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THE CHALLENGE OF STRENGTH GRADING UK HARDWOODS

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Abstract: *Recent research in Europe is bringing a wider range of wood species to the construction market as structural timber and glue laminated products. This option would also open markets for currently underused UK species, foremost hardwoods, but testing efforts when developing strength grading assignments for any minor UK species are prohibitive, as the resource is small and scattered. Grading approaches that require less material for destructive testing could be employed to open routes to market for structural hardwood products. In addition, the European hardwood research has been revealing some gaps and uncertainties in grading standards. In particular, data are lacking to support adjustment equations for size, moisture content, and testing arrangement for hardwoods. This paper outlines a new PhD project that will focus on these problems and aims to develop an easier route for strength grading hardwoods.*

Key words: *small clear testing, full-size testing, mechanical properties, EN 384, minor species.*

1. Introduction

Hardwoods have long been neglected as a modern structural material, but their increasing availability and outstanding mechanical properties have prompted researchers in various European countries to characterise the properties of local hardwood species [15, 21, 36, 42, 46, 52, 56]. Six new species-origin combinations will be added to the new version of EN 1912 [17] for European hardwoods, complementing the existing six visual grading assignments of European hardwood species, various machine-grading assignments and technical approvals for engineered wood products [1].

Meanwhile only two hardwood species grown in the UK, oak (*Quercus petraea* (Mattuschka) Liebl. and *Q. robur* L.) and sweet chestnut (*Castanea sativa* Mill.), can be visually graded, thanks to historical data on the mechanical properties of these species and the non-contradictory complimentary information to Eurocode 5 given in PD 6693-1 [13]. Some historic data on wood properties of other UK hardwoods are also available [25, 26, 39], but this testing was mostly done on small clear specimens from a small number of trees. These data are not sufficient as a

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basis for strength grading assignments according to current standards, and it is possible that timber properties have changed since this research was done (due to changes in forest management and/or climate). New testing is needed to characterise the properties of UK hardwoods. However, test regimes like the ones carried out in Europe are not feasible in the UK for reasons outlined below.

Research has also uncovered more general challenges when grading hardwoods, namely with EN 338 strength class profiles [9] and the calculation of secondary properties and adjustments according to EN 384 [10]. The objectives and research strategy of a new PhD project addressing these issues are outlined in this paper.

2. UK-Specific Challenges

Despite the fact that only 13% of the UK's land area is covered in forest, the country harvests significant volumes of softwood timber, comparable to the volumes harvested in countries like Spain and Norway (Figure 1). The UK's hardwood harvest, however, is negligible, even though half of the forest area is broadleaved. In 2022, 823 thousand green tonnes of hardwood were harvested in the UK, compared to 10.4 million green tonnes of softwood [27]. The material that comes to market is rarely used to its full potential (in terms of carbon storage, if nothing else) - more than 85% of the hardwood harvest is burned for energy production [27] instead of long-term uses, e.g. as structural timber. This is even though there is evidently demand for these products, as more than 80% of timber used in construction is imported [27].

Currently, more than 90% of the UK's broadleaf forest is privately owned [27] so that hardwood production is largely dependent on the owners' attitudes, perhaps more so than in many European countries where more forestland is publicly owned (Figure 2). Ownership is also particularly scattered, with ca. 40% of private owners holding less than 20 ha of forestland [49].

