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FIRST STRENGTH GRADING, PHYSICAL AND MECHANICAL TESTS ON TURKEY OAK BEAMS FOR STRUCTURAL USE

Marco Togni[1], Alberto Cavalli[2], Daniele Cibecchini[3], Giacomo Goli[4]

ABSTRACT: Many different hardwood species characterize the Italian forests due to the high variability of climates, exposures, altitudes etc. Among all broad-leaves, there are also many oak species, currently not used for structural purposes. New oak beams for structure are typically coming from other countries, because no studies have been yet carried out on structural oak wood, in compliance with the national rules for building construction. In particular, among the other oaks, the Turkey oak (*Quercus cerris* L.) has a significant role in Italian forests, with a potential annual production of around 3'000'000 m³, considering only high forests. The aim of this work is the realization of a first study for the mechanical characterization of this species for structural purposes. A batch of logs has been sampled in the South of Italy and 51 structural beams (cross section 125x45 mm; length 2.6 m) have been sawn. The beams have been visually graded, tested by means of non-destructive methods, characterized through mechanical tests in bending until failure. Then mechanical properties and characteristic values have been determined showing that Turkey oak could be fully addressed to structural use, as it can fit to the Strength Class D40, although this class has to be considered a provisional allocation.

KEYWORDS: *Quercus cerris* L., Structural timber, Visual strength grading, Machine strength grading

1 INTRODUCTION AND AIMS

The Italian Forest and Carbon Sink Inventory [1] confirmed the strong extent of Turkey oak forests, nearly to 1'000'000 ha, and the potential annual production of the related high forests (example in Figure 1) which can be assessed around $3x10^6$ m³. This species has been recently studied in order to try to improve some properties of the material such as homogeneity of the colour, durability and dimensional stability [2-6] and the quality of gluing [7] and finger jointing [8]. The purpose was to give this species higher added value. Other studies have been conducted in the past about the prospects to achieve wood based panel with good performances as l.v.l. (laminated veneer lumber) [9], solid wood panels [10], plywood [11] or generally to add value to the raw material [12]. Nevertheless, despite many efforts on this species, currently there is no data on structural properties of full size timber, neither research studies about structural uses, as solid wood or glulam. The aim of this work is the first evaluation of Turkey oak potential use in construction. For this purpose the current research for the computation of characteristic values has been conducted on one sample of structural size timber, visually graded and machine tested, for physical and mechanical properties. The purpose is also to find the most suitable Strength Class [13] for this wood species. At the same time, the grading efficiency of some visual strength grading rules for other kinds of oak has been tested, to assess the adaptableness on Turkey oak.

Figure 1*: Turkey oak high forest*

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2 MATERIAL AND METHODS

2.1 TURKEY OAK

Turkey oak is a species considered minor against other oaks (European oak - *Q. robur* L. and *Q. petraea* (Matt.) Liebl.) and also in comparison with the groups of American oaks (American red oak – *Q.rubra* Lam. and others, and American white oak – *Q.alba* L. and others). The heartwood is irregular, brown-grey and less durable in comparison to the other oaks (Class 3 - *moderately durable* against Class 2 – *durable* [14]); its heartwood is difficult to be seasoned due to its low permeability, prone to split due to internal growth stresses and with some problem of dimensional stability [15], therefore it does not result enough suitable for the typical use of oaks (e.g. joinery, flooring etc.). As a matter of fact, this species is principally used as simple firewood.

2.2 TIMBER SAMPLING

Turkey oak logs were sampled in the South of Italy, in Basilicata region, inside an old high forest, at 900 m above the sea level, grown in a Northern-East exposure and with 15% of slope. The annual average rainfall is 816 mm, the average minimum temperature of the coldest month is 0.7°C, while the average maximum temperature of the warmest month was 27.8°C. From the sampled logs, a group of 51 beams was formed after the saw-mill operations. The chosen cross section was 125x45 mm for a length of 2.6 m. The beams have been air dried outdoor, covered, for approximately 1 year.

