood species from being assigned to any strength class, and in that it would offer more realistic assumptions for the prediction of secondary properties from density. The option of using constant density is therefore presumed to mean a constant density for each species-origin combination rather than for a strength class in the remainder of this paper.

https://doi.org/10.52202/080513-0267

Depending on which solution is chosen, this might have different implications for secondary properties that are calculated from density or are related to density. If the characteristic density is assumed constant in different strength classes, secondary properties might be assumed constant as well. Whether this assumption holds true remains to be determined.

5.2 IMPLICATIONS FOR SECONDARY PROPERTIES

Compression Strength (perpendicular to grain)

The characteristic compression strength of the sample was 6.1 N/mm^2. The characteristic density of the compression sample was also slightly higher than that of the ungraded bending sample, at 490 kg/m^3 (as not all battens could be used for compression strength measurements). A moderate relationship between density sample density and compression strength of a batten was observed in this dataset (R^2=0.29), so using density as a predictor seems feasible. Other authors find even stronger relationships in different temperate hardwoods, e.g. Collins and Fink report a strong relationship in birch (R^2=0.62), while Westermayr reports no relationship in ash and beech [15].

If grading by dynamic stiffness does not achieve a separation by density it does not affect compression strength either, as compression strength is poorly correlated with dynamic stiffness. This means that when grading only by dynamic stiffness, assuming a constant density and constant compression strength for all strength classes seems like a realistic approach.

One could, on the other hand, also use whole piece density as an IP to sort more effectively by density. This would indeed also raise compression strength in higher grades, i.e. in this dataset characteristic compression strength could be raised to 6.3 N/mm^2 by rejecting very few pieces with a density below 494 kg/m^3 and to 6.6 N/mm^2 by rejecting densities below 553 kg/m^3 with a yield of 73% (Figure 4).

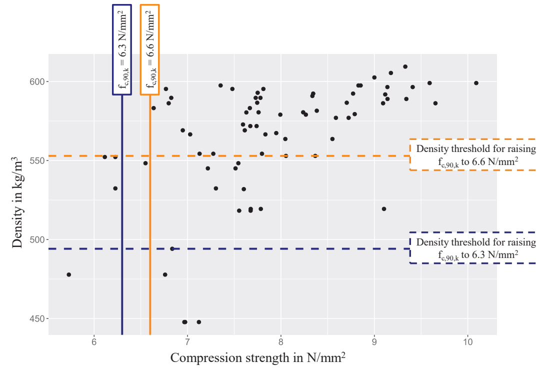

Figure 4 Whole piece density and compression strength with IP thresholds for a compression strength of 6.3 N/mm^2 (blue line) and 6.6 N/mm^2 (orange line)

It is notable that the measured characteristic compression strengths are well above characteristic compression strengths that are assumed in EN 338 strength classes, i.e. compression strengths that are calculated from density according to EN 384, even though the density is virtually identical to the strength class requirement. For a characteristic density of 490 kg/m^3 one would assume the characteristic compression strength to be 4.9 N/mm^2 (1), underestimating the real value by nearly 20%. It is desirable to make conservative estimates of properties that are not directly measured, and need to work safely for all species, but this underestimation seems extreme given that a compression strength of the ungraded sample would meet the requirement for strength class D45, while other properties are limited to D18.

$$f_{c,90,k} = 0.01\ \rho_k \tag{1}$$

where $f_{c,90,k}$ is characteristic compression strength in N/mm^2 and ρ_k is characteristic density in kg/m^3.

For other hardwood species, this might even be exacerbated i.e. in cases where the characteristic strength class density greatly underestimates the actual characteristic density of a timber source. For example, Schlotzhauer reports a characteristic compression strength of 7.41 N/mm^2 for a sample of German beech [16]. The sample has a characteristic density of 653 kg/m^3, but the highest strength class that can be assigned to visually graded German beech, according to EN 1912 [2], is D40 with a characteristic density of 550 kg/m^3 and a characteristic compression strength of 5.5 N/mm^2 – both properties would be highly underutilised.

At the other end of the spectrum, density and compression strength might also be underestimated severely when hardwood species with relatively low density are assigned to softwood C-classes, which is permitted under EN 338 for hardwoods with properties

https://doi.org/10.52202/080513-0267

similar to softwoods. This would also mean that the EN 384 softwood equation is used for calculating compression strength. Sycamore is one of the lower-density species that might be considered for a C-class assignment. In the present example, it would not be logical to consider grading the sycamore sample to C-classes because of the low stiffness, but the ungraded sample would theoretically meet the requirements of C18. This would mean the strength class characteristic density of 320 kg/m^3 would be used as basis for calculating compression strength, and the softwood equation (2) would be used, resulting in a characteristic compression strength of 2.2 N/mm^2.

$$f_{c,90,k} = 0.007\ \rho_k \qquad (2)$$

where $f_{c,90,k}$ is characteristic compression strength in N/mm^2 and ρ_k is characteristic density in kg/m^3.

