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THE MECHANICAL AND RESONANCE ASSESSMENT OF LARGE CLEAR SAMPLES OF UK-GROWN BEECH WOOD

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Abstract:

The paper presents the results of non-destructive longitudinal resonance (impulse excitation technique), and mechanical flexural testing, of a batch of European beech wood (Fagus sylvatica L.), grown in the United Kingdom. The material was largely free from visible defects and straight grained, having been visually appearance graded by the sawmill. The dynamic modulus of elasticity of original length boards is compared to density and global modulus of elasticity results from short lengths cut from a subset of those boards, tested in four-point bending about the minor axis. A method of weighting, based on the first mode wavelength, is shown to improve the correlation, partly accounting for variation within the boards, and the relative contribution to the resonance behaviour. The results are used to estimate the structural grading of the full batch and shown to be similar to results from previous small clear testing of UK-grown beech (within 5-10%). The relatively small number of boards from a single batch, from a single location means that the results are only an indication of potential quality, but they give confidence that further research should be done into the potential of UK-grown beech, especially for glued-laminated construction products, as has been done in Europe.

Key words: *beech; non-destructive testing; acoustic methods; strength grading.*

INTRODUCTION

European beech (*Fagus sylvatica L.*) is one of the most abundant and widespread hardwood species in Europe (Houston Durrant, de Rigo & Caudullo 2016). The wood has many historical uses, but it is relatively underutilised in the modern wood products industry. Under the European harmonised standard for structural timber, EN 14081-1 (CEN 2016a) there are assignments for visual strength grading in EN 1912 (CEN 2012a), for beech grown in Germany, to EN 338 hardwood classes D40 and D35 (CEN 2016c). There are approved assignments to be incorporated into a revision of EN 1912 for beech from France and Belgium to also be assigned to D40 or D35, with the addition of D24 or D18 in combination. There are, at present, no approved settings for machine controlled grading of beech, although there has been work for glulam production (e.g. Frese and Blaß 2007).

In the United Kingdom there is only a very small hardwood industry, despite half of the woodland area being broadleaf, of which beech represents about 7% (Forest Research 2018). In 2017 the removals of roundwood were 0.7 million green tonnes of hardwood, compared to 10.9 million green tonnes for softwood (Forest Research 2018). The majority of the hardwood removals (~80%) were used for woodfuel, with about 10% going to sawmills (Forest Research 2018). Despite these current low levels, the public perceptions of broadleaf forests, and especially native species like beech, are much better than for commercial conifers so it is worth looking at potential future markets. The warming climate may see greater productivity for beech in northern UK (Forest Research 2019).

OBJECTIVES

The objective of the work covered by this paper was to undertake an indicative characterisation of the bending strength, bending stiffness and density of the beech, relevant to strength grading. The secondary objective was to examine the variation of those properties within boards, and to assess how this influences non-destructive assessment by longitudinal resonance, even when the boards are clear and uniform.

METHOD, MATERIALS AND EQUIPMENT

As part of a construction innovation project, a batch of 181 UK-grown sawn, planed and dried, beech boards was obtained from East Brothers sawmill (Wiltshire, South West England). The timber had been visually graded at the sawmill according to appearance grading rules, with specification for F-D1R or F-D2 in accordance with EN 975-1:2009 (CEN 2009). The mass and first mode resonant longitudinal frequency was measured for all boards with a Brookhuis MTG960 grading machine. Three boards were removed from the set for failing to get reliable frequency values, leaving 178 for the analysis. These boards were further appearance graded at Edinburgh Napier University to select 10 nearly clear, straight grained timbers (similar to F-DAR, allowing small knots) without fissures for bending testing, and also which represent the range of dynamic stiffnesses measured (see below). While these appearance grading rules are not visual strength grading, they do have influence on the mechanical properties by limiting knots, which are strength reducing defects. This, combined with the relatively small number of boards from a single batch, from a single location means that the results presented below should not be taken as generally applicable to UK grown beech, but are instead an indication of potential quality only.

Non-destructive data for the whole sample of 178 beech boards

The batch of 178 beech boards (of planed rectangular cross-section) were all 30 mm thickness and had widths of 100, 105, 125 and 140 mm. Lengths varied from 1.6 m to 3.5 m, with about half the boards being 2.1 m (Table 1). The actual dimensions of each board were measured manually, and used in subsequent calculations.

