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Beech sawn timber for structural use: A case study for mechanical characterization and optimization of the Italian visual strength grading rule

D. Cibecchini, A. Cavalli, G. Goli, M. Togni

Department of Agricultural, Food and Forestry Systems (GESAAF), School of Agriculture, University of Florence, Florence, Italy

ABSTRACT: The potential use of beech (*Fagus sylvatica* Linnaeus) sawn timber for structures has been investigated. Beech stands in transition from coppice to high forest after thinning interventions have been sampled from different Italian sources. A sample of 160 beams of two different cross sections was extracted and tested, according to the normalized procedures for the characterization of wood for structures. The specimens were visually graded considering the strength relevant defects, according to the Italian standard. To determine the mechanical properties of the timber (namely strength and stiffness), four-point bending tests were performed and the main characteristic values were derived. The results of the study reveal that knot ratio was the principal defect that influenced both resistance and yields. The potential strength class D30 was achieved with the resulting characteristic values, although, due to the small number of samples tested, the reached class could not be formally assigned. To improve the effectiveness of the grading rule in the Italian standard, some modifications and a new grade were proposed for the beech sawn timber. Finally the D40 strength class could be theoretically reached, but with reduced yields.

Keywords: *Fagus sylvatica*; grade; modulus of elasticity; modulus of rupture; strength class; strength determining defect

The beech (*Fagus sylvatica* Linnaeus) wood has not yet been used for structural purposes in Italy, even though it is widespread in Italy and in Europe, and offers outstanding technological properties (Lo Monaco et al. 2014) and many non-structural applications. On the contrary, this hardwood provokes a strong interest in Europe where it is already utilized for load-bearing structures (Aicher et al. 2013). Therefore, several studies have focused on its mechanical performances as solid sawn timber (Frühwald, Schickhofer 2004; Frühwald 2008; Lagaňa, Rohanová 2011; Lagaňa, Babiak 2012; Widmann et al. 2012), glued laminated timber (Frühwald et al. 2003; Frese, Blass 2005; Ohnesorge et al. 2009; Aicher, Ohnesorge 2010) and laminated veneer lumber (Knorz, van de Kuilen 2012). The standard EN 1912:2012 about visual strength graded timbers includes the German beech. Moreover, the German Institute of Civil Engineering in Berlin has issued the technical building approvals Z-9.1-679 for glulam of beech timber, and Z-9.1-837 for beech laminated veneer lumber. However, due to its low natural durability and high shrinkage/swelling coefficients, the glue laminated timber can currently be used only in service class 1, according to Eurocode 5 (EN 1995-1-1:2004).

The aims of this work are: (*i*) the assessment of the potential of Italian beech lumber for structural purposes through physical and mechanical characterization, (*ii*) the assessment of the ability of the current Italian visual strength grading standard in classifying the beech wood and finally, where appropriate, (*iii*) to propose improvements of the specific rule, suitable for beech structural beams.

MATERIAL AND METHODS

The study was carried out in pure beech stands of agamic origin, in two regions of Italy: Liguria and Tuscany. Since those beech coppices were no longer managed, they were in conversion to high forests, carried out by progressively reducing stand

Table 1. Main characteristics of forest stands

Region	Altitude (m a.s.l.)	Fertility	Age (last coppice cut) (yr)	Growing stock (m^3)	Age of thinning(s) (yr)	Thinning intensity
Tuscany	1,150–1,350	medium	75	485	37–66	moderate
Liguria	800–950	medium	50	315	35	very strong

density with repeated thinning of the shoots. Data about the stands are reported in Table 1.

19 trees were harvested for the research, 10 from Tuscany and 9 from Liguria. They were selected simulating a new thinning operation. From each trunk only the first log was used and delivered to the sawmill. Logs were sawn using a plain-sawn cutting pattern to achieve large planks that for dimensions could be used in joinery. From the planks were obtained 160 beams 2.5 m long, with two different cross sections (Table 2). Timber was air seasoned for two years. The surfaces of the beams were not planed.