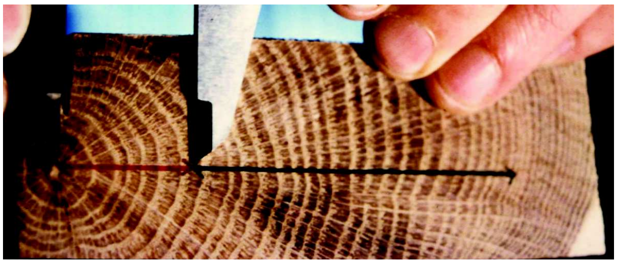

Figure 2*: End grain of one of the beams. Pith, annual growth rings, heartwood and sapwood are well visible*

2.3 VISUAL STRENGTH GRADING

The oak beams have been visually graded by means of Italian grading rule for hardwood, included in UNI 11035-2 [16]. At present, this rule for hardwood has been used on oak species timber only for experimentation. Moreover, we decided to take into account and test different national standards for the visual strength grading of hardwood. Particularly the British Standard BS 5756 [17], rule for European hardwood, and the German Standard DIN 4074-5 [18], rule for oak. The first one has been used also for grading the American red oak and American white oak as resulting in EN 1912 [19] while the second one has been used for European oak [19]. The first and principal distinction between the three grading rules are the number of grades: one grade only for the Italian (Grade S), two grades for the British one (TH1 and TH2, for smaller beams, under 200 cm² end grain area, or less than 100 mm in one dimension) and three grades for the German standard (LS13, LS10 and LS7). Among all the six grades indicated in the three rules, *de facto*, in the EN 1912 only two grades are present for oaks: grade TH1 for BS [17] and LS10 for DIN [18], allocated respectively in Strength Class D50 & D40 (for American oaks) and in Strength Class D30 (for European oak). Other grading criteria, which differ between the rules, are the systems for measuring the knot in relation with the face of the sawn timber and the thresholds for each one. The last criterion to be noted is the presence/absence of boxed heart that, for small cross size section beam, could be considered as another limiting factor: DIN rule for oak does not accept boxed heart on sawn timber with thickness under 100 mm; i.e. the pith must not be present (beam in Figure 2 is rejected), while it is accepted for larger cross section. Other criteria are reported in Table 1.

Table 1: *Principal criteria of the grading rules for the sampled oak timber beams*

	UNI 11035	BS 5756	DIN 4074-5
grades	S	TH1, TH2	LS13, LS10, LS7
knots	Yes	yes	yes
measures	minimum Ø / the face	Ø perpend. / the face	minimum Ø / the face
threshold	1/2	1/4, 3/4	1/6, 2/5, 3/5
slope of grain	yes	yes	yes
threshold *(1/x)*	6.0	10.0, 4.0	14.3, 8.3, 6.3
fissures	no	yes	yes
boxed heart	no	no	yes
wane	yes	yes	yes
deformation	yes	yes	yes
other defects	yes	yes	yes

Currently Turkey oak is not included in any visual strength grading rule of European Countries; in the BS and DIN standards it is not explicitly stated any reference to *Quercus cerris*, as well as in UNI, and it does not appear in the standard EN 1912 [19], where the only oak species are the ones here indicated in section 2.1 (*Quercus robur*, *Q. petraea*, *Q. rubra* and *Q. alba*). The rules described in this research were applied to Turkey oak sawn beams, intended as an extension of use toward not typical oak timbers.

2.4 MACHINE STRENGTH GRADING

Before the mechanical test for elastic and strength characterisation, some non-destructive dynamic tests have been performed. These tests could be considered as a simulation of machine strength grading methods, since similar techniques are typically used in specific grading machines. Dynamic modules of elasticity have been

determined by means of ultrasounds (US – ultrasonic waves transmission) and vibration techniques (flexural free vibrations).
About ultrasound test, a basic ultrasonic device has been used with cylinder-shaped piezoelectric transducers, with 54 kHz operating frequency, using a petroleum jelly grease as acoustic coupler between wood and still. The two transducers were applied on the ends of the beams, and the "time of flight" has been recorded, to calculate the US velocity (v). The datum has been used to calculate the first dynamic modulus of elasticity, using equation n.1

$$E_{us} = v^2 \cdot \rho \qquad (1)$$

where E_{us} is the ultrasonic modulus of elasticity in N/mm², ρ is the density, in kg/m³ and v is the velocity of the ultrasounds in km/sec.