Table 1

Nominal dimensions and numbers of beech boards

Nominal length [mm]	**Nominal width [mm] (Nominal thickness = 30 mm)**				**Total n**
	100	**105**	**125**	**140**	
1600	2 (1)	0	1 (1)	0	**3**
1900	0	1	0	0	**1**
2000	1	0	1	1	**3**
2100	43	8	29 (2)	4	**84**
2200	1	0	0	0	**1**
2300	7	0	1	1	**9**
2400	4	0	1 (1)	0	**5**
2500	1	1	0	0	**2**
2600	3 (1)	1	0	1	**5**
2700	12 (1)	0	1	3	**16**
2800	14	1	1	8	**24**
3100	1	2	8 (1)	0	**11**
3500	2	3 (1)	9 (1)	0	**14**
Total	**91**	**17**	**52**	**18**	**178**

Note: Number of boards selected for destructive testing is given in brackets

The mass of each board was measured using the balance of a Brookhuis MTG960 grading machine at the same time as the longitudinal first mode resonant frequency. The MTG960 software was operating in "frequency mode" allowing the measured basic values to be used directly. This avoids the adjustments for moisture content and modelled static modulus of elasticity within the software, allowing them to be done separately as outlined below.

The moisture content of the whole batch was assumed to be 10% at time of measurement, based on gravimetric measurement on the subsample of boards later tested destructively. At this time, the air temperature in the laboratory where the samples were stored was about 13°C and the relative humidity was about 45%. The theoretical equilibrium moisture content (Simpson's method after the Hailwood-Horrobin equation) for the preceding month varied between about 8% and 11%.

The whole board density ($\rho_{u\%}$) was calculated (equation (1)) using the measured mass ($M_{u\%}$) and dimensions (thickness $T_{u\%}$, width $W_{u\%}$ and length $L_{u\%}$) and adjusted to 12% reference moisture content ($\rho_{12\%}$) using the equations in EN 384 (CEN 2018) (equation (2)). The dynamic modulus of elasticity ($E_{dyn,u\%}$) was calculated according to equation (3) where $V_{u\%}$ is the acoustic velocity and $f_{u\%}$ is the measured resonant frequency. This was also adjusted to 12% reference moisture content ($E_{dyn,12\%}$) using the equations for modulus of elasticity in EN 384 (equation (4)).

Although it is now a common method of grading timber in sawmills, there is no European standard for determining dynamic modulus of elasticity of timber. However, it is similar to the instantaneous excitation mode procedure in EN 14146 for natural stone (CEN 2004). In this case, the internal measurement quality algorithms of the MTG960 decided if the measurement is good, and the first good measurement was used for the calculations. Previous studies with this machine, including development of grading settings for British grown spruce, larch and Douglas-fir (e.g. Ridley-Ellis 2017a, 2017b, Ridley-Ellis & Gil-Moreno 2018), have shown that the measurement is very repeatable, and the same as measured by other similar devices, so long as the machine reports the correct frequency peak (*i.e.* the fundamental rather than a harmonic). Since some of the boards were relatively short compared to the cross-section width (ratios as low as 13:1), the correction factor in EN 14146 for dynamic modulus of elasticity was applied, assuming a Poisson's ratio of

0.4. This, however, makes very little difference to the results as the maximum correction factor is less than 1.001 (equation (5)).

$$\rho_{u\%} = \left(\frac{M_{u\%}}{T_{u\%} \times W_{u\%} \times L_{u\%}}\right) \quad (1)$$

$$\rho_{12\%} = \rho_{u\%} \times \left(1 - 0.005 \times (u - 12)\right) \quad (2)$$

$$E_{dyn,u\%} = \rho_{u\%} \times V_{u\%}^2 \times S = \rho_{u\%} \times (2 \times L_{u\%} \times f_{u\%})^2 \times S \quad (3)$$

$$E_{dyn,12\%} = E_{dyn,u\%} \times \left(1 + 0.01 \times (u - 12)\right) \quad (4)$$

$$S = 1 + \frac{\pi^2 \times \nu^2 \times W_{u\%}^2}{12 \times L_{u\%}^2} \quad (5)$$