Visual grading and mechanical testing. The samples were graded by the rule "Hardwood" of the Italian grading standard UNI 11035-2:2010, considering only the strength determining characteristics: knots, slope of grain, density and shrinkage fissures going through the thickness. Regarding the slope of grain, more in detail, the general grain angle was measured by a scribing test or shrinkage cracks, if present, on a length of 1 m, according to the standard. Because of the variable slope of the grain, likely due to the agamic origin of the forest where the specimens were sampled, it was difficult to measure correctly a general grain inclination. Thus, in the course of mechanical tests, for the beams failed because of the slope of grain, the grain deviation was measured again following the fracture pattern (the worst inclination was assessed) in order to compare it with that one detected during the visual strength grading. The two criteria considering wanes and deformations, given in the rule, were excluded from this grading pattern because many studies proved that they do not have any effect on the mechanical properties (Bonamini, Togni 1999; Ranta-Maunus 1999; Brunetti et al. 2013; Togni et al. 2013) although they could have some negative outcomes during the assembling on a building site. Decay and insect attacks were rejected by the visual grading because not acceptable. Since the relationship between density and annual ring width in beech is not expected to be inverse (e.g. Bouriaud et al. 2004), the actual rule disregards the measurements of the ring width because this parameter is overcome by the direct density determination.

Table 2. Cross section and size of the sampled beams

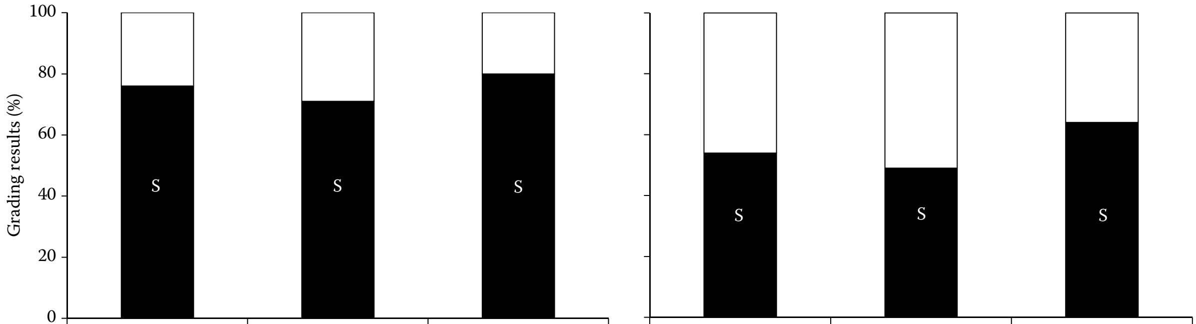
Region	Cross section 85 × 55 mm	Cross section 120 × 55 mm	Total
Tuscany	42	50	92
Liguria	43	25	68
Total	85	75	160

The principal mechanical properties of the specimens, namely local modulus of elasticity in bending (modulus of elasticity – MOE) and bending strength (modulus of rupture – MOR), were determined according to the European standard EN 408:2010. The tests were carried out by means of a universal testing machine (METRO COM Engineering s.p.a., Garbagna Novarese, Italy; 200 kN), using some linear variable displacement transducers (Monitran Ltd., Penn, United Kingdom) for measuring the deformations under loading conditions. For each sample, two small clear woods were cut as close as possible to the point of rupture for the physical characterization. In addition, the strength determining defect and the failure mode were recorded. The density and the moisture content of specimens were determined as indicated by the standards ISO 3131:1985 and EN 13183-1:2003, respectively. Edgewise bending tests were performed on the beams graded as S (structural) in accordance with the Italian grading rule "Hardwood". The characteristic values of the bending strength, modulus of elasticity and density were calculated for the beams selected in the S grade, according to the European guideline EN 384:2010. The factor for adjusting the characteristic value of the MOR to the size of the sample and to the number of samples (k_s) was not applied. This choice was justified by the necessity to check the feasibility of this species for structural uses, considering this test only as the first attempt needed to set a program on future tests and a suitable extended sampling. For these reasons, the strength classes successively assigned have to be considered as provisional allocations.

RESULTS AND DISCUSSION

Visual grading

The graphical and numerical results of visual strength grading are presented in Fig. 1. They show that the structural quality of the Tuscan sample was better than that of the Ligurian sample: 76 and 54% of specimens were assigned to the S grade, respec-



	Total	85 × 55 mm	120 × 55 mm	Total	85 × 55 mm	120 × 55 mm
☐ Rejected (%)	24	29	20	46	51	36
■ S (%)	76	71	80	54	49	64
	Tuscan sample			Ligurian sample		

Fig. 1. Grading results of the sampled beams (cross section: 85 × 55, 120 × 55 mm; total) according to UNI 11035:2010: Tuscan and Ligurian samples; S – structural grade

tively. Among the considered characteristics, only the size of knots, which is connected with the stand history (coppices in origin) and the silvicultural practices, caused the rejection of the beams. The worst strength quality was found for the specimens of 85 × 55 mm nominal cross section that represented 54 and 69% of the total beams discarded from the Tuscan and the Ligurian sample, respectively. From the whole sample only two-thirds of the beams were accepted for structural uses.