The frequencies of natural free flexural vibration are tightly related to stiffness. The first frequency of vibration of timber beams have been measured through an accelerometer fixed on the centre of the beam. For this test each timber beam was supported at its theoretical nodal points (0.224 of the beam length); the vibration was induced by a hammer impact, then it was collected by a piezoelectric accelerometer whose signal was fed and conditioned by the instrument PCB 480E09, connected to a notebook. The first vibration frequency (fundamental resonance) was determined by FFT analysis using GS Spectrum Analyser Software. Dynamic flexural Modulus of Elasticity (E_f) was calculated using standard equation n. 2

$$E_f = \rho \left(\frac{f_m l^2}{\sqrt{\frac{I}{A}} 3{,}5608} \right)^2 \qquad (2)$$

where E_f is the dynamic flexural modulus of elasticity in N/mm², ρ is the density in kg/m³, f_m is the fundamental vibration frequency in kHz, l is the beam length in m, I is the moment of inertia in mm^4 and A is the cross section area in m².

2.5 MECHANICAL TESTING AND DERIVATION OF CHARACTERISTIC VALUES

The principal mechanical properties of the beams, namely local Modulus of Elasticity (MOE) in bending and bending strength (MOR – Modulus of Rupture) were determined according to the European standard EN 408 [20]. The tests were carried out by means of a universal testing machine (MetroCOM - 200 kN), using linear variable displacement transducers (LVDT) for measuring the deformations during the loading tests.
For each timber element, two small clear woods were cut as close as possible to the point of rupture for the physical characterization. In addition, the strength determining defects and the failure mode were recorded. The density and the moisture content of specimens were determined as indicated by the standards ISO 3131 [21] and EN 13183-1 [22], respectively.
The characteristic values of the bending strength, modulus of elasticity and density were calculated for the beams, selected through the grading rules, according to the European standard EN 384 [23]. 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 a first attempt, needed to set a program on future tests and a suitable extended sampling. Usually the dimension of the sample needed to completely characterize a new species for structural use is ten times bigger, with more than one cross section. So, in reference to the Strength Classes successively assigned, the results have to be considered as a provisional allocation.

3 RESULTS

3.1 A GRADE FOR TURKEY OAK

The yield of the sub-sample of Turkey oak beams, selected in the grade *S – Hardwood* of the Italian grading rule [16], resulted 88.2%. The other rules have given similar results, if considered on the whole (rejected beams excluded): BS 5756, 92.2% for a hypothetical grade TH2 & better, DIN 4074-5, 78.4% for a hypothetical grade LS7 & better. All the results are in Table 2.
Differently, for the presence of two or three grades in the rules, there was a dispersion of the graded beams in each grade. The main ones were TH1 of BS 5756, which included the 3/4 of the beams, and LS13 of DIN 4074-5, which included only the 45% of the beams. Evidently, the low number of beams in each grade depended also on the dimension of the study sample.

Table 2: *Yields for the grades of each strength grading rule*

		n.	%
UNI 11035			
	Grade S	45	88.2
BS 5756			
	Grade TH1	39	76.5
	Grade TH2	8	15.7
	hypothetical grade TH2 & better	47	92.2
DIN 4074-5			
	grade LS13	23	45.1
	grade LS10	14	27.5
	grade LS7	3	5.9
	hypothetical grade LS7 & better	40	78.4

Knots were the main strength determining defect for all the grading rules, as it commonly occurs in structural timber. Moreover some problems of deformation higher than permitted (principally bow) were present, but they were not considered as selecting criterion because this

parameter does not affect the strength properties but it is only a geometrical limiting factor.
Generally all the grading rules resulted appropriate and eligible to be extended to this species.

3.2 MECHANICAL AND PHYSICAL PROPERTIES

Physical and mechanical properties of the 51 structural beams are very high as showed in Table 3. The coefficient of variation resulted high for MOR (28.7%) and rather high for MOE (17.2%). But these values can be considered just typical for the studied mechanical properties.

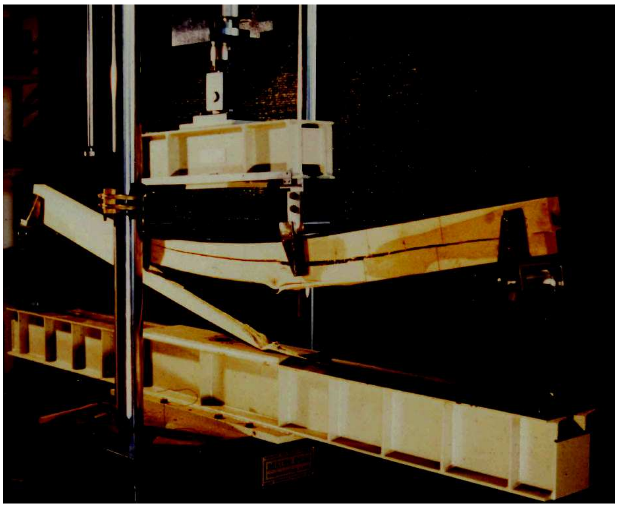

***Figure 3**: Beam n. 42 after the bending strength test. Grades: S-UNI 11035, TH1-BS 5756, LS10-DIN 4074-5. MOR 43.96 N/mm²*