Selecting 10 boards for destructive testing, and bending test results

Ten boards were selected from the batch covering the range of dynamic modulus of elasticity and density, and with almost clear, straight grained wood. These boards were cross-cut into bending test specimens (n = 37) with density samples (n = 27) between. These bending test specimens were tested in four-point bending about the minor axis to obtain bending strength and global modulus of elasticity in accordance with EN 408 (CEN 2012b), with the exception of the conditioning environment which was as described above. The standard test span of 18 times nominal depth was used. Density and moisture content determined in accordance with EN 13183-1 (CEN 2002). The global modulus of elasticity was adjusted to 12% reference moisture content using the equations in EN 384 (same basis as equation (4)) using the average of moisture content of the density samples from the same original board. The bending strength reported here are not adjusted for cross-section depth (k_h would be 1.3, *i.e.* reducing bending strength by 30%). In specimens that contain defects, the minor axis bending strength would be expected to be, overall, lower than the major axis bending strength (hence the procedure for establishing grading is normally based on major axis bending (Ridley-Ellis, Stapel and Baño 2016), but since these specimens are clear wood it is expected that the two would be similar.

Table 2

Summary of non-destructive testing, adjusted to 12% moisture content

Group	Dynamic modulus of elasticity [kN/mm^2]	Whole board density [kg/m^3]
Whole batch (n = 178)	14.7 (11%)	741 (6%)
Subsample (n = 10)	14.8 (11%)	748 (6%)

Note: Coefficient of variation is given in brackets

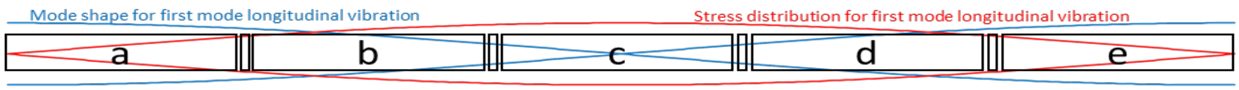
RESULTS AND DISCUSSION

The non-destructive results are summarised in Table 2 and Fig. 1i. The dynamic modulus of elasticity ranged from 9.8 to 17.7 kN/mm^2 with mean 14.7 kN/mm^2 and coefficient of variation of 11%. The whole board density ranged from 666 to 862 kg/m^3 with mean 741 kg/m^3 and coefficient of variation of 6%. Density and dynamic modulus of elasticity were correlated with R^2 = 0.34. The density and stiffness did not vary by cross-section width or length. These dynamic modulus of elasticity values are similar to the highest visual grade (German-grown) beech reported by Frese and Blaß (2007).

The results of the bending tests are summarised in Tables 3 and 4 and Fig. 1ii. Table 3 shows the values for the board subsamples, in which the lowest strength, stiffness and density in each of the 10 boards is highlighted in bold. These limiting board values are summarised in Table 4. The correlation between all board strength and global stiffness values (n = 37) was good (R^2 = 0.64) and for the limiting strength and stiffness values of the boards (n = 10) was similar (R^2 = 0.72).

Table 3 part 1

Summary of destructive testing, adjusted to 12% moisture content



Specimen		Bending strength [N/mm²]	Bending stiffness [kN/mm²]	Density [kg/m³]	Moisture content [%]	Ring width [mm]
B7	a	114	11.7			
	ab			718	9.9%	4.6
	b	112	11.8			
	bc			695	9.9%	4.5
	c	**72.7 ***	**10.9 ***			
	cd			**689**	9.9%	5.1
	d	106	11.3			
B23	a	**110 ****	**11.9 ****			
	ab			**759**	10.3%	7.3
	b	114	12.5			
B41	a	115	**12.5**			
	ab			665	10.0%	4.6
	b	116	13.0			
	bc			**665**	10.0%	4.0
	c	122	13.6			
	cd			678	9.9%	4.0
	d	**115**	13.2			
B72	a	102	11.6			
	ab			734	10.0%	5.8
	b	105	12.0			
	bc			745	10.2%	4.3
	c	111	12.9			
	cd			710	10.1%	6.6
	d	**96.6**	**11.0**			
	de			**708**	10.2%	4.3
	e	109	11.1			
B96	a	**98.9 ****	**11.7 ****			
	ab			**721**	10.1%	3.3
	b	117	14.3			
	bc			742	10.3%	3.6
	c	109	13.0			
B99	a	135	14.9			
	ab			**808**	10.8%	4.4
	b	**134**	**14.7**			
B101	a	134	16.4			
	ab			797	10.8%	4.4
	b	131	16.0			
	bc			801	10.8%	5.0
	c	**122**	15.1			
	cd			**793**	10.4%	6.0
	d	125	**14.6**			
B111	a	117	12.2			
	ab			742	10.0%	5.2
	b	114	11.9			
	bc			**727**	10.0%	5.6
	c	**109**	**11.7**			