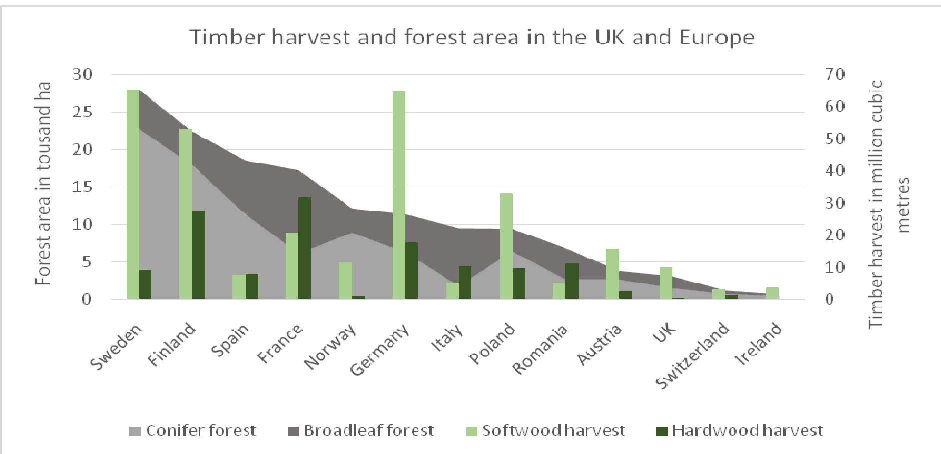

Fig. 1. *Timber harvest and Forest area in the UK and Europe, Forest area in thousand hectares on left axis [23]; Timber harvest in million cubic metres on right axis [24]*

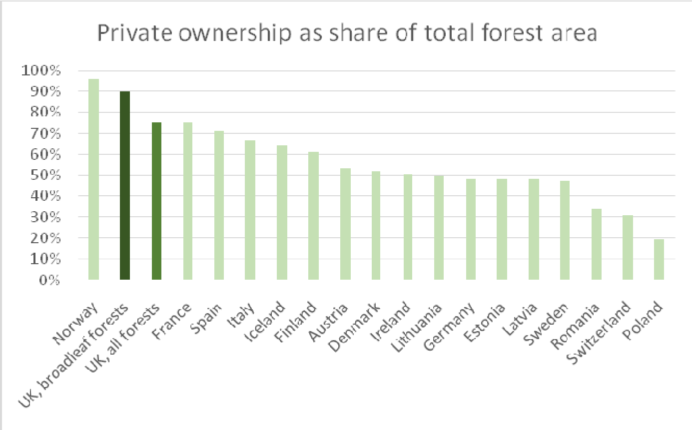

Fig. 2. *Forest ownership in the UK and Europe based on National Forest Inventories [18]*

It is estimated that half of England's forest is still unmanaged or undermanaged, despite the financial support available [20]. Significant effort was therefore also put into understanding the values and objectives of the different owner groups, which include farmers, estate holders, private businesses and, increasingly, new owners who just want to enjoy having a woodland [19, 40]. Owners are becoming more receptive to the idea of woodland management as a tool to achieve a variety of objectives, including nature conservation and creation of enjoyable spaces, and 37% of private forest owners show interest in taking up forest management activities [49]. Even forests that are not primarily managed for timber production can yield some timber, and timber production can be an important pillar in the financial sustainability of all kinds of woodlands. With increasing management activity more hardwood timber could be coming to market, however, mobilising very small timber volumes is not currently economical due to access and transport constraints which increase extraction cost [19, 31, 54]. The stem form of a large share of the undermanaged trees is another problem, as the yield of sawn timber can be drastically decreased. In this respect, the United Kingdom faces another unique challenge: The damage caused by grey squirrels, an introduced invasive species, affects many broadleaf species (more than conifers) and results in higher tree mortality and poor-quality stems [50]. These challenges could be alleviated with more active forest (and squirrel) management, which could be incentivised by increased knowledge about options for value-added hardwood products made from the UK resource.

Even without additional broadleaf forests coming into management, the near future will see increasing hardwood availability, peaking around 2050 (Figure 3) [43], and it would be desirable to use these resources more efficiently than is currently the norm.

4. Why are We not Using Hardwoods More Efficiently?

Using resources that are coming and will be coming to market more efficiently requires more knowledge of wood properties, but characterising them confidently will be a challenge, not only because of the small volumes available, but also because of the variety of the resource. A large array of species (Figure 3) comes to market in relatively small batches, and no one broadleaf species is currently dominating the woodland area, instead many species share an equal interest among growers [16]. Grading assignments are based on the destructive testing of a representative timber sample, normally at least 450 pieces for machine grading assignments and similar sample sizes for visual grading assignments [10, 14]. Property characterisation of each species would require testing of much of the available material, which is prohibitively expensive. The variety of management styles might also lead to additional variability in wood properties, which means even more testing might be required.