Main mechanical and physical properties

Strength, stiffness and density properties are listed in Table 3. The mean value of the modulus of rupture

Table 3. Summary of the mechanical and physical properties

		S grade					
		Tuscany sample			Liguria sample		
		85 × 55 mm	120 × 55 mm	whole	85 × 55 mm	120 × 55 mm	whole
N		30	40	70	21	16	37
MOR (N·mm^{-2})	mean	74.1	67.4	70.3	78.4	83.3	80.6
	min	24.0	28.0	24.0	34.0	31.3	31.3
	max	115	115	115	109	110	110
	SD	23.5	18.9	21.1	18.5	18.7	18.4
	CV (%)	31.8	28.0	30.0	23.5	22.4	23.0
MOE (kN·mm^{-2})	mean	13.0	13.6	13.3	13.0	13.4	13.1
	min	9.07	8.84	8.84	9.65	10.6	9.65
	max	15.3	17.2	17.2	15.3	15.9	15.9
	SD	1.62	2.30	2.04	14.8	1.52	1.49
	CV (%)	12.5	17.0	15.3	11.4	11.4	11.3
Density (kg·m^{-3})	mean	691	693	692	747	739	744
	min	566	627	566	668	656	656
	max	758	805	805	812	810	812
	SD	40.7	32.0	35.7	40.0	46.9	42.7
	CV (%)	5.89	4.62	5.16	5.36	6.34	5.74
Moisture content (%)	mean	9.95	10.3	10.1	11.0	11.0	10.9
	min	9.23	9.49	9.23	9.41	10.4	9.41
	max	10.4	10.8	10.8	11.8	11.4	11.8
	SD	0.281	0.368	0.371	0.532	0.253	0.432
	CV (%)	2.82	3.58	3.66	4.85	2.33	3.96

N – number of specimens, MOR – modulus of rupture, MOE – modulus of elasticity, SD – standard deviation, CV – coefficient of variation, S – structural in Tuscan beams was 70.3 N·mm^{-2}, for the S grade. For the Ligurian sample, instead, the mean value of the bending strength in the S grade was 80.6 N·mm^{-2}. The coefficient of variation as well as the range of MOR and MOE of the Ligurian sample were lower in comparison with those of the Tuscan sample. Moreover, as illustrated in the box plot graphics (Fig. 2), the specimens with section height 85 mm displayed a higher variability and a more irregular distribution of the MOR values. Finally, the density mean values for both sources were contained in the ranges of variability indicated in literature (Giordano 1981) and the coefficients of variation were low.

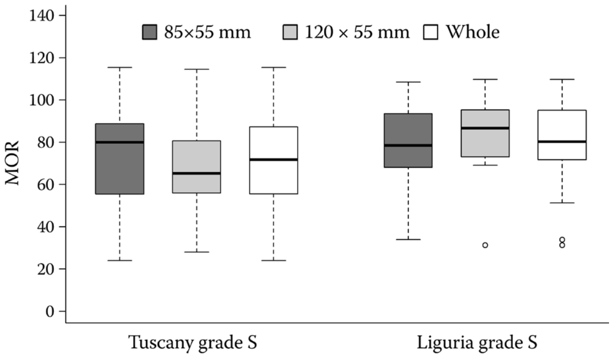


Fig. 2. Boxplot of the modulus of rupture (MOR) of beech samples from Tuscany and Liguria; S – structural

Characteristic values

The characteristic values of the main mechanical and physical properties were calculated in accordance with the procedure given by the European standard EN 384:2010. For each sample, the 5-percentile non-parametric values (calculated by ranking data) of bending strength ($f_{m,\,k}$) and density (ρ_k) as well as the mean value of the local modulus of elasticity parallel to grain ($E_{0,\,mean}$) were determined.