Note 1: * B7c had a 20 mm knot in the shear span and failed there. ** B23a & B96a had inclined grain.
Note 2: Longest specimens had 5 parts (a-e) & shortest specimens had 2 parts (a-b) …continued

Table 3 part 2

Summary of destructive testing, adjusted to 12% moisture content

Specimen		Bending strength [N/mm^2]	Bending stiffness [kN/mm^2]	Density [kg/m^3]	Moisture content [%]	Ring width [mm]
B114	a	**108 ****	**12.6 ****			
	ab			**756**	10.0%	6.6
	b	118	14.1			
	bc			769	10.2%	8.2
	c	119	13.9			
	cd			768	10.2%	6.8
	d	114	14.5			
	de			769	10.4%	6.4
	e	123	13.8			
B176	a	115	13.6			
	ab			722	10.5%	4.0
	b	117	13.3			
	bc			722	10.5%	4.4
	c	109	13.6			
	cd			711	10.4%	4.6
	d	117	13.5			
	de			**699**	10.4%	4.7
	e	**107**	**12.1**			

Note: ** B114a had inclined grain.

The dynamic modulus of elasticity was strongly correlated with the average global modulus of elasticity of the individual test pieces (Fig. 1iii, R^2 = 0.97), but this correlation can be further improved by weighting the average according to the shape of the first mode of longitudinal vibration. Since there is a node in the middle of the length and antinodes at each end, the weighting can be done using half of a sine wave. This accounts for the relative greater contribution of wood in the middle of the length to the first mode resonance frequency, and brings the R^2 value to 0.99. The weights are: for 2 parts =(0.50,0.50), 3 =(0.25,0.50,0.25), 4 =(0.15,0.35,0.35,0.15), 5 =(0.10,0.25,0.31,0.25,0.10).

There was a good correlation between bending strength and global modulus of elasticity and whole density, allowing strength values to be estimated for all boards in the batch with equation (6). Bending test stiffness can be estimated with equation (7) and density sample density with equation (8). Note that these attempt to predict the lowest values within a board. The within board coefficient of variation for strength was 4%, except in case of B7 where it was 19% due to failure at a knot. For global bending stiffness the coefficient of variation was 5%, for density 2% and ring width 10%.

$$\{\text{Board min bending strength}\} = 4.79\times\{\text{Dynamic MoE } E_{dyn}\} + 0.12\times\{\text{whole board density}\} - 50.5\ \text{N/mm}^2 \quad (R^2 = 0.54) \qquad (6)$$

$$\{\text{Board min bending stiffness}\} = 0.72\times\{\text{Dynamic MoE } E_{dyn}\} + 1.68\ \text{kN/mm}^2 \quad (R^2 = 0.80) \qquad (7)$$

$$\{\text{Density sample density}\} = 1.03\times\{\text{whole board density}\} - 41.6\ \text{kg/m}^3 \quad (R^2 = 0.97) \qquad (8)$$

These prediction equations allow comparisons of grade determining properties based on the whole batch, to previously published mean values from small clear testing of UK-grown beech (Table 5). They also allow estimation of characteristic values for comparison with EN 338 strength classes (Table 6), for which the parametric method confidence adjustments of EN 14358 (CEN 2016b) have been applied. To be conservative, the confidence adjustment for mean stiffness is also applied even though this is not normally done for stiffness values.

Table 6 compares to EN 338 strength classes D and C (hardwoods may be assigned to softwood strength classes, C), although the hardwood D class can be seen to fit better. It appears that the stiffness is the limiting property in both cases. However, since this is just one batch of timber, and a relatively small amount of testing that is not conducted in line with requirements for grading assignments (EN 14081-1 and EN 384), these numbers are indicative only. They do, however, compare well to existing visual grading assignments for beech grown in Germany, France and Belgium, but with slightly lower stiffness.