These cases could be mitigated if density was to be directly declared for a species-origin-grade combination, but nonetheless the equations for calculating compression strength from density might need to be adjusted to reflect true values more accurately.

Crushing Strength (compression parallel to grain)

One would not assume that crushing strength would necessarily be affected if density assumptions for hardwood strength classes were to come into effect. As per (3), in EN 384 crushing strength ($f_{c,0,k}$ in N/mm^2) is predicted from characteristic bending strength ($f_{m,k}$ in N/mm^2). This is the same for C- and D-classes (i.e. softwoods and hardwoods are both treated the same).

$$f_{c,0,k} = 4.3\ f_{m,k}^{0.5} \qquad (3)$$

The characteristic bending strength of the ungraded sample would therefore be predicted to be 21.4 N/mm^2 and that of timber graded to strength class D24 would be assumed to be 21 N/mm^2. The actual characteristic compression strength of the ungraded sample was 36.1 N/mm^2, more than 65% higher than the predicted value and meeting requirements of D70. It seems that the crushing strength of sycamore would be almost unaffected by grading, irrespective of indicating property. No relationship was observed between crushing strength and bending strength (R^2=0.01), dynamic MOE (R^2=0.00) and density (R^2=0.04). Certainly, no systematic increase in crushing strength can be achieved when grading based on dynamic MOE or density. This confirms findings by other authors: Van de Kuilen and Torno find a weak relationship between crushing strength and both density (R^2=0.14) and MOEdyn (R^2=0.19) in ash, and a slightly stronger relationship with knot size (R^2=0.28) [17]. Collins and Fink report good correlations between density and crushing strength in knot-free birch specimens (R^2=0.44), but a much weaker relationship in specimens with defects [13]. The strongest relationship they observe is with ring width (R^2=0.62), which they attribute to differences in cambial age.

The weak relationships for IPs used in machine grading suggests that crushing strength could be assumed constant for a species-origin combination, irrespective of strength class, although the apparent relationship between visual characteristics and crushing strength might mean that real differences in crushing strength might occur in different grades of visually graded timber. In any case, better predictions are needed to avoid severely underestimating crushing strength.

5.3 INTER-SPECIES RELATIONSHIPS FOR BETTER PREDICTIONS

It was so far shown that crushing strength has a poor relationship with IPs and mechanical properties that are typically measured as part of a strength grading assignment. While it is unlikely that the crushing strength of a timber species would differ in different strength classes, it is to be expected that the crushing strength of different timber species (or even different sources of the same species) are quite different. This can be seen in the results of crushing strength for the eight hardwood species tested (Table 3). It is therefore desirable to get a good prediction of the crushing strength of a timber source that is constant in different strength classes.

Table 3 Crushing strength of eight hardwood species. Crushing strength and density are adjusted to 12% moisture content. The sycamore sample includes the 78 specimens of the SIRT project.

Species	Number of specimens	Mean compression strength in N/mm^2 (COV in %)	Mean density in kg/m^3 (COV in %)
ACPS	88	47.8 (13)	564 (7)
ALGL	4	40.7 (12)	556 (3)
BTXX	39	46.6 (14)	593 (5)
CTST	8	37.4 (15)	531 (10)
FASY	9	55.6 (22)	700 (9)
FXEX	15	46.1 (17)	676 (11)
POXX	16	31.9 (30)	391 (11)
QCXE	4	55.9 (11)	738 (6)

ACPS – Sycamore (*Acer pseudoplatanus*); ALGL – Alder (*Alnus glutinosa*); BTXX – Birch (*Betula pendula* or *B. pubescens*); CTST – Sweet chestnut (*Castanea sativa*); FASY – Beech (*Fagus sylvatica*), FXEX – Ash (*Fraxinus excelsior*); POXX – Poplar (*Populus sp.*); QCXE – Oak (*Quercus petraea* or *Q. robur*)

https://doi.org/10.52202/080513-0267

If the strategy of using a constant density, irrespective of strength class, was to be adopted, one could conveniently use this density for a prediction of crushing strength. A tentative relationship between density and crushing strength that spans different species was established using above results. Due to the low specimen number for some species, the data were supplemented by literature values, where available: 1) Van de Kuilen's and Torno's testing of 457 ash specimens from Germany [17]; 2) Collins' and Fink's testing of 54 birch specimens from Finland [13]; 3) Skala's testing of 24 beech specimens from Slovenia [18]. Testing had in all studies been according to EN 408 and results were given at or adjusted to 12% moisture content.