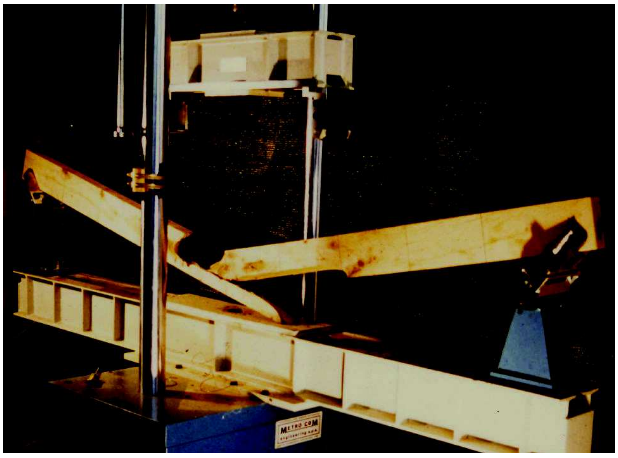

***Figure 4**: Beam n. 35 after the bending strength test. Grades: S-UNI 11035, TH2-BS 5756, rejected by DIN 4074-5 because of the presence of boxed heart. MOR 47.58 N/mm²*

While the C.V. of density was only 4.4% when the typical value for this physical property is 8-10%. The homogeneity of density could be determined by the uniformity of the sampled population, as growth rate and silvicultural management.

***Table 3:** Main physical and mechanical properties*

	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	51	51	51
Average	70.1	14.6	819
Minimum	27.8	7.7	749
Maximum	109.7	19.1	926
Standard deviation	20.0	2.5	36
C.V.	28.7%	17.2%	4.4%

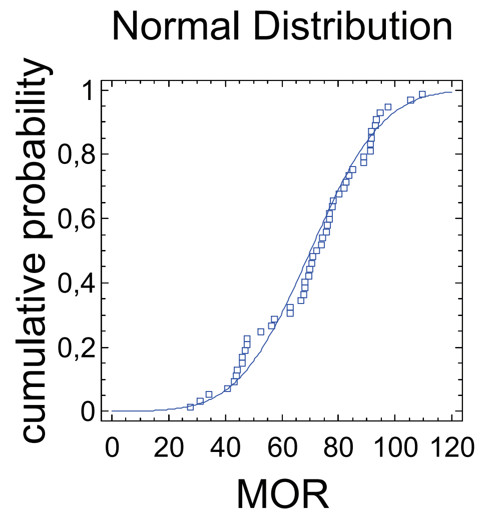

***Figure 5**: Distribution of MOR. Continuous line represents the Normal cumulative probability.*

3.3 CHARACTERISTIC VALUES

45 beams were graded in grade S by means of UNI 11035 and the respective data were used for the calculation of the characteristic values (Table 4). Similarly, the computation of the characteristic values regarded the beams graded with DIN 4074 in three grades and with BS 5756 in two grades. This computation was performed only when the number of beams in the grade was above twenty.

***Table 4:** Characteristic values for the 45 beams in Grade S by UNI 11035. In bold type the characteristic values determining the Strength Class.*

UNI 11035 grade S	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	45	45	45
Average	70.0	**14.7**	779
Minimum	30.2	7.7	713
5-percentile (p.)	-	12.4	-
5-percentile (n.p.)	**40.0**	-	**717**

The 5-percentile of bending strength, derived by means

of non-parametric method (n.p.) was adjusted to 150 mm depth by the factor k_h [23], while MOE and density have been adjusted for the moisture content and the 5-percentile derived according to parametric (p.) and n.p. method, respectively.
The outcomes of the better grade TH1 of BS 5756 (Table 5) resulted close to the grade S. Through the conception of hypothetical grade TH2 & better (Table 6) all the results, including the yields, can be consider very similar.