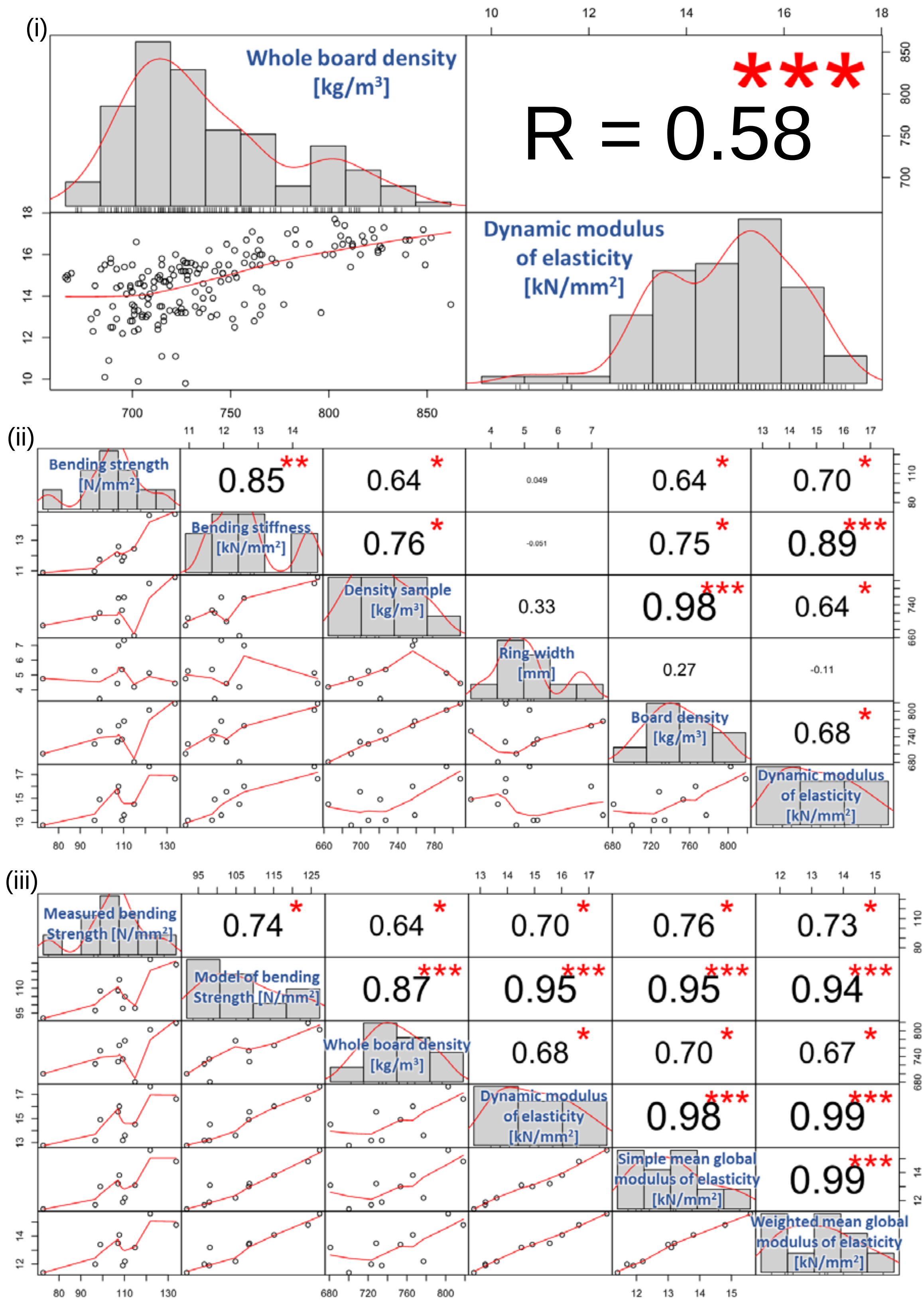


Fig. 1.
Matrix of scatter plots and Pearson correlation coefficients (R) for (i) non-destructive measurements (n=178), (ii) destructive measurements (n=10) and (iii) prediction models (n=10).
Significance levels are shown as stars: p *** = 0.001, ** = 0.01, * = 0.05
(ii) and (iii) dynamic modulus of elasticity is uniform because of the subsampling method
Since beech is diffuse porous, the poor correlation between ring width and wood density is expected