The future of the UK's hardwood supply might see certain species becoming more important in woodland area and timber supply. Owners of productive forests are more and more appreciating the added resilience of mixed forests, so that certain (fast-growing) broadleaves might be grown in the future as a secondary crop within conifer plantations. It is currently unclear, however, which species are suitable for which growing conditions and which species can thrive in a changing climate. Research will continuously be needed to investigate the influence of provenance and silviculture of broadleaf species that will be grown as part of productive forestry.

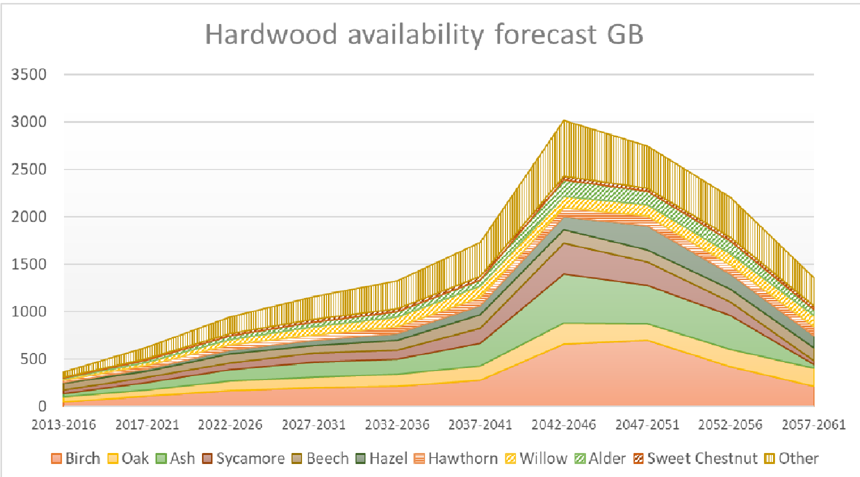

Fig. 3. *Hardwood harvest by species in thousand cubic metres, projections from 2012 in the 50-year hardwood availability forecast [43]*

Even if and when hardwoods become more important as a productive crop, the hardwood sawmilling industry in the UK will not likely operate in the same ways as softwood production. Even in countries like Germany, France, Italy and Spain, where significant hardwood volumes are being produced and strength grading procedures for some species are in place, only 5 to 16% of the harvest is used for sawlogs, and much hardwood ends up as biomass for energy production [24]. This is largely because sawn hardwood products come at lower yield and higher cost, e.g.

ash lamellae for glulam production cost ca. three times more than equivalent softwood products, and the increased price cannot always be outweighed by the enhanced mechanical resistance that many hardwoods offer [53].

In the UK the biomass sector has been consuming increasing timber volumes since 2008 [27], and the profitability of wood fuel remains a barrier to the increase in long-lasting uses, especially for hardwood [54]. The hardwood processing industry currently operates on a small scale, often sawing and drying hardwoods as they are ordered. There is also no large-scale local mass timber production that could generate a steady demand for strength graded hardwood in the near future, as might be the case in Europe. The state of the industry, the added cost of hardwood products, and the profitability of biomass mean that strength graded hardwood is likely to remain a niche product for some time, and in-line high-speed grading procedures are not what producers currently need. Such procedures might become desirable in the future, especially for hardwood species that could be grown, processed, and sold as a mix with softwoods.

Even though hardwood resources in the UK are small and chronically undervalued, there is an appetite for locally-grown value added products [16]. It is evident that a grading approach is needed to bring suitable resources into structural use without the need for prohibitively large test regimes. A new grading approach needs to be easy to use even for small processors and be suitable for one-off timber batches to be graded for specific projects. Ideally, it would also be scalable to future large-scale productions.