The 5-percentile of bending strength was adjusted to 150 mm depth by the factor k_h (EN 384:2010) given in Eq. 1, also to compare it with the other structural timbers collected in the European standard EN 1912:2012:

$$k_h = (150/h)^{0.2} \quad (1)$$

where:
h – depth of a bending specimen.

The density and the MOE values were also adjusted to 12% moisture content and the local modulus of elasticity was used to calculate the characteristic value of the stiffness – $E_{0,\,mean}$ (Table 4). Then, all the samples are reconsidered together according to EN 384:2010, with the aim to evaluate the actual potentiality in structure for beech in general. The synthetic results of the computation of the characteristic values are reported in Table 5.

Prospective strength class

In order to evaluate the obtained results, the S grade was informally allocated to a strength class, as listed in EN 338:2016. The resulting characteristic values allow reaching the D30 strength class. As described before, this strength class must be considered as a provisional allocation, because of the low number of specimens and because the factor k_s was not applied. At present the only structural beech listed in EN 1912:2012 is the German one, in the respective strength classes D40 and D35 for grades LS13 and LS10 of the national standard DIN 4074-5:2012. Table 5 also shows the values of the beech selected in the Italian grade in comparison with D30 class.

New visual grading parameters for beech timber

Hence, in order to improve the effectiveness of the Italian standard, an adjustment of the grading rule for the beech timber should be studied. To

Table 4. Characteristic values of graded beech timber – S (structural) grade for each provenance and cross size

	Tuscany		Liguria	Whole sample	
	120 × 55 mm	85 × 55 mm	unique sample	120 × 55 mm	85 × 55 mm
N	40	30	36*	55	51
MOR ($f_{m,\,05}$, N·mm^{-2})	34.1	**24.1**	**30.2**	32.9	28.7
MOE ($E_{0,\,mean}$, kN·mm^{-2})	13.3	12.7	13.0	13.3	12.8
Density (ρ_{05}, kg·m^{-3})	637	**598**	**677**	646	642

N – number of specimens, MOR – modulus of rupture, $f_{m,\,05}$ – 5-percentile, MOE – modulus of elasticity, $E_{0,\,mean}$ – mean value of the local modulus of elasticity parallel to grain, ρ_{05} – 5-percentile, *one beam was rejected during the mechanical tests due to the failure mode, in bold – values not to be considered for the number of beams lower than 40 (EN 384:2010)

Table 5. Characteristic values of the beech timber population – S (structural) grade in comparison with the required value for the D30 strength class

	Whole sample	Required values for D30	Closeness to D30 values (%)
MOR ($f_{m, k}$*, N·mm^{-2})	31.0	30	+3.3
MOE ($E_{0, mean}$, kN·mm^{-2})	13.0	11	+18.2
Density (ρ_k, kg·m^{-3})	644	530	+21.5

MOR – modulus of rupture, $f_{m, k}$ – characteristic value of bending strength, *factor for adjusting the characteristic value of the MOR to the size of the sample and to the number of samples (k_s) not applied, MOE – modulus of elasticity, $E_{0, mean}$ – mean value of the local modulus of elasticity parallel to grain, ρ_k – characteristic value of density

evaluate the main visual characteristics that affect the bending strength, the relations between the mechanical properties and the grading parameters were assessed. Therefore, a correlation matrix was carried out between knot ratio, slope of grain, density and MOR. As shown in Table 6 and in Fig. 3, the best correlation was between MOR and knottiness, concerning the smallest cross section. The ring width, which in theory does not affect density in diffuse-porous hardwoods (Bouriaud et al. 2004), was not considered as a classification criterion for beech timber. No correlation between strength and density was found, as reported also by Frühwald and Schickhofer (2004), Frühwald (2008), and Lagaňa and Rohanová (2011). The resulting correlation coefficient for the whole sample between MOR and the values of the slope of grain was not significant. However, excluding the beams where the knot ratio was the reason for failure (51% of the total sample) such a correlation coefficient significantly increased to $R = -0.63$ for the whole sample. Frühwald (2008) described the same trend in her research. Hence, as expected, the slope of grain was one of the main strength relevant defects of the tested timber.

Based on these outcomes, a new visual rule for beech was proposed on the basis of the obtained results and a new grade was added for high-level performances called B1 in the standard UNI 11035:2010. The existing grade was renamed B2. For the B1 grade a new knot ratio limit was proposed with the threshold 0.25, while the existing one for B2 grade (previously S grade) was left to the original value 0.5. Consequently, all the other parameters for the each grade have been upgraded. Table 7 shows the grading criteria and the other parameters.