Table 4

Per board summary of destructive testing, adjusted to 12% moisture content

Specimen	Minimum			Mean		Dynamic MoE E_{dyn} [kN/mm²]
	Bending strength [N/mm²]	Bending stiffness [kN/mm²]	Density [kg/m³]	Moisture content [%]	Ring width [mm]	
B7	72.7 {91.9}	10.9 {10.9}	689 {683} (700)	9.9	4.8	12.8 [11.4]
B23	110 {105}	11.9 {11.5}	759 {762} (777)	10.3	7.3	13.6 [12.2]
B41	115 {98.0}	12.5 {12.2}	665 {663} (681)	10.0	4.2	14.5 [13.2]
B72	96.6 {96.6}	11.0 {11.2}	708 {706} (723)	10.1	5.3	13.2 [12.0]
B96	98.9 {108}	11.7 {12.4}	721 {738} (753)	10.2	3.4	14.9 [13.4]
B99	134 {124}	14.7 {13.7}	808 {805} (818)	10.8	4.4	16.6 [14.8]
B101	122 {128}	14.6 {14.4}	793 {789} (803)	10.6	5.1	17.7 [15.6]
B111	109 {97.9}	11.7 {11.2}	727 {718} (734)	10.0	5.4	13.2 [11.9]
B114	108 {115}	12.6 {13.2}	756 {751} (766)	10.2	7.0	16.0 [14.1]
B176	107 {109}	12.1 {12.9}	699 {712} (728)	10.4	4.4	15.6 [13.5]

Note: Predicted strength is given in {} brackets and whole board density is given in () brackets. Weighted bending stiffness for comparison with dynamic modulus of elasticity is given in [] brackets

Table 5

Summary of mean mechanical properties, compared to previously published values

Reference	Bending strength [N/mm²]	Bending stiffness [kN/mm²]	Density [kg/m³]
This study (subsample, all)	114 (10%)	13.0 (11%)	734 (5%)
This study (n = 10, board min)	107 (15%)	12.4 (11%)	732 (6%)
This study (estimate of batch)	106 (11%)	12.3 (9%)	725 (7%)
Lavers (1983)	118 (9%)	12.6 (10%)	689 (6%)

Note 1: Lavers (1983) is based on three point bending tests of small clear specimens
Note 2: Coefficient of variation is given in brackets

Table 6

Summary of estimated characteristic properties, after EN 14358 adjustment (CEN 2016b)

5th %ile bending strength [N/mm²]	Mean bending stiffness [kN/mm²]	5th %ile density [kg/m³]
87.3	**12.2**	643
D80 (80)	**D35** (12×0.95) almost D40	D50 (620)
C50 (50)	**C30** (12×0.95) almost C35	C50 (430)

Note 1: The grade limiting property is highlighted in bold, strength class requirements are in brackets
Note 2: EN 338:2016 allows any hardwood to be assigned to a C-class rather than a D-class

CONCLUSION

A batch of UK grown beech, graded to high appearance grade, was found to be comparable to clear wood properties published in the literature, with differences of only 5 to 10%. Bending strength was reasonably well correlated with longitudinal dynamic modulus of elasticity and density. The dynamic modulus of elasticity was strongly correlated with the global modulus of elasticity of portions of the boards, especially when the average was weighted according to the shape of the first mode of longitudinal vibration. Density sample density was very strongly correlated to whole board density and about 2% lower. The grade determining properties match most closely to hardwood strength classes, with stiffness as the limiting property. The grade indication for this largely clear batch of UK-grown beech is similar to that for the highest EN 1912 grade assignments for Germany, France and Belgium, and the dynamic modulus of elasticity is similar in mean and standard deviation to the values of the highest visual grade German-grown beech reported by Frese and Blaß (2007). The relatively small number of boards from a single batch, from a single location means that the results presented should not be taken as generally applicable to UK grown beech, but are instead an indication of potential quality only. However, since the results are similar to those previously published, and the grade limiting property is stiffness, which can be easily assessed non-destructively, there is merit in further research into the potential for UK-grown beech, especially for glued-laminated construction products.

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Errata: 7/11/2019 corrected equation 7 (should be + 1.68 kN/mm^2 not - 1.68 kN/mm^2)