5. General Challenges in Hardwood Grading

5.1. Strength Class Profiles

The desired outcome of a strength grading process is often the assignment of a strength class, usually one listed in EN 338 [9]. For a timber resource to be assigned to one of the listed strength classes, the graded timber needs to meet thresholds for the three primary properties, strength, stiffness, and density. All three properties have to fulfil the minimum requirement, and it might happen that only one of them will be limiting the assignment while the others are comfortably met. The strength class profiles have originally been developed for "traditional", high density, mostly tropical hardwood species and this means they might not well describe the properties of other hardwoods coming to market now. This has been accounted for in recent revisions of the standard, which saw the addition of strength classes that might be more fitting for temperate hardwoods [6], and the option to assign low-density hardwoods to "softwood" C-classes [9]. It has been suggested to use this option even for medium-dense species like birch [41], which stems from the fact that D-class profiles do not necessarily match these resources either. Specific rules when it comes to assigning hardwoods to C-classes remain subject to refinement by standards committees, and it is crucial to assure that such assignments do not have unintended consequences, i.e. that equations for secondary properties and adjustment equations remain safe (see below). The current strength class definitions will continue to be further adjusted to fit new resources coming to market, and research on the mechanical properties of UK hardwoods can influence these decisions.

Hardwoods can also be assigned to tension T-classes, but research suggests that separate hardwood T-classes would be more appropriate [36, 37, 42]. However, different studies suggest markedly different strength class profiles depending on the tested species. Kovryga et al. [36, 37] suggest a constant density requirement for all hardwood T-classes, as visual grading of hardwoods can often not achieve a difference in density between grades. However, the authors acknowledge that between-species density variation is large even in "medium-dense" hardwoods, so that it might be better to make density non-mandatory for hardwood grading and instead declare density directly, which would allow to make use of the actual species properties [29, 36]. The tensile properties of UK timber could inform the formulation of tensile strength class definitions for hardwoods, although no research on the tensile properties of UK hardwoods is planned within this project.

5.2. Secondary Properties and Adjustment Equations

Strength grading under the EN 14081 framework requires the destructive testing of a representative timber sample to determine characteristic values for strength (either bending or tension strength), stiffness, and density [11, 12, 14, 44]. While these primary properties are measured directly, all other properties can be calculated using equations given in EN 384 [10]. This standard also offers adjustment equations, to account for the effect of specimen size and moisture content, and for converting between global and local modulus of elasticity (MOE). However, existing equations might not be suitable for all species graded under the framework. This is true for both new and existing assignments and both softwoods and hardwoods, but the large inter-species variability in hardwoods compared to softwoods exacerbates the problem.

Equations have often been reported to be inaccurate in the best case and unsafe in the worst case (Table 1), and it is unclear how well they work for UK hardwoods. EN 384 suggests equations for secondary properties, but also allows them to be derived from testing. If better values or equations can be found for certain (UK) hardwood species, this might optimise their use in construction products.

6. Contributions of the PhD Research

6.1. A Simpler Grading Approach

A grading approach that requires destructive testing of little material could alleviate the challenges with the UK hardwood supply, outlined above. It used to be common practice to base grading assignments on testing of small clear specimens, applying a reduction factor to full-size specimens with certain sizes of strength-reducing defects, as reflected in the withdrawn standard CP112 [4, 55]. Early versions of EN 384 [5, 7] allowed a similar approach of obtaining ratios between small clear and full-size characteristic values of bending strength and stiffness from at least three species and applying them to similar species for which only few clear data are available. Nowadays this is only allowed for tropical hardwoods [10]. A new ISO standard for the determination of characteristic values from small clear testing is under development [33], and a technical report presented to the Technical Committee for Timber Structures TC 165 highlights that there is evidence that the historical approach of CP112 does not always work in a safe manner [34]. However, a grading approach could still be based on the testing of (mostly) small (clear) specimens, if it can be evidenced that this is safe to do. Ravenshorst [47] demonstrates that the modelling of defects as weak zones can predict the properties of both softwoods and tropical hardwoods if dynamic MOE and density are used as modelling parameters. This or a similar approach might also work for temperate hardwoods.