Characteristic values of B1

All the samples were reconsidered together and the data were reprocessed. A new group was formed, taking into account the modified thresholds for the B1 grade, with the yield reduced to 42%, and the characteristic values recalculated. With the use of such new grading limits the characteristic value of the sample were enhanced. In fact, the B1 group could be allocated to the D40 strength class, as the characteristic value of the modulus of rupture ($f_{m, k}$) was 46.6 N·mm^{-2}. Conversely, there were not enough beams included in the B2 grade to calculate the characteristic values. The allocation to B1 depended only on the $f_{m, k}$ value (Table 8), because the characteristic values of density (ρ_k) and stiffness ($E_{0, mean}$) were nowise limiting factors to D40.

CONCLUSIONS

In order to investigate the potential of the Italian beech timber for load-bearing use and to evaluate the grading efficiency of the standard UNI 11035:2010, the mechanical characterization of two samples of structural beams, previously visually graded according to the strength properties,

Table 6. The values of Pearson's correlation coefficient for the beech from two regions and for the whole sample

Correlation	Tuscany			Liguria			Whole sample
	120 × 55 mm	85 × 55 mm	together	120 × 55 mm	85 × 55 mm	together	
Knot ratio-MOR	–0.61***	–0.80***	–0.71***	–0.53***	–0.65***	–0.62***	–0.70***
Slope of grain-MOR	ns	–0.35**	–0.20**	–0.50**	–0.29**	ns	ns
Density-MOR	ns	ns	ns	ns	ns	ns	ns

MOR – modulus of rupture, ***$P < 0.01$, **$0.01 < P < 0.05$, ns – not significant

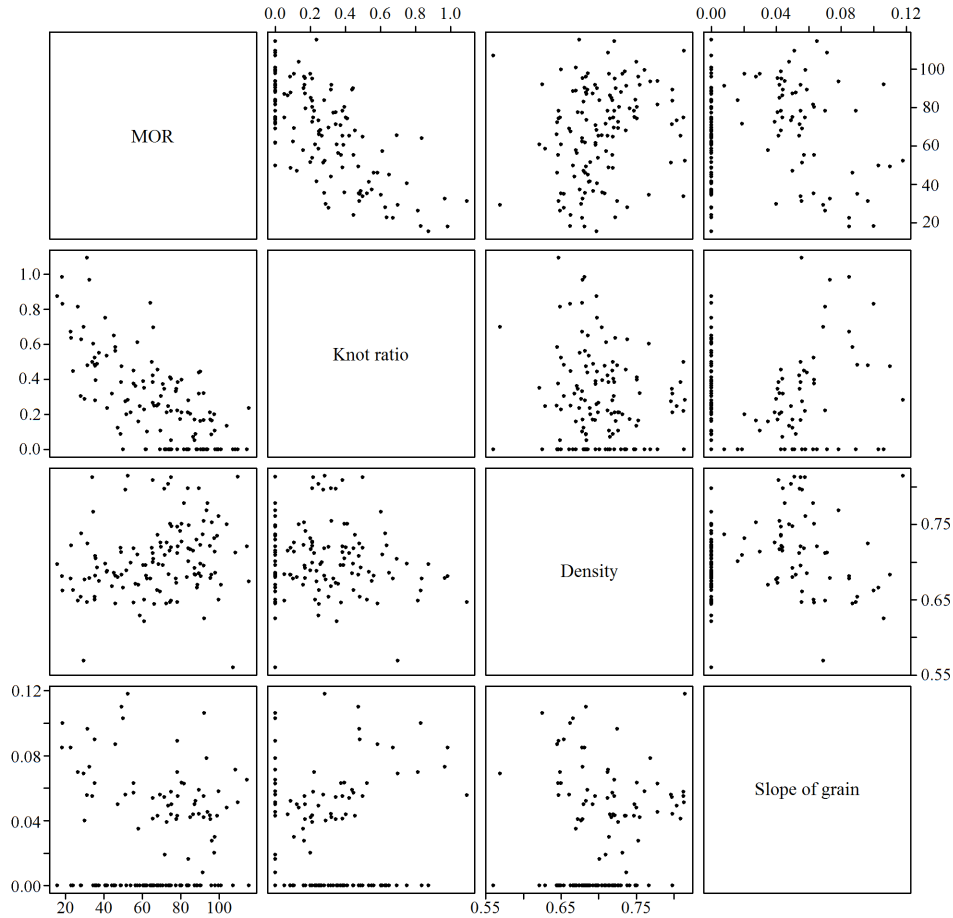


Fig. 3. The scatter plot matrix of correlations between strength and visual grading parameters for the whole sample; MOR – modulus of rupture

was performed. From the obtained results, it can be concluded that:

(*i*) The mechanical properties of beech full-size sawn timber are very interesting from the aspect of structural uses;

(*ii*) With the current Italian grading rule, the beams could theoretically be allocated to the D30 strength class;

(*iii*) Some differences have been found between the sources (37.2% of total rejected beams, 46% from Liguria and 24% from Tuscany), due to the origin of the stands, in transition from coppice to high forest, and to the management (i.e. the intensity and frequency of thinning). Particularly the combined effect involves a high volume of low-quality timber for the irregular shapes of the logs and for the dimension of the knots;

(*iv*) Knots were the visual parameter that mainly influenced both the mechanical properties and the grading results;

Table 7. A proposal of the visual strength grading rule for the Italian beech timber

B1 grade	Wane $s \leq 1/3$, single knot $A \leq 1/4$, $d \leq 40$ mm, $D \leq 150$ mm, density > 590 kg·m^{-3}, slope of grain ≤ 1/10 (10%). Fissures: shrinkage cracks permitted with restrictions*; ring shakes and cracks due to lightning, frost, lesions not permitted. Fungal decay not permitted. Tension wood no restrictions. Insect damage not permitted. Mistletoe not permitted. Warp: bow 10 mm every 2 m of length; spring 8 mm every 2 m of length; twist 1 mm every 25 mm of width on 2 m of length.
B2 grade	Wane $s \leq 1/3$, single knot $A \leq 1/2$, $d \leq 70$ mm, $D \leq 150$ mm, density > 510 kg·m^{-3}, slope of grain ≤ 1/6 (16.5%). Fissures: shrinkage cracks permitted with restrictions*; ring shakes and cracks due to lightning, frost, lesions not permitted. Fungal decay not permitted. Tension wood no restrictions. Insect damage not permitted. Mistletoe not permitted. Warp: bow 15 mm every 2 m of length; spring 12 mm every 2 m of length; twist 2 mm every 25 mm of width on 2 m of length.

s – ratio between the wane projection on a surface and the width of such surface, A – knot ratio, d – minimum diameter of the worst knot, D – maximum diameter of the worst knot, *if going through the thickness, permitted at one end with a length not greater than twice the depth of the piece

Table 8. Characteristic values of the beech timber according to the proposed new rule

	B1 grade	Required values for D40	Closeness to D40 values (%)	B2 grade
N	67			39
MOR ($f_{m,k}$*, N·mm^{-2})	46.6	40	+16.5	**26.3**
MOE ($E_{0, mean}$, kN·mm^{-2})	13.6	13	+4.62	12.0
Density (ρ_k, kg·m^{-3})	625	550	+13.6	**650**

N – number of specimens, MOR – modulus of rupture, $f_{m,k}$ – characteristic value of bending strength, *factor for adjusting the characteristic value of the MOR to the size of the sample and to the number of samples (k_s) not applied, MOE – modulus of elasticity, $E_{0, mean}$ – mean value of the local modulus of elasticity parallel to grain, ρ_k – characteristic value of density, D40 – strength class, in bold – values not to be considered for the number of beams lower than 40 (EN 384:2010)

(*v*) An implementation of the Italian visual grading rule was proposed, adding a new grade for high-level performances of the sawn beams of this species, theoretically reaching the D40 strength class but reducing together the graded sample to 42%.

In conclusion the yields for beams of beech stands seem generally low, because of their origin as coppice, but the structural use can give a valuable contribution to the positive utilization of such kind of forests. The number of tested beams, not large enough to provide definitive results, was adequate for the first assessment of the beech as a structural material. However, in order to actually utilize it, an increase of the number of samples and an extension of the sampling sources are indispensable.

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Corresponding author:

Prof. Marco Togni, Ph.D., University of Florence, School of Agriculture, Department of Agricultural, Food and Forestry Systems (GESAAF), Via San Bonaventura 13, 50145 Florence, Italy; e-mail: marco.togni@unifi.it