Table 5: *Characteristic values for the grade TH1 - BS 5756. In bold type the characteristic values determining the Strength Class*

BS 5756 grade TH1	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	39	39	39
Average	77.0	**14.7**	779
Minimum	39.4	7.7	713
5-percentile (p.)	-	12.3	-
5-percentile (n.p.)	**41.5**	-	**716**

Table 6: *Characteristic values for the 47 beams in the hypothetical grade TH2 & better by BS 5756. In bold type the characteristic values determining the Strength Class*

BS 5756 h. gr. TH2&better	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	47	47	47
Average	70.0	**14.6**	780
Minimum	30.2	7.7	713
5-percentile (p.)	-	12.3	-
5-percentile (n.p.)	**40.2**	-	**717**

The outcomes of the better grade LS13 of DIN 4074-5 (Table 7) resulted very interesting for MOR, whose characteristic value grew of 13%; characteristic MOE and density resulted similar to the previous grade.
Again, through the hypothetical grade LS7 & better (Table 8) all the results, including the yields, became very similar to grade S (MOR 39.4 vs 40, density 716 vs 717, the same MOE).

Table 7: *Characteristic values for the grade LS13 - DIN 4074-5. In bold type the characteristic values determining the Strength Class*

DIN 4074-5 grade LS13	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	23	23	23
Average	80.3	**14.7**	775
Minimum	41.7	7.7	716
5-percentile (p.)	-	12.3	-
5-percentile (n.p.)	**45.4**	-	**719**

As indicated in 2.3, the characteristic values of the MOR were not adjusted for the size of the sample and number of samples (coefficient k_s).

Table 8: *Characteristic values for the 40 beams in the hypothetical grade LS7 & better by DIN 4074-5. In bold type the characteristic values determining the Strength Class*

DIN 4074-5 h. gr. LS7&better	MOR N/mm²	MOE kN/mm²	Density kg/m³
Sample size	40	40	40
Average	71.1	**14.8**	779
Minimum	30.2	7.7	713
5-percentile (p.)	-	12.4	-
5-percentile (n.p.)	**39.4**	-	**716**

3.4 PROSPECTIVE STRENGTH CLASS

To check the potentiality of Turkey oak the characteristic values have been used to identify the best fitting Strength Class. As indicated in EN 338 [13] generally a timber population may be assigned to a Strength Class if its characteristic values of bending strength and density equal or exceed the values for that Strength Class, and its characteristic average modulus of elasticity in bending, equals or exceeds 95% of the value for the same strength class.
The results of the different grades and hypothetical grades were very similar (Table 9): the principal Strength Class of allocation was the D40. The limiting factor was always the MOR, while there was a wide safety margin for MOE and density, in relation to that Class.

Table 9: *Strength Class for each grade, with more than 20 graded beams*

Rules and Grades	Sample size	Strength Class	Limiting factor
UNI 11035			
Grade S	45	D40	MOR
BS 5756			
Grade TH1	39	D40	MOR
Hypothetical grade TH2 & better	47	D40	MOR
DIN 4074-5			
Grade LS13	23	D40	MOR
Hypothetical grade LS7 & better	40	D35	MOR

The main differences among the principal grades were the number of graded beams, whose percentage was varying from 45% to 92% of the whole sample. Hypothetical grade LS7 & better did not fit D40 because of a very small gap between the Class and the minimum characteristic bending strength of the grade (grade reached only 39.4 N/mm² on the threshold of 40 N/mm²).

Due to the proximity of the required values for the Strength Class D40, in Table 10 is represented the range of the characteristic values, determining the Class, in relation to the required values.

Table 10: *Characteristic values of Strength Class D40 in comparison with the achieved values for Q. cerris beams*

Strength Class D40	Required values	Achieved	Closeness to required values
MOR N/mm²	40	39.4 ~ 45.4	-2% ~ +14%
MOE kN/mm²	13	14.6 ~ 14.8	+12% ~ +14%
Density kg/m³	550	716 ~ 736	+30% ~ +34%

These outcomes shall not be considered as absolute allocations due to the small number of tested beams and the lack of sample size coefficient (k_s).

3.5 MACHINE STRENGTH GRADING

All dynamic moduli of elasticity resulted with a low correlation coefficient (R) with the physical and mechanical properties as showed in the Table 11, except for relationship with MOE.

Table 11: *Correlation coefficient R matrix*

	MOR	MOE	Density	$E_{v,h}$
MOE	0.227	1		
density	-0.153	-0.123	1	
$E_{v,h}$	0.479	0.703	-0.054	1
$E_{v,b}$	0.403	0.738	-0.122	0.927
E_{us}	0.228	0.649	-0.081	0.796

In particular the density is poorly correlated with MOR, MOE and dynamic moduli, although a kind of self-correlation was expected with E_{us} (dynamic MOE determined by ultrasonic testing) $E_{v,h}$ and $E_{v,b}$ (dynamic MOE determined by flexural vibration testing edgewise [h] and flatwise [b] respectively).