Table 1

Examples of issues with EN 384 adjustment equations and calculation of secondary properties reported for several hardwood species in literature; cells shaded in red indicate that equations were found to be non-conservative, which makes them potentially unsafe

EN 384 equation	Observation	Source
Mean shear modulus from mean MOE (Table 2 of EN 384)	The ratio is found to be much higher than assumed for massaranduba (and spruce). The shear modulus seems not to be correlated with MOE.	Ravenshorst et al. [48]
Local MOE from global MOE (Equation (7) of EN 384)	The equation might be inaccurate for sweet chestnut (and three softwood species), although the consequences for grading where the assignment is not limited by stiffness are small.	Nocetti et al. [45]
Tension and compression strength perpendicular to grain from density (Table 2 in EN 384)	No relationship of tensile strength with density was found and a constant value of 3.4 N/mm^2 is suggested. A weak relationship between density and compression strength was found and a constant value of 6.6 N/mm^2 is suggested.	Kovryga et al. [36, 37]
	For ash, and potentially other ring-porous hardwoods, compression strength tends to be slightly lower than assumed by EN 384 and the German Building products approval for glulam.	Schlotzhauer [51]
Compression strength parallel to grain from tensile strength (for assignments to T-classes, Table 2 of EN 384)	The ratio is found to be conservative. Higher values are suggested that could apply to hardwood T-classes.	Kovryga et al. [36, 37]

It has been demonstrated for various softwoods [30, 38] that bending stiffness tends to be higher in full-size specimens than small clears, while bending strength is significantly higher in small clears than boards and density is similar in both specimen types (also because density is measured on a small, defect-free section according to EN 408 [8]. Krajnc et al. [38] explain the differences in MOEs with a variety of factors, including the difference in test set-up (three-point vs. four-point bending), the difference in height-to-depth ratio, and the variation of MOE along the length of full-size specimens. Both studies explain the difference in strength by the presence of defects. Moderate relationships between the strength and MOEs of both test sizes are reported for the softwood species, with R^2 ranging from 0.24 to 0.51 for bending strength and 0.29 to 0.68 for static MOE [30, 38]. Although few data are available for hardwoods, these findings give hope that, at the very least, density and stiffness for full-size specimens can be predicted from small clear testing, with strength being somewhat harder to assess. Keeping in mind that strength grading does not need to predict the properties of a piece of timber accurately, but rather needs to be able to derive characteristic values for a population which are firstly safe and secondly reasonably accurate, the PhD research will focus on the following questions:

- Can the variability of strength, stiffness, and density be characterized on small (clear) specimens?
- Can the relationship between properties be characterised on small (clear) specimens?
- Can this help set thresholds for population-based grading?
- Can this help identify species that could be grouped for grading?

Even though current grading approaches work on population-level predictions, a grading approach that uses piece-based predictive models is also imaginable. Bather suggests such an approach for in-situ assessment [2], which highlights that a piece-based probabilistic description is especially useful when the pool of timber members to be used (or, in Bather's scenario, in-use) is known. This could be a realistic scenario for UK hardwoods, given the often small batches of timber harvested and processed on order. The PhD research will therefore also explore if a predictive model for piece-based grading approach could be derived from small (clear) testing.

6.2. Research Strategy

To limit test effort and the strain on local resources, a large batch of birch from Sweden is used for small (clear) testing. The respective full-size specimens have been tested by Lemke et al. [41] as part of research on a new grading assignment, so that sampling and full-size testing comply with current standards. In addition to the ca. 500 birch specimens, material of several home-grown species will be tested in much smaller quantity, to assess if differences in relationships between full-size and small (clear) properties can be observed between species. For the home-grown timbers, four-point bending tests are carried out on specimens that are cut from the same board as small (clear) specimens. To assess the feasibility of the grading approach and the optimum test parameters, the following tests will be performed on small (clear) specimens:

- Three-point bending test on 2-centimetre specimens according to BS 373 [3];
- Four point-bending according to EN 408 [8] including measurement of local and global MOE;
- Three- and four-point bending tests on 2-inch specimens according to BS 373;

- Dynamic MOE measurements using ultrasonic pulse and longitudinal vibration frequency.

The tests will allow to assess the influence of specimen size and test set-up (three-point vs. four-point bending). Small specimens with defects are also sampled, to assess the influence of defects on mechanical properties.