As can be seen from Figure 5, the mean densities and crushing strengths from literature align well with the inter-species relationship found in the present study. The relationship for averages over a wide range of species with different densities is moderately strong (R^2=0.6), although for some species, foremost ash, crushing strength seems to be lower than would be expected from density alone.

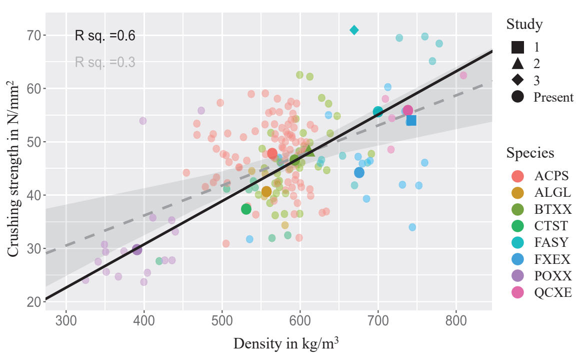

Figure 5 Inter-species relationship between crushing strength and density (grey with confidence range – this study; black – mean species values and literature). Mean species values of the present study and literature are shown with larger points.

With some adjustments to assure a conservative estimation for all species, the relationship could be used to predict crushing strength from characteristic density of a hardwood source. Using the (unchanged) inter-species relationship (4) to predict crushing strength ($f_{c,0}$ in N/mm^2) from density-sample-density (ρ in kg/m^3) for each batten in the sycamore sample results in a characteristic crushing strength of 38.1 N/mm^2, a slight overestimation of the actual strength of 36.1 N/mm^2. This suggests that a slightly more conservative relationship could work well.

$$f_{c,0} = -1.7 + 0.08\rho \quad (4)$$

As observed by other authors, crushing strength is negatively impacted by knots and tends to be lower in specimens with wide rings. The relationships are, however, quite weak, with R^2 values of 0.08 and 0.12 respectively. In addition, the ring width relationship is overlapped by species effects, as very wide rings were only observed in alder and poplar, which also tend to have lower crushing strength than some of the other species. In the sycamore sample, the relationship between crushing strength and ring width was non-existent (R^2=0.03).

Even so, adding knot size into the prediction model for crushing strength from density (5) improves the coefficient of determination from 0.30 to 0.41.

$$f_{c,0} = 13.5 + 0.06\rho - 33k \quad (5)$$

where $f_{c,0}$ is crushing strength in N/mm^2, ρ is density in kg/m^3 and k is knot size as ratio of face width.

Most of the reviewed literature did not give information on average knot sizes, and the relationship established in this paper draws heavily from the species for which more specimens were tested, i.e. sycamore and birch. The relationship should therefore be improved with additional testing and adjusted to be conservative for all species and grades. This could then yield a less conservative prediction model for visual grades in which knot sizes are limited.

6 – CONCLUSION

It is common that strength grading of hardwood that uses only dynamic stiffness as an IP does not have a sorting effect on density. This has been shown to be true for a sample of UK-grown sycamore. This problem could be dealt with by a) using a constant density across strength classes for any timber source, or b) using separate IPs, such as whole-piece-density, for achieving higher densities in higher strength classes.

Compression strength perpendicular to grain in the sycamore sample was well enough correlated to density so that it could be raised into strength classes with higher density. The standard equation for predicting compression strength from density, however, underestimated the true characteristic value by nearly 20%. A conservative value is both expected, and desirable, but the underestimate is compounded by assigned density also being considerably less than the actual density.

Compression strength parallel to grain of the sycamore sample showed no relationship with any other mechanical property measured, suggesting that it is unlikely that it could differ in different strength classes. A constant density value for a timber source would therefore lend itself better to predicting crushing strength than characteristic bending strength, which, used in standard prediction equations, underestimated the crushing strength of sycamore by 42%. A relationship between density and crushing strength across eight hardwood species was established from testing and literature values, that could be adjusted to yield safe predictions for characteristic crushing strength. Since crushing strength seems to be affected by knot size, the option of adding this parameter to the equation seems promising for allowing higher crushing strengths in higher grades of visually graded timber.

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