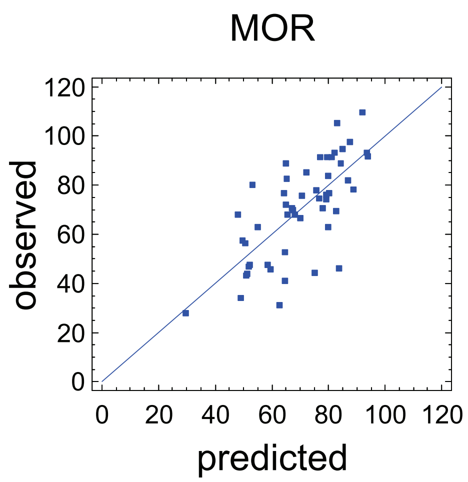

Figure 6: *Multiple regr. anal. R²=51.3% R²-adjusted=49.3%. Predicted_MOR=25.2+ 5.76*10⁻³E$_{v,h}$ - 42.2knottiness Significance level for model and parameters p<0.01 (***)*

On the basis of $E_{v,h}$ it has been possible to obtain an automatic allocation in the Strength Class D40 with the threshold of 9500 N/mm² and a yield of 80.4%, as a simulation of machine strength grading by means of free vibration. For the grade elaboration, the values were not modified by k_v factor (dividing strength by 1.12, as indicated in EN 14081-2 [24]).
The results did not allowed significant improvements in comparison to the visual strength grading. The poor results were because of the weakness of the relationship between parameters and to the low number of specimens.
Some improvements of the results has been obtained by means of a combination between different parameters concerning global quality of the beams and local one. It was carried out looking for an optimal grading system for predicting the bending strength. The coefficient of determination significantly increased when the dynamic modulus was combined with the knot ratio in a multiple regression analysis (Figure 3). The result of this multiple regression analysis was the equation n. 3

$$y = 25.2 + 5.76 \cdot 10^{-3}\, a - 42.2\, b \qquad (3)$$

where y is the predicted MOR, a is the dynamic modulus of elasticity $E_{v,h}$, and b is the knottiness. The adjusted coefficient of determination R^2 is 49.3% (R^2=51.3%) and the significance level for model and parameters is high ($p<0.01$). Comparable results were achieved also with other species [25, 26].
The results of the tentative machine grades are reported in Table 12.

Table 12: *Results achieved by mean of a strength grading machine simulations*

	$E_{v,h}$	Predicted Parametric MOR
Threshold	9.5	50
Sample size	41	47
Percentage	80.4%	92.2%
MOR N/mm²	41.7	40,2
MOE kN/mm²	15.3	14.9
Density kg/m³	719	724
Strength Class	D40	D40

It is well-defined there were not evident enhancements in comparison to the results of visual strength grading, both for the percentages of graded beams and for the characteristic values combination or Strength Class. These first results on Turkey oak, must be implemented with a larger number of beams to test and with additional non destructive testing.

4 CONCLUSIONS

Turkey oak, due to its interesting properties, resulted easy to be allocated in Strength Class D40. The species offers interesting prospects for the structural uses,

considering that, at present, the visual graded timber with best performances in Italy is Douglas fir for softwood, in the Strength Class C30, while the best hardwood is the chestnut in D24. The allocation class D40, although only provisional, was the same of American red oak, in TH1 grade (BS 5756).
These outcomes shall not be considered as absolute allocations because of the small number of tested beams (1 sample, 51 beams) and the lack in the application of sample size factor (coefficient k_s).
The different strength grading rules and selecting parameters conducted to a quite similar yields and final values. Practically, excluding only the rejected beams and without any grade partition, the three standards are comparable for the achieved results.
Generally all the grading rules resulted appropriate and eligible to be extended to this species.
The first tentative of machine strength grading did not give results enough significant. Even if the results do not seem promising, some other investigations are needed. One way could be the test of better performing strength grading machine systems, and check of their adaptability to the species.
In conclusion, to be confirmed and validated, these first results on Turkey oak, must be implemented with a larger number of beams and with additional investigations.
This potential development is also relevant because the species is widespread in the forests of the Italian country. Further studies and samples in other regions are needed to confirm all the achieved values and to open the way for its structural use.

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