6.3. General Hardwood Grading

It is necessary to investigate the ratios of the three primary properties, strength, stiffness, and density, for UK hardwoods, and to investigate how well UK hardwoods could be graded to existing EN 338 strength classes. Custom strength classes for certain resources and products might also be proposed, to better fit the resource. The three primary properties bending strength, bending stiffness, and density will be characterised for this purpose, so the potential assignment of UK hardwoods to EN 338 D- and C-classes, but not T-classes, can be evaluated.

The relationships between primary properties and secondary properties in different hardwood species will be investigated. Specifically, the relationship of characteristic bending strength with compression strength parallel to grain as well as shear strength, the relationship of characteristic density with compression strength perpendicular to grain as well as mean density, and the relationship of MOE and shear modulus are evaluated. The relationships will be compared to the ones given in EN 384, with special regards to hardwood species that might be assigned to C-classes and might therefore use C-class adjustment equations. Furthermore, it is evaluated whether the following adjustment equations given in EN 384 work for United Kingdom hardwood species or if more fitting equations can be suggested:

- Calculation of local MOE from global MOE and the influence of shear modulus on the relationship;
- Relationship of MOE and compression strength with moisture content;
- Effect of specimen size on bending strength.

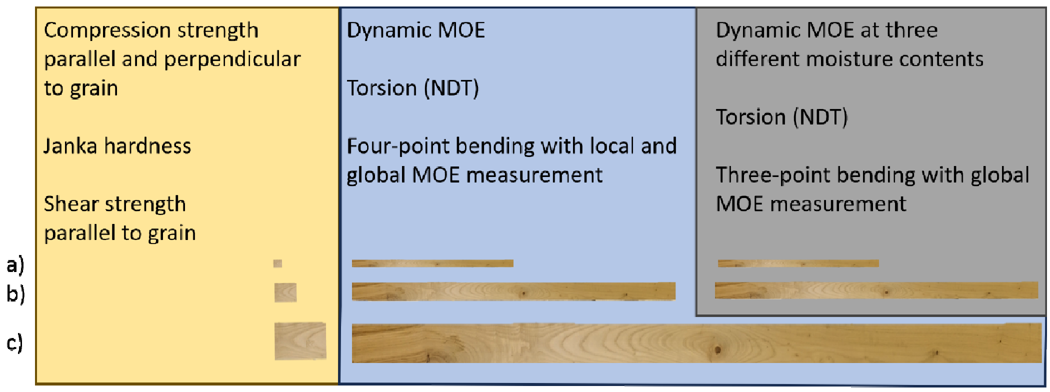

Fig. 4. *Overview of tests planned for different size timbers. Sizes correspond to: a. BS 373 2-centimetre standard; b. BS 373 2 inch standard; c. full-size with testing according to EN 408*

6.4. Research Strategy

Boards of 12 UK-grown hardwood species[2] are procured from English and Scottish sawmills. The species and cutting patterns represent timber that is typical for the local production, and even though boards cannot typically be linked to particular trees or stands, they are assumed to reflect a variety of growth regions and management practices that are typical for the resource. Small (clear) specimens and full-size specimens are cut from the same board and are made subject to a number of non-destructive tests (NDT) and destructive measurements, as shown in Figure 4.

Data collection for the PhD project is currently underway, but results will not be available on a large scale until 2025. The thesis publication with suggestions for a simpler grading approach is expected in the first half of 2026.

Acknowledgements

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[2] Some "species" might be a combination of different species of the same genus, where these are commonly processed and sold collectively. In any case, the wood species is not confirmed with anatomical sampling so that a mix of species or varieties might be present for most genera. Species include: Alder (*Alnus glutinosa* (L.) Gaerth.), ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.), birch (*Betula pendula* Roth and *B. pubescens* Ehrh.), lime (*Tilia cordata* Mill.), oak (*Quercus robur* L. and *Q. petraea* (Mattuschka) Liebl.), poplar (*Populus* spp.), red oak (*Q. rubra* L.), sweet chestnut (*Castanea sativa* Mill.), sycamore (*Acer pseudoplatanus* L.), willow (*Salix* spp.), wild cherry (*Prunus avium* L.).

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